Studies in Pest Control for Cultural Property

GOTHENBURG STUDIES IN CONSERVATION 30

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Abstract

This volume considers discrete problems of protecting cultural property from pests and examines some of the solutions. Recent decades have seen a large change in how fumigants and pesticides are used in collections of cultural property. To reduce health hazards and deleterious interactions with materials, alternatives such as thermal treatment and controlled atmosphere fumigation have replaced applied residual chemicals and exposure to reactive gases in many applications. The shift has introduced new risks. Establishing efficacy, considering side effects of unfamiliar control applications, and how to construct systemic programs to reduce the risk of pest damage across a wide range of conditions are common challenges to the decision process. The papers included in this volume were written to introduce sufficient data, or discuss complicating factors in a way which would address key concerns and enable collections care professionals to have greater confidence in their decisions.

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To my parents Beryl and Ken,
for a childhood
with books, tools, and nature.

List of papers

1

Strang T.J.K. 1992. A review of published temperatures for the control of pest insects in museums. Collection Forum, 8(2), pp. 41–67.

2

Strang, Thomas J.K. The effect of thermal methods of pest control on museum collections. pp. 199–212 in *3rd International Conference on Biodeterioration of Cultural Property, 4–7 July, 1995, Bangkok, Thailand: Preprints.* Bangkok: Organizing Committee of ICBCP–3, 1995.

3

Strang, T.J.K. Sensitivity of seeds in herbarium collections to storage conditions, and implications for thermal insect pest control methods. Chapter 4, pp. 81–102 in *Managing the Modern Herbarium, An Interdisciplinary Approach.* Ed. D.A. Metsger and S.C. Byers. Elton-Wolf, 1999, Vancouver. 384 pp. ISBN 0–9635476–2–3

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Strang, T.J.K. Principles of heat disinfestation. Chapter 18, pp. 114–129 in *Integrated Pest Management for Collections. Proceedings of 2001 A pest odyssey.* Edited by H. Kingsley, D. Pinniger, A. Xavier-Rowe, P. Winsor. James & James, 2001, London. 150 pp. ISBN 1 902916–27–1

5

Strang, T.J.K. and Kigawa, R. 2006. Levels of IPM control: Matching conditions to performance and effort. Collection Forum, 21(1–2):96–116.

6

Strang, T.J.K and Grattan, D. 2009. Temperature and humidity considerations for the preservation of organic collections — the isoperm revisited. e-Preservation Science, 6:122–128. E-ISSN 1581 9280

7

Kigawa, R., Strang T., Hayakawa, N., Yoshida, N., Kimura, H. and Young, G. 2011. Investigation into effects of fumigants on proteinaceous components of museum objects (muscle, animal glue and silk) in comparison with other non-chemical pest eradicating measures. Studies in Conservation, 56(191–215).

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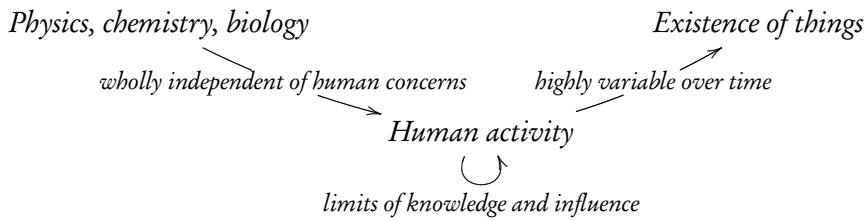
Foreword

"What do you think-a make-a-this
painting disappear huh? Moths!
Moths eat it! Left handed moths!"

Chico Marx as Ravelli in 'Animal Crackers', Paramount Pictures 1930

The process of protecting cultural property is a necessary mixture drawing from two pools. The first supplies the inherent material properties of objects expressed over time and the frequency, duration and magnitude of natural forces which deleteriously affect material culture. The second is a filtering gloss of human supplied elements: definition of and societal expectations for culture; the passing or uptake of responsibility through time; activities governed by developing professional ethical concerns and technical ability, serendipity and will.



The act of protecting cultural property and in fact all our goods from pests has often used crude tools. Crude in the sense of pervasive treatments, or indirect in terminating the root cause of harm.

Have ants ⟶ *Spray patio stones*

The propensity of available responses to affect more than just the pest entrains concerns from both biological and material sciences. To effectively contribute to pest control for cultural property one must work to formulate a 'most good with least harm' action.

The contents of this volume contain works undertaken over a period of two decades to resolve both academic conflicts rising from the state of knowledge and applied concerns stemming from a need to control of pests in cultural materials. They are works undertaken to find this balance between possible good and possible harm.

This thesis is arranged in two parts. Chapters one to four were developed for this volume to show pest and consequent material risks through examining documented historical developments within the museological discipline and from the enveloping field of stored product protection. The chapters discuss: Change in use of fumigants and pesticides which affected museum practices and concerns which spurred adoption of alternative methods and a systematic approach to pest management; Demographic concerns in insect populations and how pest models are constructed for prediction of harm and application of control tied to retaining desired values; Historical challenges reflecting modern approaches to retention of key values while risking losses in treatment; Mould and insect environmental limits and their implications for prevention, reduction of harm and full control.

Those who are charged with caring for cultural property are often neither intimate with this background matter (differing education), nor necessarily practised in various ways of thinking about it and interpreting the risks. These chapters are thus designed to help the reader understand the tiny foes of collections in terms which can convey both

tenacity and limits, and explain possible outcomes of actions. This author considers the presented material fundamental to developing expert guidance in decision making for preventing and eliminating pest harms, and even for understanding why our desired outcomes may occasionally fail despite having been 'right' in our choices.

The second part begins with chapters five and six which are preambles to introduce the seven attached previously published works from reviewed journals and reviewed book chapters. These papers address problems in the responses made to finding pests and in developing a systematic discipline of integrated pest management for cultural property. The majority of the papers present novel collations of information to guide decision making for reducing both pest activity and attendant harms and risks to material culture. Where information was lacking or needed supplement, laboratory studies were undertaken to explore the potential of hazard to materials found in museum collections by pest countering treatments.

Cartesian plots are used frequently throughout this text and the attached papers to reveal trends, extents, and maximum variability gleaned from numerous independently published sources of data. By including much of the archived responses from experiments spread over a century of human scientific effort this author has educated first himself and then others to the landscape of risk / reward presented within the axes. These graphs will often require methodical viewing and the accompanying texts point to relevant detail. Logarithm plots are used frequently to visually compress the responses which spread over many orders of magnitude, so care in their reading is needed. The graph axes are commonly temperature, moisture and time, the three most emphasized natural properties within the material culture preservation community.

Epigraphs for each chapter have been carefully chosen for their ability to compress a realm of topical introspection into a simple essence.

1 Introduction

> Some primal termite knocked on wood;
> And tasted it, and found it good.
> And that is why your Cousin May
> Fell through the parlor floor today.
>
> Ogden Nash (1902—1971) [1]

Museums harbour pests that time forgot. Early on, I approached a large entomology collection to ask them if they might spare a couple clothes moth specimens for my nascent didactic collection. The entomologist I talked with replied, "We only have twelve specimens, they are practically extinct." He wasn't being entirely serious, except about the number they held which reflected their declined importance in modern society. Several months later my problem was solved when I was called to a museum rampant with webbing clothes moth.

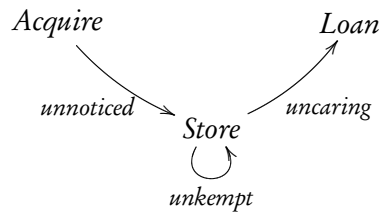
This juxtaposition of events strongly illustrated the situation facing those who care for cultural property. Through the nature of their operations and holdings, museums can become refugia for stored product pests which eat the materials of yester-year's industry, and without precaution loans can echo the commercial vectors which distributed the same pests worldwide. From the volume of extant publications and investment in controls, household, commodity and even structural pests are of less concern compared to those affecting agricultural production and human health. While this is a fully understandable

ratio, it must be recognized as it has a negative effect on the relative fullness of knowledge we can call on to counter collection pests. Our closest allies are the agricultural stored product pest researchers.

Shifts in focus of biological research have curtailed study of life cycle ecology of whole organisms that had among the greater body of work generated the relatively few papers on pests we find harming cultural items. Any exceptions to this are those pests which remain important to predominantly agricultural or human health concern. On top of this the late 1900's saw increasing restriction of fumigants that had been in common use in museums, and direct use of pesticides on cultural property become less desirable under conservation ethical concerns and for workplace safety reasons. As an end result, effort to combat the problem of pests in collections had to come mainly from the community closest to the problem.

Communication with Canadian federal regulators involved in the review of fumigant labels in the late 1980's, particularly on ethylene oxide which had been the dominant fumigant in Canadian museums and archives quickly led the author to the conclusion that museums needed to establish alternative methods that would give them independence from coming changes and uncertainty about future access to fumigants and their use on cultural property.

The simplest worst case scenario for pests within collections is:



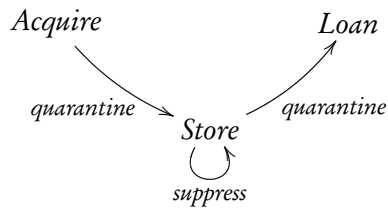
To a collection manager, discovery of a possible pest in collections opens up a number of troubling questions: How many more pests are in the space? Which objects are now in danger of disfigurement or

loss? Where are the pests distributed? What was the chain of probable cause? What can I do?

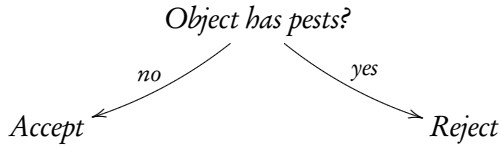
Newly acquired or loaned objects often have the highest perceived risk of infestation. This would hold true when prior pest control activities in the receiving collection have reduced pest findings below the frequency of bringing in new ones. The suspicion is an incoming object's prior environment has worse pest control than its future environment we already know and are doing something about. Worst case, the object contains a novel destructive species.

> "It is the unknown things that you cannot find that we have to protect this country from."
>
> C.L. Marlatt, 1919 [2]

A managed scenario for pests within museums is:



The uncertainty around seeding one's collection with new pests warrants attention to items before integration with the main collection. Quarantine involves inspection and suppression, so for incoming and outgoing items quarantine substitutes all the uncertainties of detection and control methods for the raw probability of pests on the incoming objects. The simplest method to avoid pest hazard was voiced by Leechman [3] in 1929: "Shipping infected material to a museum is so dangerous a proceeding that it would almost be better to do without the specimen." This bespeaks of large uncertainty around control of pests at the point of entry.



As most institutions look to acquire objects irrespective of pests, they rely on the likelihood of a successful quarantine treatment to let them acquire objects with low risk to the collection. This is asymmetric risk as the determination of "no infestation" is not without error, especially in the case of borers or very tortuous surfaces, while rejection of the object is a sure bet to avoid subsequent infestation from that source. Treatment of an object wrongly suspected to harbour pests does not affect pest risk.

$$P_{\textit{object infested}} \times P_{\textit{quarantine fails}} = P_{\textit{object as infestation source}}$$

To further lower the probability of infiltration of pests a response is to choose to treat all incoming objects and suspect display materials (prophylaxis). This can greatly increase the annual volume to be treated and scheduling discussion, yet still applies the same probability of treatment failure to more items, widens risk of unwanted treatment side effects if there is greater variety in objects and maximizes the risk of 'end runs' around the quarantine process in times of pressing need, for example late delivery before an exhibit deadline, or by less convinced staff who see the quarantine as a hindrance to the flow of 'their' items.

Again, from Leechman [3]: "Specimens infected, or suspected of being infected, with cloths moths, or other insect pests, should be sprayed or drenched with gasoline and then dried in the open air." To the modern ear this sounds gravely injurious and likely to contravene current regulations. However, it should just calmly raise the same questions about efficacy and effect as any other chemical proposal. Sprays of

this nature were actively studied at the time against agricultural pests such as scale insects. It was notably part of a suite of methods recommended for clothes moth control by Back in his U.S.D.A. publication from 1923 [4] to which Leechman no doubt had access. In Back's recommendation gasoline was only for cautious treatment of building cracks and crevices along with permanent sealing of the harbourages. Leechman clearly extends the 'use pattern' in looking for a treatment.

Prophylactic pest treatment in quarantine is stringently used when collections are within an enclosing structure with open shelf storage which makes the assemblage highly vulnerable (material, size, exposure). As an example, a strong sterilant (ethylene oxide) is chosen for items acquired overseas and any follow on treatments are restricted to controlled atmosphere or thermal treatments at the exhibition and research facility of the National Museum of Ethnology, Japan (N. Sonoda, pers. comm.). Another example, the mandatory running of all acquisitions and specimen transfers through a $-30\ ^{\circ}C$ freezer before integrating into the Natural History Museum, England off-site storage for full display mounts of large mammals and cetacean skeleton collection (D. Pinniger and R. Sabin, pers. comm.).

These decisions are readily understandable as there commonly exists an imbalance in effort to treat incoming objects versus the greater effort to treat a collection store. Storage requires a structure which is itself prone to housing both pest and non-pest even without the collection, will have porosity connecting through to the exterior environment which supports candidate pest organisms and its own intrinsic decay which must be combatted by maintenance.

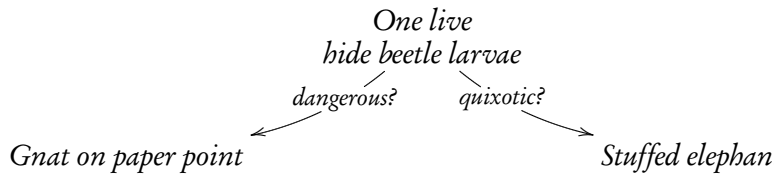
Storage furniture provides support and organization to the interior space but every cabinet can be a shield against or protector of pests inside the building. Shelving often hides half of the floor from view or isolates walls, drains become islands of pests associating with high moisture and sparingly visited attics and crawl spaces easily harbour pest sources primed by structural gaps.

Evaluating display and storage structure's for pest prevention capability and determining pest sources (incoming objects, staff activities,

building porosity, exterior environment, etc.) can possibly explain persistent numbers of pests found around a collection. Whereas, a facultative response is to muse about accepting a threshold of 'tolerated' pests at which remedial actions should be triggered, refined to relative hazard by species and general susceptibilities by location, rather than enforcing a 'zero tolerance' policy which imposes demands at every least sighting [5]. Other industries have some form of this problem solved by tracking trends and applying 'acceptable daily limit' or 'threshold' values.

Given the purpose of preserving material culture, opting for a response every time is arguably ethical (maximizes on-paper safety from pests) and even likely to do some good. The difficult question that arises when pests show up in the collection is how many times and to what extent can one afford to respond to a pest finding and still carry out the other necessary work.

The key to untangling this requires understanding something of the life cycle and ecology of the organisms, to describe the hazards posed proportional to numbers of pests, and the sensitivity of the collections where sensitivity is not only the ability to be chewed, but also the relative size which affects the rapidity of loss when no-one is looking.



An entomology collection with type specimens in the scale of an evening meal for a dermestid larvae might have zero tolerance finding a larvae in a case and treat the cabinet contents straight away. A natural history mammal specimen range might tolerate finding an adult dermestid in the aisles in a month yet none in the adjacent cases, but would it tolerate five, or fifty? The positing of a 'transfer function' between room and case examines the threshold of tolerance, largely

hinging on porosity of the cabinet seams and seals and musings about 'open time', individual's work habits and the building's failings.

Recognition of a minimal numbers of pests as tolerable invokes some form of management (housekeeping) and implicit cost balancing. A countering argument against tolerance comes from recognition that any pest especially a parthenogenic insect like the herbarium pest *Reesa vespulae* (Milliron), has great capacity for growth in numbers, and surmise that in an undefended collection it would run amok until the stored materials are consumed. Responding will be a constant "stitch in time saves nine" economic decision, in effect an annually incurred maintenance cost.

The key to slowing losses thus depends wholly on effective inspection with frequent enough extent of access to prevent the cryptic development of pests, tolerated or not.

Damage, deterioration, and degradation are qualitative terms to describe the negative effects of both pest and pest treatment. Ethically we should not harm the object further in the course of eliminating the damaging pest. The interesting tussle is when decisions request acceptance of some partial, minor or envisioned harm from the treatment in order to probably stop the pest.

$$P_{tf} + P_{th} - P_{tf}P_{th} = P_{tf} \cup P_{th} = P_{\textit{object deterioration}}$$

In simple terms, P_{tf} is probability of treatment failure, P_{th} is probability of treatment harm. Properties probably harmed equivalently by both pest and treatment $P_{tf}P_{th}$ are not counted twice (for example, mint condition ruined by either pest or pest treatment).

Problems in judgement of present object 'values' and forecasting future values become inhibitions to actions when undesired effects of a treatment are unknown, or suspected yet unproven (high uncertainty embedded in all elements in the decision). Disconcertingly to conservation a negative change can even be argued as a positive, say considering increased cross linking as a stabilizing 'tannage', an in-distinction

which would blur the terms 'pest treatment' and 'conservation treatment'. Consider heating paintings for wax infusion or infrared lamps for disassembling of recalcitrant glue joints in musical instruments. These treatments subject objects to greater heat than required for disinfestation. The ultimate decision is balanced against the expected recovery of positive 'values': flatter and supported, soundly reconstructed, no longer infested.

In preserving collections there is also a potential for conflicting actions through the use of a cheap unsustainable activity to protect a valuable resource when under budgetary pressure. An example of this was to use a known ozone depleting fumigant between 1992 to 2005[1] to protect irreplaceable timber objects (temple, church iconistas, etc.). The incremental cost to the planetary environment by your one use might be relatively small compared to total application of the gas both past and current, but the moral cost is not reduced, we 'know' it is still a harmful cumulative action and ethically unsustainable. Situations like these spawn either early adoption of alternatives or brinkmanship right to the finish line.

We tend to trust our eyes because material evidence can be quite clear: something is being eaten, it looks worse than last year, it is now falling apart even if the cause is not readily visible. However, in practice even simple sounding judgements quickly become less certain:

	No pest damage	**Pest damage!**
No pest	*Have I missed something?*	*Is this old damage?*
Pest!	*Is this a new infestation?*	*I must treat this now!*

Finding clear sign of pest but no evident harm generally leads to a treatment. The other mixed signal, finding harm but no pest evident, evokes the thought 'maybe it is old damage' and seems for people to

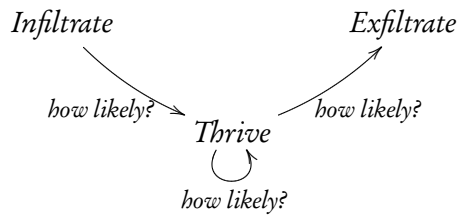
[1] MeBr was slated for cessation by 2004/5 in many countries and 2015 worldwide from its inscription onto the list of controlled substances [6]. See chapter 5.

be the most difficult situation of the four to resolve unless other evidence supports the conclusion (oxidized wood in exit holes, bagged quarantine for months with no activity, etc.).

Ambiguous situations evoke thoughts about whether or not to incur pest treatment, a possible unnecessary expenditure of time, money, and physical resources. Reduction of ambiguity by thorough visual examination, isolation and waiting for signs, whole collection survey, statistical sampling or mapping incidents are responses looking to confirm or deny worries about the least certain issues affecting collection loss.

Questioning the likelihood of a pest problem lends itself to a Bayesian application of probability, testing the uncertainty of our knowledge about states. But for most practical people, we cannot push off the hard question: "Should I act or not?". In the main, the papers included in this volume were undertaken to question assumptions, assist decisions, reduce barriers to action, and help organize coherent response to pests.

The probabilistic approach to collection harm by pests is most simply characterized by the following states:



Irrespective of whether they are fully measurable as likelihoods, these states are what a full IPM program would be addressing in the course of its application of sanitation, barriers, observation and remediation.

Beyond 'how many pests warrant a response', improving or sustaining pest control may meet the the following question: "Why continue applying these [list] efforts if things are 'under control?", or restated, "Why spend resources when nothing is happening?". The countering

argument is simple: "Then why not remove these costly fire detectors, extinguishers and door locks until you need them".

Running from things that ain't chasing us

We must not be in a constant state of high alarm about pests in our collections. There are competing priorities for our attention and labour which more properly justify the collection's existence. However we do need to find the balance so the collection is not unduly reduced in values which support its purposes.

There is no problem in principle with scaling back efforts as an outbreak is measurably reduced. There is a problem from imagining no continuing effort need be expended once the final clean up is done. Proper investment in the lull protects us from crisis. This is why Hartnack [7] championed the word 'fight' rather than words which evoked closure that was not likely to exist given the natures of pest and people. Integrated pest management (IPM) navigates these continual uncertainties of outbreaks by pairing response to detection, and accomplishing reduction of sources through commensurate avoiding and blocking actions [8]. An approach to this problem of distributing pest control efforts across the spectrum of cultural property's exposure to pest hazards is presented in paper five.

As thought experiments, the exploration of pest risk can be an informative pursuit for reducing significant hazards when combined with experience of occurrences, supplementary investigation, a practised choice of action and subsequent observation of results. Without some measure of effectiveness of components of the defence against pests and solid appreciation of hazards posed the uncertainty remains large and even imagination of consequence is of little applied value, where possible and probable are confounded as eloquently captured in the following tale:

> One day there was a traveller in the woods in California, in the dry season, when the Trades were blowing strong. He had ridden a long way, and he was tired and hungry, and dismounted from his horse to smoke a pipe.

But when he felt in his pocket he found but two matches. He struck the first, and it would not light.

"Here is a pretty state of things!" said the traveller. "Dying for a smoke; only one match left: and that certain to miss fire! was there ever a creature so unfortunate? And yet," thought the traveller, "suppose I light this match, and smoke my pipe, and shake out the dottle here in the grass — the grass might catch on fire, for it is dry like tinder; and while I snatch out the flames in front, they might evade and run behind me, and seize upon yon bush of poison oak; before I could reach it, that would have blazed up; over the bush I see a pine tree hung with moss; that too would fly in fire upon the instant to its topmost bough; and the flame of that long torch — how would the trade wind take and brandish that through the inflammable forest! I hear this dell roar in a moment with the joint voice of wind and fire, I see myself gallop for my soul, and the flying conflagration chase and out-flank me through the hills; I see this pleasant forest burn for days, and the cattle roasted, and the springs dried up, and the farmer ruined, and his children cast upon the world. What a world hangs upon this moment!" With that he struck the match, and it missed fire.

"Thank God!" said the traveller, and put his pipe in his pocket.

The Two Matches, from 'Fables' by R.L. Stevenson (1850–1894)
Quoted in Blyth [9]

2 Reflecting reality through pest models

A butterfly
Asleep, perched upon
The temple bell.

Yosa Buson (1716—1783),
Blyth [9]

Models are built to mimic systems in a way that allows the application of causative logic with which we can apply tests and challenge with data. Models guide research, 'theoretical' in the sense of testing a thesis against actual outcome. Models are also described to illustrate concisely how people and systems are operating to allow positing of interesting alternatives. These models can expose the consequences of major decisions (ban on a fumigant) or instruct newcomers in a discipline (what to do and when). Day to day activities in any endeavour result from some model of intended outcome.

People prepared to manage closer to 'crises' than 'proactive' may reject any modelling for just doing, but that decision in itself is a model. They have rejected the 'development cost' of modelling as too high and are satisfied with events happening irregardless of whether a model could predict beforehand or guide moderation of the consequence.

Undertaking modelling there is an expectation that reasonable coverage of factors gives us guidance toward an effective decision and favourable result. Consciously or not, some degree of *ceteris paribus*[1] is invoked to dispense with discounted or insufferable complexity. The construction of simple models is not naive, it is almost prerequisite to more effectively achieving complicated ventures; it is inappropriate application of simple models beyond founding assumptions that becomes perilous.

To confer 'reality' models include the up- and downside of events, the factors that produce and reduce a desired result, and unintended consequences are explored for notable debilitation or improvement of outcome. When projection to a future date is desirable and seems possible mathematics are applied (algebra, calculus), when probabilities are assignable (statistics) then risks are estimated[2], and when conflict is involved game theory strategies are developed. With sufficient coverage of a problem 'expert systems' are a goal for 'client service', built to incorporate verified models into decision support tools for audiences who will not want to manage the underlying data or mathematics directly in order to assist in how they work.

The application of modelling in population ecology and stored product pests has been a formative and informative one in biology spanning over a century of effort [11] [12] [13] and it has been contentious throughout it's history [14] [11] [15] [16]. Within the stored product context Longstaff [12] briefly reviewed the history of model types re-stating Levins' qualification on modelling that one can best hope to achieve two out of "general, realistic, and precise":

[1] All other conditions staying the same.

[2] Formal discussion on the means by which risks are expressed can be found in many sources. This author referred to the Standards Australia and Standards New Zealand Handbook [10].

General–Realistic	Graphical, maps, qualitative, trends
General–Precise	Simple, analytical models, 'classical' equations (exponential, logistic, Lotka-Volterra)
Realistic–Precise	Very specific, highly detailed

The exact phrase Levins [17] used was "sacrifice" one for the other two. These are not exclusive rules on orthogonal principles, they are linguistic indicators of the efforts needed to model a workable solution to a problem. In 1966, Levins was struggling with how to simplify 100 simultaneous partial differential equations, 100's of parameters, and cope with time lags in modelling ecologies, and thus had to find a way to progress. Two decades later Onstad [15] could take Levins to task stating the advent of computational power eliminated 'simplification'[3] as a trump. Mertz [18], who modelled stored product pests, viewed Levins' three states more as progressions in desirability or inevitability towards realistic–precise outcomes.

However, an invested cost of producing a realistic–precise model for *Tineola bisselliella* demographics does not help those people with *Necrobia rufipes* or *Dermestes scrophularia* infestations. A general–realistic model for collection pest incidence and resulting harms can both educate many practitioners in IPM and direct which organisms to study in more depth.

Onstad [15] saw precision as degree of refinement, realism as incorporating maximum knowledge, and generality as "applicable to many situations" defining true generality as having to be realistic. "*Mathematical models* concisely and explicitly express the assumptions within the hypothesis or theory." [15]

Caswell saw models and theory as non-equivalent, with mathematical models as an essential scaffold for inquisition of real processes, and supplanting is expected. "In the long run, however, the incorporation

[3]Sciences' seeming adherence to Occam's Razor where the simplest explanation is avowedly the best, or as Onstad quotes Bradley: mathematician's "spurious elegance in the analysis of messy and incompletely comprehended reality".

of mathematical models usually improves the quality of ecological theory." [16]
It is Levins' concluding remarks that were not widely quoted:

> "A mathematical model is neither a hypothesis nor a theory. Unlike the scientific hypothesis, a model is not verifiable directly by experiment. For all models are both true and false. Almost any plausible proposed relation among aspects of nature is likely to be true in the sense that it occurs (although rarely and slightly). Yet all models leave out a lot and are in that sense false, incomplete, inadequate. The validation of a model is not that it is "true" but that it generates good testable hypotheses relevant to important problems." [17]

Putting the problem simply in model terms, the forward challenge to preserving from pests of any stored product is:
AVOID, BLOCK Improve or maintain quality of passive systems which reduce harm.
DETECT, RESPOND Effective discovery and treatment for pests.
To whit the end point of minimizing efforts and costs is a form of abandonment of the object[4], but only one form rests in some safety.

Confident abandonment
Sustainable care
Lavish care
Disruptive crises
Desolate abandonment

The field of stored product protection started with mammalogists, microbiologists and entomologists classifying and studying the lives of agricultural pests. Early approaches to pest reduction were systematized farm based practices which are forms of environmental control

[4]One is not always watching the object.

(tillage, drying, turning, cooling, airing). With this, economic pressure has been traditionally responded to by publication of best practice and systematic instructionals on control methods and standards around food safety (storing milk, preserving root vegetables etc.).

Applying ecology research in the early 1900's on predator-prey control through parasitic insects required the modelling of populations and factors that affected them. This proved more complex than first seemed from earlier work on human and animal population growth which incorporated pioneering application of and limits for the use of exponential (Malthus) and logistic (Verhulst, Pearl) curves [11].

Full ecologies are arguably much more complex than laboratory cultures or single organism infestations. In ecological modelling Hall states there was a significant amount of wish fulfilment to find convenient mathematical descriptions for problems, and poor substantiation of the models in the data [19].

Hall puts forward "three rarely stated but fundamental questions" in his critique: "to what degree is it possible to extract the essence of a problem in few rather than many (or even very many) equations"; "to what degree do the solution of those equations by mathematical means give you additional insights into the operations of real ecosystems and / or their components"; and "what is the relative importance of biotic vs. abiotic factors in determining the basic properties of species and of ecosystems, and their dynamics over time." [19]

These can be turned around as imperatives for any employed mathematics:

Encode maximum description of variation.

Expose non-trivial outcomes.

Integrate physical factors with measure of living systems.

Systematic work in natural control efforts were supplanted by widespread turning to chemical controls which operated successfully on simpler efficacy and economic models (dose response, timing response, production cost, delivery cost, application cost) and relied less on unpredictable conditions in the environment (daily weather).

In the 1980's and 90's models for control of stored product pests became an emphasized subject in major centres of stored product research. These organizations had been subject to reductions in their historic research and education capabilities yet the need to assist producers with sound economic decisions within a more complex market environment had increased [20]. The promise of cheap computing power in this period enabled calculation based developments to be considered for everyday use by their audience.

The results of these later modelling efforts are informative for considering similar work in collections care, but not necessarily in terms of 'success' or 'failure' as each form of model development either met its particular requirement or spawned the next approach. There is also a body of criticism that has to be considered as the long experience and investment in protecting food and health have had their share of simplistic or misapplied approaches which had to work their way through the disciplines. At the very least demonstrating that modelling populations is a difficult challenge in of itself, let alone predicting perturbations [19] [11].

This chapter reviews some of the work on stored product pest models for the purpose of discussing the relevant factors, modelling strategies that may be possible, and particulars of the data required to improve understanding of pest risk to cultural property. Review of the literature gives the following themes and while they are discrete in definition, determining risk and making a decision can require them to be combined.

Pest distribution models

What are the large geographic distributions which govern local likelihoods (can you have termites), and consequence of foreseeable range extension (will you have termites around).

Population growth models

What are the potentials for increase of pest populations once introduced (virulence). What are the potentials for moderation and decline?

Cultural property harm models
What are the potentials for harm from pest activity exploiting material vulnerabilities and changing attendant values associated with the objects (damage, deterioration, degradation).

IPM decision models
What are the appropriate activities and static features that combat pests which relate to the supported endeavour (fur collections, grain silos, dried pork).

Continuous reduction models
What are the proportional reductions of pests through IPM activities (minimizing attractors, sanitation). These are useful to combat pests as they are essentially continuous in effect such as the relationship between habitable temperature and insect development rate.

Discrete threshold models
What are the necessary conditions for effective treatment (efficacy). Are there sharp constraints on pests which can be used to prevent harm. Are there definable levels of intolerance of damage and presence of pests in collections to trigger response. Any hazard which has discrete states can be approached in this manner, the notable one with pests being: alive or dead.

Risk from pests is provided globally

Individual pest risk is geographically non-uniform, however there are essentially no localities on earth free of some risk to cultural property given the pervasiveness of microbial, insect, and mammalian life.

Pests of stored products have promoted themselves locally with the human magnification and aggregation of common foodstuffs (stored product pests). Restrictions imposed by geographic barriers (mountain ranges, oceans) have been broken by historical and current lines of trade (invasive species). Continental quarantine activity against these re-distributions still hold pests back, but largely for pests identified currently as having potential for economic harm. These quarantine operations are also probabilistic in nature and often filter by likelihood of pest transport in certain material goods. However it is cer-

tain that museums have been complicit in moving species of collection pests into novel regions [21] and domestic species have been seen to change with time through regional introduction, augmentations to domestic habitat that favour their cryptic development such as the rise in abandoned fireplace chimneys, and exploitation of other displaced pest's habitat. Dermestids surmounted moths as fibre pests over the last 50 years [22] and now moth findings have seen a resurgence in English museums (D. Pinniger pers. comm.).

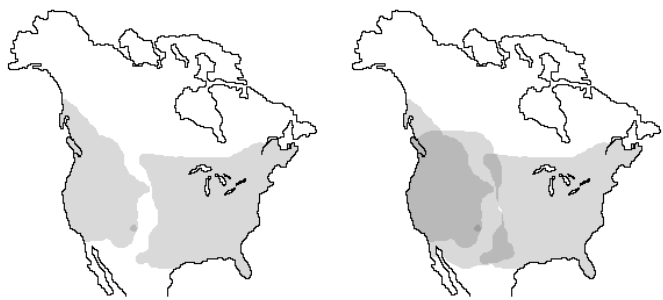


Figure 2.1: Left: Range of *C. modoc* and *C. pennsylvanicus* with wide separation and localized introduction of *C. pennsylvanicus* in the range of *C. modoc*. Right: Overlapping range of *C. vicinus* which chooses warmer and dryer habitats than *C. modoc*. Range data from Hansen and Klotz [23].

An example with range maps

Pest species proposing equivalent harms can be found in adjacent regions. Figure 2.1-left shows ranges for *C. modoc* and *C. pennsylvanicus* the two most damaging carpenter ants in western and eastern North America. Carpenter ants nest in rotten wood or nearby earth burrows and sometimes cutting into living trees. Before discussing them as a problematic insect, the positive benefits from carpenter ants are they improve forest health as predators on severe defoliating insects, support colony 'guest arthropods', and themselves are common food for birds, especially woodpeckers [23].

The problem for cultural property is some species will nest in structures using convenient voids as they do with hollows in trees. A smaller number excavate solid wood causing structural harm to buildings [23]. Niche filling by multiple species creates a more uniform distribution of the threat to materials irrespective of one damaging species' boundary. Small fragmented ranges show localized introduction, relic populations or discontinuous habitats. Figure 2.1-left shows a small population of *C. pennsylvanicus* in montane forest cover north of Santa Fe overlapping the range for *C. modoc*, possibly through introduction by the movement of infested wood. The long vertical gap between populations is a 'natural boundary' region of semi-arid climate neither species exploits.

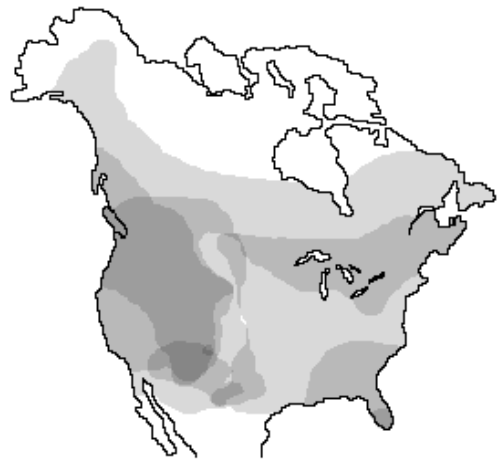


Figure 2.2: Using overlapping range maps for seven North American *Camponotus* species (carpenter ants) to predict regions with most opportunity for harm to structures (category 's' in table 2.1). Range data from Hansen and Klotz [23].

Figure 2.1-right shows a western damaging species *C. vicinus* bridging

the ranges of *C. modoc* and *C. pennsylvanicus*. *C. vicinus* commonly exploits lower elevations than *C. modoc* [24]. This illustrates how localized utilization of warmer and dryer locations than *C. modoc* [23] inhabits avoids some competition and seems to predispose *C. vicinus* for its more eastward extension in range where it overlaps *C. pennsylvanicus*. The intolerance of *C. modoc* to reducing colony humidity to 70 %RH from 100 %RH compared to *C. vicinus* is a key factor [23].

Species	**Harm**	**Species**	**Harm**
C. pennsylvanicus	s* 10000–15000	*C. caryae*	v 300
C. modoc	s* 50000	*C. decipiens*	v 300
C. vicinus	s* 100000	*C. essigi*	v 300
C. herculeanus	s* 3000–12000	*C. nearcticus*	v 300
C. tortuganus	s	*C. clarithorax*	v
C. floridanus	s	*C. varigatus*	v
C. acutirostris	s	*C. sayi*	n
		C. planatus	n
C. noveboracensis	(s) 3000	*C. hyatti*	n
C. chromaiodes	(s)	*C. castaneus*	e
C. laevigatus	(s)	*C. semitestaceus*	e
C. subarbatus	(s)	*C. discolor*	e
		C. americanus	e

Table 2.1: Carpenter ant (*Camponotus*) hazard ranking created from descriptions in Hansen and Klotz [23] with species sorted into categories by maximum risk posed: **s*** major structural damage, solid wood, insulation; **s** minor structural damage, rotten timber, insulation; **v** nest in structural voids; **n** nuisance; **e** restricted to environment. Numbers are colony sizes.

Figure 2.2 shows the overlapping ranges of seven species of the most severe structural infesting ants listed in table 2.1. Regions with the darkest shading have the most species to contend with. Wood destroying carpenter ants have greater continental range than termites, are as harmful as termites in the Pacific Northwest (affecting 42,000 to 50,000 structures per year in Washington state), are the key structural

pest in temperate North America where there are no termites, and have been moved into new regions through movement of whole timber and firewood, and changes in land cover [23].

Excepting the far north, all of continental North America has some form of carpenter ant risk whereas termites are largely restricted to the U.S. lower 48 states (some activity in southern Ontario and British Colombia). Ranking of hazard to structures comes from relative occurrence compared to other distinguished wood destroying groups (fungi, termites, beetles). Providers of services and researchers for these groups may have arguments for local preeminence, which consultation of range maps, comparative findings on recorded incidence and loss estimates can cut through for estimating national risk.

One can project a dilution of severity of carpenter ant incidents when accounting for the number of less severe and nuisance ant species associating with structures where these overlap range with the most damaging species (compare relative harms in table 2.1). Further refinement of impact is to know the proportion of structures affected annually in a contiguous climate zone (50,000 affected buildings, but to what number vulnerable yet unaffected per year?).

From range maps, one might conclude the region most threatened should be the most harmed, the southwest region with four to five species overlapped is the darkest grey area in figure 2.2. But this is not clear cut as Hansen and Klotz emphasize the two ants in the Pacific Northwest as "particularly destructive". Michigan, Minnesota, New York, Ohio and Virginia are also picked out as significant sufferers culled from pest service statistics. The answer to this may lie in the relative density of human structures in harms way rather than the territory held by particular ant species, but pest range maps cannot disentangle this problem on their own, needing a geographic information system (GIS) merging pest distribution with local climate, building structure density, prevailing construction methods and so on.

Where environmental limits strongly apply coarse distinctions such as 'have termites / don't have termites' remain along predictable geographic lines. For these, range maps can be used to evaluate the local

risk, but maps' authority are also challenged by lack of current survey data capturing range extensions and reductions (changes in land cover). Concerns raised by changes in climate do not ensure reductions in habitat. Pest species can profit greatly from the climate change scenarios as they have with the spread of human influenced environments: less trees in woodlands, more trees in prairies. As an example, severe storms drop trees and subsequently boost general populations of wood devouring species including insects harmful to nearby structural timbers (D. Pinniger pers. comm.).

Seasonal climate is a key moderator of pest numbers and timing of hazards (gravid adult insects, autumn rodent entry into buildings), and range of temperature can lead to gradations of prevalence and duration through climate zones (annual generation or multivoltine). As heat is a major limitation for insects, temperature controlled buildings negate the extremes of season and can support insects well outside their natural ranges.

Modelling global pest risk

Howe [25] published a much cited set of data on insect growth rate and limits for the purpose of categorizing possibilities for pest colonization in climates by evidence of drought resistance, cold hardiness, and heat tolerance. The model categories were somewhat arbitrary thresholds of 10 %RH and 50 %RH between 'low', 'moderate' and 'high' humidity, with 20 $^{\circ}C$ between 'low' and 'high' minimum temperature and 30 $^{\circ}C$ between low and high 'mean optimum' temperature. Cold hardiness, moderate hardiness and cold susceptibility were applied as additional categories.

Figure 2.3 illustrates Howe's values for the rates of population growth for pest insects [25]. Table 2.2 lists these rates, along with an intrinsic rate of increase[5] r_m back-calculated from Sinha's I_p values based

[5] r is defined by Birch [26] as an idealized value of "infinitesimal rate of increase which a population of *stable age distribution* would have when growing in a constant environment in which space was unlimited." Howe's values are normalized over a 28 day period by counting adults matured inside a lunar month.

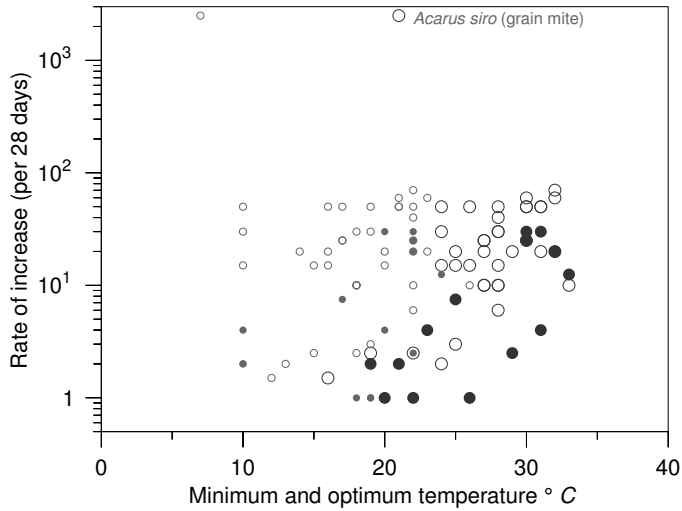


Figure 2.3: Insect population growth rates from Howe [25] plotted against minimum (small circles) and lower optimum temperature (large circles). Subset of museum pests highlighted (solid circles, table 2.2). Higher rates appear to correlate to higher optimum temperatures for development. Rate for ptinids (spider beetles) <5, other coleopteran pests >5. Label notes extreme ability of the grain mite *Acarus siro*.

on Howe[6]. The symbols r_m and r are used in insect population literature with semantic distinction of r_m qualifying a rate for a specific environment [27] leaving r as the 'true', 'inherent', 'infinitesimal', or as Birch preferred the "intrinsic rate of natural increase" obtained by means arguing the best possible conditions to maximize population growth [28]. That conditions alter rate is the key point, and until a lot of work is done distinguishing a peak r from myriad possible r_m stemming from altered environment variables differentiating them as symbols is moot. So, for the purposes of this text r is also used to gen-

[6]Given the relationship $r = lnR_o/T$ where T is the time step for tabulating population growth back-calculation was the best route to determine r_m from Sinha's work.

erally refer to population growth rate for an exponential model. The rates used by Howe, R_o, listed in table 2.2 are the individual fecundity in eggs laid per female minus infertility losses normalized over a convenient fixed interval as described by Birch [28].

Birch [28] laid out the methods, errors, and caveats for determining rate of insect increase noting that unlike human populations which are measured *in situ*, insect rates are only readily determinable in laboratory culture. Continuing on this, Howe described the strength and weakness of information available for calculating rates, stressing the rate of development data (stage to stage transition) is often available but the oviposition patterns are not. Without the latter, short lived adults (moths) can be modelled more confidently than ones with longer reproductive lives (beetles) [25]. Birch has also laid out the overwhelming contribution of early versus late oviposition to population growth within a species [28].

Extending Howe's predictive approach Sinha laid out worldwide cereal pest hazards [29] by Köppen climate zone by applying a trapezoid 'climate plasticity index' model[7]. Insects with higher values of I_p (≈ 500) have are described as 'cosmopolitan' and those with lower values as 'specialized' (≈ 100) [29]. The intrinsic rate concept has also been investigated for use in estimating quarantine hazard [30].

Both Howe's and Sinha's methods are 'equilibrium' models in that they do not directly accommodate fluctuations that are obvious in more detailed studies of life cycle which realize changing values of r_m for life stage in development, fecundity, pest density effects etc. [30]. More detailed models have been developed to look at 'species abun-

[7]Sinha's index of plasticity (I_p) model to numerate "climatic adaptability" was calculated as follows: $I_p = r_m/2(t_3 - t_0 + t_2 - t_1)(h_1 - h_0 - 5)$ where: r_m is the intrinsic increase rate for a lunar month, t_0 minimum reproductive temperature and t_3 maximum reproductive temperature. $t_{1,2}$ are low and high optimal temperature limits using an assumption from Howe [25] that $t_3 = t_2 + 4 \circ C$. $h_{0,1}$ are minimum and maximum %RH reduced by 5% to model reproduction response to humidity decrease [29]. Data from Howe [25]

Species	**Rate** (Howe)	$\mathbf{I_p}$ (Sinha)	$\mathbf{r_m}$
Maximum	70	700	2.0
Dermestes frischii	30	285	0.667
Necrobia rufipes	25	250	0.556
Dermestes maculatus	30	360	0.545
Lasioderma serricorne	20	200	0.364
Stegobium paniceum	7.5	67.5	0.214
Trogoderma granarium	12.5	131.3	0.169
Gibbium psylloides	4	42	0.073
Ptinus tectus	4	42	0.089
Mezium affine	2.5	23.8	0.045
Niptus hololeucus	2	21	0.044
Ptinus fur	2	23	0.044
Ptinus sexpunctatus	1+	9.5	0.022
Ptinus clavipes	1+	10	0.022
Ptinus pusillus	1+	5	0.032
Minimum	1	5	0.022

Table 2.2: Published rates of increase for some agricultural beetle pests which also affect collections. Net maximum rate for a four week period ('lunar month') [25] [29] is individual fecundity. Plasticity index I_p was back calculated to give intrinsic rate of increase ($r_m = \ln(N_t/N_o)/t$) from Sinha's formula [29] rearranged as $r_m = 2I_p/((t_3 - t_0 + t_2 - t_1)(h_1 - h_0))$ with RH of 80, 90 and 100 assigned respectively for low, medium and high upper RH limits (h_1). Data from Howe [25].

dance' which model[8] density and spatial distribution for their predictive utility for managing campaigns against forestry pests [31][32]. Combined with GIS databases incorporating significant environmental factors and ground truthing, the output of models are realized as range maps, but with more flexible utility for prediction of spread and timing of control efforts [30].

The climate and range approach has applicability when there is a tight coupling between the pest, the collection's store and the outdoor climate. It would therefore apply most to the lower 'IPM levels' developed in paper five which contain significant aggregate quantity of cultural property in objects and structures which are least separated from the outside environment[9] Another example for consideration of large scale approach is Sinha et al.'s [35] examination of Canadian prairie grain pest risk for multi-year storage through principal component and canonical correlation methods applied to climate data and local measures of problems. Appropriate factors to quantify hazards faced by the collections spread thorough differing structures, frequency of pest, type of pest and climate history would have to be gathered after the forward utility of such a model for national heritage preservation was established.

Climate controlled museums can act as refugia for species 'in trade' not found in adjacent natural environments. Because of the historical prevalence of collection damaging pests in commerce having already gained foothold, it is uncommon to date that a museum would have to examine whether species leaking out of the museum are a threat. This only occurs when the species is reportable to the national quarantine assessment process [36] and usually results in nationally approved treatment. Whether an introduced pest survives, and how well it will

[8]The beginning point is the Poisson distribution $p = 1 - e^{-u}$ for random and independent species distribution [31].

[9]Enclosure categories for changing IPM strategies were proposed by Strang and Kigawa [33]. See figure 6.2. The national distribution of Canadian and Japanese institutions with respect to IPM planning and training were presented by Strang and Kigawa [34].

thrive indoors is a specific fraction of the problem being tackled by the climate approach, irrespective of whether the pest source is local or foreign.

Sinha's approach was further developed into an ecosystem model for evaluating nationwide risk to Canadian granaries [37], a task which required synthesizing years of climate and production figures with pest infestation data [38]. The same trapezoid population growth rate model was recalculated into somewhat more detailed grain pest[10] development rate models by Subramanyam et al. [39].

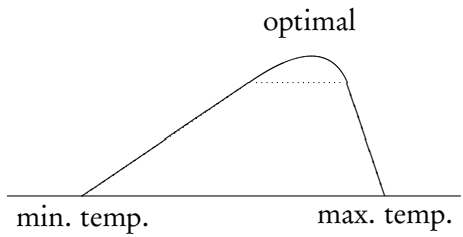


Figure 2.4: Temperature effect on growth rate (trapezoid model [29]).

The characteristic trapezoid shape for growth rate also applies to the temperature response by microbes but Adams and Moss caution against assuming Arrhenius law for the minimum to optimum region as microorganisms modify their cell membrane fatty acid composition to adjust membrane melting point and maintain function with changing temperature [40]. The steeper fall off in population growth rate at high temperatures is common to both insect and microbe response.

Risk from pests is assumed locally

The potential impact of the global pest pool is thankfully reduced by collection facilities occupying a particular location. A Midwestern university gallery is not open to all pests, but may be open to all pest harms. Any geographically circumscribed species (forest pest crossing over as structural timber pest) can be included or excluded from

[10]For species: *C. ferrugineus, C. pusillus, O. surinamensis, R. dominica, T. castaneum, T. confusum*.

consideration by range maps barring the caveats given above. In this regard probability of being affected by these pests (termite, carpenter ant) can be treated like risk from geographic threats like earthquakes.

The potential for exposure provided by the global pest pool is filtered by local supply (a geographic sub-sample), the frequency of collection acquisition and range of loan activity, level of containment and procedural features.

Pest species have adaptive capability rising from their diversity in potential for survival of extrinsic factors. Facultative use of marginal food resources, infrequent or adaptive use of habitat and the measurable increase in resistance to pesticides in the latter part of the 1900's that even led to abandoning pesticide use [41] all argue for this flexibility.

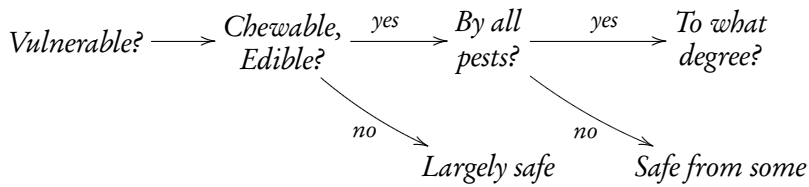
Once present in a collection, a pest's capability to accelerate (population growth models) is governed by environmental cues (nutrition, heat, moisture, photoperiod etc.) which are primarily influenced by the presence of a surrounding structure. In part, the conservation discipline's emphasis on temperature and humidity bounds have great importance in control (explored in detail in chapter 4). However, the pervasive emphasis on sanitation is the IPM approach to reducing contribution of food, water, and shelter that support life where temperature and humidity are clement (chapter 6 and paper five). In this regard pests are treated somewhat like fire and its supporting triangle of oxygen, fuel and ignition. Where we can hope to bar access we treat them like thieves emphasizing observation, resistant materials and structure.

Collection risk from pests is non-uniform

People rank harms implicitly by the terms used to describe damages: deposit, stain, hole, weakening, loss. Do we mind residual mildew spotting more than the silverfish grazed book covers, both of which are codependent on high storage humidity? When do consequences of 'contamination' outweigh observations of 'loss'? While 'mint condition' crowns some object collections we also accept the state of any ar-

chaeological survival with equanimity compared to digging an empty hole in the ground. Conservation could rank incremental pest harms by unit restoration cost if the discipline accounted for this information, but only when restoration is a desired state, plain existence often suffices.

The straightforward triage of serious object vulnerability[11] to pests is by default their material vulnerability:[12]



Pest risk by vulnerability of materials are often implicit in the common name classification of pests (wood borer, hide beetle, clothes moth, cheese mite) which provide a rough education to the novice. In aggregation, rodent shredding, silverfish grazing, anobiid boring, microbe digestion and any organism causing staining are all considered bad. However, across collections the quantitative rates of consumption are tied to key influences (temperature affects the time elapsed per generation, nutritional value affects the volume consumed per individual) which can be ill documented although we do have many examples of pest and collection interaction from untouched to destroyed.

A sub-category of material vulnerability is food preference and nutrition. This appears in conservation advice in another guise: soiling. Food preference is a 'choice box' experiment. As an example figure 2.5 shows the time series of choice between different foods by a population of cockroaches in a large container.

The result showed a marked preference for sugary carbohydrate and little to none for greasy protein. Now consider a clean object with

[11]Pests can defecate on any object, but are more discriminating about what they ingest.

[12]These get overlain by values of cultural meaning which are obviously unimportant to the pests.

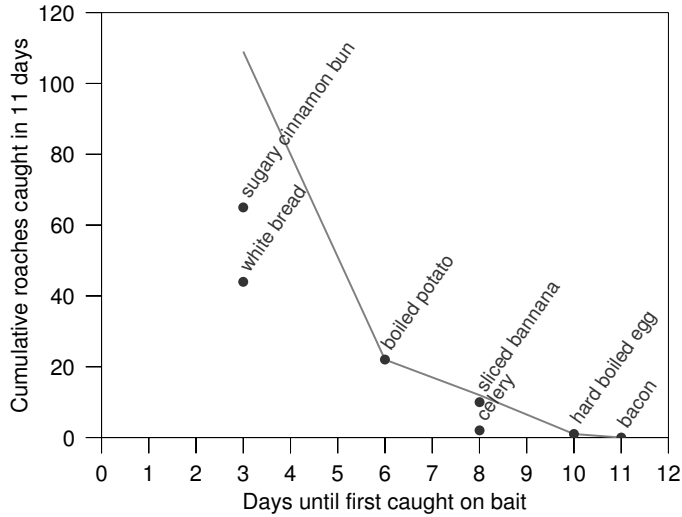
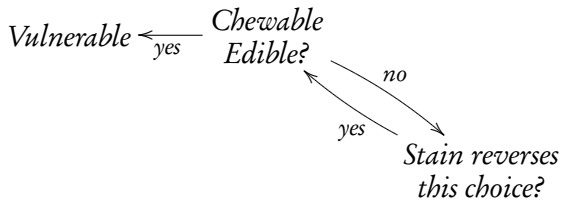


Figure 2.5: Cockroach (*Blattella germanica*) food preference. Time to first attraction to samples (points) and cumulative preference (line) are plotted. Data from Rau cited in Cornwell [42].

discrete stains. Clearly a carbohydrate stained portion of an object or starch adhesive will be most attractive and would likely suffer harms as a by-product of cockroach feeding. The protein stained portion or animal glue will also potentially suffer harm (random access not limited) but one might assume much less harm than the carbohydrate based on previous evidence of cockroach attraction from the experiment. Such observations might be used as a Bayesian prior to model likelihood of a particular pest attack on a well characterized collection. While there are insects with specific diets, the more successful pests can be somewhat omnivorous resulting in a distribution of preference.

However, if all that is available to a larvae is an intrinsically marginally nutritious object (not fatally devoid of sustenance), the larvae will have to consume more of the object to complete development although rate of development and some ultimate size can suffer. When a choice is not present, low nutrient objects could then suffer more harm per

insect through gross consumption than high nutrient objects.



This runs somewhat opposite to conservation advice: cleaning objects for storage to reduce attraction of pests on the assumption that gross harm is also reduced is a condition which only occurs if pests can exploit freedom of access and have a detectable choice of 'dirtier' objects to go to. What people will see which reinforces the perceptions around cleanliness is that a stained area suffers significantly more harm than the surrounding material. They are less likely to see the dispersal of smaller 'tasters' across large or multiple objects. Multiple sites of consumption per larvae are seen in tests on otherwise uniform substrates [43].

However, reducing nutrition when able is an activity to be encouraged as it can very significantly lower overall rate of insect pest population growth as much as it should 'fairly' distribute residual pest harm incurred over long time. Griswold and Greenwald noted Takahashi and Uchiumi [44] observed twice as many eggs produced for a dermestid species when 'food' was present [45].

Figure 2.6 shows objects as choice boxes. Such intrinsic nutritional values cannot be altered without application of their inverse: toxins, and even that is subverted by increasing population tolerance to pesticides (termed 'resistance').

Human concern and evident reality

Does human concern respond proportionally (equivalent to threat) to the thought of pest increase? Does human concern scale inversely to the surface area or volume of affected object which dilutes the loss by pest activity? How many pests per collection tonne? Does human con-

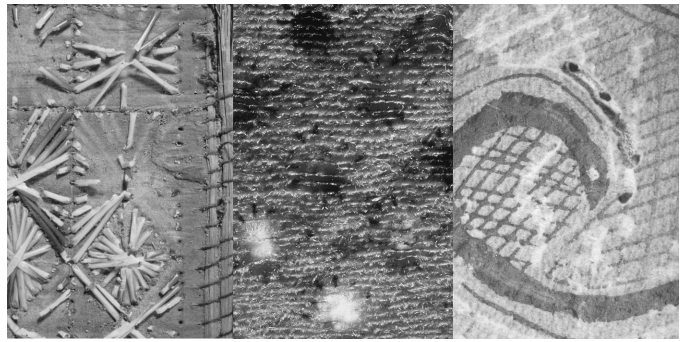


Figure 2.6: Three shades of vulnerability to insects. Left, porcupine quill was food, birch bark and grass were not food (insect digestive capability). Middle, textile is all food but black wool polka-dots are extra nutritious or red background wool is somewhat toxic (different mordants and dyes). Right, hide mitten is all food, coloured decorations were nutritious (pigment binder). Photos, CCI.

cern scale to the surface area presented to intercept an insect? Which to inspect daily and which to inspect yearly: the elephant or the gnat?

The measure of relative concern to actual incidence is a confounding dimension when one looks for rational pest control decisions to be made. Through a survey of pest control procedures Bell and Stanley [46] noted North American collection professionals' perception of hazardous pests and their recorded incidence in collections. The survey covered a mix of collection types and volumes. The result plotted in figure 2.7 shows general pest threat tends to be underestimated against incidence, and dermestids represent the largest real threat but Bell and Stanley felt this was due to endemic assumption of the causative pest rather than actual identifications[13]. They noted high suspicion of loans as pest vectors, but only half the respondents effected controls on them. These simple but significant lapses in procedure, and their concerns on haphazard and flagrant pesticide use be-

[13]To give some credit to the respondents, dermestid larvae as a group are somewhat distinctively banded and tufted, and dermestids are common pests.

came a major focus of collection pest eduction from the time of publication to the present. After reading their results one clearly has the sense that an uneven and sometimes irrational process was in force with talisman application of preventive measures like mothballs and preferring home brew fumigants[14].

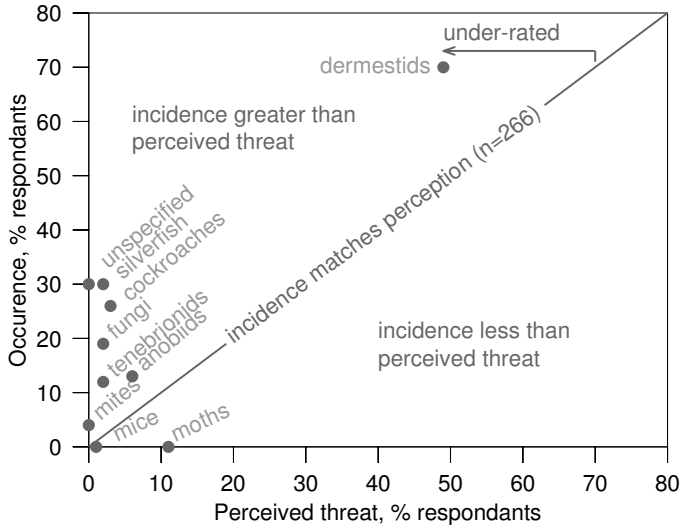


Figure 2.7: Difference of response between perception and incidence of pests. Data from 266 respondents, Bell and Stanley [46]

Looking at the problem from the side of the causative agents, a national compendium of cultural property pests categorized by material harm exists for Japanese collections [47]. Materials harmed, pest material utilization or activity harm, and risk ranking were classified by Yamano and Kigawa as a means to systematically present expert opinion and literature summary (K. Yamano and R. Kigawa pers. comm.). Three classes of relative harm were ascribed to Japanese cultural property pests. Of the 135 species described, 18 ranked high and 42 mod-

[14]This has greatly changed since the survey through the combined efforts of professional organizations, education, and statute.

erate. While often multiple material categories are affected by each species the listing is roughly evenly divided between cellulosic and protein. The ordered ranking of materials harmed and activity harms descending by number of contributing species were: object as food; wood; miscellaneous materials; nesting and contamination; animal specimens; paper; tatami and dried plants; stinging and noisome; bamboo; parchment and fur; silk; wool; cotton.

Figure 2.8 shows the same structured descriptions of the 135 species with relative association[15] of material and behavioural harms with risk perceived from experience. Emphasis of risk lies with thin structures and fine art materials followed by animal or plant based objects (distance from high risk class 'A'). Wood and bamboo with both structural and art application have 'diluted' risk through non-consumptive pest activity. Figure 2.8 provides a concise model of pest risk to materials extracted from methodically structured textual material.

An illustrated card series (figure 2.9) was developed by Strang and Kigawa [48] to reflect the more common species and work as a quick introduction to pest hazards and risks for participants of IPM training courses and museum volunteers.

Decision analysis, thresholds and risk models

Mumford and Norton [49] provided an overview analysis of pest problems in stored product protection pointing out cost-benefit models are designed for the presence of pests and are not adequate for examining the "threat of pest attack". They preferred to apply 'decision analysis' flowing from individuals' objectives through their situation to the choices made:

[15]Partial Least Squares-Discriminant Analysis, acronym PLS also defined as Projection to Latent Structures. Used for analysis when the values defined in the source are not orthogonal in meaning as there is likely correlation between some materials with pest actions (interchangeable utility). Performed with Simca P+ 12.0, Umetrics AB.

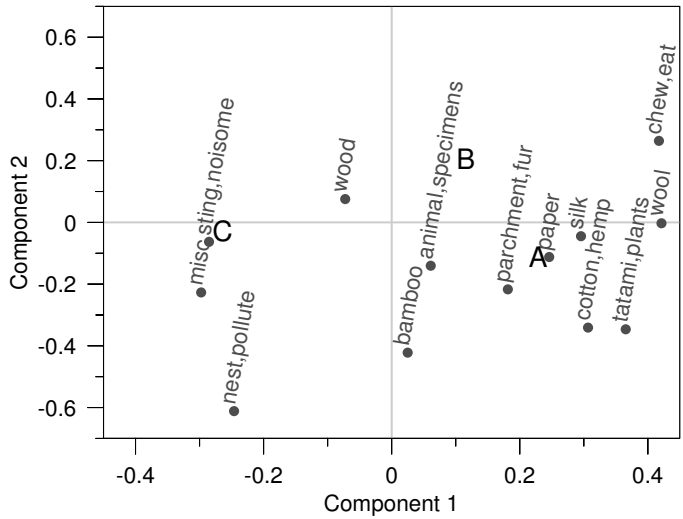


Figure 2.8: Partial least squares discriminant analysis (PLS-DA) loadings plot of 10 groups of materials harmed, 3 pest activity harms (eat, nest, noisome), 3 classes of qualitative collection pest risk ('A' high and frequent, 'B' moderate or less frequent, 'C' low and infrequent) for 135 described arthropod species. Emphasis of risk appears to lie with materials composing thin structures (fine arts, textiles) followed by specimens and structural (increasing distance from 'A'). Data and risk estimate from descriptions in Yamano et al. [47]. Software: Simca P+ 12.0, Umetrics AB

Situation	**Goals**
Farming without a market	Quantity, then quality.
Farming for domestic trade	Quality, low pre-harvest loss
Farming for international trade	Quality [49]

Mumford and Norton then point out resulting divergences from socially positive goals. For farmers without markets there are "constraints of capital and expertise" which could limit both quantity and quality of food. Domestic markets perversely gain from post-harvest losses through "price inelasticy of demand" where markets are less able to substitute goods, price change rises markedly with moderately

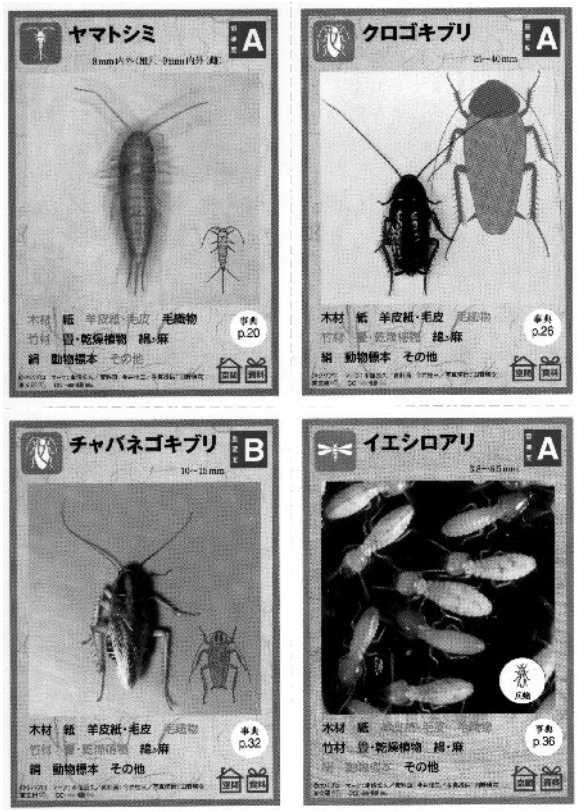


Figure 2.9: Examples of 'Mushi no meishi' (insect business cards) introducing hazards to materials (bold face kanji matrix below photograph), relative risk (A B C), illustration with actual size and key to national cultural pest compendium [47]. Strang and Kigawa 2009 [48].

decreased quantity (worst case is hoarding). International markets tempt contributing individuals to cheat the commons by cutting corners on inputs which govern quality despite the 'implicit incentives' to high quality for maintaining market access. Countering these undesirable elements are education, having farmers store grain until sale into

the market and national and international regulation for the common good [49].

By comparison, having museums store their own objects should keep retained quality high when there is market demand for their production (exhibitions, study, domestic and international loans, cultural icons). Orphaned collections certainly suffer in neglect. Without a clear 'market purpose' do heritage collections do as well as they might?

Values

So what motivates and limits collection care staff to combat pests in public institutions? Is it retaining quality given the aesthetic drive of galleries and museums or its handmaiden 'uniqueness' with high curio or monetary values. Or is it retaining quantity such as scientific coverage of a discipline or completeness of an artistic genre where secondary quality is an interpretive value, a measure of 'variation' or 'developing talent'. Are there 'subsistence' museums which favour quantity to quality more than museums with a 'domestic market' outlook? Would an internationally contributing museum skimp on pest control before travelling an exhibit overseas letting the recipient find the problems?

Perhaps not always an exact fit due to the nature of the substance being marketed (sense of history and place, archival voucher, blockbuster viewing), but there are certainly enough parallels to consider. There is an 'inelasticity' to cultural properties that are relatively unique (twelve kilometres of packed shelving but only one fond on a particular company or individual). There are hierarchies at work in collections that incorporate relative elasticity in values from a 19th century natural history type specimen to the interpretive centre stuffed squirrel with a ratty tail. The species and physical condition may be identical in these two examples, but their values are quite different making them non-interchangeable as objects.[16]

[16]Unable to move up-scale without considerable pressing need and academic effort (credible designation of holotype, neotype, paratype, allotype, isotype, lectotype, syntype, isosyntype) or move down-scale without similar effort, accident, or dereliction of discipline training.

Another example, from the author's experience, was partitioning of historic site collections into a reference collection set apart from those used for display with interpretative and operational functions. In the course of restoration easily harmed components (original textile, wood panels with decoration and original paint etc.) were preserved for reference while copies were applied to implements exposed in exterior locations. While lowering the sum of original parts in any one outdoor exhibited item, this raised the likelihood of preservation of relatively rare large implements through partitioning highest 'at risk' elements (eroded delicate and original wood surface details) from the lowest (acquired rusted and subsequently re-conditioned iron frames).

Value is arguably always plural in reference to collections and the discussion of values in Waller [50] covers application to risk modelling for a composite of economic, informational, cultural, and emotional lines. These can be summed within the human concept of 'having meaning'. Collection's values fluctuate [50] and can be resurrected over time through intellectual activity or physical interventions (akin to undertaking grain cleaning before sale).

Museum collections have the benefit of subdivision for treatment to the object level. Most stored agricultural products are treated in considerably greater mass and volume than a museum would experience, in the form of flowing grains, bags on pallets, concrete and steel bins, and massive ship holds. However crafted and individually conservation plies its attention to the object, many collections benefit greatly from having good capability for mass pest control when needed as quarantine support or during a collection move or after a disaster.

There is a bifurcation of requirement stemming from values that need decision to protect them from any damage whatsoever (precipitous value loss) or willingness to protect with minimized damage (resilient value loss). The former has an absolute threshold against harm while the latter can accept a low rate or distribution of losses. Note that the latter case need not fatalistically accept certain loss but must honestly assume some probability of loss.

Some values adjusted by pest infestation, an asymmetric distribution

of values from negative to positive indicates strength of 'pest' status:

Negatively	Total loss, aesthetic surface loss, structural strength loss, chemical contamination, information layer loss, collection care resource diversion, becomes repulsive or health hazard.
Not affected	Remembrance of past utility, historic status.
Positively	Visual proof of elapsed time (witness faked 'woodworm' in furniture), spalted wood grain, decorative appeal (figure 2.10), reinforced need for consistent care and craft knowledge.

Figure 2.10: Decorative panel on Japanese gate cut from termite damaged wood. Gotō Museum garden, Tokyo.

There are different thresholds to model; those where the outcome is punctuated by discrete changes in value (mint / mangled) and where pest data purports definition of outcome (control / no control).

The latter case seems preferential to people over probabilistic risk models as they can be built around specifications with definable 'set points',

but these are in reality often proffering a high likelihood of control and can contain hidden variation that was skimmed over leaving either some exposure to risk or opportunity for savings. Chapters 4 and 5 contain discussion of this issue around pest data.

Mumford and Norton's 'decision components for threshold model' relate to where 'volumes' can be defined in multi-dimensional parameter space which represent different values for the grain [49]. As an exercise, their components are listed in table 2.3 with units altered to map to collections preservation. Tonnes of grain can be substituted by an arbitrary 'object quantity' (number of objects, kilometres of shelving), but uncertainty about preserving 'values' depends on specifics ascribed to the items within the institution, culture and time.

Component	**Measure**
Pest species number	number/object quantity
Monitoring cost	cost/object quantity
Monitoring accuracy	number/object quantity
Temperature	$^{\circ}C$
Moisture	%RH
Pest growth rate	1/time
Pest tolerance, threshold for action	number/object quantity
Residue tolerance	contamination by treatment, loss of object values
Control capacity and available methods	object volume/day/cost
Alternative market prices	acceptable values/object quantities, thresholds for pest harm tolerance

Table 2.3: Decision components for threshold model (after Mumford and Norton [49]). 'Number' refers to pests. Those components which this author deem under-represented in work to date on collection pests are highlighted in bold, and those which are well developed set in italics.

Making decisions with pest population models

Oversimplified, the problem from pests in collections is the devastating intersection two master curves where historic growth in collection holdings may arguably limit to a logistic curve strategy[17] with an estimable carrying capacity limited by space / human will / resources in the institution, while pests can exploit a near exponential growth strategy[18] causing irreversible harm within this stored mass. The decisions to increase and partition storage, discard infested goods with replacement and kill pests with enthusiasm, are all non-modelled choices which immediately illustrate failings in this simple model.

Still, the discipline of economic entomology must incorporate practical application of population models to decision making within a greater context. Mumford and Norton discuss the importance of relating control decisions to the expectation of exponential increase of pests *in the short term* [19] and this term's relation to the scale of time over which control decisions are made.

$$N_t = N_o e^{rt} \tag{2.1}$$

The continuous exponential equation (2.1) computes the equivalent of the geometric equation (2.2) matching pest reproduction in discrete quanta (young, eggs, spores).

$$N_{t+1} = N_t R \tag{2.2}$$

The exponential model's replacement of individuals in populations assumes equal sex ratios, so any measured fecundity (egg production per female) must be halved before calculation. This equally becomes the

[17] All good things come to an end. Initial emptiness fills up quickly, then slowly pack the rafters.

[18] Party hearty. Grow without knowledge of limits, eating everything in sight.

[19] Equation (2.1) where N_t is population at elapsed time t, N_o initial population, r innate capacity for increase [51] or population growth rate under optimal conditions [30].

convention of only modelling the female population by counting female eggs per female (♀ / female). Sex ratios for collection pests[20] are roughly 1:1 in work that reports them [45] [52].

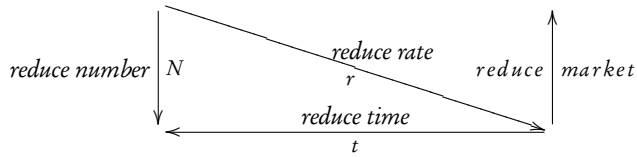
Another aspect to note for the exponential model is the value N_o (initial population) counts those individuals which give birth or oviposit. However, the number of descendants is not 'recognized' by the curve until the full generation time has lapsed and is read as N_t. Potential utility of integrating the exponential demographic model to resemble incremental accumulation of collection harm (consumption by developing larvae) is discussed later.

Mumford and Norton argue the exponential model introduced by Lotka [53] (equation 2.1) and applied for insects by Birch [28] is representative of grain storage under reasonable initial control, not near pest carrying capacity when food supply limits growth, nor subject to significant inter- and intra-pest competition. Supporting this point, consider Thorpe et al. [54] describing "devastated" grain in 135 days by a weevil species (*Sitophilus oryzae*) achieving 3000 adults per kilogram from an initial 1 adult per ten kilograms. For comparison to the possible museum pests, Howe [25] published an intrinsic rate for *S. oryzae* equal to that for *Necrobia rufipes*[21] in table 2.2. In another measure of pest impact Scoggin and Tauber list historical complaints against *Dermestes maculatus* among which the Hudson's Bay Company's London fur warehouses were so affected the corporation offered a £20,000 reward in search of a control [55].

With higher incidence of a pest the signal is usually very clear to people that something must be done and uncertainty around whether to act against the pests is eliminated. Uncertainty with low numbers of pests combined with low market tolerance for pests gives rise to a search for least-cost combinations of "four general options for pest control" [49] whose connected influence Mumford and Norton illustrated as:

[20] Those which are not colony forming.

[21] Infests some natural history collections.

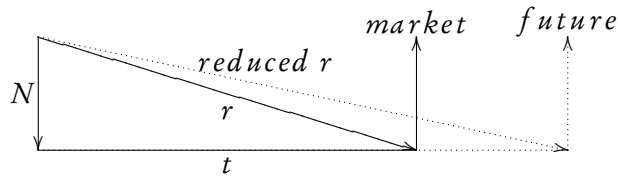


For collections, the optimal outcome of IPM is minimal market reduction through low N and r, minimal loss of imagined collection values at a long future time t. While it may be easy to discount a plain exponential model and certainly the logistic which even failed in simple application [26] let alone multi-generation multi-factor ecological population modelling [11], we must examine the need to develop a more complex growth model. If the best of the object is eaten before the insects slow down from crowding, cannibalism, migration dispersion and accumulation of waste or parasites then a simple model will suffice. In their tidy sheltered museum case, pest insects (or rodents for that matter) avoid perils they would face in the outside world which could also seriously damage the object in some way. By this thought, complications in pest ecology models can be reduced for the museum pest. As with many other risks, primary shelter reduces them or we would not bother huddling inside.

For stored-products reducing the span until the future time t will shorten the period N pests can cause harm, lessen repeated costs of controlling pest N and r over longer t, and while lessening the period for amortization, realize a profit sooner. Collections rarely consider this as a goal for the obvious reason: they are in the business of retention. However it does occur with museum shop items, 'display props' and possibly specimens intended for near term destructive analysis or use by the researcher. This is why the value of IPM is often heavily discounted for these items and their unimagined (sometimes real) consequence of a new infestation risk runs into conflict with surrounding long term preservation activities. Food services operating in museums are less dismissive of IPM concerns as they are commonly under some

standard addressing hazards to health. For them, IPM impositions vary mostly around effective service line sanitation, cooking the meat at temperature, and disposing the rush of event generated garbage to control flies, roaches and other sources of illness. Connection to collection IPM concerns is a matter of proximity, procedure and overlap in likely pests through collection vulnerabilities.

Reducing market is a lowering of the expectation of fully retained values, accepting more damage to the goods at a future time t and by implication lessened emphasis on controlling N and r (IPM costs). It is possible this strategy is consciously taken in museums as research focus changes. There are experiences of university herbarium collections becoming orphans and suffered near total loss to pests before acquisition by national institutions (M. Shchepanek pers. comm.).



Reducing r gives a slower rate of population growth causing equivalent N to be achieved at a future time (dashed lines in above diagram). This slows damage over the shorter term but equal accumulated harm can ultimately occur over the longer time. However, the goods are in better shape on arriving at the shorter term.

Can collection staff operate consciously around such a model for the benefit to themselves and their collections?

While some foodstuffs are banked for a considerable number of years, their eventual sale provides a simplified clarity for decision making which cultural collections can lack. Museums are justly renowned for hanging onto collections indefinitely. Even when objects deteriorate or are damaged in their care, they are often retained in collections for their residual voucher (caretakers accept ‘reduced market’).

Constructing a simple model

Mumford and Norton's population risk model approach determines a threshold N for significant change of market value (sold dear, sold cheap, discarded) [49] then back calculates using estimates of rate r to a time t_o. Estimates of N_t allow inspection of where the produce resides in the model. This works for grain where the threshold for markets is a contamination count approaching N insects per tonne.

To make this method work for collections, one would have to expose objects to pests and determine time of loss of materials and physical features mapped to key values; body features, structural integrity and aesthetic disruption. The rate, time and population involved to achieve these losses can be mapped to population growth models to describe thresholds. The area under a population model integrating destructive pest numbers and elapsed time might then project loss of key values in various classes of objects.

IPM guides emphasize inspection and trapping as necessary sampling methods [56]. The intention is to determine pest numbers $N_{o,t}$ or pest trends giving an estimate for r under current conditions (r_m). IPM guides request a continued plan for estimation over time, multiple times per year (integrate seasonal differences, sampling variation) and multiple years (relative rate of growth or decline) but do not commonly apply any population model to the results, relying on comparison with previous counts to find 'hot spots' for closer investigation. Following from a largely absolute intolerance for pests, results of trapping then tend to be used as guides for just where to treat, rather than when and where to treat as applied to crop IPM.

Influencing $\mathbf{N_o}$ and $\mathbf{N_t}$

Determining numbers for initial population N_o that came into a collection is problematic. We do know the lowest number is one, a mated or parthenogenic female. A modestly larger number will possibly be needed to allow for losses to the nascent population before achieving reproductive success. Methods with decreasing effort and degrading utility of information towards finding N are:

Direct inspection	Sampling certain volume with defined time.
Adhesive trapping	Sampling uncertain volume with defined time.
Adventitious discovery	Sampling uncertain volume with uncertain time.
No inspection	Sampling no volume with infinite time

Comparisons of detection methods for grain pests are a long examined area of stored product research, yet even with the ability to reduce an aliquot of 'object' to powder for pest sampling there are uncertainties in the numbers from errors induced in drawing samples from uneven distributions. Methods themselves also contribute to error. As an example, the following sequence of decreasing certainty of finding proper values for four species of insects in grain, rice and beans was established: rearing [head count], ninhydrin [foreign protein], X-ray [imaging pest], carbon dioxide [pest respiration], flotation [separating damaged product] [57].

In figure 2.11 there are two samples taken at the time t marked as 'now'. Without an estimate of errors on determining N_t (a versus b) there will be some uncertainty about where you are on the exponential population curve as we do not know time back to N_o and may have poor understanding of r in these conditions.

Underestimation of N_t

Sample 'b' underestimates actual value 'a' (same as N_o estimate off tenfold), giving the impression of lower potential harm (unit consumption by larvae) in the estimated time that has elapsed and projects taking five times what population 'a' actually takes to reach the threshold for response marked 'Act?'.

Overestimation of N_t

Sample 'b' overestimates the actual value (now the solid grey line below 'b') by sampling a 'hot spot' and staff extrapolate this to the whole collection fearing 'd'. This invokes pest eradication measures across

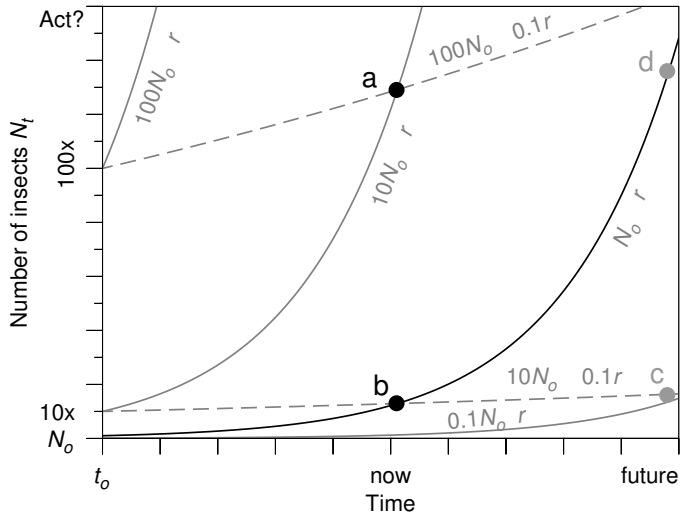


Figure 2.11: Exponential population model with decade increments for rate r and initial numbers N_o. Points a and b are at similar time from initial infestation showing different time to act on risk posed by estimates of insect population and their growth. Points c and d are future uncertain outcomes from sampling measures. Lines labelled with initial conditions.

collections which do not reduce N_t appreciably and the cost of treatment only kills up to 'c' insects.

Keeping N low

A focus on the causative agent has led many IPM actions to be aimed at reducing N_o and N_t. These activities have been laid out in systematic manner by Strang [58], Strang and Kigawa [8] and are embedded in the structuring of paper five. Actions which avoid attracting pests and block motion of pests lower N_o. Detection coupled with response activity lowers N_t.

Why vacuum now and again?

Reducing N represents loss of current individuals and is proportional to reducing harm causing individuals. Not all insect stages feed on

objects and with some exception for adults only larvae (and nymphs) feed in any way significant to collections. Yet numbers in non-feeding stages are also reduced in some control measures as well as by 'natural causes'. Reducing egg numbers once will reduce N_t in the short term (one generation) with reasonable possibility of population rebound. Frequent reduction of egg numbers such as the householder example of vacuuming or beating wool carpets periodically through the seasons, will drop r through consistent lowering of effective fecundity.

With the example of figure 2.11 an action with roughly tenfold efficiency in reducing N provides a fivefold delay to population recovery with no additional work ($a \Rightarrow b \Rightarrow d$). *Ceteris paribus* the loss prevented (ratio of area under curves) is proportional to change in N. Periodic sanitation which destroys pests (such as aspiration by vacuuming) is a mainstay for pest control where a pest is occupying crevices in floor and wall surfaces or in and under carpeting.

Figure 2.12 examines control measure timing and efficacy on an exponential model for pest populations. Any efficacy is beneficial but it may not be cost effective when compared to residual object values if control is done to little or too late. Figure 2.12 shows the result of a single treatment of 99% efficacy at time 'now'. The accumulated harm (all area in grey) from t_o to 'now' represents the lost fraction of values contributing to detection of the pest, and that forward to 'future' is yet to come[22]. Re-treatment at 'b' based on the same triggering threshold will reduce the volume of pest harm beyond the dashed vertical line. Not treating will allow losses to continue to rise matching the 'no control' line in object consumption. Losses of any values by the treatment are not accounted in this view, there could just be utility losses (temporarily unavailable) or actual harms (damage).

The white area marked 'forestalled harm' represents the direct benefit of treatment preventing physical loss, a return on investment from the first treatment saved by the second, both preserving object values and prolonging object 'lifetime'.

[22]For discussion of exponential and consumption harm, see page 64.

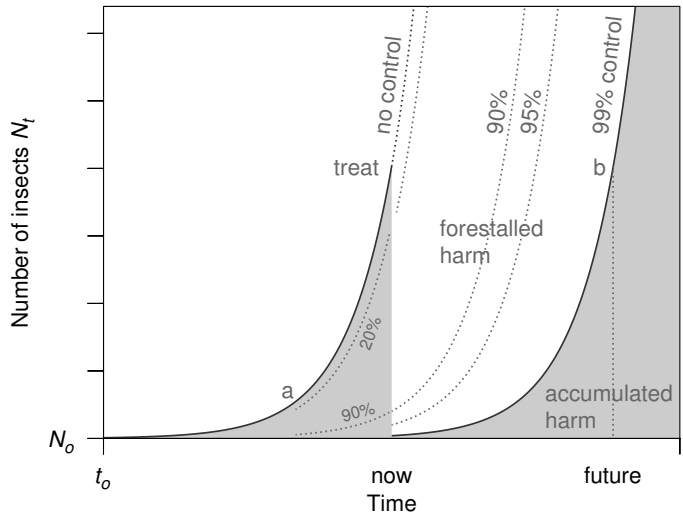


Figure 2.12: Single treatment with 99% efficacy. Area of forestalled harm under extended curve for 'no control' is direct benefit of the treatment. Detection of problem is somewhere along face 'a'. Time from 'now' to re-treatment 'b' at 'future' time is unknowable until pest growth rate can be estimated. An assumption for IPM trapping data is the triggering information along the line from 'a' to 'treat' is reproducible.

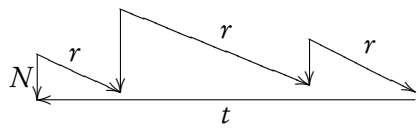
Multiple re-treatment at high efficacy will preserve significant values going forward, yet the accumulating sawtooth of harm will ultimately equal total loss. However, with episodes of complete efficacy in treatment this prospect no longer holds true and rests on the time lag to re-infestation.

Earlier treatment at 'a' even with only 90% efficacy saves the area above the 90% curve, a significant amount. Inefficient control measures killing 20% make little change and will require rapid or more effective re-treatment to avoid runaway loss. With insufficient control of the sawtooth area, there will be finite points where accumulated harm subverts object values.

This example shows why the focus on repeated early detection and

good treatment efficacies are core IPM tenets.

Like repetition of control measures for N where post fumigation re-colonization from survivors[23] leaves $N > 0$, leakage of pests N_o into collections through object acquisitions, loans and building porosities are not directly encoded into equation 2.1. With an expectation that N never reaches zero in long t the initial model assumption that t is short enough that r remains fixed would hold if repeated application of control over long t keeps N low enough r altering conditions stemming from larger populations are not incurred. Ironically, these rate alterations often lower r by higher inter-species competition, diapause induction, parasite load and waste concentration, but at a greater cost in collection contamination and losses over long t at high N.



The impact of inward pest leakage is a significant relative risk to a fairly clean facility but likely not noticeable in an infested one. However, truly clean facilities have taken pains to seal off structural vulnerabilities so leakage is likely to be small compared to acquisition risk that must be met by quarantine. Lapses in building design or maintenance have the potential to increase N through leakage of local pest species, and through improving pest habitat in a way that increases r. This is why structure maintenance and HVAC perforations are key concerns. Blocking to reduce influx, the simple window screen is an N_o reduction strategy originally developed for reducing transmissible disease via airborne pests (mosquitoes, flies).

The housing for one object (rather than per unit cost) is a pyramid of expenditure and a Markov (probability) chain to confer protection. An insect on a tall pin, in a tight box with a glass lid, on a cabinet

[23]The once standard practice of in-cabinet treatment with liquid fumigants was thought to leave populations underneath cabinets to re-establish infestation. Cabinets had poor seals. J. Jacobs pers. comm.

drawer, in a closed cabinet, in a closed room, in a building, with someone devoted to its care bespeaks considerable expression of human effort and concern. A carpet rolled on a Mylar™ sleeved tube, sheathed with clean cotton drawn closed, and supported on a pipe rack are layers of care. Both examples address keeping N low and responsible professionals would likely use less intensive systems if they continued to meet all their goals including pest control. While museums evolve systems for curating objects they are also restrained by these discipline norms of storage by large collections where extent of previous investment argues against radical alteration just for pest control. Improvements are commonly made by testing and literally thinking 'within the box' [59] [60].

Influencing r

Controlling numbers is tactical, but controlling rate is strategic. Evidence of differing pest impact are seen when 'collection health' is compared between tropical and temperate regions, and a significant portion of this variance is due to modification of rate.

To alleviate the consequence of uncertainties from difficulty in accomplishing inspection[24] to confidently establish N, Mumford and Norton consider an alternative practice:

> "The sampling problem makes stored product decision making more like some field disease action thresholds than field insect thresholds. Pathologists often base action thresholds on the growth rate potential without an accurate estimate of the initial inoculum level. With high potential growth control is against the risk of damage rather than known actual presence." [49]

This essentially argues to ignore N and base control efforts on those pests whose estimates of r come with notable risk of harm.

[24]Mumford and Norton relate the relative ease of field crop sampling to that of even inspecting piled sacks of grain [49]. This is somewhat akin to examining open shelving versus ranges of closed cabinets where the access cost is higher.

Uncertainties in the potential growth rate r will also lead to misguided actions. In figure 2.11 underestimation of rate at 'b' tenfold (including overestimating N_o by 10) leads one to put off treatment through expecting outcome 'c' and subsequently experiencing infestation 'd'. Ability to properly quantify r for a situation is key.

	N	**r**
Overestimate	Higher cost of control per individual pest killed	False crisis
Underestimate	Delayed control, greater losses than expected	Heavy crisis

However, there is is utility in this approach given the broad adoption in collections IPM of adhesive traps. Trapping is likely better at finding the presence of pests than estimating their number. The latter quantity properly requires more sophisticated direct sampling or mark and recapture methods that go somewhat against a conservator's sense of propriety ("What? You painted it and let it go!").

On the debit side, estimation of rate for quantitative establishment of risk is marked by lack of readily available summary for the less common stored-product pests historically assigned as mainly 'household' problems and now known as museum pests. What data exists may not provide a proper estimation of rate (discussed later).

Moderating r, figure 2.13 shows the effect of a 99% reduction in population and subsequent cutting the growth rate by half. Reduced rate can be achieved with lowered storage temperature (summer air conditioning, heat less in winter), egg parasitism, or strategies affecting fecundity such as pheromone interference with mating success[25]. Examining the half-rate area swept out in grey to the treatment population level at 'c' compared to the full rate population recovery (dashed line cusp at 'b') shows significant reduction in accumulated harm at the same future time in figure 2.12. The disquieting observation of

[25]Such as mass pheromone trap campaigns or Exosex™ male-confusion strategies for clothes moth.

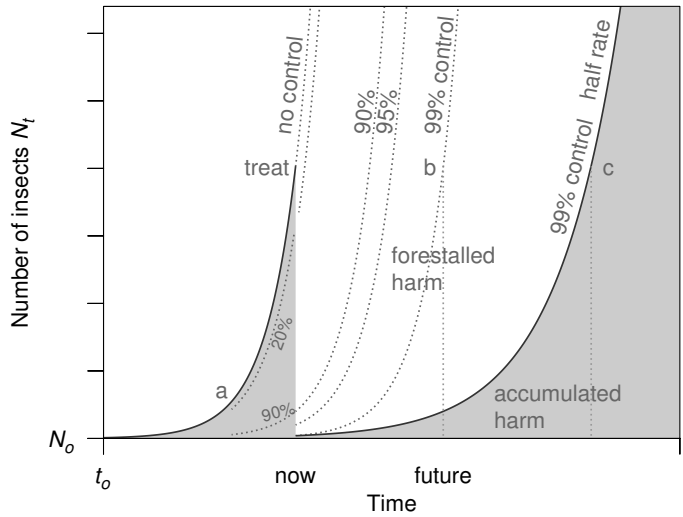


Figure 2.13: Treatment with 99% efficacy followed with half reduction of growth rate. Area of forestalled harm under extended curve for 'no control' is direct benefit of the treatment. Additional benefit of the forestalled re-treatment is area 'b' to 'c' within exponential lines from 'now'. Figure 2.12 lines retained for comparison (dashed).

marginally greater accumulated harm before re-treatment at 'c' than at 'treat' is offset by the greater forestalled harm over time by skipping 'b'. Barring lowering the treatment threshold, further rate reduction improves this, further suppressing residual long-term low infestations.

Rate control strategies are taken when stored grains are fumigated then cooled, to reduce the amount of chemical used over time, combat the presence of pesticide resistance in a portion of the pest population, and to prolong the positive effect of treatment [61] [62].

Figure 2.14 expands the scale for N_t tenfold to show the dramatic growth scenario projected in the uncontrolled exponential model. The large area of forestalled harm preserved by 99% control and more by 99% control with subsequent half-rate of growth is equally dramatic.

To illustrate the implication of r_m values figure 2.15 presents the rates

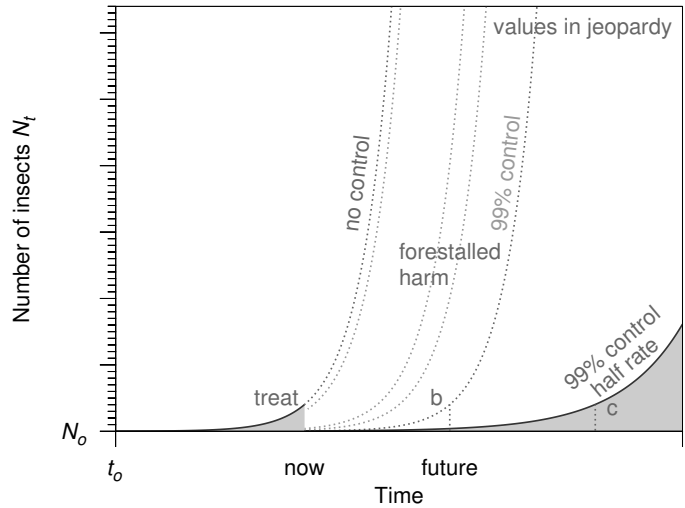


Figure 2.14: Tenfold higher plot of figure 2.13 with lines retained for comparison. Projection to crisis proportions is more clearly seen along with positive effect of treatment and subsequent rate control in preserving object values. Points 'b' and 'c' indicate pest levels equivalent to that when treated. At some level values are in jeopardy.

of population growth for museum beetle pests listed in table 2.2.

Driving an IPM program by growth rate will need more information of this type properly worked up as rate descriptions for many museum pest insects are absent from publications.

A more complex model has to cope with downturns in growth rate as limiting factors come into play, but there is validity in the simple exponential model when the carrying capacity of pests can be much higher than the level needed to have greatly reduced object values (thin aesthetic surfaces and small volume objects destroyed)[26].

[26]Experiments limiting space, food, or population have been carried out with insect pests. These exhibit self-limiting factors with lowered rate and individual size resulting in prolonged undulating population numbers deviating from initial rough exponential and logistic curves [63] [64].

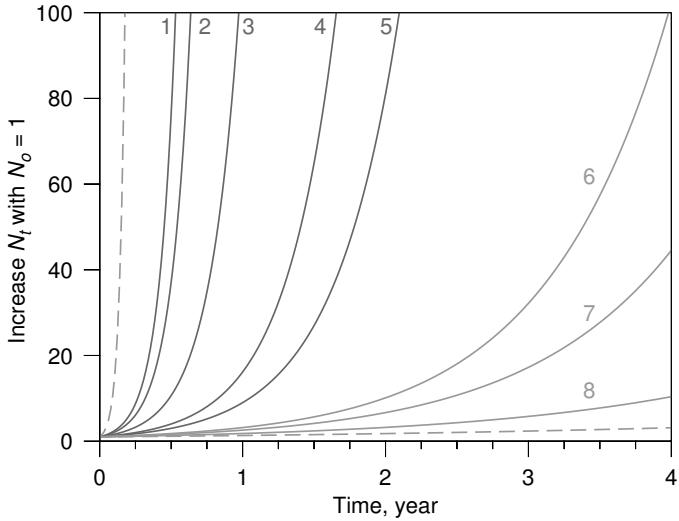


Figure 2.15: Relative rate of pest species population growth plotted as $N_t = N_o e^{r_m t}$ with r_m from table 2.2. Lines marked 1) *Dermestes frischii*, 2) *Necrobia rufipes*, *Dermestes maculatus*, 3) *Lasioderma serricorne*, 4) *Stegobium paniceum*, 5) *Trogoderma granarium* are representative of severe dermestid and anobiid beetle pests. The ptinids (spider beetles) 6) *Ptinus tectus*, 7) *Gibbium psylloides* 8) *Mezium affine*, *Niptus hololeucus*, *Ptinus fur* are slower growing pest species. Dashed lines show maximum and minimum beetle population growth rates in sources [25][29].

Other models (discussed below) could be superior in assessing the risk as they adjust for significant influences from thermal fluctuation, time lags in stages of development and induced diapause. However the simple exponential does allow examination of the degree of urgency in the short term upon identifying a pest in quarantined goods, or a collections area. Arguably any necessity to understand consequences of non-exponential models is more important for the pest discoveries one decides not to control and long running low grade infestations than the early discoveries which are clearly to be responded to.

More values on fecundity, lifespan and approximated r_m are given in

table 2.4. These are very problematic for defining rates that can be confidently applied as they are based on fecundity documentation presented at a summary level, the common approach found in many pest guides. The necessary information outlined by Birch [28] for proper calculation of rate is absent.

Reviewing the ranges in table 2.4 shows how conditions of estimation are less than ideal without more information. Oviposition data, less uncertainty on which value for lifespan to use, and better indication of environment effect are preferred. As an example *Ptinus tectus* evaluates as a high rate here, but Howe assessed it much lower with more information at his disposal (see value in table 2.2). Formal treatment of rate of increase is required instead of the *ad hoc* demonstration values tabulated in table 2.4.

The encapsulation of this minimal demographic data in tabular form is in effect a second pass model[27], selecting species for relatively strong threat as cultural pests. Source texts will provide more developmental stage information and capability for harm (substrates affected, threshold environments). For example, the modest population growth rate of *Xylocopa virginica* is disturbingly offset by knowing the cigar-sized egg-chambers carpenter bees readily bore to accomplish it.

Decision support tools will require clear selection by pre-screened conditions (warm or cool, moist or dry) in choosing or calculating which rate to apply. However the precis of data for pest rate modelling in tables 2.2 and 2.4 shows what likely exists for basic work through literature review, before proposing laboratory studies to cover notable absences.

Thresholds for pest development, r approaches zero

Studies which determine overall limits and maxima for common pests of collections can be used for threshold models where development is essentially zero[28]. Among food pests, Howe [25] reported limit data for *Lasioderma serricorne*, *Stegobium paniceum* and *Ptinus tectus* which

[27] First pass is selection from all organisms by their utilization of cultural property.
[28] Used in degree-day calculations as the 'development threshold'.

Species	Fecundity	Lifespan	$\approx r_m$
Tineola bisselliella	40–50	(50–90d) 4yu	0.54
Ptinus tectus	100	94d	0.51
Thermobia domestica	50	45–135d	0.50
Blattella germanica	(120–150)240	65d@35°*C* (103df) 54–215d (200)	0.50
Anthrenus scrophulariae	60	77–110d	0.46
Lepisma saccharina	100	3–4mf 2–3y	0.41
Anthrenus flavipes	60	93–126d	0.39
Periplaneta australasiae	480–720	213d@30°*C*	0.33
Supella longipalpa	(182)	130d@28°*C* 250d	0.22
Xylocopa virginica	5–6	84–99d	0.15
Blatta orientalis	310@28°*C*	360d@28°*C* (450d) 740d	0.14
Lyctus planicollis	18–122(51)	98df@31°*C* (9–12m)	0.13
Dermestes lardarius	100	1y 2mf	0.13
Anthrenus verbasci	40	249–354d	0.12
Anobium punctatum	(18, 28, 55)	(1yo 2–3yi)	0.09
Lyctus brunneus	17–21	6–7mf (9–12m) 2.5–4y	0.09
Periplaneta americana	(128)	210d@28°*C* 600d	0.08
Lyctus linearis	15–20	6–7mf (9–12m)	0.08
Syrex longicauda	300–400	2(3–4)5yo	0.05
Hylotrupes bajulus	150–200	(3–5y)2–10y	0.04
Xestobium rufovillosum	(40–60)201	1yf 10yu 3–7yo 4.5yi	0.02

Table 2.4: Collation of data for estimating collection pest fecundity and lifespan. Fecundity given as total eggs / ♀ with any noted decreases (fractional survival) factored in. Lifespan average or value for indoor environment used to approximate r_m (days/28 to match convention in table 2.2). Values obtained from pest descriptions in Ebeling [24]. Averages are in parenthesis, ranges with hyphenation. Time is abbreviated as day d, month m, year y, and outside o, indoors i, favourable conditions f, or unfavourable conditions u, with rearing temperature given when noted.

become museum collection pests. There is sufficient evidence developed to postulate general environmental boundaries to pest life[29]. The

[29]See figure 2.11, discussion in chapter 4.

pressing issue is can collections managers obtain, maintain or sustain these beneficial conditions to supplant the more probabilistic nature of effecting control where pests still have the advantage.

Objects are very similar to grain in storage where allowable temperature and moisture content are also governed by preserving non-pest related market requirements (chemical stability, milling quality etc.) and like collections, the cost of reducing grain moisture and temperature ensure storage will be optimized to just below where significant harms can develop. Under sustainability pressures we can expect museums to perform similar calculations. Those institutions which have adopted lowered temperature to greatly reduce pest incidence in collections will be under the greatest pressure to re-substantiate its value or switch (a setback to previous loss rate).

For estimating impact on cultural pest insect growth there are few studies which widely explore responses to environment (generation time, fecundity, duration of harmful stages, nutrition effect on consumption, consumption) unless the pest has had great significance for food production or human health[30]

Using consumption rate as r

There is another way to assign and calculate r than population growth rate which is directly useful in calculating risk. Unfortunately with museum pests there is a major lack of consumption data against other influences on pest growth. Consumption r (roughly proportional to population r) gives the bulk rate of object loss from which to model the potential for collection harm posed by pest species against vulnerable structures and materials in collections.

Chittenden [43] recounts the discovery of *Attagenus piceus* (now *A. unicolor*) a severe pest of the silk trade and measuring 'half-grown larvæ' each producing four to five small holes in silk bolting within 17 days of placement on the fabric. The linear growth of the larvae

[30]Longstaff and Cuff [65] provide an informative example for the grain weevil *Sitophilus oryzae* merging a degree-day population demographic model with continuous function physical models.

was measured, being visible from hatching in one week, 1/10 of an inch at 5 weeks, 2/10 at 10 weeks, 3/10 at 14 weeks and just "a possible broadening toward the head" at 18 weeks. Egg and young larval lengths are also reported by Griswold and Greenwald [45]. The linear growth of *A. piceus* is plotted proportional to time in weeks in figure 2.16. Volumetric increase from the egg (ellipse) near 0.14 mm^3 to final larval instar (truncated cone) near 10 mm^3 roughly follows an exponential curve as shown in figure 2.17.

Figure 2.16: Lines show *Attagenus piceus* larval lengths proportional to numbered week. Data from Chittenden [43].

The larval growth in volume is proportional to damage incurred (mass conversion to cellular constituents, fat body, exoskeletons, etc.). This substantiates an approximation of harm is represented by integration of the continuous exponential function in figures 2.12, 2.13 and 2.14. However, larvae will not feed continuously for growth, with a broken pattern expected around ecdysis (larval moults) and diapause. Moults increase for larvae with a longer life[31]. Water is often obtained solely through consumption of 'dry' matter providing a second motive for consumption.

Stengaard Hansen et al. [66] address the lack of consumption data with a study on a significant Nordic European pest *Attagenus smirnovi*, Zhantiev. Consumption rate proved largely insensitive to RH at both 50% and 75% but showed clear differences with temperature. Figure 2.18 shows the overall trend with zero feeding indicated by data for other species. The expectation is information from this type of

[31] Cast skins are common evidence of infestation found in drawers. Their production is not fixed, but may range from 7 to 17 with *A. piceus* [45].

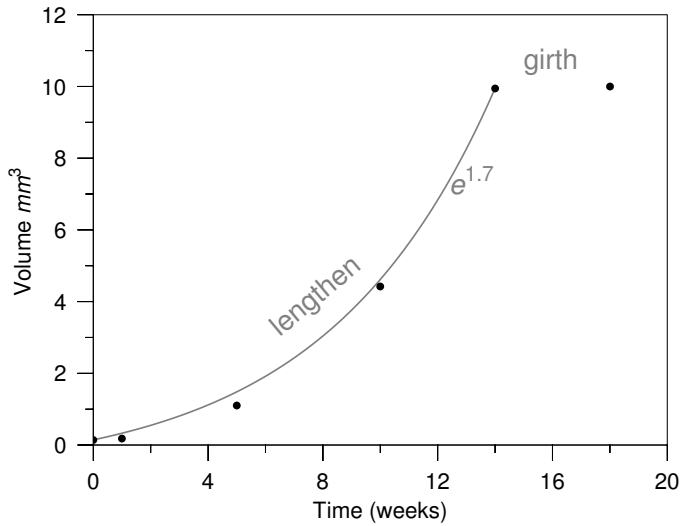


Figure 2.17: Retained volume after consumption in developing *Attagenus piceus* (body size) closely follows an exponential while length increases. Some increase in head girth once elongation ceases. Data from Chittenden [43] modelled as egg ellipsoid and truncated cone larvae.

study can model likely outcome to change in climate [66], but equally models differential loss rates from pests depending on extent of building climate mitigation (turn the HVAC knobs, use or save energy).

Why 'when to act' is not a fixed N_t

A question is sometimes put forward 'what is the minimum pest number at which I should act?'

Equation (2.1) does not model this connection directly except through rough equation to food consumption. Uncertainties allow a flexible 'justification of expense' knob for killing pests at any number. This approach is easy to sustain if the problem is isolated and treatment is quickly done and cheap (bag object, gently place in freezer, clean afterwards), but harder to sustain if the problem is recurrent, widespread and treatment difficult and expensive (tarp building, evacuate staff and

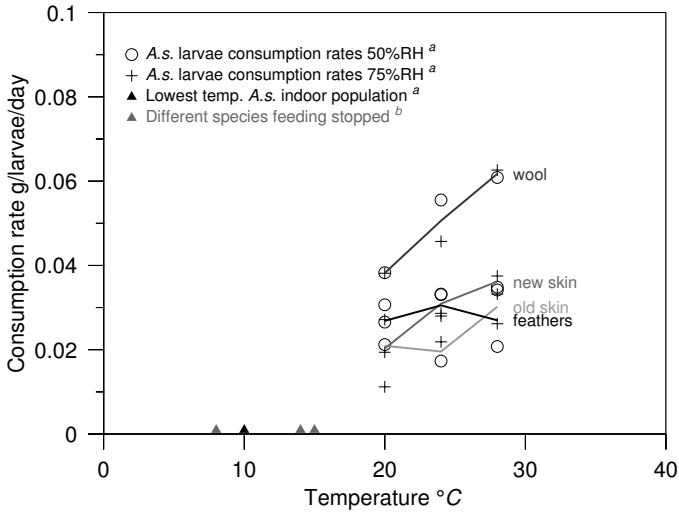


Figure 2.18: Measured food consumption rates for *Attagenus smirnovi* larvae. Lines of RH averaged consumption by foodstuff and envelope of points project back to region of zero feeding marked by values reported for other collection pest dermestids and lowest monthly average temperature recorded for areas supporting *A. s.* populations at National Museum of Denmark. Data (a) from Stengaard Hansen et al. [66] and (b) from Strang [67]. A trapezoid response curve (figure 2.4) could be fitted over this data similar to that for population growth rate discussed earlier.

sensitive operations, fumigate termites, fix structural damage).

There is some measure of 'aggression' that represents the per pest harm. The more aggressive the harm along the scale of *webbing, flyspecking, grazing, perforating, shredding* the less tolerated pest numbers become irrespective of low population r. The losses and concomitant restoration costs visibly mount with N_t which implies there should be a determinable threshold by back calculating from a maximum budget allocation for pest control and recuperation out of annual expenses. A smaller budget then implies less tolerance to the consequences of pest

activity[32]. This may not translate to heightened action by institutions having 'subsistence' attitudes with harsh limits in finances. However where there is a higher degree of pressure on quality of collections the work gets done on the back of individual initiatives, or institutional policy. Papers attached in this volume were written specifically to show how efficacious and inexpensive pest control could be achieved to assist marginally funded institutions.

Currently, preservation disciplines vary their response to threatened objects' apparent vulnerability and values under attack by 'gut estimate' rather than estimate of guts. Likewise, it is unsurprising that without the will or means to determine a tolerable number beyond 'one is too many' this becomes the default.

Demographic models are fundamental to estimating r

Griswold and Greenwald chose to study four species of dermestid beetles [45] in the late 1930's for the following still topical reason:

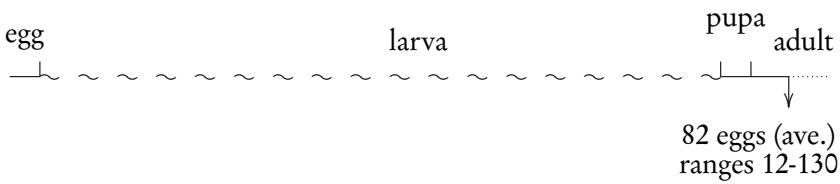
> "Satisfactory control measures for carpet beetles cannot be devised until the biology of these insects is better understood. Because of the present interest in air conditioning, it is important to determine the effect of temperature and humidity on carpet beetles and other household pests. In a furnace-heated building, the temperature remains fairly constant through out the entire year but the humidity is much lower in winter than in summer .... Since any type of equipment that alters the temperature or the humidity in homes may have an indirect bearing on the control of household insects, studies concerning the effect of temperature and humidity on such pests become of economic importance". [45]

Unlike a previous study on clothes moth [68] Griswold and Greenwald showed that humidity was not a significant factor in length of

[32] "Tell me a cheap / free way to save it or I have to throw it out" has been a common enough thread in discussions between the author and callers for advice.

development in dermestids, their work on temperature effect showed the duration of egg, pupae and adult stages were highly governed[33], but this did not extend to affecting duration for ovipositing females nor numbers of eggs laid. Egg production is the closest primary estimate of population growth rate r. Similar to other authors pursuing the understanding of insects and environmental factors, they list food composition and survival numbers but sadly do not track concomitant volume or mass of consumption which one could convert to model estimations of object harm.

It is informative to look at the life history of a population of the dermestid pest *Attagenus piceus* (now *A. unicolor*) as a caution to adopting any rate calculated without reference to demographic details. From data in Griswold and Greenwald [45] the graphically proportional life cycle of an individual female reared at 25 °*C* can be depicted as:



where the dashed line represents the elastic period over which larval feeding and development will occur (258 indicated, to 639 days). The egg stage averaged 10 days (9–12), the pupal stage averaged 9 days (8–10) and median pre-oviposition stage 5 days (3–16) and average oviposition period of 11 days (3–18). The non-larval stages exhibit relatively short and tighter distributions than larvae so discerning patterns of adaptive larval development are the primary complication in modelling insect populations. Post-oviposition lifespan (dotted line) poses less harm to collections as the production of new mouths has ceased, just giving time to distribute adult bodies as food for sustaining the next generation (temporarily distracts from eating objects).

[33] Plotted stage durations as 1/time against temperature exhibits similar slope.

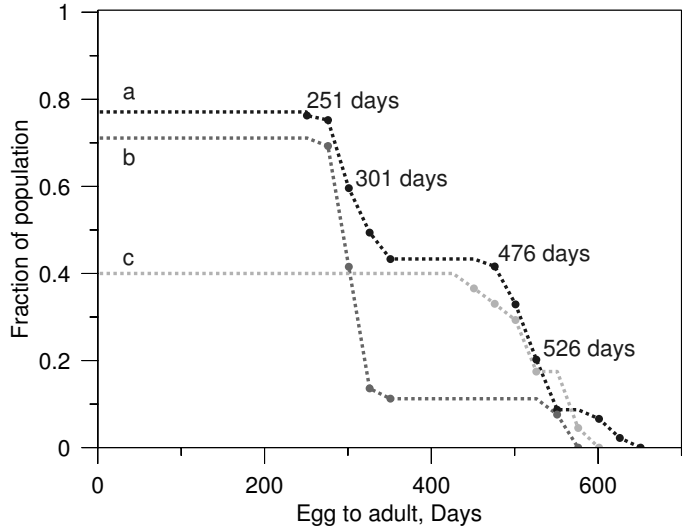


Figure 2.19: Distribution of maturation (egg to adult) for *Attagenus piceus* (now *A. unicolor*). Lines show three cohorts on differing substrate and temperature: 'a' rat fur, fish meal, 25 °*C* to 26.7 °*C* ; 'b' rat fur, fish meal, cereal, 'room temperature' (+18 °*C*), 'c' chicken feather, oat flakes, room temperature. Points are times in Griswold and Greenwald's tables 3 and 4 [45] reporting groups of matured adults. These are indicative of points at which a new generation could begin (vertical faces). Initial vertical offset from unity shows cohort mortality for the rearing conditions. Lines 'a' and 'b' developed as two sub-cohorts broken by diapause while 'c' did not.

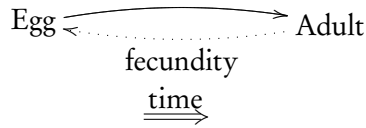
Modelling demographic response to conditions

Figure 2.19 depicts three cohorts of *Attagenus piceus* (now *A. unicolor*) from tabular data collected over a two year period by Griswold and Greenwald [45]. The profiles show ability of an infestation to exhibit differing patterns of development as a response to conditions. Some animals of the same cohort finished in the first year while the remainder developed over two years (see lines 'a' and 'b')[34].

[34]This pattern was also noted with 1/3 the population in *Ptinus clavipes* entering diapause to delay development, Howe cited in Ebeling [24]

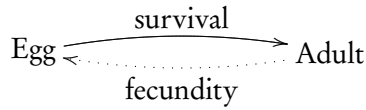
On less nutritious substrate they all responded by developing slower: figure 2.19 line 'c' reared on bird keratin and carbohydrate, rather than those reared on mammal keratin and protein 'a', or mammal keratin, protein and carbohydrate 'b'. Intervals of diapause were not reported.

The simplest growth model from summary literature at hand such as in table 2.4 is:

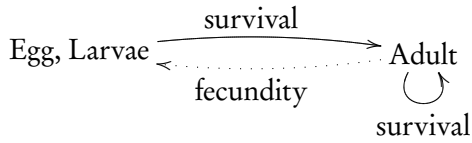


where all we may have are a range of numbers for eggs laid and overall lifespan.

A little more detail includes observations of survival lowering the rate of increase under natural or measured conditions:



It is possible to use partial life cycle information with two stages when age of maturation, fertility, and survival is known to determine some of the properties of a population [69].



The simple model gives a rate of increase r_m while ignoring influences such as temperature related seasonal effects. Adding observations on additional stages and variables requires more complex demographic models to incorporate relevant effects, for example the figure 2.19 illustration of *A. piceus* bimodal development response with good nutrition and elevated temperature, but uni-modal with lower temperature and poorer nutrition. Also, Birch [26] noted from life-table work

that immature insect mortality greater than 50% swamps the influence from temperature and humidity.

Including the accumulation of dead adults gives an additional and large contribution to a detection probability model for coordinating trap and inspection studies, posing the side question: do dead insects increase probability of discovery more than live ones. Visual inspection will find live and dead insects, while dead insects generally do not walk into traps. This simple fact reinforces IPM programs recommendation to carrying out both these means to increase overall probability of detection. Even rudimentary efforts will inform of the species one has to contend with, and that can be responded to by invoking a risk model based on rate of growth, environment, nutrition and other relevant factors.

There are transition matrix methods for examining population growth and a wide variety of ecological information. A stage to stage transition matrix (designated **M** by Lefkovitch [51]) can be used when age distribution data is difficult to obtain[35].

Demographics of age grouped transitions using a more detailed life cycle history than that with stages can be dealt within the Leslie matrix (designated **A** by Leslie [70]). Direct incorporation of temperature using degree day classes have also been employed for modelling both linear and non-linear temperature response [65].

The type of data available often dictates the models people apply to the problem when they cannot expand on the information. Lotka' s equation (2.1) is useful with minimal data (and subject to distortion by sample variation) yet it underpins other approaches which refine the determination of r_m.

Simpfendorfer [27] lists other fundamental equations supporting different approaches to the problem of establishing demographic knowledge for difficult cases:

[35]Lefkovitch developed the stage based approach to model population fluctuations in *Lasioderma serricorne* (tobacco beetle), a species which can also become a very serious pest in collections.

The exponential model r intrinsic capacity for increase (Birch [28] [26]), also qualified for specified conditions r_m (Krebs [71]) and 'G' is generation time (also represented as 'T_c' in Beckett et al. [13]) are equated as:

$$r_m = \frac{\ln R_o}{G} \tag{2.3}$$

Equation 2.3 is the simple rate calculation for the exponential model (equation 2.1). Again, R_o is the fecundity, 'multiplication factor per generation' or 'net reproductive rate' which is equated from life tables as:

$$R_o = \sum_{x=\alpha}^{w} l_x m_x \tag{2.4}$$

where l_x is fraction surviving to time x, m_x is ♀/♀ fecundity [26] [27]. Matrix models examined below use a 'finite rate of population growth' λ (Leslie [70], Birch [26], Lefkovitch [51], Caswell [69]) equated to r as:

$$\lambda = e^r \tag{2.5}$$

Life tables are generated with distributions represented by the Euler-Lotka equation [27] as:

$$\sum_{x=\alpha}^{w} l_x e^{-rx} m_x = 1.0 \tag{2.6}$$

Choosing a time increment for comparing species which can have greatly varying lifespans is a problem. In calculating rate of increase, various authors use convenient time scales within commonly measurable values between species such as the 28 day span for determining R_o adopted by Howe [25] [72] for determining rate of increase by counting and removing new adults every lunar month or Beckett et al. [13] choosing to compare R_o over a maximum of 8 weeks when deriving comparable values for several species. Beckett et al. [13] applied a demographic approach to previously collected life cycle data

of grain pests integrating temperature and humidity responses[36]. Projected development threshold temperature and RH for four grain pest species by this method are plotted among other data in figure 4.10.

As Birch [28] determined on one week intervals that using the early portion of total fecundity over time does not greatly distort the calculated intrinsic rate, these various pragmatic time base adjusted results are considered useful. Time base choices can also be readily incorporated into matrix model approaches [69].

In equation 2.3 there is no mechanism for directly encoding and evaluating the ongoing structure of populations since the rate is extracted from life-tables assuming an equilibrium value for a monotonic exponential model. Life-tables (equation 2.6) also require age structured demographic data determined from reared populations in controlled environments. This form of data may only be available for species of keen commercial concern due to its cost of production.

Equation 2.5 is an exponential model used to map the intrinsic rate r to a value λ from a transition matrix describing the life cycle from age or stage classed values. Lefkovitch's transition matrix incorporates as much stage classed information as can be determined from observations which influence population outcome as probabilities that each life stage will progress to a subsequent one or remain within the stage. To summarize the mathematics, the largest matrix eigenvalue λ_1 is determined[37] and converted to the intrinsic rate r through equation 2.5. The ratio of eigenvalues λ_1/λ_2 reflects the time for converging on a constant rate of growth [73] (stable population distribution).

More measures can be taken after re-iterative calculation (multiplying

[36]Finite weekly rate of increase $\lambda = e^{r_m}$. The model at any temperature humidity pair is: $r_m = log_e R_0/T_c$ based on 8 week period data for R_0 and l_x where: R_0 net rate of reproduction (product of female fertility and survival); l_x adult survival percentage at several temperatures and humidities; r_m weekly infinite rate of increase; T_c cohort generation time; λ follows a trapezoid shaped rate curve [13].

[37]Each stage in a population whose survival, development to the next stage and fecundity contribute partially to the reproductive success of the whole population is represented by a dimension in a matrix (row and column entry). The principle eigenvalue represents the largest response of the aggregated contributions of the stages.

the population matrix by the transition matrix) and plotting of outcomes for each step models population fluctuations or relaxing to an equilibrium state. Caswell uses the term 'projection matrix' rather than transition on the distinction that these models 'project' a future from the currently measured (mathematically codified) states rather than 'predict' it [69].

The Lefkovitch matrix may be the most detailed demographic model that can be populated with available information on collection pests as stage development times are commonly summarized in literature whereas breakdown into age structured information is less common. While Howe [25] noted influential oviposition data is often lacking which reduces accuracy of life table methods, stage based demographic approaches are taken when more detailed data is sparse and hard to come by [27] and the method has a lot of flexibility in application to various cases [69].

Utility of demographic models to IPM

The application for demographic growth models to IPM is to stand as a measure of risk through growth and consumption potential, but it could extend further. One of ecology's goals is testing for sensitivity to changes to determine how best to assist organism survival through management plans [27]. In protecting cultural property this would be inverted to focus on assessing control by attacking critical stages.

The criticism of early ecology models for being artificial 'closed systems' studied for their likelihood to joust with extinction [15] is beneficial as these are the precise conditions we aim to hold true in collections through IPM practice. Lefkovitch developed his variant matrix approach to analyze laboratory populations of *Lasioderma serricorne* when establishing constant increase and survival with "infinite food and space", undulating plateau and survival in populations with "ample food and limited space" and extinction with "limited food and space" [51] [64] [74].

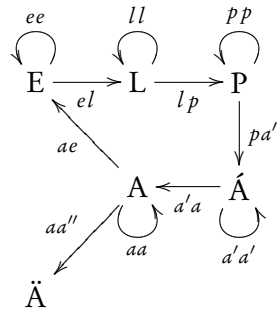
Confirming sustained decrease of population growth rate allows some assessment of outcome and efficacy in applying IPM methods. Or-

ganisms with low rates (low recovery or rebound potential) will be managed by a less frequent control application, or with less efficacious but possibly cheaper means at higher frequency or duration.

Longstaff [73] considers the use of the transition matrix for examining the effect of control methods which are stage dependent on the population growth rate (example: a program capable of killing only adults such as with flying insect lures). Caswell [69] also discusses the application of matrix models and applied demographics to the inverses of species conservation: pest reduction, halting invasive species, and extermination.

Another possible application is to model relative proportions of larval and adult numbers, the two stages commonly found by trapping programs. Initial demographic profiles of early infestations can be modelled to reveal highly fluctuating or stable development patterns, which in turn influence expectations for detection and control.

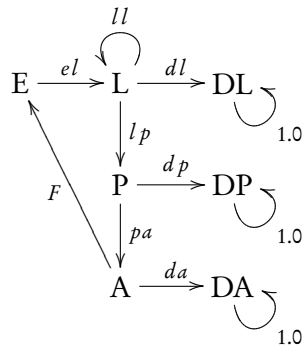
The following life cycle diagram shows egg E, larva L, pupa P, preovipostion adult Á, ovipositing (egg laying) adult A, and post-ovipositing adult Ä stages which were determined in Griswold and Greenwald's study [45].



Dead from larval studies are not shown on the diagram as their loss is incorporated in the stage to stage survival probabilities but not counted outright as part of the population. Where an amalgamated survival count is reported it can be interpolated across all stages if constant losses are presumed, or put into the most likely pre-mating stage where

large losses are seen (lowered egg fertility, young larvae mortality). Diapause conditions can also be modelled [69] as delay loops.

Life stages can be observed on regular time increments in experiments, but this information cannot readily be applied to classifying captured live specimens within a life stage when there is no sure way to determine age from visual cues. However, a straightforward $E \rightarrow L \rightarrow P \rightarrow A \rightarrow D$ model[38] can be used match trapping and inspection results of live and dead stages. Incomplete metamorphosis could use size classes for the nymphs (small, medium, big). Still, determination of survival probabilities and fecundity must rely on estimates obtained in experiments with recorded conditions. A life cycle graph with as much complexity as we might be able to observe from an infestation is:



Complexity from any loops and converging paths in life cycle graphs can be simplified[39]. A life cycle stage graph is transferred into a square population transition matrix as shown below. The transition matrix **M** can be read as members of stages labelled along the top will transition to the stages in the next time step labelled down the left side

[38] D dead, DL dead larvae.

[39] A z-transformed graph is produced as an intermediary, combining multiple inputs and 'self-loops' into a single path [69].

wherever non-zero probabilities occupy the matrix:

	E	L	P	A	D
E	P_{ee}	0	0	F_a	0
L	G_{el}	P_{ll}	0	0	0
P	0	G_{lp}	P_{pp}	0	0
A	0	0	G_{pa}	P_{aa}	0
D	0	0	0	G_{da}	1.0

The fecundity (females per female) is F_a. When fecundity changes significantly over the adult phase, it is modelled with added steps in adulthood.

The probability of growing from egg to larvae is G_{el} and the probability of larvae surviving in the larval stage is P_{ll}. Dead D is encoded in the matrix as simple accumulator for adults, perhaps more recognizable than discerning a chewed larval skin versus a cast, or expecting to not find highly predated small larvae and cryptic pupae. Unless one is modelling a delay in adult development with P_{aa} it will be zero and G_{da} will equal one.

Coping with less than perfect information through stage based matrix models is covered by citations found in Caswell's book [69] with approaches to incorporating knowledge about time in stage, diapause, mark recapture, suppression, and more. Simpfendorfer shows examples of other author's shark demographic models where "limited age information for a species or the time spent in stages is variable" is a close match for some of our information on collection pests and provides some guidance on means to calculate appropriate P and G values [27].

Multiplication of the transition matrix developed by a population matrix (accumulated individuals in each stage as a column matrix) gives the projection to the next state. N_{t+1} is the sum of all members distributed in all stages. **M** can be modified to accept stochastic influences in each step, deterministic ones such as rising or falling pest density, and variable length stages as can be found in Caswell [69].

$$|\mathbf{M}| \times |N|_t = \left| \begin{matrix} n_e \\ n_l \\ n_p \\ n_a \\ n_d \end{matrix} \right|_{t+1} = |N|_{t+1}$$

Lefkovitch asserts: "When the various stages have different durations, it may be possible to derive **M** from **A**, should the latter be known; it does not seem possible to derive **A** from **M**." [51]. This means we can develop stage based approaches to match information in detection programs from existing life table and age-based matrix work. Lefkovitch continues: "However, no matter in what way the population is classified, its rate of increase in the stable state is unchanged; it is therefore obvious that the dominant root of **A** is equal to that of **M**, both being equal to e^{r_m}." Which leaves us with the apparent utility of **M** for modelling long running (stable) infestations in collections and assisting in their decline without detailed life-table data.

In addition to natural mortality, treatment survivability can be applied to the population matrix to model treatment efficacy and population recovery from a projected distribution in N_t. As an example, survival values of 0.001 for eggs and larvae, 0.1 pupae and 0.01 for adults are described as a model for post fumigation of grain by Adam [75].

Diapause and rate calculation

Resuming with the didactic application of Lotka's equation (2.1), figure 2.20 shows population growth from one generation using the simple exponential model to represent each half of the cohort of line 'a' in figure 2.19 by their mean rate of increase, treating them as discrete simultaneous populations. The leftmost grey curve shows maximum rate of increase for average fecundity, all in shortest time with no mortality. The leftmost black curve shows modelled first half-cohort generating around 16 replacement individuals at time 'A', and 250 at time 'C'. The rightmost black line shows population development of the

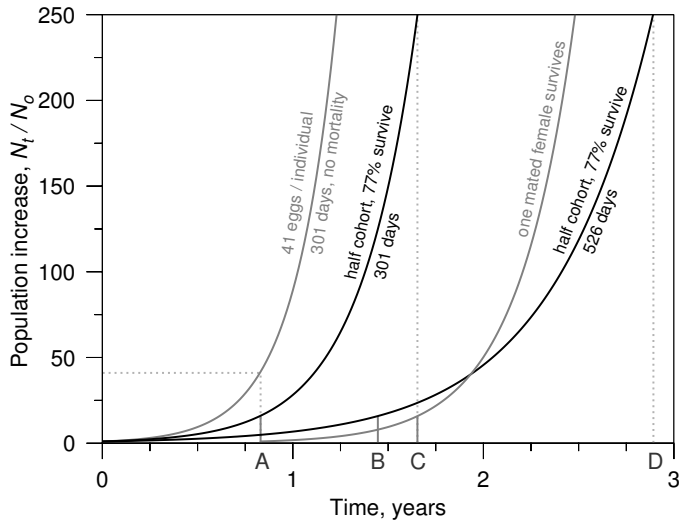


Figure 2.20: Rate of increase at earliest completion of two half-cohorts of *Attagenus piceus* from line 'a' in figure 2.19. Average of 82 eggs/female, 77% survival and approximate 1:1 sex ratio [45] gives about 32 replacing individuals/individual. Rate of increase using $r_m = \ln(.77 * 82/4)/t$ (equation 2.3) for the start of each of the two half-cohorts in figure 2.19 gives lines for median generation times of 301 days and 526 days. Vertical lines A and C mark the early cohort generation at 301 days and subsequent early cohort at 602. B and D mark the late cohort at 526 then 1052 days.

late half-cohort, adding roughly 250 individuals at 'D'. The early half cohort could be maturing a second generation at 'D' of just over 4000 individuals, so the late developing cohort would contribute just 6% of the total at that time.

To illustrate the power of increase, the rightmost grey line shows a surviving mated female at 'A' with a 301 day first generation at 'C', outproducing the entire late developing half-cohort which matures at 'B' before its replacement diapausing generation matures at time 'D'. This simple breakdown is useful in examining the rough impact of slewed out demographics better handled by matrix models. Los-

ing a percentage of larvae to later development does lower early peak numbers. Even so, with longer adulthood high fecundity pests, in the absence of full demographic models there is still reason to look at values representing the earliest bulk of maturation than the mathematical central tendency of the whole distribution (see figure 2.21).

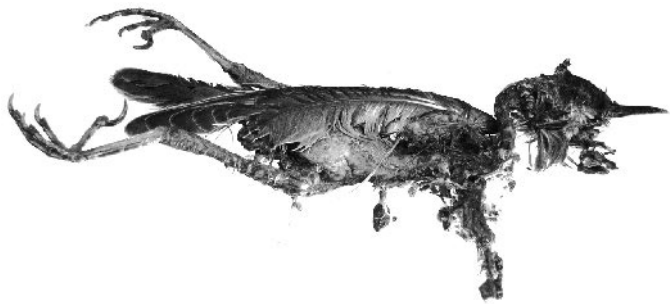


Figure 2.21: The early 'worms' get the bird.

Late development may be deleterious to larvae as it exposes them to predation longer, but it confers population robustness by ensuring an early colonizing population does not remain reliant on lock / step crops of vulnerable eggs once it is established. Late developing larvae can also take advantage of eggs, young moulting larvae and dead adults as food, an act which alters population structure and restrains growth. Indoors, Griswold and Greenwald [45] observed carpet beetle (dermestid) larvae can be found year-round and adults are seen nearly year round except winter months. A probable cause of this pattern would be larval diapause not producing adults in the cooler period combined with short adult life eliminating the existing adults.

The figure 2.19 line 'c' population was forced into a long lived single cohort by circumstance of marginal conditions. While this slowed development and reduced survival, the induced lock / step ensured the necessary condition of mating adults maturing at the same time, in conditions generating lower overall numbers. Demographic changes from food quality play a key role in adjusting growth rate of the most damaging insect stage.

Increasing chance of overlap also improves mating success. Unmated *Attagenus piceus* lived almost twice as long as mated, the females longer than males when unmated, and shorter when mated. Male *Tineola bisselliella* (clothes moth) average 20 to 31 days while females 8 to 20 depending on humidity [68].

With similar inflections for the bulk of their populations, line 'c' in figure 2.19 would closely match the 526 day / generation curve, and line 'b' the 301 day / generation growth curve shown.

If the maturation data for 12 colonies of three dermestid species illustrated in figure 2.22 are considered as tracking infestation inocula, the patterns of maturation and relative survival indicate different initial rates of population growth and subsequent demographics which in turn influence IPM trap and inspection data.

Without a demographic model to guide experiment design and structure the data existing publications on collection pest insects may not have covered required factors, followed sufficient numbers, or presented data in a useful format. Even in their long running study Griswold and Greenwald could not provide a complete picture of the four species they followed through inability to determine sexes within a species. Results of a simple rate calculation[40] are shown in table 2.5.

Insect diapause strategies which adjust how they develop or wait through inclement times affected Griswold and Greenwald's work that spanned two years. Although the coleoptera (beetles) predominantly diapause as adults, the dermestid beetle pest *Anthrenus verbasci* will diapause as a "fully fed final instar" (larvae) [76]. *Anthrenus verbasci* and *A. sarnicus* appear to also have single or multi-year larval development, the former diapausing on a 41 week interval [76]. Photo-period and temperature are the predominant cues for inducing diapause, and only in *Trogoderma granarium* has low and high RH appeared to induce larval

[40]Fecundity tabulated is all eggs laid, divide by two for calculation of rate assuming 1:1 sex ratio. Fecundity indicated with /2 was further divided into half cohorts to match development. Rate calculated as $r_m = \ln(N_t/N_o * \text{survival})/t$ where t =days/28 giving the same convention as Howe in table 2.2 and incorporating documented survival rates.

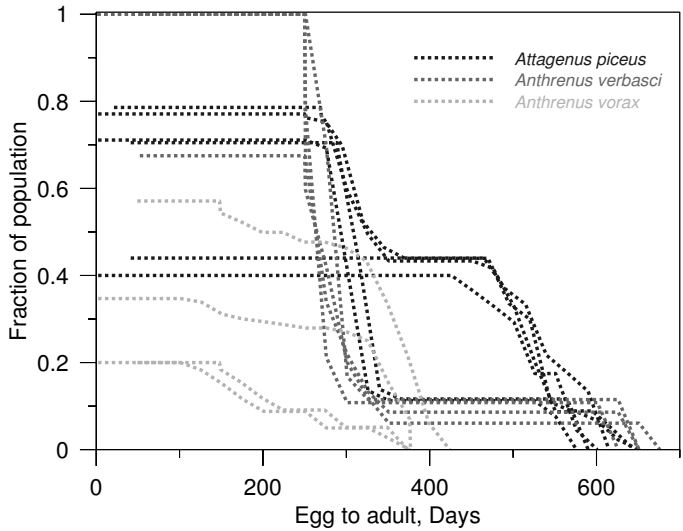


Figure 2.22: Distribution of maturation *Attagenus piceus* (now *A. unicolor*) from figure 2.19 including replicates only following larval development offset by average egg + pupal development time, 39 days (room temperature) and 19 days (25 °C). *Anthrenus verbasci* maturation (egg + pupal development time of 50 days). *Anthrenus vorax* maturation (egg + pupal development time of 48 days). Data from Griswold and Greenwald [45].

diapause [76] so the central tendency of conservation approved storage environment humidity would ensure faster development time for the Khapra beetle.

Long larval life also speaks of expecting a relatively stable food supply [76], which we can recognize as a property of hair, hide and feather objects in collections. This combination leaves the insect with greater options for surviving vagaries of climate.

Howe [25] notes some *Ptinus* species are restrained from being "serious pests" because certainty of diapause ensures single generations per year which combine with low intrinsic rate of increase.

Knowing more about our collection pest's propensity for diapause

Species	Eggs/♀(range)	°C	Days	r_m	Surv.	r_mS	Nut.
A. piceus	82(12–130)/2	25	301	0.281	0.77	0.257	rf
A. piceus	82(12–130)/2	25	526	0.161	0.77	0.147	rf
A. piceus	61(20–91)	18	301	0.318	0.71	0.286	rfo
A. piceus	61(20–91)	18	501	0.191	0.40	0.140	co
A. verbasci	30(13–44)	18	251	0.302	1.0	0.302	c
A. verbasci	30(13–44)	18	251	0.302	1.0	0.302	r
A. vorax	67(37–96)	18	301	0.326	0.35	0.227	rf
A. vorax	67(37–96)	25	150	0.557	0.20	0.301	rf

Table 2.5: Example values derived from Griswold and Greenwald experimental data for three species of dermestid collection pest. Rate r excludes survival information and r_mS includes survival, with days/28 to match work by Howe and Sinha tabulated above. *Attagenus piceus* (now *A. unicolor* days to middle of half-cohorts. *Anthrenus verbasci* and *Anthrenus vorax* days are to 25% cohort development. Fecundity are listed as total eggs laid, not just the female portion. Those marked as divided by 2 are the half cohorts in figure 2.20. Survival is amortized over the entire population but most originates as larval mortality. Nutrition is r rat fur, f fish meal, o oats, c chicken feathers. The first two entries match figure 2.20 line 'a', the next two are lines 'b' and 'c'. *A. verbasci* and *A. vorax* development is plotted in figure 2.22. The high rates factored with survival fall between lines 3 and 4 in figure 2.15.

and the conditions triggering it would allow more accurate projection of population rate of increase through matrix methods. More importantly it would help quantify the contribution of cooler environmental set points with less winter heat and reduced investment in summer cooling that are being considered in museum sustainability scenarios. We need to know if projected indoor environment changes are marginal or greatly significant for altering r of the species at hand. One can project that sustainability efforts affecting storage environment could be beneficial or detrimental, prediction of which will allow us to adjust IPM programs appropriately.

Density of pests adjust individual growth rates

For collection pests there are noted changes in larval and nymphal growth rate which are governed by increased numbers as seen from Danks [76] and Birch [63]:

Blatta germanica, faster with crowding
Periplaneta americana, faster with crowding
Dermestes vulpinus, slower with crowding
Trogoderma granarium, slower with crowding
Ephestia kuehniella, slower with crowding
Sitophilus oryzae, smaller, less fecund with crowding
Rhizopertha dominica smaller, less fecund with crowding

As their population develops cockroaches would exhibit some acceleration of harm per nymph (consumption to support higher growth rate). Beetle pests likely exhibit the opposite if they tend to smaller sizes and lower fecundity as indicated by Birch [63]. As an example, the rice weevil *Sitophilus oryzae* reaches an optimum density and fecundity with the rate falling off either side [72] near one insect per 2000 grains. Disentangling probability of predation from other factors is another key element. Lefkovitch [51] summarizes several authors: "a linear response to density (ϕN) is an over-simplification not supported by experimental data".

Distributed opportunity adjusts population growth rate

Hagstrum [77] elaborated on Howe and other's work on pest population growth in field conditions which provide greater free volume to resource ratios necessary for realistic decisions on part of the insects[41]. From examining population growth patterns for the moth *Ephestia cautella*[42] by distributing peanuts in non-uniform groups in an empty warehouse [77] they found "subdivision of food resource can suppress population growth" which created "over-crowding at some locations

[41]Hagstrum's model: (specific survival + fecundity)/time [77].
[42]Not a common collection pest, confined to hard seed.

and under utilization at others". As a result population "growth rate (♀/♀/generation) was reduced from roughly 7- to 3-fold as the number of locations increased from 1 to 24." Females in the main remained local to mating sites and this behaviour governs the colonization pattern (a pheromone attracts wide flying males). The discovery cost of new egg laying sites significantly cut the infestation rate. Determining the rate of increase for this moth across several commodities over a month found a 2-fold increase in emptied to 50-fold in filled warehouses. Scarce resource distribution suppressed population growth rate between three to twentyfive fold [77].

Hagstrum's clusters of peanuts in some ways models a sprinkling of leaky old cabinets through a natural history range or highly pest attractive items dispersed over open shelving. Identifying these peak sources for refurbishment or sequestration gives a good return in long term protection from pests and reducing diversion of care efforts. If such dynamics apply to collection pests, being able to state that sealing the cabinets up and remembering to close them significantly cuts potential total population growth rate is quite useful. Similar performance requires the costs of lowering annual storage temperature 10–20 °*C* below warm climate ambient.

Distribution affects detection Pinniger [78] reviewed complexities of pest detection across storage as bulk commodities, in transit and structures. When detecting insects in fixed volume ratios (grain spear samples from storage bins) the results are governed by proportion and probability.

> "Insects are under-dispersed or clumped in grain and it is a depressing thought that the detection of anything other than a heavy infestation of grain insects is more a matter of good or bad luck .... Sampling of insects in buildings has always presented more problems than those of sampling bulk commodities. Counts of crawling or settled insects on predetermined areas is only practical when large numbers of insects are present." [78]

Clustered observations apply to early stages of insect infestations unless the species has a habit of wide dispersal of eggs. The *Ephestia* work cited above shows active hindering of discovery of the egg-laying locations (dispersion of resource) lowered the overall egg laying (lack of perceived sites) and not the egg numbers laid at any one successfully discovered location. This sets up the conditions needed for a multigeneration run of infestation as virgin sites without competition are eventually discovered by the pest [77]. From this observation we may expect a pool of post-treatment survivors to be in a missed optimal location, rather than expecting an equal number of survivors spread diffusely throughout the entire suboptimal volume. A higher proportion of insects found in cabinets with prime food than found in corridors among scatterings of marginally edible detritus.

Reaching the carrying capacity (severe infestation) approaches a uniform spatial distribution where food distribution is either homogeneous or marginal pest foods are substituted. This latter substitution can mark more harm per pest generation if nutritional value is low yet a significant percentage of pests survive (see discussion around figure 2.5).

A factor which likely reduces r is the presence of poisoned specimens throughout a collection (discussed in chapter 3). The probability of pests being harmed lowers N proportional to the total eggs laid. Unpoisoned specimens dispersed throughout older poisoned collections will act like Hagstrum's clusters of peanuts. Traps deliberately set with attractant collection materials do the same but are more easily viewed, as were the baits in Merrill's approach to detecting herbarium pests (see Strang [58]).

We need to determine measures of collection pest migration, for their movement within collections, if there are any discernible patterns with which to guide detection programs. The study of "open nonequilibrium systems requires the explicit incorporation of dispersal and spatial effects into the theoretical models." [15]. With clustering, finding a 'hot spot' of pests somewhere is less likely to indicate widespread infestation than one imagines by linear extrapolation from that finding.

The resulting search is undertaken to reduce uncertainty related to the time elapsed which allows daughter clusters to establish after that initial infestation. A default model would be equipotential radiation in all directions by larvae or adults but, as with search and rescue efforts for moving target, the volume to investigate grows with time and is not as efficient as when some part of the collection volume can be discounted and only highly attractive sites polled. Use of this effect was reviewed by Strang in a paper on early and systematic herbarium IPM methods [58] and is also the role of semiochemical lures.

Influencing t

In Mumford and Norton's model [49] t represents time to market. Collections parallel stored-crops where neither grain nor most collections are immediately perishable so t is varied largely by extrinsic factors. As a result, both grain and collections have uncertain and potentially long time for t.

How long is long? The relatively short existence of public and private collections inside the full span of human history and the losses we know about argue there is a time t for collections and objects, we just don't know what it will be due to the varied ways their existence is terminated.

Human societies will have produced many important wood cultural buildings, but few have made it near the 1000 year mark. Hōryū Gakumon-ji complex in Japan pre-747 A.D. and stave churches in Norway circa 12th century such as at Hopperstad are exemplars (profiles illustrated). While these few survived when many others fell to various calamities or became post-hole archaeology it is certain that without pest control in the minds of their architects and craftsmen none of them would have survived wood borers and fungi to now (table 2.6).

Paper five reports some numbers that could be determined as 'natural' maximum rate of deterioration which can be the benchmark to support prognoses of losses in the IPM levels. With appropriate features in place the loss in collection storage should be significantly slower unless conditions approach equivalent to outdoors. Akin to the popula-

Design large, maintainable water diverting roof.	lower r
Choose healthy trees with resistant quality wood.	lower r
Paint exposed end grain with gofun pigment or surfaces with urushi or pine tar to exclude wood borer egg laying and water.	lower N, r
Foundations partition timber from soil, ground moisture and rain splash.	lower r
Remove, replace infested parts, prune nearby forests of dead timber, maintain firebreaks.	lower N
Relatively stable society for a millennium which appreciates the structure.	long t

Table 2.6: Influencing millennial wood structure's duration against pests. Left, half profile of Hopperstad church, Norway. Right, half profile Hōryū Gakumon-ji, Japan.

tion intrinsic rate of increase, these are intrinsic rates of loss, maximal estimates which can be used for determining relative 'lifetime multipliers' under more benign conditions.

'Obdurate' was used to evoke low vulnerability objects in paper five. Low investment in this class is not necessarily bad as they are considered proof to pest hazard. 'Delicate' objects on the other end of the scale of vulnerability in the face of pests clearly need significant infrastructure and / or care invested to manage even short duration existence.

What is cultural property 'time to market' if not from now to forever? Choosing an unfortunate t (chewed, lost) is not useful for *when* the terminal event will happen is unpredictable and not useful for planning investment in care. Longest t for any of the key imagined values less than bare survival is a possible choice, but this is recasting of the unfortunate event scenario without proper 'life tables' for cultural property.

Unlike a grain market, museums will utilize objects many times where-

as one eats a loaf of bread once. Objects are in this way a form of currency, not commodity, moving values forward through time. Ascribed values will also be adjusted upward and downward through time [50]. Individual values can also have different time to market. Field sampling of natural history specimens can have a short term information value for an immediate DNA study by the collectors, whereas specimens subsequently banked for long term comparison and voucher by future researchers will *hopefully* support confirmation, analytical refinement, or subsequent techniques while combatting loss of present proved utility. With this scenario, the time to market is substantially 'now to forever' a roughly uniform distribution, which therefore allows slicing it into self similar repeatable sections for planning purposes.

When collections have non-pest degradation mechanism which cannot be stopped these cumulative functions do predict a zero value discount future. It is a matter of ascribed human meaning whether the addition of pest attack is more horrifying for accelerating the loss, or inconsequential because the item is clearly doomed anyway. Pest control decisions are made in this light, compounded by layers of human meaning. Totem poles[43] will rot naturally on site as their makers wished, with efforts to slow some loss maintained around them.

Activity horizon and discounting remedies

Mumford and Norton [49] present decision frequencies for grain storage ranging from 'weekly' to 'planning' recognizing the effect of time horizons on separating out pest control activities:

Weekly	Monitoring environment, control measures
Yearly	Standard practice, cleaning bins when empty
Decade	Design of storage, construction

They argue a short horizon lends itself to threshold models for control, whereas longer horizons (greater uncertainty) predispose risk mod-

[43] Haida Gwaii, Nan Sdins, UNESCO World Heritage List No. 157

els, especially "if it is not possible to monitor early enough to take any action" [49].

Within the scope of sanitation there are different time horizons applied in IPM. Cleaning to reduce pests and supporting detritus is effected in collection buildings as daily to weekly cleaning of floors for safety and preventing wear from grit, to annual 'deep cleaning' of collection exhibit halls and storage furniture that has been adopted in some institutions as a key IPM method [79]. An example of altering 'standard practice' are the application of pest risk classification for high vulnerability and valued sites across a national heritage service [79] and to operational areas within a major natural history museum [80] to enable organization wide effort and compliance. These programs take several years to develop, educate staff, and implement.

Changing time horizons obviously forces a different payback calculation on a control activity. Frequent inspections shorten time t at increased carrying cost if market value is a **threshold** of continual clean bill of collections health with minimized harm in the face of high likelihood pest infestation. Infrequent inspections where market value is an object's mere existence when we need to next use it will lengthen time t and acceptable **risk** is moderate incidence of low harm, or low incidence of high harm. Permanent loan, deaccession, sale or trade in collections terminate t and local activity aimed at their long term protection.

In the common case of loan, equivalent protective or better pest control are requested in the loan agreement (**threshold**) or the peer locality is judged equivalent in its standards and control of incidence prior to loan (**risk**). The latter practice has been adopted in quarantine and export around certifying agricultural products once a region of origin can be declared 'pest free' and audited control practices are commonly in place to reduce the risk of lapse [81] so access to market and market values are kept high. However, ensuring sustained positive action at the suspect periphery is essential.

One can consider ways to select t for pest control actions:

1. Choosing t with arbitrary length for whole object irrespective of possible lifespan for values (estimated discount to a planning horizon).
2. Choosing t with informed durations for object values (known discount from research into museological practice).
3. Choosing t by informed duration between pest reduction actions (discount within period of protection effectiveness).

Option three is interesting as it strikes at the heart of the residual / non-residual pesticide debate discussed in chapter 3. How long can we give to discount the positive effect of a pest treatment? It is quite reasonable to reduce N_t to zero with some certainty by treatment when high efficacy has been established by research (see chapter 5) and we have straightforward means to forestall re-infestation, holding N_o to zero by effective containment (see chapter 4).

As illustrated in figure 2.12 the difference generated by severely reducing the pest foothold is a period of 'saved lifetime' we can bank against the object's t whether object t is arbitrary (century from now), required (ten years of display quality until deemed dowdy) or until next infestation whenever that happens.

With non-residual treatments the object is still protected for a calculable time if re-infestation likelihood (*ceteris paribus* historical data) is determined from the collection inspection cycle. The argument for IPM programs and building tight museum exhibit and storage case designs is to more assuredly set t long for expected retained values in the face of some pest exposure.

Amortizing collection pest control cost when t expands with the success of control measures makes the cost-benefit one of 'buying time' for many protected values. Calculating cost of applying control measures as a function of their own discount horizon for effectiveness at extending t is why 'one-shot' toxic residue treatments are argued as more 'effective' as all other effects on retained values are ignored (it is cheap *because* it lasts indefinitely). However, when values such as research utility or stability are measurably reduced by the toxic agent

(see paper seven) the formerly low cost / high efficiency treatment is *post-hoc* heavily discounted and alternatives are sought.

To eliminate uncertainty over t, collection risk modelling establishes an arbitrary yet reasonable time horizon to 'deliver' the holdings with highest aggregate values. An adopted number is projecting a century for collection existence over which agents have time to act and adjust collection values [50]. Interval t is then not a discount to objects with zero values nor a discount of individual action effectiveness but a projected likelihood that three generations hence someone will still care.

Expert systems for preservation guidance

Directly relating to population models can be useful in quantifying risk, but it is not optimal for providing advice *per se*. With marketable goods, expert systems look to encode thresholds for market tolerance to discrete changes in value and the resulting value as conditions change (pest and environment). Sampling strategies and statistical support can be provided by the system, but any uncertainty in pest growth models for coping with changing conditions will dominate system utility [20].

An example of this approach for pest control advice is the 'Stored Grain Advisor ™' software[44] produced and maintained by the USDA as a service for farm storage of grain. The program uses results from simulations that merged population growth models with other factors modifying pest growth and grain value before the delivery of grain to market [83]. To do so, a large body of experimental data on insect response to controlling factors had to be generated to adequately characterize each species' population growth, which is why these models only currently exist for the key agricultural stored product pests where there are significant economies and trade at stake (P. Fields, P. Flinn and A. Campbell pers. comm.)[45].

[44]USDA's Stored Grain Advisor and manual are available for free download. `http://www.ars.usda.gov/Services/docs.htm?docid=12268` and is designed around farm practices. 'Stored Grain Advisor Pro' is designed for methods used by grain elevator managers [82].

[45]There are several available models assisting similar goals: Canstore, Canada [84];

To create rules to advise on control measures, pest population models were run from categorized ranges of initial conditions. Advice is generated by mapping catch amounts and other supplied data including forecasted times for any control actions to the categories of initial conditions, and advice is based on the previous outcome of the model calculations utilizing economic thresholds established from polling expert experience. A user query elicits instructive commentary on scheduling re-sampling, mitigating procedures, fumigation treatments or alternatives, to forecast "if and when insects are likely to become a problem and the effects of management actions on the population" [83]. Years of field testing refined its utility for the intended clientele [85].

Summation

In their discussion on why IPM is not universally adopted in grain handling, Adam et al. [75] note problems arising from estimating economic value within the decision process. They list uncertainties about current pest population, future pest population, post-applied efficacy of treatment options, how and when to treat for best result, the influence of pest influx rate and the cost estimates needed for treatment, pest damage, monitoring and labour.

Not monitoring for pests is actually the act of deferring the cost of monitoring and accepting the cost of object damage as the primary indicator of pest activity.

One can see the accountancy problem of when to treat. No treatment accrues the cost of harmful events (real depreciation). The worst case scenario for collections is also the most 'efficient' expenditure model with least effort and spending, where collections preservation relies wholly on the intrinsic material stability and scale of individual objects where their time for total loss to pests can run from overnight to longer than the span of staff careers.

Integrated Grain Storage, UK; Pestman, Australia; Grain Management Expert System, China and QualiGrain, Europe [82]. These address different climates, pests, agricultural products, structures, practices and marketability, so are not completely equivalent.

Early or unnecessary treatment 'wastes' some or all the cost of treatment but salves our consciences. Late treatment incurs both the treatment cost plus the interim damage. Ineffective treatment further compounds expense by a near-future retreatment cost and values lost to the interim damage. Effective retreatment cost increases with delay due to pest spreading (higher uncertainty). The corrective onus shifts onto rapid determination of need for retreatment of infested collection areas and post-quarantine quality assurance before integration of objects into a larger collection.

Prophylactic quarantine treatment may commonly be a 100% waste of time and expense as no pests were entrained in the objects to be killed. Yet such treatment is readily and repeatedly done against probable pest threats on the grounds the recipient collection is valued much higher than the running expense of quarantine and any treatment induced loss in values of the incoming objects.

The cost of inaction can be minor to catastrophic hinging on the object vulnerability and values, variant performance of collection storage, the institution's peripheral activities or sheer dumb luck. This argues at least for the minimum frequency of application for IPM procedures to be concomitant with an estimated minimum time for threshold of loss within differing categories of objects. Material vulnerability (pinned insects versus wood tools), proportion to pest (gnat versus elephant), ascribed value (type specimen versus touch and feel) are navigable complexities once they are identified.

Without prior experience of pest infestation people will both over- and underestimate the harm and disruptive crisis pests can cause. Narrowing the variance between these conditions is the role of applying IPM knowledge. When faced with a pest discovery, without appreciating the contributions of IPM elements already in place nor a plan for reducing the plague of uncertainty, the match awaits striking, hoping the best and fearing the worst.

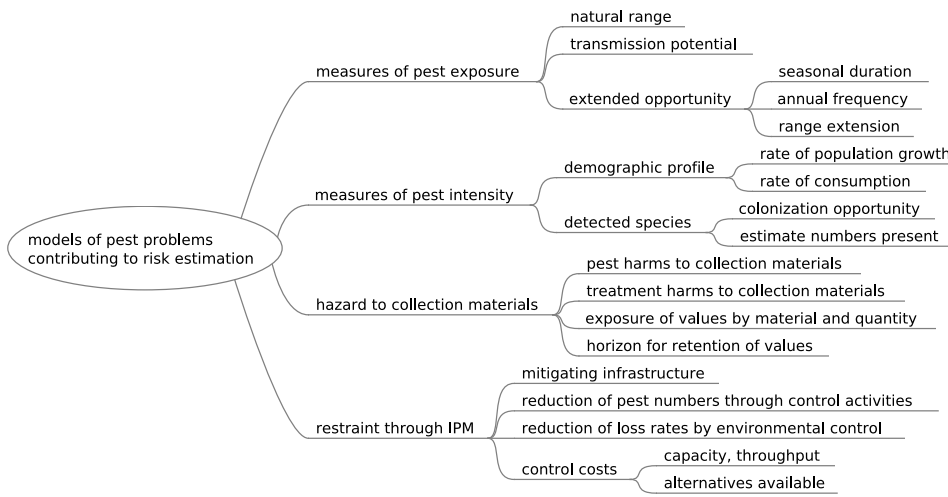


Figure 2.23: Major branches of discussed pest models listing measures (or assumptions) influencing pest risk estimation.

3 Skirting hazard while retaining value

Look! the dried rice cakes
At the end of the verandah—
The uguisu is pooping on them!

Matsuo Bashou (1644–1694),
Blyth [9]

In 1770, T.S. Kuckahn [86] reported by means of four letters to 'Philosophical Transactions' the process by which he preserved bird specimens. At the end of these communications Kuckahn describes how he baked finished taxidermy preparations to preserve them from destruction by insects.

We might currently regard this latter report as non-scientific. It contains no temperature data, no efficacy data, no numerically defined limits on harmful effects on taxidermy materials. In all it could be considered isolated and nearly anecdotal information on the early use of heat to disinfest museum objects, however there is more in these reports than this criticism suggests.

A growing demand for protecting specimens

Taxidermy of specimens in Kuckahn's time was moving from the period of cabinets of curiosities into the age of systematic acquisition

and classification of our planet's biodiversity as the more scientific approaches to collection, growing paths of commerce and expeditions of discovery lead to the period of maximum growth of natural history collections through the 1800's [87]

Concomitant experimentation and resulting knowledge on efficacy of methods for protecting masses of commercial goods in trade and military supplies was also just beginning. However at the time of Kuckahn's letters, this information was still quite limited in both quantity and circulation. Kuckahn's report was read by J.C. Lettsom who cited sections of Kuckahn's work including the use of heat as disinfestation in his 1792 guide to the preservation of natural history specimens [88], a volume which was likely used by early British contributors to museums during the growth of worldwide systematic collecting (D. Pinniger and A. Mendez pers. comm.).

Lettsom indicated by footnote (1792 first edition page 13, not present in 1799 third edition) that he personally reviewed specimens he considered successfully preserved by Kuckahn's methods, but they would only be a few years old at that time. Lettsom's seminal publication appeared in two subsequent revisions with reduction to summary of Kuckahn's quote on heat by the third edition [89], however none of the three versions reiterated Kuckahn's stepwise methodology for ensuring safe treatment of the specimens that is reviewed below.

By 1884, Browne's treatise on taxidermy out of Leicester [90] does not mention Lettsom, preferring to cite cyclopedia and French sources on natron and corrosive sublimate of mercury. Brown's 1885 taxidermy instructions [91] relied on arsenical soaps. Knowledge of Lettsom's writing had apparently ceased some time prior (D. Pinniger pers. comm.) as neither of these volumes nor others apparently reference him.

Farber's account on the development of taxidermy of ornithology specimens mentions Kuckahn's work being reviewed in French by Mauduyt [92] but with strong criticism (translation presented in Farber 1977 [93]):

> "The author concludes his four letters by warning that birds prepared by his method will be destroyed by moths in a short time if they are not enclosed in well sealed cases. But this drawback is precisely the weakness of all the other methods. If this is the case, as he admits, then his method is not preferable to those used by other men. I would say, in addition, that it is not even equal to the other methods, for it demands precautions and expense which the others do not require, and by following it one nevertheless equally fails to obtain one's goal. But more importantly the reason that we must reject his method is that it exposes one, for no purpose, to the great risks of fire and poison." [93]

The goal of unfettered access versus tight cases continues unabated to this day. They are exactly opposed points of view on how specimens should be viewed and stored. The argument is how much to invest in protecting objects in our care while tacitly ignoring them as we are busy elsewhere.

Mauduyt floated an appropriate caution on turpentine varnish making which can become wildly exothermic. However to be fair, Kuckahn's full account describes several precautions to greatly increase safety when blending his mixture of raw turpentine, camphor and spirit of turpentine.

> "Break the camphor into very small pieces, and put the whole into a glass vessel open at the top, place it on a sand heat till thoroughly warmed, then increase the fire gradually till the ingredients are perfectly dissolved and mixed, which will be done in about half an hour. Great care must be taken that the materials do not catch fire: to prevent accidents, it would be better (especially where the process is made in the house) to place the glass vessel in another of any metal, two thirds filled with cold water, which place over a gradual fire till it boils, keep it so, till the ingre-

> dients are dissolved and incorporated; then take the glass off and let it stand to cool, and the liquor will be fit for use." [93]

A glass vessel prevents metal catalysis of the polymerizing oil. The phrase "place it on a sand heat til thoroughly warmed" is not a typographical error for 'stand'. Until the advent of electrical heating pads, heated sand baths were used in chemical laboratories to moderate and conduct heat evenly to reduce chance of cracking a glass vessel. Specifying gradual increase in the heat source and encouraging use of a double boiler further reduced chance of harm by limiting temperature to 100 $°C$. By indicating only half an hour is required would encourage the manufacturer to be present the whole time.

Such use and cautions continued as a century later Brown's taxidermy manual [91] still instructs on turpentine varnish making, but with hazardously less detail than Kuckahn, adding only to have a lid ready with which to bravely contain any incipient blaze.

Mauduyt did not comment about the actual heating the specimen, his rejection was aimed at Kuckahn's use of poisonous corrosive sublimate (of mercury) which was not out of line with current practice and later adoption of arsenic. Instead, Mauduyt substituted burning sulphur for fumigation which would have left strongly acidic residual products to attack the materials and, after all his deprecation of Kuckahn's reliance, tight cases [93]. Harmful consequence of the sulphur fumigation were soon stressed by Bécour's response in defending his secret arsenical formula which he had privately developed from the late 1730's against Mauduyt's attacks on his method [94].

Prevailing use of arsenic for dry museum specimen preservation was yet to follow some decades after Kuckahn, with Bécour's formulation revealed in 1800 by Daudin [94] and only after the method became public through shared communications between preparators and clear attribution of its success in preservation [95] [93].

While agricultural use of arsenic was not initially received with acclaim in all quarters mid 19th century such as the case for use on

potato pests, it did achieve acceptance through its performance as Fernald [96] related on 1850's American agriculture:

> "It was some time in the sixth decade of this century that arsenical compounds were proposed. There was bitter opposition to the use of these insecticides for a long time, and the reports of cases of poisoning, which were said to have occurred at the at time, were startling in the extreme. It was even claimed that potatoes would absorb the poison to such an extent that the tubers would carry poisonous doses, so that after each meal it would be necessary to take an antidote for the poison. There is something in the human mind that leads it to accept the dreadful more readily than the prosaic, and as many believed the fabulous stories so widely circulated at that time, and for a long time after the advent of the [potato] beetle into the extreme east of this country .... Little by little, however, one farmer after another abandoned the "stick-and-pan" method and adopted the use of Paris green, till it came into very general use. This seemed to give it popularity, and there developed a readiness to use any kind of substance that bore the name of insect poison, till now the market is well stocked with a great variety of substances which are claimed to kill all kinds of insects." [96]

By 1895 annual agricultural application of Paris green in the U.S.A. amounted to greater than 2000 tons [97] diluted in water and sprayed on crops. This perception trend reversed somewhat in the 1970's (see figure 5.7). In 1979 Snelson [98] reviewed the factors affecting changing attitudes to the use of pesticides and fumigants which had "been widely accepted on the assumption that they were volatile and thus disappeared completely from treated commodities. Modern analytical techniques are disturbing this blissful ignorance."

Gold [100] rebutted the trend to eliminate pesticides: "Society in the developed countries has become so removed from the knowledge of

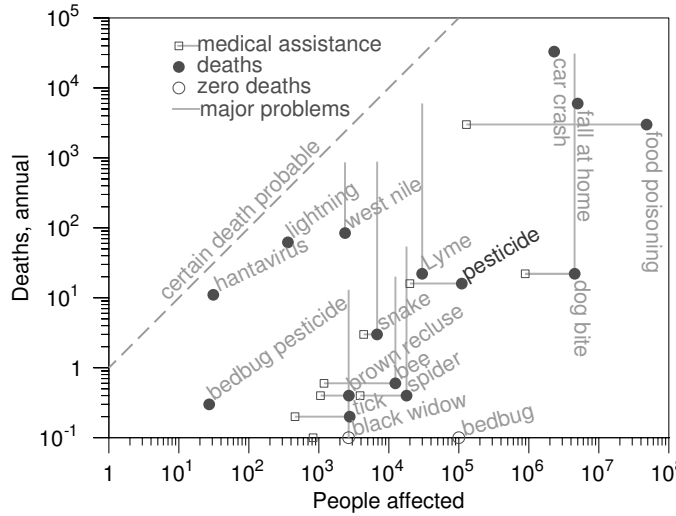


Figure 3.1: "Natural risks" in the U.S.A.: deaths from acute pesticide poisoning, pest bites, food poisoning and every-day hazards in recent decades. Terminal points and lines show persons seeking medical assistance or suffering major problems. Data from national sources tabulated in Quarles [99].

what is involved in providing even the basics of a healthy life and the survival of such enormous populations and population centers that now exist, that it does not understand what will result when modern technologies are banned or even condemned." He states adults have "lost the set of values that takes into account the equation of the benefits of what they have, the risks of obtaining these benefits and *the risks of not obtaining the benefits* (risk-risk)." And, "They do *not* understand that if there are certain risks they wish to minimize or remove, they don't have to accomplish this by destroying the benefit or worse, the source of the benefit."

Before the transformation to modern society through scientific progress against disease and want took place, museums and early preservation science took part in the same essential discussion: what is dangerous and what is beneficial?

Retaining value

Against the background of experiment in diverse methods and changing moods towards use of poisons, Kuckahn's work is a concise well documented pre-arsenic model to be examined. He begins his discourse in his first letter:

> "Considering the number of vertuosi, who apply themselves to the collecting of natural curiosities of the insect, bird, and beast kinds, it is surprizing that so few have endeavoured to discover effectual means of preserving their curiosities, when collected .... they have the mortification of seeing their collections, which have been made with great trouble and expence, continually dropping into decay." [86]

Kuckahn chronicles his first hand experience of the shortcomings of current practice with raw "allum", salt, and black pepper as chemical preservatives of whole birds. Subsequent salt deliquescence into a weeping "pickle" and incomplete penetration are described modes of failure. "Spirits" (alcohol) are recognized as capable preservatives for long voyages but Kuckahn questions subsequent ability to display these specimen's "proportions, attitudes, graces". "Skinning" has the drawback of not preserving the original form of the specimen, and subsequent reliance on the previously deprecated preservatives.

> "I think I have tryed most, if not all, the methods that have been published or practised for many years past, with all the care and attention I could, and it was not till after the loss of much time and many fine subjects, birds in particular, that I set myself to find out such methods, drugs, and liquors, as would effectually penetrate and perfectly cure all the parts, so as to keep them plump and full." [86]

His second letter, on collecting methods, cautions against staining by blood, and avoiding mechanical damage to the carcass's proportions.

Kuckahn clearly values most the full adult plumage and lively appearance after preparation. His goal was the full artistry of taxidermy, not the 'study skin' approach now characteristic of most museum's holdings. Kuckahn's work precedes the age of numerical and geospatial analysis of life on Earth.

The third letter lays out both recipe and manufacture of his two preservatives: a penetrating varnish of turpentine and camphor (discussed above) and a dry mixture which includes several compounds we now recognize as contributory pesticides and biocides: namely tobacco (later nicotine was used then banned as an insecticide) and sulphur.

The fourth letter lays out how to physically prepare the specimen, apply the varnish and dry mixture to the skin, and where to incorporate additional materials: tansy, wormwood, hops and tobacco as desirable stuffing materials in addition to a cotton covered varnished wood mannequin.

Only once the bird is collected, prepared, posed, and the varnish allowed to penetrate and air dry that Kuckahn states "the bird must be baked in an oven" as the final step to speed the cure of the varnish, and drive off any undesirable smells from earlier decay. There is a further purpose woven through this step, the destruction of insect pests.

Kuckahn is cautious:

> "...but care must be taken not to put them into the oven while it is too hot, as it would blister the bill and nails. The best rule to know when the oven has a proper degree of heat is this: while the oven is cooling, throw in now and then a tail feather taken from any fowl, which must be placed about the middle of the oven. If it is too hot, the feather will have a motion and be bent: we must therefore wait a while, and put in another feather, till we observe there is no motion or bending; then upon taking it out, and bending it with out finger, if it breaks, the oven is still too hot, and we must wait till feathers that have been in for a few minutes will bend without breaking. When the

> oven is thus fit, the birds must be put in, and the door of the oven closed, til it is quite cooled." [86]

What was not conveyed in the letters and likely so because it was commonly known was the everyday activity from which this process had been derived. Baking operations in the 1770's commonly progressed without reference to oven temperatures as we now enumerate them. Bakers would heat a refractory clay or brick oven by burning fuel inside, and when sufficient heat was delivered to the refractory, the fuel was raked away. Experience informed the charge of fuel required to this point, then a direct analog measurement was then used to ensure final success. A baker would cast a thin layer of corn meal or its equivalent across the oven floor and look for hot spots to gauge the potential for scorching the dough. Once the strewn meal responded in a manner indicating the bread would be baked and not be burned, the oven could be safely charged with the valuable dough.

Residual vulnerability to insect infestation is also addressed by Kuckahn:

> "The birds in this manner will be perfectly preserved; but as there still remains some oily matter in the feathers, the moths and other insects will deposit their eggs and generate their young in the plumage, if the birds are not carefully cased up. The cases must be first well washed on the inside with the following camphorated spirits . . . and, as soon as dry, place your birds in, and close it up, and guard the joints of the doors or seams with paper or putty." [86]

Throughout the recent shift to non-chemical treatments against pests the issue of 'no residual protection' has sometimes been raised as a detriment by people familiar with the 'residual protection' of applied pesticides. Kuckahn used straightforward physical seals to prevent ingress. The 'residual protection' value has today been turned on its head by the acknowledgement of arsenic, mercury, DDT and other persistent pesticides on objects as a serious collection contamination

problem [101]. As an indication of extent, Sirois and Sansoucy [102] reported arsenic in 86% of ornithology collections sampled, and 81% arsenic and 5% mercury across sampled natural history specimens. A more detailed summary account of inorganic and organic pesticide findings can be read in Sirois, Poulin and Stone [103].

After warning about fading of specimens exhibited in direct sunlight Kuckahn concludes:

> "Baking is not only useful in the fresh preservations, but will also be of very great service to old ones, destroying the eggs of insects; and it should be a constant practice once in two or three years, to bake them over again, and to have the cases fresh washed, as above, which would not only preserve collections from decay much longer, but also keep them sweet." [86]

While the hazard posed by a pest was the same then as now, something like one grain—one weevil, it is reasonable to estimate that the overall risk of loss to pests was higher. European people's everyday lives were then based wholly on use of pest vulnerable wood, plant fibres, wool, leather, and feathers. They also lived in close contact with pest sources: household stables and barns, greater openness of their dwellings, pantries and proximity to stockpiles of food and materials in rural and urban landscapes, integration of housing with local industry, and widespread transport of goods in waggons and ships with bales, sacking and other easily infested packaging, and any rudimentary quarantine was focused on protection of profit not place.

The western record of pest harms and responses begins with such volumes as 'Ortus Sanitatis' (1480) [7] with some entries and illustration depicting home and livestock pests, the notable one is mechanical removal of moth from clothes with a whisk. Modern views on the benefit of sanitation to reduce pests and improve public health were still developing alongside concentration of people through industrialization and publicly funded research, culminating in early national departments of agriculture which published summaries of applied pest

research findings for farmers and householders (for example the extensive U.S.D.A. Farmer's Bulletin series).

Against this background can one become censorial about objects of value being subjected to a baking treatment? Can one do so now when informed with current art conservation ethics and scruples? Do imagined hazards outweigh the perceived advantages? Do real hazards outweigh quantifiable advantages?

The purpose of revisiting these letters two hundred and forty years later is to show how Kuckahn managed the complexity of achieving his most difficult goal: lively appearance of a dead bird from far away lands, through examination and dismissal of ineffective methods by critical practical tests, development of a method not prone to those same failures, developed cautions against pitfalls in the acquisition, transport, storage and preparation of specimens that would reduce properties contributing to specimen's final value, recommended steps for protection against major environmental hazards (light, pests), addressed residual risks, and scheduled key maintenance steps for the specimens. With his letters sent to a scientific journal, detailed enough to allow peers to repeat his methods and review the outcomes, Kuckahn was clearly interested in furthering his discipline and reducing losses of valuable specimens.

Skirting hazard

Kuckahn's letters contain many of the issues recognizable in the modern field of conservation. He integrated elements of preservation research that focused on retention of valued properties. The level of synthesis discriminating harm from acceptable change is prevalent in Kuckahn's letters continues to be required of scientists working today in the area of preservation of cultural property.

While heat has been used on many kinds of materials for disinfestation, exposition of the factors Kuckahn navigated was little examined until recently. The thermal response of feather keratin was reported in 2004 by Takahashi et al. [104]. The production of feathers and subsequent waste problem is being addressed by developing

ways to use feather keratin as an industrial feedstock for thermoplastic bio-polymer films [105]. These publications use differential scanning calorimetry (DSC) transitions as the means to characterize keratin response to heat. Suspension in water or modifiers (urea, glycerol) all have the property of lowering the temperature at which keratin responds compared to those samples run in dry conditions.

Endotherm	**Onset T_o**	**Peak T_p**	**Completion T_c**
Wet (peak one)	116.2 °*C*	127.1 °*C*	—
Wet (peak two)	—	140.3 °*C*	147.6 °*C*
Dry	188.4 °*C*	191.8 °*C*	195.8 °*C*

Table 3.1: Feather barb DSC response. Presence of water shows two separate peaks at lower temperature than single peak for dry sample, Takahashi et al. [104].

Which portion of the feather constituted Kuckahn's first observed motion is not stated. In feathers, barbs (largest area of feathers) are of much finer structure than the rachis (visible centre spine) and calamus (portion embedded in skin). Takahashi et al. [104] detected calamus and rachis dry transition onsets just above 170 °*C* , somewhat lower temperatures than for the barbs (listed in table 3.1).

A conclusion could be the values for wet and dry DSC onset and peaks somehow bracket the likely range of feather motion response to heat in Kuckahn's oven. Kuckahn did not specify the moisture content, yet is is likely to be quite low given the nature of baking ovens and his requesting the drying of specimens beforehand. Lack of moisture confers thermal stability in polymers of biological origin [104] so dryness is advantageous in heat treatment to reduce harm.

DSC evidence sets a plausible treatment temperature somewhere below 170 °*C* to 188 °*C* depending on whether the transition indicated by DSC is also a visible one. From the same data, a worst case argument could even be made for treatments starting below 116 °*C* if the sample was rather damp.

Kuckahn's only way to report the outcome of heat exposure was from keenly observed perceptible change in fine structure ("motion") and harm to mechanical properties ("breaks").

To quantify similar observation of the heating process, excised white turkey feather barbs were placed on a carbon disk in a microscope hot stage (Linkam THMS 600) with modules (Linkam CI 94 and LNP) providing controlled heating and nitrogen cover gas. Images were captured at an 8 bit level (mono) with a Qimaging Micropublisher 3.3 RTV camera through a Leica MX12s microscope with two LED array illuminators. Each image depicts a one degree centigrade rise of a 2 $°C$ per minute heating ramp. Using Image-Pro Plus (Media Cybernetics, version 5.1.2.59) a region of interest (ROI) on the side of a barb above the barbules was chosen to sample average image intensity against temperature. Every tenth image count is marked (circle) on figure 3.2. The data was fitted (solid line) with a B-spline with optional adjustment for knots (R^2 0.999974 inside 90% delta normal stabilized probability curve) using TableCurve 2D (Jandel Scientific, vers. 5.01.01). Thermogravimetric analysis (TGA) performed with a TA Instruments TGA Q5000, constant ramp at 2 $°C$ per minute under dry nitrogen and air. DSC results from scans at 5 $°C$ per minute that were reported by Takahashi et al. [104] in their figure seven are plotted (dotted lines) to compare with the measured browning.

Inspecting the full image sequence, fine motion of the barbules started at 236 $°C$, and by the vertical line at 239 $°C$ obvious shrinkage was underway in barbules and barbs (see 239 and 249 in figure 3.3). From this, Kuckahn's "motion" damage may actually be near 236 $°C$.

At temperatures below visible shrinkage Kuckahn's test feathers were still unduly brittle. The evidence from thermal microscopy is this region likely falls within the same region as browning (greater than 137 $°C$, figure 3.2), an observation which also indicates damage to the feather molecules. Both native and de-oiled feathers (washed three times in reagent grade acetone) exhibited this browning. Kuckahn however does not mention colour change, which in its earliest stages would only be visible on very light coloured feathers.

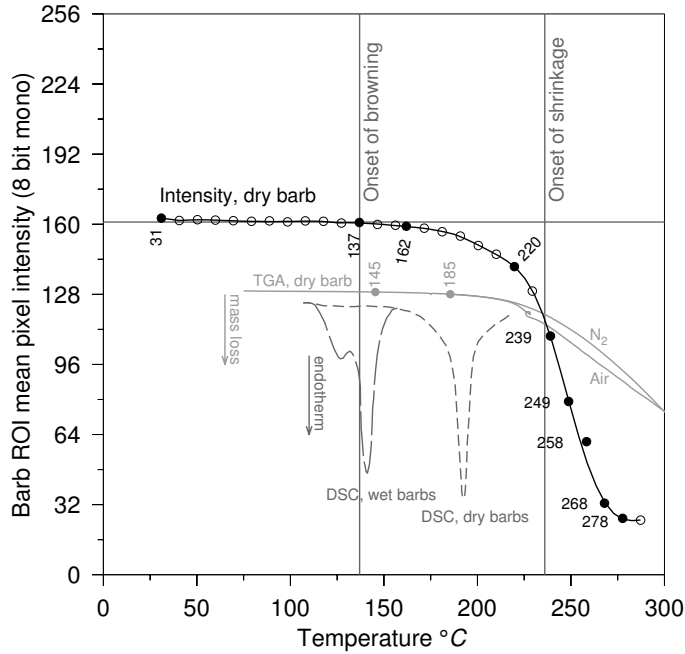


Figure 3.2: White turkey feather browning (image intensity under ROI). Heated microscope stage at 2 °*C* per minute under nitrogen. Labelled points refer to temperature of images in sequence (figure 3.3). Thermogravimetric analysis 2 °*C* per minute under nitrogen and air, 0.25% and 1% weight loss indicated (145 °*C* , 185 °*C*), increase in oxidation (loop, TA Instruments 'high-res' mode) near 220 °*C* . Experiments conducted by the author. Differential scanning calorimetry (DSC) results from Takahashi et al. [104] shown for comparison.

The TGA curve exhibits greater oxidation associated change only above 220 °*C* , below which both nitrogen and air mass loss curves are identical. A fuel fired baking oven would have an atmosphere bounded by these two conditions.

The dry DSC curve from Takahashi et al. [104] appears to follow the browning curve (similar onset) until it abruptly peaks at 191.8 °*C* so

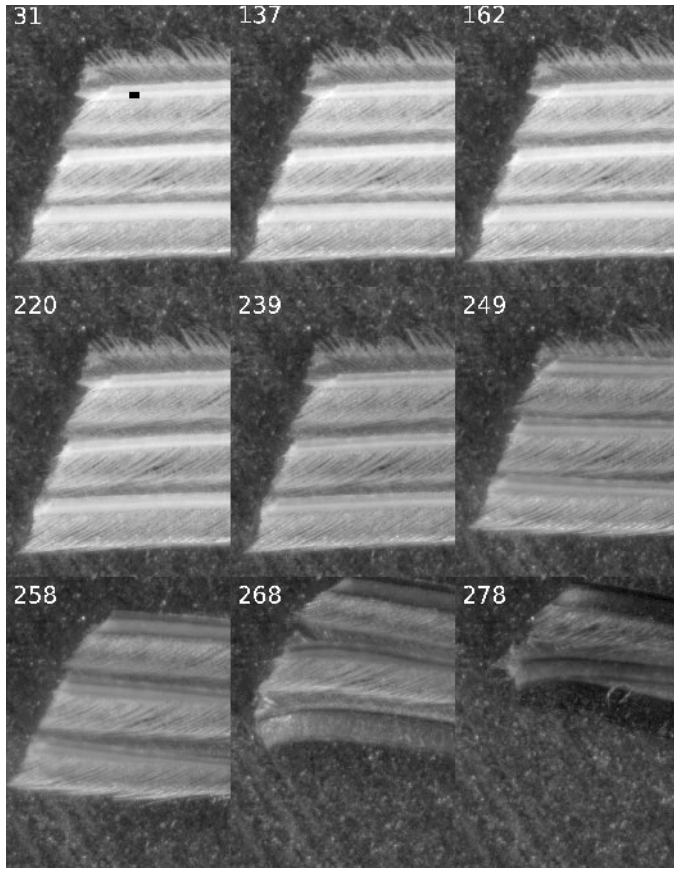


Figure 3.3: White turkey feather browning and shrinking, heated at 2 °C per minute under nitrogen. Labels are temperature in centigrade. Area on barb sampled for intensity is indicated by black rectangle, ROI was moved to remain centred in this band as the sample shifted. Intensity values enhanced for legibility of reproduction.

the DSC data indicates a transition at lower temperature than physical shrinkage and with very little browning showing on the feathers. Kuckahn's method was to wait past the point embrittlement ceases, so

this may have guarded against early browning by default. Feather keratin (crystalline β pleated sheet) is a different form to mammalian hair keratin (α-helix microfibrils) and is made stiffer for structural roles by a surrounding amorphous cysteine disulphide bonded protein [106]. This gives at least two differing materials in feather across which to apportion failure while electrophoresis studies indicate a minimum of five constituents [107]. The DSC peak is indicative of a 'melt', which could be interpreted the pleated sheet microfibrils restrained by the cross-linking protein until higher temperatures allows the latter to degrade and the sample shrivels.

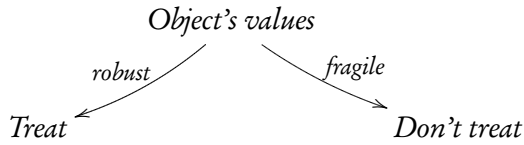
The minimum temperature Kuckahn needed to kill pests quickly was near $55\,^{\circ}C$ to $60\,^{\circ}C$ (see paper one). Little physical clue in descending over $100\,^{\circ}C$ to this proximity would be available to Kuckahn from his test feathers in the oven. Placing live insects in the oven as proofs is a diversion he does not mention. Kuckahn's described method would generally favour success through some overheating for efficacy and the flattening decay curve of temperature for the ceramic mass of a baking oven would provide a long 'soak' time for heat to penetrate his stuffed birds, while still avoiding the obvious and testable harms to the plumage he valued.

Summation

This example from the early literature of preservation illustrates the method to establish safety to collections from treatments. First, gross aesthetic or structural failings are avoided as they are easy to determine. Afterwards, two possible paths are presented. One—subtler changes with lesser impact on utility should then be judged whether to deserve attention. Two—occasionally an inversion in 'traditional' values occurs where a formerly un-valued component becomes significant, such as the rise in importance of DNA preservation for taxonomy. When this second path presents itself, sampling and storage strategies will change to greatly favour the required value, such as did the invention of 'study skins' and 'herbarium sheets' to store voucher samples that represent diversity and biogeography of ecosystems op-

posed to taxidermy specimens which favoured illustrative and curio values.

When promotion of a new value occurs, museums then have to struggle with reevaluating the forward utility of their back catalogue of holdings and continue to cope with deleterious aspects accumulated by storage and treatment. Papers three and seven in this volume are investigations into this problem of whether some of the object's desired molecular properties are robust or not in the face of current and historical pest treatments.



Investigation for harms terminates in examining alterations that are only detectable with instrumentation that surpasses our own faculties. These techniques are used to detect change, but the attribution of 'desirable', 'neutral' or 'undesirable' to the change is a following and potentially difficult step. Pragmatically, a test method has to contribute to detecting decline in desired values of objects in a way that can be applied, otherwise the preventive conservation community cannot integrate the information into their practice, and has a right to shrug 'so what'. Bridging this divide between application of science and determination of utility is a role which must be wholly grasped by conservation science working with their community.

In modern interpretation, Kuckahn was 'heat ageing' his specimens, and the fragility and shrivelling of his test feathers are part of a spectrum of change. Below the obvious damage thresholds Kuckahn was neither aware nor concerned with the constant 'burn' of collections which proceeds even at room temperature from hydrolysis or other reactions characterized by Arrhenius with:

$$k = Ae^{-E_a/RT}$$

These fall into the category of subtle with lesser impact—but only over short time. Over long time, ostensibly the very realm of museum collections, persistent increase in avoidable rates of damage are of consequence. Paper six looks at the core model for heat ageing that is taught in conservation, and works out an alternate that was originally proposed as desirable [108] but never expounded. This paper was a necessary step in further questioning and improving reliability of heat ageing models based on experimental evidence and chemical principles which correlate to properties we desire to conserve in the certain climate of energy conservation and sustainability.

Ultimately, where people's concern stops intellectually and where it must stop in practice are separated by greater pressing need, limits of resource, or their period in history. It is inappropriate to fault historical treatments unless they ran significantly counter to the prevalent knowledge and best capabilities of their day. We are however, free to critique, innovate and progress.

4 Dry, cool and contained

Fleas, lice,
The horse pissing close by,—
A lodging for the night.

Matsuo Bashou (1644—1694),
Blyth [9]

The environment both supports pest hazards and limits them. As Hartnack [7] pointed out, either a potential pest adapts and tolerates a novel environment or it dies. In the museum parlance 'environment' has largely meant temperature and humidity whereas in the biological literature it includes many factors beyond these two.

To preserve collections we limit large losses from harms caused by organisms through the general protocol of keeping objects dry, cool, and contained. When running a building with heating and air conditioning becomes a more expensive proposition this increase eventually raises questions of sustainability to balance cost and effort with preservation — what degree of dry, cool, and contained are necessary? To help answer this question it is important to properly qualify and quantify where protection from harmful organisms can be found through specifying conditions for environment.

Primary biological hazards to preservation of collections are: staining and digestion by moulds; perforation and consumption by insects; contamination and destruction for nesting by rodents. The environ-

mental means by which we may restrict damage by these organisms differ between these groups.

The following sections examine in some detail the museum environmental requirements essential for deleterious organisms to survive, with the implicit goal of then taking these necessities away to preserve our collections. It illustrates where possible 'threshold boundary conditions' are to be found, and conveys their degree of 'fuzziness' stemming from the adaptive capacity of organisms through speciation and specialization and even the influence of progression in experimental understanding[1].

Lessons on "Dry"

Between the 1920's and 1940's scientific investigation of biological deterioration became a topic of great importance to safe processing and stockpiling of goods for commercial and military use [109]. At this time, controlled experiments on mould looked for a minimum humidity or moisture content which supported growth [110].

The advent of mechanical control of environment created a requirement for set-point values within achievable ranges of controlled temperature and humidity. Moulding of materials figured significantly in this along with corrosion of metal and strength of cardboard. Some basic lessons from mechanical dehumidification were learnt in quantitative terms [111] which have since applied widely to preserving collections from moisture and temperature harms through mechanical climate control in buildings. Although these rules were known for millennia as qualitative guides for the storage of foodstuffs in local agrarian practices (damp: bad for grains, good for root vegetables), thermometers and psychrometers allowed specification by 1918 of desirable conditions for a matrix of produce [112] subdivided by handling factors, warehouse requirements (construction, environment, containers, inspection) and expectations for retention of high values.

[1]The core of this chapter was presented to the Japan Photographic Society at their invitation on the topic of environment and biological problems to photographic collections. Tokyo Metropolitan Museum of Photography (SYABI), Yebisu, Tokyo, November 5, 2010.

Wait long enough for mould growth

Tomkins' study [113] was one of the first to systematically look at mould growth on inert surfaces (clean glass) or with nutrients, and independently varied humidity and temperature. The experimental problems with such work favoured microscope measurement in conditions for early stage of growth (sampling of threshold, probability and rate) rather than later colony measures which were used to evaluate response (qualifying extent). Figure 4.1 shows Tomkins' results for time for germination against relative humidity. Dammar and shellac are significant object varnish components and Canada balsam a common microscopy mounting media. Tomkins also concluded decreased humidity decreased the temperature range for germination while optimum temperature remained largely independent of humidity.

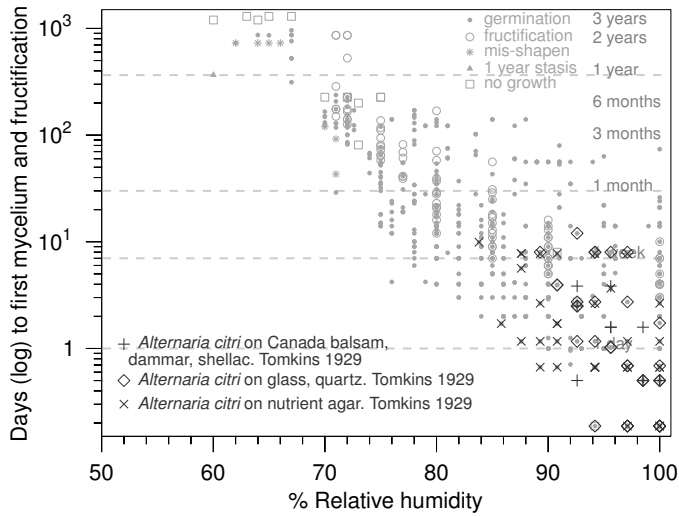


Figure 4.1: Time for mould germination ascertained by Tomkins 1929 [113] (points in black). Grey background points for comparison aggregate data from sources used in this review [113] [114] [110] [115] [116] [117] [118] [119] [120] [121] [122] [123].

Early studies did not always run long enough to test the extreme limit

of mould's potential to grow [116]. A discovery of note was finding the change in relationship between moisture and ability below 75 %RH [116] where previous work had set a limit for growth [110] and put onus on the species present rather than the substrate. Mould studies vary in their blending of emphasis on the causal agent or material vulnerability.

The onset of mould was predicted by high moisture short term studies to be near 75 %RH as seen by looking at the right hand side trend of figure 4.2. With enough time and species, the ultimate boundary for mould germination and growth past the two year mark was determined to be just below 65 percent [116]. Figure 4.2 shows maximum values of 961 days on oats and 867 days on grasses. The implication for experiences in collections is people will find mould growth in short term high moisture events, but sufficient possibility demonstrably exists to find mould growths from sustained marginal conditions. The pressure on climate control for 'sustainability' (lowered cost of operation) in collections storage and display is going to further test this boundary so it is worth some examination in detail and to illustrate available evidence for guiding responsible decisions.

Mould fructification (spore formation) follows a similar pattern to germination [116], changing rate below 75 %RH and requiring roughly two to four times the measured time for germination to develop propagules. In colloquial usage, 'spores' refer to mould propagules, but more specifically to those variants of spores from moulds that underwent sexual propagation. Where specificity is desired the term 'conidia' refers to mould's asexual propagules.

In practical terms both these forms are of equal potential harm to collections as they often disperse in marginal humidity conditions and ultimately generate the damaging hyphal phase when damp. When held at 60 %RH, *A. glaucus* spores maintained viability for a year, losing viability with longer storage [115]. There is wide variation in spore (sexual and asexual) survival as reviewed by Sussman [124] marking from a few days to more than thirty years depending in part on species and conditions. Even those vegetative phases geared for survival (sclerotia,

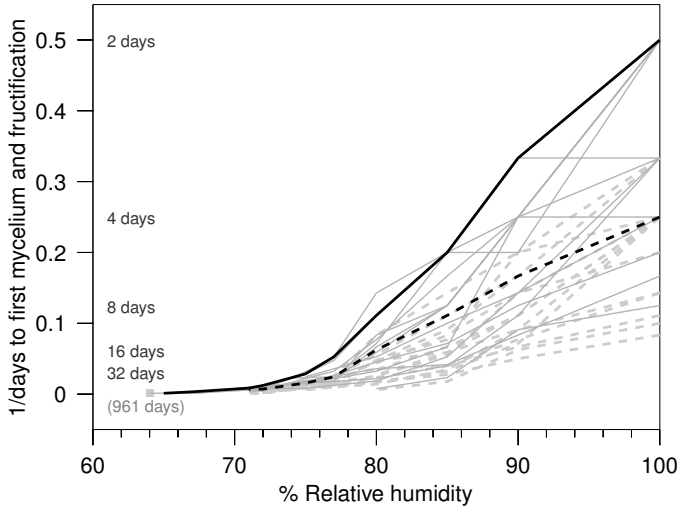


Figure 4.2: Change in rate of mould germination (solid lines) and fructification (dashed) becomes much slower with relative humidity below 75 %RH. Replotted from Snow et al. [116] figure 4, highlighting mould on locust bean (dark lines) and including data from all the source's tables (grey) for other materials and mixtures to show breadth of response: linseed cake, bone meal, oats, scotch beans, bran, locust beans, grass, protein, starch and plant fibre.

mycelia) have longevity in years to decades [124].

Holding mould spores in marginal dry conditions (low 60's) on gelatin and observing for germination showed increasing delay until beyond two years time [115] (upper points in figure 4.5). Germ tubes grew slowly, misshapen and less than 100 μm in length. Post-germination mould extension rate increases as humidity conditions elevate with measured maxima of 2 to 3 mm per day [125].

Restriction of mould germination is an obvious primary control of mould harm, restraining subsequent growth is a close second and preventing propagules is a third. The problem for setting standards requires settling the question 'when does harm begin?'

Use relative humidity to indicate mould risk

Tomkins had shown a clear relationship with relative humidity on limits and rate of mould growth spores distributed on glass [113]. While later papers introduced and made common the term water activity a_w for work with mould the two terms are effectively interchangeable[2].

A discussion in the literature across decades was the occasional focus on 'importance' of humidity (water activity) versus moisture content (regain). Galloway [110] stated: "Here there is no *a priori* reason for declaring whether moisture in the material or humidity in the atmosphere is the factor of greater importance." It is important to keep in mind how the two influence each other, domination is determined by the degree of enclosure and the mass contained. Galloway also puts deliquescent additives in perspective: "Certain deliquescents are undoubtedly capable of causing increased 'liability' to mildew but the effect is much less than if all the extra moisture were available for growth, and is here attributed to nutrient or stimulant action." The argument favouring RH as the definitive measure rested with Galloway's using the wide hysteresis of viscose to show germination occurred at the same rate at 87 %RH even when moisture content in the substrate differed by 4.6% [110].

Rose and Turner [126] examined this issue with leather hysteresis but were unable to establish "accurate comparison of the effects of adsorption and desorption at the same R.H." nor did they record onset times. They also did not comment on any previous work on germination of spores on glass which removes the substrate RH buffering effect leaving only the organism's latent capacity.

Block [127] inoculated fourteen mould species onto six materials with decreasing moisture contents: leather, cheese, wood, wool, cotton and glass wool held at fixed humidities between 100 and 76 %RH . He concluded mould risk depends on the material not (just) the humidity; shorter exposure in optimal humidity avoids germination; toxic compounds slow growth rate with less needed at lower humidity; non-

[2] $a_w = p/p_o = RH \times 100$, p/p_o measured/reference vapour pressures of water.

equilibrium results may differ. Block also proposed a limiting mechanism "…fungus is incapable of obtaining moisture for mycelial development directly from the atmosphere (except at 100 per cent R.H.) but derives it from the substrate which obtains the moisture from the atmosphere."

There is an element of 'chicken or egg' in any discussion on moisture content as buffering of air humidity (enclosed state) versus absorption / desorption from air (open state) depend on how you set up the experiment. It is worth keeping in mind what is practical for museums—conferring the mechanical stability of objects and inability for mould growth by modification of vapour pressure of water in air as navigated by limits to relative humidity and temperature.

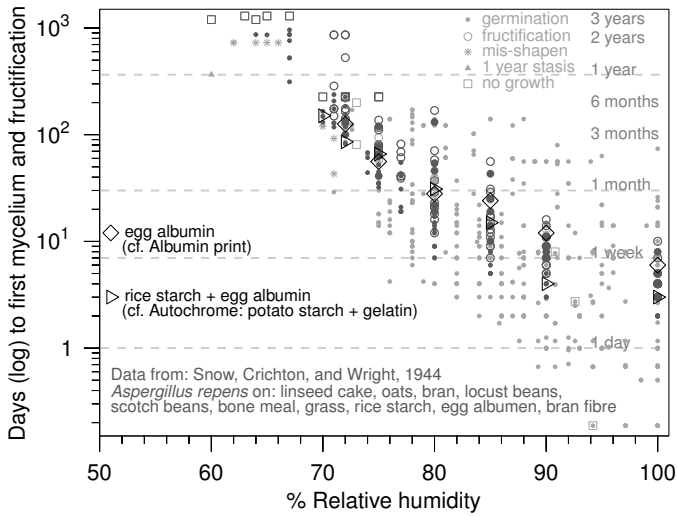


Figure 4.3: Humidity and substrate have a clear effect on time to mould germination and fructification. Snow et al. [116].

While understanding the relationship of moisture content to mould risk in specific products such as the feedstuffs shown in figure 4.3 gives an easy assay for the hazard by direct measurement of the product's moisture content, when we mix products with different water sorp-

tion isotherms in storage this method becomes cumbersome.

Museums, galleries and archives are a mix of products in long term storage. Being able to make decisions based on relative humidity allows us to avoid the labour of determining moisture contents for individual products to assess if it will be prone to mould. HVAC control systems are programmed on the basis of relative humidity, which requires translating concerns about mould risk and other thresholds (fracture, brittleness, blooming, softening, deliquescing etc.) into humidity setpoints as part of museum climate guidelines.

In discussing these setpoints, a hedging value is commonly introduced to prevent mould in worrisome micro-climates, or more properly areas that are cooler than the setpoint temperature leading to higher humidity when supplied by the conditioned air, or improperly ventilated spaces receiving moisture conveyed through the structures fabric. This concern leads to backing down from wagering success on measured mould limits to germination or growth to some conservative rounded value like 50 %RH or 60 %RH . Sustainability driven energy conservation initiatives require removing building level vulnerabilities to allow more time at higher internal humidity on a seasonal basis; or isolation of collections to ride out periodic damp. For the latter case, the four ways to induce mould in sealed containers was laid out in paper two so that they may be avoided.

Largely monolithic collections with a clearly vulnerable component (paper archives or photographic emulsions or animal skins) could use partitioned environments to restrict mould only if the thresholds were significantly different (trusting Block's cotton $<$ 92 %RH versus leather $<$ 76 %RH [127]). However for mixed collections where the most sensitive materials drive the lower limit and are not easily isolated into special storage or even recognized, the collection is exposed to varying risk from multiple mould species with somewhat differing tolerances for dryness.

In defining environment standards for museums, the report by Wilson and Wessel [128] covered summary information on fungal limits to growth as a pers. comm. from mycologist P.B. Marsh who most likely

Temperature	Observation
−7.5 °C	lowest limit of growth
−6 °C to −2 °C	slow growth of some bacteria and fungi
0 °C	slow growth of many bacteria and fungi
5 °C	few exhibit rapid growth below this temperature
15–35 °C	optimal growth and reproduction
58 °C	upper limit of fungal growth
65 °C	upper limit for actinomycetes
78 °C	upper limit for bacterium

Humidity	Observation
70 %RH	lowest supporting microbial growth
75 %RH	numerous reports of slow growth
80–95 %RH	"most forms grow well"
90 %RH	some microorganism growth still inhibited
95 %RH	"growth is luxurious"
95–100 %RH	optimum for fungi
30 °C (86 °F)	
100 %RH	optimum for fungi
37.8 °C (100 °F)	

Table 4.1: Microbial growth limits, temperature and humidity. P. B. Marsh as pers. comm. to Wilson and Wessel [128].

reviewed some of the extant sources cited in this chapter. Other than recommending storage below 70 %RH, their section summarized into table 4.1 provided some guidance for the reader to navigate proximity to harm from mould regarding conditions of storage but none on material susceptibility and time of adverse exposure.

Wilson and Wessel recapitulate the risk of damp from thermal swings and long retention of moisture in volumes of paper allowing mould which reinforced recommending constancy of humidity and tempera-

ture as a principle [128] to avoid mould. Given the tabulated information, constancy (a rigid form of thresholding) is the easiest method by which to imagine prevention even though many collection environments are not constant, having either short term weather induced or climatic seasonal swings into mould territory.

Even the misconception of tropical environments as perpetually hot and humid is criticized by Aluko's comments in discussion [129] indicating 'hot **or** humid' lies closer to actual observations, and emphasizing that thermal swings are important as they create high surface moisture. Constancy of environment is largely a construct of the modern air conditioned museum and therefore most matches the profile of static-environment experiments which are more readily performed and hence collated in this chapter.

Scott [130] specifically undertook an investigation to look at potential for mould growth in tropical conditions on the observation that mould was more isolated in occurrence than presumed for tropical museums concluding the moisture absorption / desorption response of materials was sufficiently fast that "mould growth rates can be expected to be determined by conditions prevailing at any particular point in time near surfaces". The effect of surface coatings limiting moisture wicking (lowered surface moisture) was noted in short term (two weeks) at high humidity (90 %RH) exposure of enclosed natural history specimens [130]. This is not at odds with the laboratory studies cited here, merely the manner in which the substrate is being 'humidified', it is the difference between 'standing start' and 'running start' races. The implication is a longer term at high humidity in the absence of inhibiting chemical agents would allow all materials to support moulds once the surface was not being efficiently dehydrated by adsorption into the interior.

For fungi which consume dead organic matter (saprophytes), rather than the fungi which infect living organisms[3] the relationship between high humidity and short time to begin growth is shown by the left side

[3]Plant infecting powdery mildews have lower moisture limits for germination, even germinating at 0 %RH [131] against the prospect of moisture from the plant sustaining them.

edge of the germination data in the figures illustrated in this chapter. The 'thickness' of the background sweep of data (grey points in figure 4.3) gives an indication of the 'fuzziness' of any mould history which museums would experience and why individual controversy persists. For example, mould in a week or mould in several months are both first evident at 80 %RH dependent on species and substrate.

As early concerns in microbiology were for reducing economic harm, even without direct experiment on objects of interest (photographs for example) we can find equivalents to those in museum collections giving us some indication of what to expect. Figure 4.3 highlights experiments where the addition of starch to a protein decreased the time for mould to begin growing at humidities greater than 80 %RH. Mapping to collections of similar composition projects somewhat differing responses for Autochromes and albumin prints at high humidity, but less distinction from 68 %RH to 80 %RH.

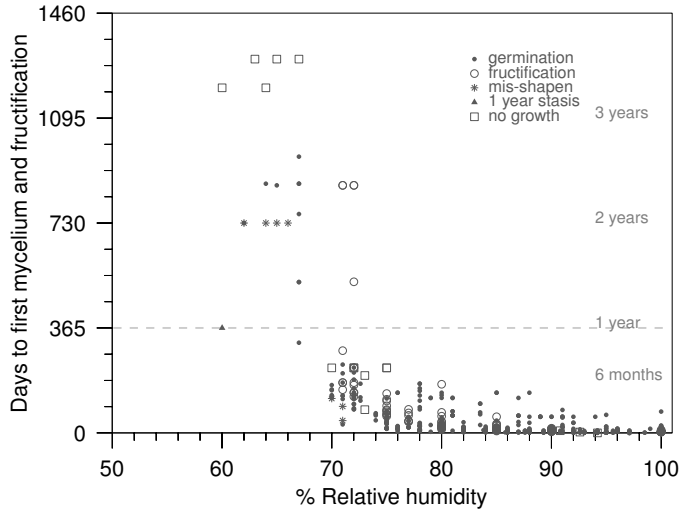


Figure 4.4: Mould germination (linear time scale) showing asymptotic trend less than 70 %RH, compare with figure 4.2. Low humidity data paucity shows few long term studies.

So where does harm to objects begin? One can propose several thresholds. Not germinating any mould avoids the harm of digestive and staining damage to objects. With less control at the threshold, eliciting germination, quickly followed by desiccation killing the nascent mould would be useful for reducing possible extent of harm. Germination followed by preempted minor growth would be harmful where damaging glossy surfaces harms aesthetics and to those with high information density incurring distributed losses. Germination followed by sustained major growth would be of obvious grave concern to much of collections. Finally, germination and propagule dispersal increases contamination if amenable conditions are sustained and poses a respirable hazard to human health.

Determining rate of mould growth becomes difficult beyond when individual hyphal length can be accurately measured as in the work reported by Tomkins [113], Snow[115] or Grant et al. [125]. Most authors resorted to qualitative terms for logging the intensity of mould development with no metric (area covered per unit time). Symbolic representation of qualitative amount of growth (+, ++, <) is not directly useful for quantifying harm to substrates, but the researchers were interested in measuring growth limits not loss. It would take some effort to re-map these designations to object harm. A direct approach like the calorimetric measures recently applied by Li [132] for examining mould growth on building materials bypasses the qualitative problem when comparing growth to environmental factors.

'Good nutrition' increases mould risk

Implicit in the choice of experimental substrates is the role of 'nutrition'. In research papers nutrition defines additives to some base material. For collections, this base material is often of principle nutrient importance and added nutrients might be termed 'soiling'. For example, mould growth on gelatin with and without supplementary nutrients (figure 4.5) can be considered to demarcate mould growth hazard to important collection materials: animal glue size, adhesive and photographic emulsions. These experiments on gelatin [115] did not run

for longer than one month at lower humidities so there is an apparent step in the left side boundary data near one month duration. The critical value for long term mould free storage remains below 65 %RH .

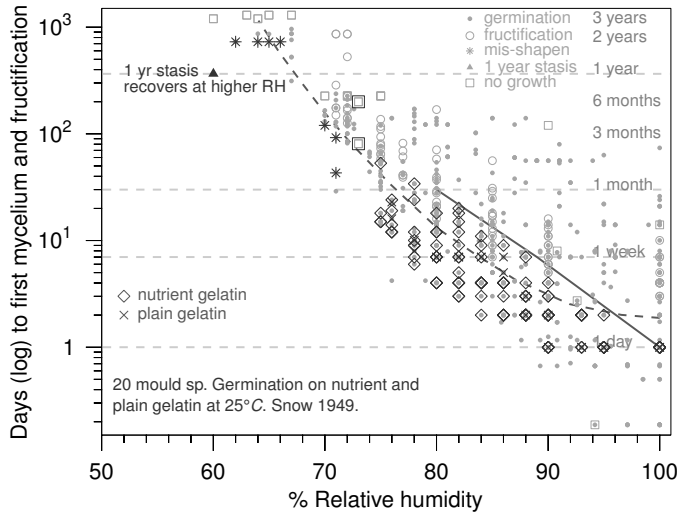


Figure 4.5: Extension of hazard to lower humidity with gelatin substrate (Snow 1949). Mould limit from Michalski [133] (dashed line, defined a fructification limit from cited data) is well inside possible germination region on gelatin, likewise for the IEA mould threshold for calculating 'temperature ratio' mould risk (solid grey line) [134]. Snow's data also overlaps that of Tomkins [113] on nutrient agar (figure 4.1).

Low nutrient gelatin (figure 4.5) show some restriction in germination and slowed rate of growth. Parchment and vellum are relatively intact collagen and their susceptibility is restricted to collagenase assisted digestion. Gelatin is a highly distorted collagen and prone to wider range of enzymatic attack (G. Young, pers. comm.). This loss of specificity would make photographic emulsions and animal glue more prone to damage by a wider selection of moulds.

Adding nutrients to gelatin and the vulnerability of gelatin alone have a combined mould germination limit at a lower humidity than the

mixed food crops used in the previous plotted studies (figure 4.3). Optimal mixtures establish a "worst case scenario" that guides choosing a trouble free storage standard. Efforts to accrue energy savings that float these standards without some care (dehumidify less) risk intermittent problems.

Block [127] also added nutrients when investigating mould environmental limits (figure 4.6). Czapek-Dox broth lowered humidity sensitivity of mould on leather and wool but not the nutrient poor glass and cotton nor nutrient rich cheese. Unfortunately his experiments were not of equivalent length, raw substrate were only five weeks duration while nutrients ran a year providing a long tail for germination results. Inclusion of glass wool illustrated the power of mould to colonize clean low moisture adsorbent surfaces (two weeks at 96 %RH) with sensitivity to a narrow environmental range. Block concluded that nutrients (growth enhancers) or fungicides (growth inhibitors) decreased and increased the respective time to germination or the measured rate of growth, but significantly they did not alter the minimum relative humidity at which the moulds would grow on a particular material when given enough time.

The first document to present a graphical outline for mould tied to specification for environmental control for collection preservation was by Michalski [133] recapitulating work on mildew of library materials and high nutrient cultures [114] [116] [117]. This was also incorporated into the ASHRAE chapter on museum environment [135] [136].

However, Michalski's summation shows little of the underlying data and was missing the impact of the most capable low moisture group (*Aspergillus spp.*) implicated in gelatin deterioration (see figure 4.5). The line indicated from Michalski [133] (grey dashed in figure 4.5) does not fully protect the more vulnerable collections which are essentially applications of gelatin represented by photographic images or animal glue layers (sizing, adhesive bonds) as it defines an apparent fructification limit but not for germination and mycelial growth. Between germination and fructification lies a region of increasingly persistent mycelial growth and consumption of substrate. Photographic

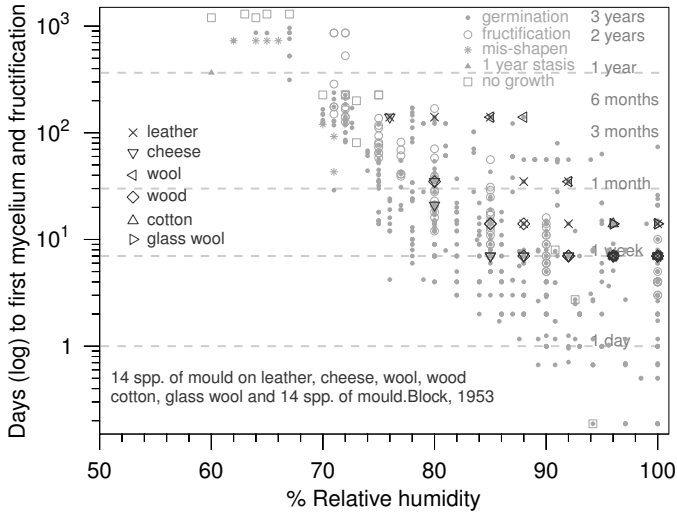


Figure 4.6: Minimum times to mould growth (14 spp.) on various substrates with and without added nutrients (Block [127]).

images would be harmed in early mould attack by optical marring affecting their high information density and their stability by increased film solubility.

Changing the mould risk boundary condition to include gelatin substrates shown in figure 4.5 has some ramification for papers two and four where time thresholds from Michalski [133] were used to illustrate mould potential in heat disinfestation and storage scenarios. In part, this chapter can be considered an extended amendment for the mould limits cited in the attached papers.

Parchment (raw skins), leather (book binding), and paper fibre products covered the common materials of archives and libraries were studied by Groom and Panisset [114] for their latent time to germination (see figure 4.7). These also would include photographic objects where these materials were used to box, bind, sleeve, and display them as well as the surface and structure of early household and industrial objects.

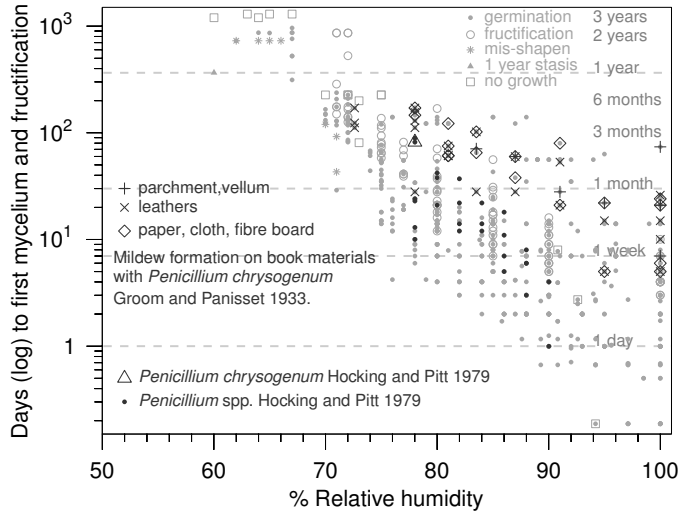


Figure 4.7: Capacity for mildew *Penicillium chrysogenum* on different substrates. Mould risk for book materials appears less than for gelatin photographic emulsions and glue.

This study was limited to one species of mould *Penicillium chrysogenum* and exhibits considerably less hazard than the gelatin studies with different species. However the use of animal glue as an adhesive would possibly lower any safety factor from the choice of covering. Leathers sustained mould growth earliest and at the lowest humidities tested as was also confirmed by Block [127].

Hocking and Pitt [120] examined *Penicillium* moulds in glycerol based media and determined a single minimum water activity and time for germination for each of 26 species at 25 °*C* . These are also plotted in figure 4.7 with *Penicillium chrysogenum* highlighted. In their review they did not cite the work of Groom and Panisset [114] on this species which appears to function at lower humidities and less time on book materials than Hocking and Pitt report with glycerol media (figure 4.7, triangle).

Moulds are successful in germinating on glass slides in very moist air,

showing their ability to germinate and grow for some time without nutrients [114] [113] [127]. Under these conditions glass plate negatives and optical lenses are not immune to contamination and damage from mould growth and this proved to be a wartime problem on optical instruments [137].

Diversity increases assessment of capability

Including as many species of fungi from multiple studies to develop guidelines is a reasonable stress-test for the concept of a lower limit since a wide biodiversity driven increase in environmental response is more likely to be seen. Several of the cited authors took this approach by using mixtures of species in their experiments to bolster arguments and applicability of the results. Surveys on materials often turn up multiple species. Flannigan and Miller [138] listed 53 moulds which can be isolated from building materials whose a_w minima span 0.64 to 0.97 at 25 $°C$ (incorporated in figure 4.11). With diversity in the background, biology is inherently "messy" and fostered the development of statistical methods to cope with experimental data [139].

Illustrated in figure 4.8 are germination minima for 63 moulds found in soils [118] largely measured between 15 $°C$ and 25 $°C$, of which some are representing those species found attacking organic matter in studies plotted previously (encircled grey points). There are a few higher temperature points along the humidity minima. This diverse sample does not appreciably change the boundary for growth (shown by the aggregate of background points) as highlighted points are largely spread throughout the other findings.

Bacteria are more reliant on moisture than mould

Bacteria are a lesser concern than moulds in general collections since the damp conditions that support bacteria are allowed less commonly than the elevated humidities which continue to foster growth of mould. However, in extreme conditions (flood or very damp) bacteria can greatly contribute to deterioration. Of the bacterial data shown (figure 4.9), the lowest limits to activity are those of bacteria which contaminate fresh meats [121] [122] [117]. Those bacteria forming an en-

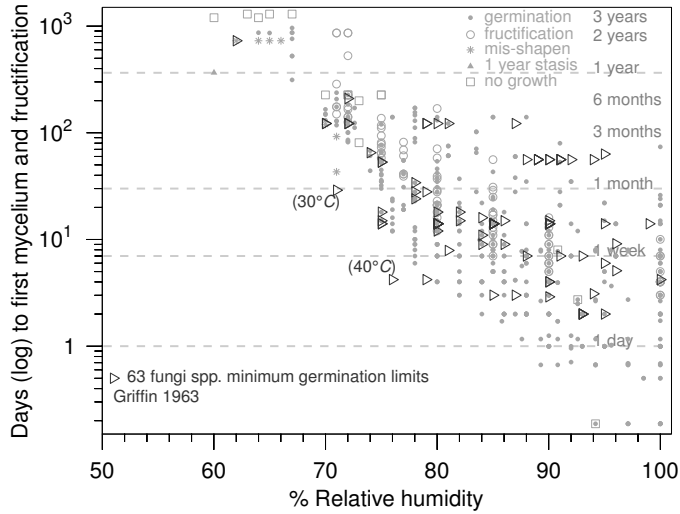


Figure 4.8: Examining recorded diversity of environmental limits of 63 mould species to test 'worst case' boundary. Data from Griffin 1963 [118]. Background points from Griffin suppressed to reveal differences with other author's data.

dospore, notably pathogenic *Clostridium* spp. will survive much lower humidity although they are not active at that time. The potential for bacterial survival in fluid preserved collections was examined in Waller and Strang (1996) [140] where ethanol controls the water activity of the preservative solution, and further information on some of the potential survival of spore forming pathogenic species added in Strang (1998) [141].

Gelatin is very prone to bacterial breakdown, a primary concern to photograph collections exposed to high humidity or flood. This problem with gelatin lead to the alternate use of agar as the media for culturing bacteria [142]. Recent studies testing the capabilities of bacteria and fungi to deteriorate gelatin (collagen) [143] [144] closely match these earlier studies in the identification of active species. While the earlier cited microbial studies were not specific to photographic collections, gelatin and collagen are pervasive components of material

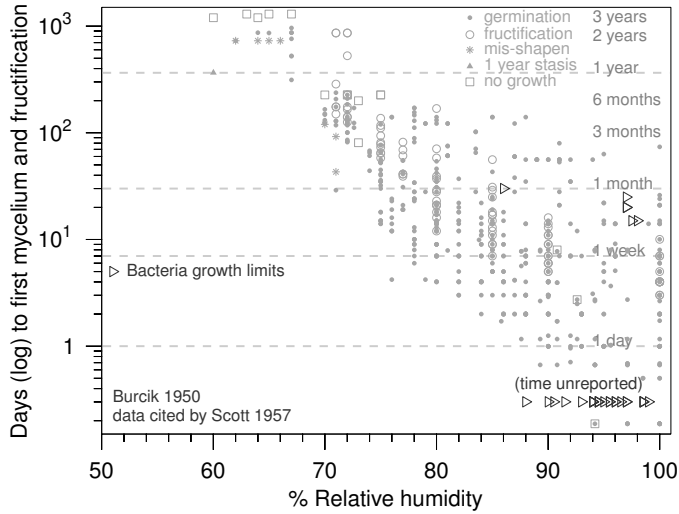


Figure 4.9: Bacterial growth confined to higher humidity than for mould.

heritage in thin films or as binder.

Comparing bacterial limits[4] to those for moulds illustrates controlling moisture to limit fungal damage will also protect against bacterial hazard. An increased measure of harm comes when both mould and bacteria can digest materials although competitive exclusions do come into play.

Insects are less controlled by humidity

Insects are less susceptible to control by humidity having developed the ability to extract, replenish, and harbour water carefully to support their mobile lives.

While there is less data on humidity limits to insect development than for mould Howe [25] plotted tabulated data on growth minima and optima for stored product pests. Howe's definition of minimum was

[4] An example of presenting bacterial hazard data is made available through the web database ComBase[145] classified by foodstuff, organism and influences.

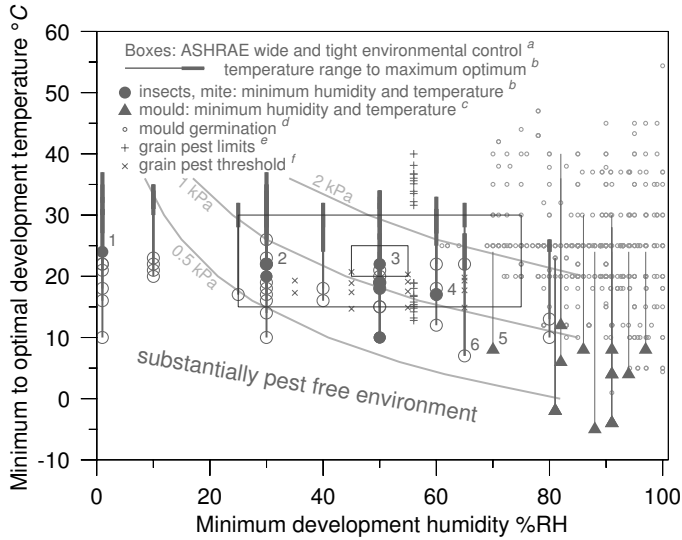


Figure 4.10: Distribution of mould, mite, and insect development (grain storage pests) as composite hazard to collections. Museum insects shown with solid circles. Minimum humidity and temperature indicated for species with symbols, temperature range to maximum optimum indicated with vertical lines, thickened for insect temperature optima. Grey curved lines indicate constant water vapour pressure, following these avoids water exchange and most dimensional change. (a) Nested boxes indicate ASHRAE wide and tight museum environment around commonly cited norms [135]. (b) Insect growth data in Howe [25] (c) After tabulated data in ASHRAE Fundamentals [146] from Stroshine [147] and Pederson [148]. (d) Mould germination data reviewed in figure 4.11. (e) Modelled upper and lower grain pest limits from Subramanyam et al. [39] plotted at RH equivalent 12%MC on 18.3 °*C* wheat sorption isotherm (figure 471 in Iglesias and Chirife [149]). (f) Threshold of weekly finite rate of reproduction from Becket et al. [13]. Numbered points described in text.

3 °*C* to 5 °*C* and 10 %RH above that for no growth "assuming that a species must at least double its numbers annually to be a warehouse pest". A subset of these estimates was tabulated in ASHRAE [146] for discussing HVAC issues in protecting stored corn [147] [148]. An ag-

gregate plot of information in figure 4.10 illustrates the fundamental problem. Even if we avoid high humidity to prevent mould, collections are generally stored in the middle of insect environmental optima as generally represented by the ASHRAE guidelines on museum environment [135] (nested boxes in figure 4.10). Like stored grain, many organic objects provide humidity and some thermal buffering to protect the pests who can exploit it. Grain storage studies mimic some of the stability of museum climate control where seasonal swings are acceptable.

To be out of the way of both mould and insect pests we would need to shift the norms for common storage far from their current position which is primarily for human comfort. This is only seriously proposed for slowing 'deterioration' of furs and 'fading' of photographs with refrigerated storage. The few large collections using lowered temperature are herbaria and natural history stores which do so to avoid pandemic and historically long running damage from insects by greatly lowering rate of increase[5].

> "*Moths.* Moths or *Tinea*, which eat clothes, are likewise abundant here. I have seen cloth, worsted gloves, and other woolen stuffs, which had hung all the summer locked up in a clothespress and had not been taken care of, so damaged by these worms that whole pieces fell out. Sometimes they were so spoiled that they could not be mended again. Furs which had been kept in the garret were frequently so ruined by moths that the hair came off by the handfuls. I am not certain however whether these insects were originally in the country, or whether they were brought over from Europe."
> Peter Kalm's Travels in North America, 1750 [152]

[5]Kew Economic Botany Collection [150], Brooklyn Botanic Garden Herbarium [151], Missouri Botanical Garden Herbarium (J. Solomon pers. comm.), and the Natural History Museum (London) Darwin 2 storerooms (A. Mendez pers. comm.) all designed to sustain temperatures ranging from 12 °*C* to 18 °*C* for suppressing insect pests.

The lower edge of data plotted in figure 4.10 shows what might be assumed as a general boundary for avoiding collection pestilence, merging across microbe, mite and insect. It roughly follows the path of vapour pressure curves (stressor gradient) until encountering extremely low humidity tolerant insects. Museum insect pests (solid grey circles) are numbered: (1) *Trogoderma granarium* a severe grain and nut pest, also associated with natural gums (2) *Lasioderma serricorne* and *Dermestes maculatus* (3) seven Ptinids (Anobiidae subfamily) including *Ptinus fur, P. tectus, Niptus hololeucus*, also *Dermestes frischii* and *Necrobia rufipes* all which are pests of natural history collections, textiles, and (4) *Stegobium paniceum* are well placed to take advantage of most of the wide ASHRAE specification.

At the lowest RH fungi affecting stored maize, (5) *Aspergillus* is indicated outside the humidity / temperature area assembled from experiments (small grey dots). It may illustrate a kind of error introduced by reporting lowest humidities and temperatures that are each true, just not truly coincident. From all the data presented, it is clear that reporting a minima should be tempered by including the other significant environmental dimensions as organisms are not constrained to 'boxes'.

The molecular ability to access DNA and RNA limits life in vivo and is a hard boundary for many microbes along with other complicating factors within the cell, but is clearly not an issue for insects and mammals which can obtain water from food or drink independent of the atmosphere. The complications around attesting germination specifically to interactions of DNA and RNA or other macromolecules with moisture or other stimuli were laid out by Sussman [153].

Environmental limits were also explored in paper three which observes seeds as living components of collections and tests if they could be affected by pest treatments which require temporarily altering conditions of storage. Disciplines requiring stored DNA and RNA samples have burgeoned since the publication of paper three, with two camps: samples desiccated at room temperature to $-20\ ^{\circ}C$ (akin to seeds), or moist with deep cold (akin to permafrost). Kigawa et al. ex-

amined low temperature at −30 °*C* for a week and heating for 24 hours to 60 °*C* and found no significant harm to recovered DNA and subsequent PCR[6] amplification [154] from freeze-dried samples. Likewise preconditioning between dry and 53 %RH did not harm DNA recovery after heat treating at 60 °*C* for 24 hours [155] with some smearing of gels starting somewhere between 53 %RH and 83 %RH indicating progressive molecular breakdown very evident in 100 %RH and wet samples. PCR of the same samples was harmed for short chains (987 base pairs) and reduced for longer chains (3100 bp) in the 100 %RH and wet treated samples.

These results add confidence to using thermal pest treatments on infested natural history specimens which could later be sampled for DNA.

Given enough results, a picture of the bulk response of organisms to the main environmental controlling factors (figure 4.10) can serve as a reliable indicator of threshold for harm to collections and with yet more work, impart indication of rate to govern expectations of population growth and concomitant severity of harm.

Lessons on "Cool"

Temperature controls much of biology through its effect on cell metabolic rate. While mammalian pests can operate with much independence from temperature around them to a limit (rodent death above 42–44 °*C* [156]), the metabolism of insect and microbial pests of cultural property are incrementally affected by shifts in temperature.

Mould is less readily controlled by temperature

Moulds as a group are very capable of functioning over a wide range of temperature, albeit limited in rate near extremes as defined by human comfort and safety.

The range for mould germination and growth is reportedly from −6 °*C* to 60 °*C* [159] including the 'thermophiles' with optima near 50 °*C* in heating composts [160], however moulds do greatly favour the similar range we find comfortable, indicated by the trend where lower hu-

[6]PCR, polymerase chain reaction is used to synthesize copies of DNA fragments.

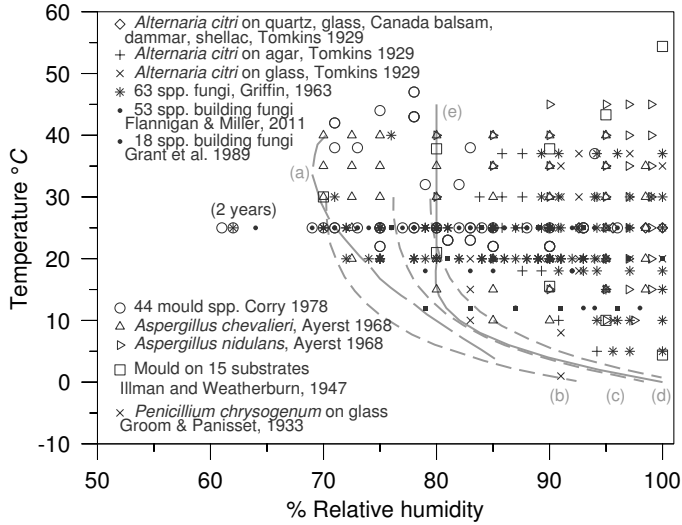


Figure 4.11: Temperature and humidity limits for mould growth including diverse substrate and species [113] [114] [118] [117] [119] [123] [138] [125]. Mould limit from Michalski [133] (long dashed line 'a') to guide collections storage environment represents most of the data. Building mould growht isopleth model, WUFI-Bio® LIM 0 for culture media (short dashed line 'b') includes most of the data, LIM I and II for most and least sensitive building materials are less inclusive (lines 'c', 'd'). LIM models from graphs in Krus et al. [157]. VTT limit function [158] plotted as solid grey line 'e'. Outliers are not overly suspicious given borderline evidence in figures 4.3 through 4.8 and indicates long term studies at marginal RH may not be well represented in temperature tolerance studies.

midities at which mould germinates and grows prolifically are near "room temperature" [123] [117] [118] [114]. Thus, we primarily limit mould through dehumidification as it is not prudent to elevate temperature to the continuous degree necessary to stop mould growth and low temperature storage while beneficial for chemical permanence would prove exorbitant except where it is most needed or came naturally.

Accidentally saturated materials are recommended to be frozen (commonly around $-20\,^{\circ}C$) rather than refrigerated ($4\,^{\circ}C$) to prevent any slow microbial action in what could become a long term of storage before treatment by freeze drying. While limiting dissolution and chemical deterioration are the other reasons for low temperature storage, microbial activity is ultimately a form of chemical degradation by organic acids and enzymes and effectively ceases by $-20\,^{\circ}C$.

The roughly vertical 'nose' of the curve in figure 4.11 substantiates the use of the left side margin for total control of mould without much concern for temperature until below $15\,^{\circ}C$ or above $35\,^{\circ}C$ as the boundary consists of points measured within the optimal temperature range between these two values. Lower temperature will lessen mould risk until higher humidity is achieved.

Mould limits in changing conditions

The mould prediction problem within changing conditions of humidity, temperature and time is a task which Block [127] succinctly noted as "difficult to study".

To a great extent, any confusion on why mould happens or fails to happen swings on complexity of the 'experiment' (see figure 4.12). Predicting mould risk is a combination of biological and physics models. The conditions for mould on materials can be sustained by the time-asymmetry of relatively rapid adsorption and slow desorption of moisture [161] [162] [138]. Permeable barriers and buffering contents can be overwhelmed by too long a duration at high humidity and both potentially enhance mould by prolonging retention of moisture despite the external moisture supply falling. Non-adsorbent surfaces reach surface humidity levels that support mould are further aided by condensation. Transport of moisture into material away from the surface delays mould onset. Intrinsic and contaminant nutrition accelerate mould, natural and applied toxins retard it. Damp air is more buoyant than dry air at the same temperature and building stack effects move air from one level to another and through thermal gradients. Cold bridging locally enhances moisture levels, enables and speeds mould onset. Moisture production in structures is non-uniform in distribu-

tion. Permeability of finishes and materials vary and water vapour is a very good penetrant.

Supplies of heat, critical to surface desorption, are locally hindered by nearby convection reducing structures [163]. Temperature gradients within containers of organics generate viable mould conditions [164] [165]. Cellulosic components of buildings have the highest risk of mould followed by organic contaminated materials [138].

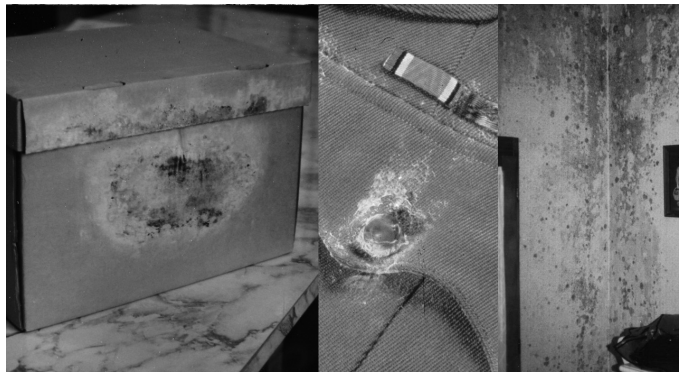


Figure 4.12: Three patterns of mould development: Left, bulging box against cold damp wall created convection tapering to diffusion controlled air gap resulting in moisture trap in central area. This also dries slower allowing more time for mould growth. Middle, leather button dressing increased mould nutrition on wool uniform allowing growth in shorter time than on surrounding wool. Right, winter heating of earth-floor basement generated moisture, stack effect drew it into upper stories, spring mould bloom concentrating in high cold corners with greatest adsorbed moisture (moist air rises). Photos left, centre CCI, right T. Stone.

To avoid mould a 'smart' monitor controlling HVAC response would have to factor in not only the temperature and humidity, but the cumulative time spent inside an envelope of mould risk, and track the time spent outside the envelope when restorative drying occurs. The occurrence of weather events would be factored for buildings which are more synchronous to outdoor conditions [166].

Some of these elements were described by Michalski [136] along with mechanical concerns about objects to assist the engineering profession with museum environments [135] but greatest progress has been made in the area of improving microbial safety in cold weather housing.

As an instructive series of papers the steps made to model environmental and biological issues for house dust mite control can be reviewed in the works of Oreszczyn et al. [163] [167] [168]. Dust mites pose severe allergic hazard to many people, flourish in conditions amenable to mould, and are considered best controlled by modifying human behaviour as well as environmental factors.

Measures to reduce mould risk while improving energy use include the International Energy Agency (IEA) Annex 14 [134] monthly average surface relative humidity value of less than 80 %RH[7] In contrast, the Canada Mortgage and Housing (CMHC) stipulates a preventive criteria as simply less than 65 %RH [169]. Expected temperature gradients inducing elevated surface humidity and moisture in wall materials are behind these numbers. For museums, preemptive measures for control rather than basing response on the detection of ongoing deterioration are preferred, and the ASHRAE museum environment guidelines [135] are in part written to allow lower humidity in wintertime to avoid mould induction in permeable structures without undue mechanical stress on the housed artifacts.

Adnan [170] examined building materials to establish growth in fluctuating conditions through integrating 'time of wetness' on mineral, paint and some organic fibre products, but not more sensitive materials like gelatin glue. The IEA Annex 14 method cites 'agar' as more nutritious than building finishes in conjunction with an *Aspergillus versicolor* minima a_w of 0.75 yet they also did not consider gelatin. See figure 4.5 for threshold comparison in the humidity / time domain.

Vereecken et al. [171] reviewed mould prediction models for struc-

[7] Oreszczyn and Pretlove [163] describe their model software 'Condensation Targeter II' including their logic of relying on a pivot of "80 %RH for half of the time." even though it may not provide complete assurance.

tures: Temperature ratio[134], VTT versions [158] and Isopleth[8] models [172] for dynamic conditions. However, the "very sensitive" class used in the VTT model is untreated pine lumber with a stipulated minimum 80 %RH as does the IEA Annex 14 method, still much higher than the limiting values for sensitive materials graphed in this chapter. This limitation to VTT, and the WUFI-Bio® LIM I curve for "sensitive" building materials in figure 4.11 argues for residual caution in unverified adoption of these architectural models for cultural property, given some of the known surfaces are clearly more sensitive than the building materials defaulted to in these models, a caveat which Krus et al. note [157] and which figure 4.11 shows may be better served by LIM 0 for architecturally discounted 'optimal cultures'.

Modelling harm, the VTT "mould index" uses classified growth to convey percent coverage over a seven point scale [158] from microscopic to full coverage. This does not map to values harmed by digestion, matting or staining but does give an index of severity which could be combined with secondary knowledge of the surface.

Evaluating mould risk in extant structures such as museums to garnering savings by decreasing active control over definably unaffected areas is economically beneficial as would being able to apply predictive tools to cultural property risk assessment.

Considering the environment as a dynamic mould inducing system, dwell time in optimal humidity and temperature is a combination of the static exposure risk delayed by moisture absorption into the substrate at the onset of higher humidity and retained by desorption after the driving humidity declines. For sustainability discussions, acknowledging a dynamic system requires people to state 'how frequent and how deep into the dangerous region can we go yet avoid disaster by relying on a reset towards safety in the periods we are out of danger?' The mould data gathered here illustrates the span from worst case to

[8]Isopleths of mould response as germination time or growth rate on RH / temperature plots. LIM, Lowest Isopleth for Moulds [172]. From the papers reviewed, these are based on a multi-month observations, or interpolated from classified sparse species data following simple rules to cohere limits [172].

best case for cultural property by including as wide a diversity of organisms and substrates made available from controlled experiments on record.

Using temperature to control insects

The insects which attack collections are largely specialized consumers of protein and cellulose. There are, as with all diverse groups of organisms, variations in capability to withstand environmental conditions which in turn creates variance in degree of control.

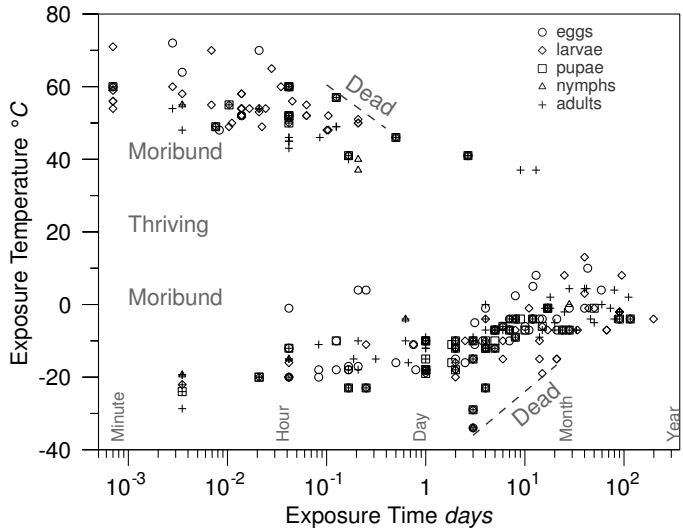


Figure 4.13: Temperature and time relationship for thermal mortality of 46 pest insect species. Modified time scale (log), after Strang 1992 [67]

In figure 4.13 the limits are shown as time to kill test populations of 46 species of collection destroying insects sorted by developmental stage (see discussion in chapter 5 and paper one in this volume). These limits were used to recommend single low temperature storage of sufficient time to kill all stages and species under consideration. Elevated temperature mortality indicated short term exposures of 55 °*C* to 60 °*C* would limit thermal harms to objects while quickly

and certainly kill insect pests.

The low temperature storage standards for vulnerable photographic materials (chromogenic dye 2 °*C* ; "low" temperature for cellulose nitrate and acetate) and the refrigeration used for fur storage will stop insect and greatly limit mould activity. Use of freezers for storage is bio-static for mould and bacteria and −20 °*C* to −30 °*C* freezers are now routinely used to kill insects. Thermal methods, sub-lethal effects and mitigating harm are discussed in greater detail in papers one, two, three, four, seven and chapter 5 in this volume.

Lessons on "Contained"

When there are practical and economic limits on our ability to place collections in environments which are safe from mould and insect, we have to rely on measures to deny the pests access. Ideally we use long-lived materials to protect contents against future harms, use materials tough enough to deter organisms penetrating the containers, and have seals tight enough to prevent ingress of organisms.

Tough enough

Rodents have no difficulty chewing through cardboard, paper and plastic sleeves, canisters and boxes and chew to wear down their constantly growing incisors. They are far less likely to puncture metal canisters but easily accomplish excavations through soils and wood construction [24]. Rat teeth have a Moh's hardness of 5.5 which lets them readily chew material up to Moh's 3.5 or 4 [156].

Many pest insects have trouble perforating plastic containers, stymied by films if they cannot obtain purchase with their mandibles, but some succeed when the materials have vulnerable seams and folds or when the films lay in close contact with the surface of material from which boring insects emerge.

The relative resistance of thin sheet materials has been studied for designing packages [173] [174]. Photographic collections are also predominantly thin films and within those listed are materials used for photographic substrates, sleeves, envelopes, and containers:

Excellent insect resistance: polycarbonate, polyester, polyurethane.
Good insect resistance: cellulose diacetate, nylon, polyethylene (250 μm), biaxial polypropylene, polyvinylchloride (unplasticized).
Fair insect resistance: acrylic, polyethylene (125 μm).
Poor insect resistance: Cellophane™, corrugated paperboard, ethylene-vinyl acetate, ethylene-vinyl acetate / polyethylene, kraft paper, polyethylene (25 to 100 μm), polyvinylchloride (plasticized), saran, spunbonded polymers [174].

Bertonazzi [175] tested insect response to food odour transmission at 25 °C , 70 %RH through packaging films 25 to 30 μm thick: low density polyethylene, high density polyethylene, polyvinylchloride, polyvinyldechloride, non oriented polypropylene, polyethylene terephthalate, ethyl-vinyl alcohol (10 μm), nylon, and Cellophane. No significant difference between films was seen for *Attagenus piceus* larvae (now *A. unicolor*) although Cellophane was penetrated within 24 hours by *Ephestia küniella* larvae.

Resistance to pests requires both strength to prevent rupture and reducing their ability to gain purchase. The latter is revealed by maximum angles of climb on a variety of packaging materials by stored-product beetle adults [176] and larvae [177]. Table 4.2 illustrates capabilities of four adult museum pests: *Dermestes maculatus*, *Anthrenus flavipes*, *Attagenus megatoma* (now *A. unicolor*) and *Lasioderma serricorne*. Paper is readily climbable (90°), but smooth plastics, metal, foil and glass all resist climbing adults and larvae to under a 40° angle with the exception of *L. serricorne* adults which climb everything.

Tight enough

Where openings must or likely exist, holes and cracks are vulnerabilities that have been studied for guiding minimal hole sizes in packaging [52] ($\leq$0.33 mm), proofing of structures against termite ingress through cracks in concrete ($\leq$0.4 mm) [178] and excluding young mice ($\leq$6 mm). The following diagram illustrates these dimensions as heights of bars.

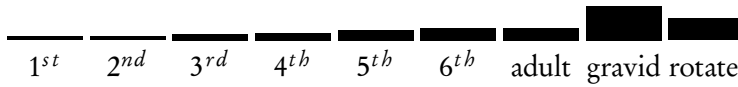
	D. maculatus	*A. flavipes*	*A. megatoma*	*L. serricorne*
Paper	90	90	90	90
PE	10	10	5	<5
PVC	10	10	<5	<5
PP	5	10	<5	<5
Foil	10	10	5	<5
ETFE	20	20	5	5
Glass	10	15	<5	<5
PET	15	15	5	<5
Cellophane	5	15	5	<5
FEP	5	10	5	5
Paper	90	90	40	90
PE	30	20	10	90
PVC	25	20	10	90
PP	25	10	5	90
Foil	20	20	<5	90
Teflon	20	5	5	90
Glass	25	<5	<5	90

Table 4.2: Maximum climbing angles for larvae and adults of collection pest insects. Larval angles listed above the break and adults below. Data from Cline [177], Cline and Highland [176].

Crevice heights (mm)

Cockroach behaviour has been well studied and the minimum *Blattella germanica* (German cockroach) harbourage in crevices progressing from 0.5 mm to 1.6 mm as nymphs develop and size of crevices passed by a gravid female carrying the developing ootheca internally and with the ootheca rotated and held externally [42]. The following

diagram illustrates them at scale:



Blattella germanica minimum crevice height for stages.

Figure 4.14 shows percentage distributions of species of adult beetles stopped by wire mesh screens. Adult stages of dermestids which consume proteinaceous collections are restricted at $\leq$1 mm [52] although some grain pests still can pass through.

To compare the efficiency of bags for textile preservation in a warm humid climate (13 °*C* to 30 °*C* winter to summer) an experiment was conducted by Bry et al. [179] with heat-sealed kraft paper / polyethylene liners for nailed wood containers. Over a five year period of storage in infested test room, no woolens in sealed liners were infested, while all folded liners allowed penetration by *Attagenus megatoma* (F.) (now *A. unicolor*), *Anthrenus flavipes* LeConte and *Tineola bisselliella* (Hummel). There was also no mildew of sealed contents but "considerable" mildew inside the unsealed packages (see also chapter 4 and paper 5).

Extruded films allow food protection research to concentrate on package toughness, while produce still shipped in coarse sacking could be penetrated through holes in the weave. Fine woven cotton liners were used to exclude keratin pests from horse hair stuffed furniture beneath decorative covering textiles and underneath the spring supports. Larval curiosity about crevices and surfaces has also been explored with insect trap design as it influences catch results [78].

The distribution in figure 4.14 shows the increased filtering effect of crevices approaching the limit of unaided human visual performance and give insight on the ability of adult pest insects to pass through our structures, collection furniture and containers. Rationally we would not pick a crevice size that filters out larger dermestids and passes damaging cigarette beetles, but a minimal pest specification for 'tight' is sub-millimetre.

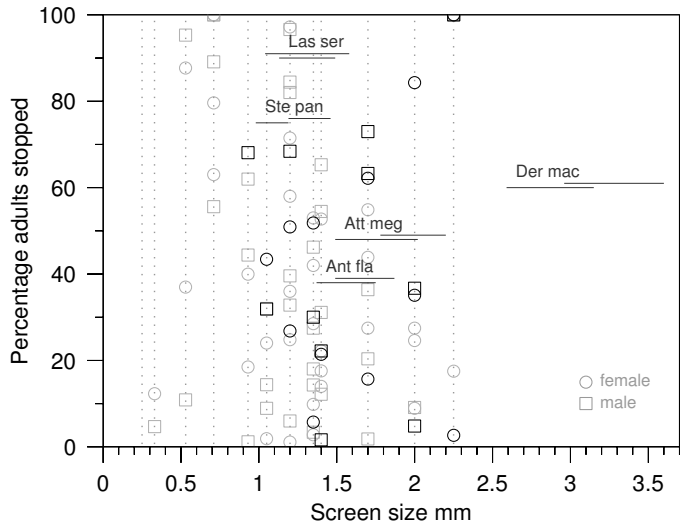


Figure 4.14: Percentage adult grain pests stopped by screen sizes. Museum pests highlighted. Lines are range of adult widths, lower male, upper female. *Lasioderma serricorne*, *Stegobium paniceum*, *Dermestes maculatus*, *Attagenus megatoma* (now *A. unicolor*), *Anthrenus flavipes*. Data from Cline and Highland [52].

While rodents are screened out by metal mesh 'hardware cloth', tight fitting lids, sealed vials, bags or cabinets are largely required to prevent access by insect pests. Containment benefits a collection when the packaging also confers organization, mechanical and chemical protection, and proofing from periods of high humidity.

The countering argument for imposing tight containment is the imposition of opening and closing the container every time access is required. Containment can also hide objects from view, adding marginally to the labour of inspection. Failure to close up containment discards all the investment, labour and some future safety of the object against many threats.

Given pest's reproductive potential and difficulty in detecting small

and distributed numbers, one can argue that it is cost effective either seal up completely and invest in more readily opened containment (good cabinets) for the most accessed items. Or, don't contain at all and accept the greater risk of pest spread in open storage which must then be countered by structural tightness, inspections and quarantine at the door.

Summation

The risk modelling approach uses distributions and probabilities to model the uncertainty around real events. The data exhibited in this this chapter applies to establishing threshold models for control and visualizes distribution of pest risk against collection environment such as shown in figure 4.10.

The disjoint nature of research over time investigating phenomenon with limited species as subjects inevitably left holes in our knowledge of environmental response for particular species we encounter in collections. By aggregating data we have on known pests, we greatly reduce uncertainty by modelling the span of survival and subsequent capability for causing harm. This approach provides a backdrop over which to better visualize where threat is rarely or commonly encountered. Equally, as data becomes shrouded in models for vetting building designs and standards, it is important to have means to determine risk to the more sensitive and often common materials used in cultural property, both as surface finishes and building contents.

In part, this chapter was produced to illustrate why conservation is also not always well served by single point recommendations for controls given the distribution of pest dimension, environmental tolerance, and nutritive range in collections. Relying solely on 'magic numbers' for control methods and not having easy reference to the underlying data puts IPM practitioners into a dangerous place by fostering inability to respond to novel situations and stripping away cognisance of the enduring capabilities of our little foes—the precise opposite of IPM's basic tenets of operating out of knowledge about the opponent and with resilience in the face of challenging situations.

5 On problems posed by responses to pests

See how it wrings
its hands, its feet!
O, kill it not!

Kobayashi Issa (1763—1827),
Blyth [9]

The single most important requirement of a treatment to kill pests is to ensure it works. Without this property of efficacy, much if not all surrounding effort is wasted.

Secondary to efficacy, the effects on objects should be well enough understood to avoid or minimize damage, deterioration, or degradation. The challenge for managing risk is when choices between different pest treatments require choosing between any side effects, deciding among which value to assign least harm. To properly inform this decision the harms must be found to be real, and their magnitude described. Ramifications to staff health are also considered.

Thirdly, the economics of the methods can be considered. While this can interplay with the secondary considerations of effects, economics should not compromise human safety and efficacy against pests.

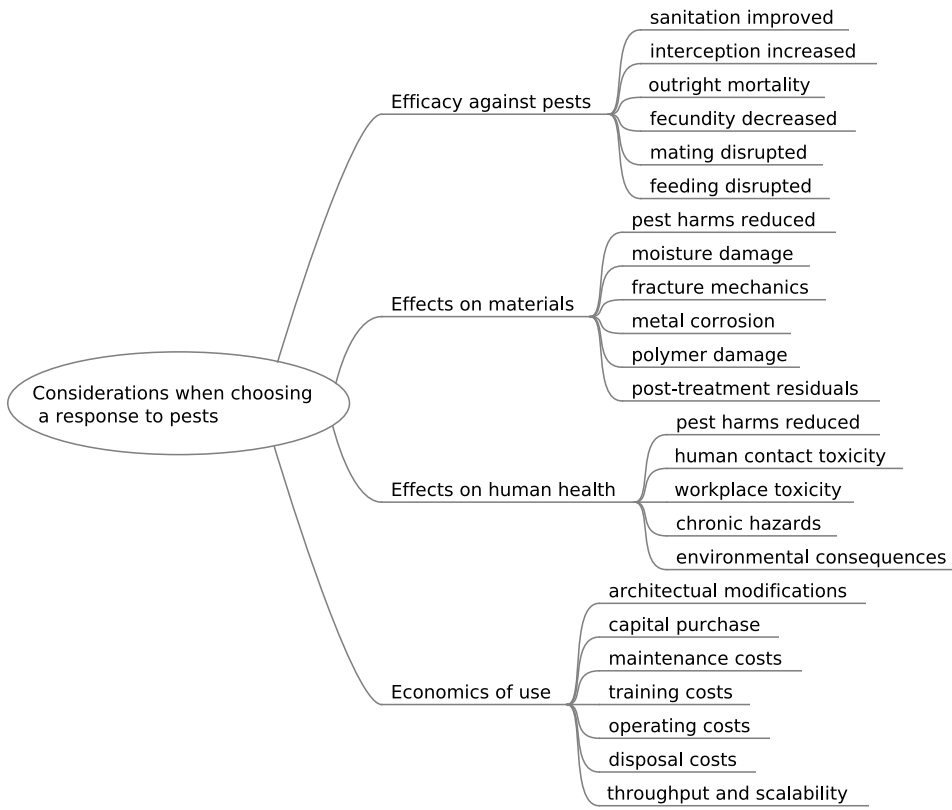


Figure 5.1: Categories for considerations when choosing a response to pest infestation and major sub-topics.

Paper One—on thermal efficacy

"A review of published temperatures for the control of pest insects in museums" was written to address a serious concern arising in the first years of my work at the CCI (1988–). The museum community in Canada undertook a rapid reduction in exposure to chemical hazards in the workplace. The conservation and restoration profession had used a large number of common and speciality solvents, paints, adhesives, and other industrial materials, but often with less than satisfactory health and safety protection. Part of the general exposure in museums was the long use of residual pesticides on vulnerable objects (arsenic, lindane, DDT, etc.) and those fumigants still being used in museums and archives such as ethylene oxide, phosphine, methyl bromide, and earlier usage of ethylene dichloride and other fumigants formulated with solvent carriers. Increased cost associated with monitoring and more stringent disposal regulations contributed to eliminating fumigation units when institutions could not afford to modernize.

In the same period of time, those reviewing Canadian government policy were looking at problems around pesticide use, particularly environmental impact, having recognized that prior to 1981 "the perception of 'safe' has undergone considerable change over the past two decades" [180] and there was insufficient understanding of effects to the environment by pesticides and other released chemicals. Resistance to pesticides had been found in insect species (304 species by 1977) which undercut their 'magic bullet' status. Mis-matches in impact assessments by a registration program dating from the 1939 Pest Control Products Act (amended 1972) were cited as problematic since pesticide technology had expanded from 1940 (30 registered chemicals) to 1981 (405 registered chemicals, 3000 formulations) and potential for environmental problems magnified by the central importance and volume use that pesticides acquired in agricultural production and government policy within this period. As increased awareness and stipulating conditions for safety were developed a sliding standard had been applied to registration through this period [180].

Complicating matters, Canada had no access to company test labs and could not verify submitted data and Canadian field conditions were not exacted of the testers [180]. A then recent case of Industrial Bio-Test Laboratories data falsification in the United States [181] which had fed into the Canadian registration process eventually forced reappraisal of 113 pesticides of concern to Canada with a projected cost of $100 million [180] [181], including two widely used in museums: pyrethrins and Vapona (DDVP) and limited use of methoprene (primarily a flea control agent).

A specific problem faced by the larger Canadian museums was the continuing review of EtO through the late 1980's and early 1990's. Ethylene oxide was the most widely used fumigant in Canadian museums until the late 1980's. During the review process, this author had several discussions with the principles involved to determine whether the revised label for EtO would match museum use, but it was becoming less likely and searching for an acceptable replacement was advised.

At that time Dawson [182], Florian [183] were warning of EtO hazards to Canadian museums and archives, citing pending cuts to exposure limits, health concerns, potential material effects and uncertain off-gassing times. The latter problem was reported in library materials by Hengemihle et al. [184] in 1986. In 1985 the U.S. National Toxicology Program listed EtO as a "reasonably anticipated to be a human carcinogen" upgraded to "known to be a human carcinogen" by 2000 [185].

A path out of the converging problems was to change museum practice to methods with lessened risk to health or removal by fiat. Conservation professionals had to become interested in adopting earlier methods: cold, heat and controlled atmospheres. Before choosing this direction some museum administrators demanded that replacement methods be proved efficacious as any process they were considering discarding.

For those who knew, especially those in natural history museums familiar with the capabilities of living organisms, there are many insects which survive freezing temperatures by avoiding or managing the for-

mation of ice in their bodies. So, the question of whether the majority of museum pest insects were capable of being eliminated by processing in temperatures of common freezers was now an open one.

The issue of cold acclimation and adaptation was investigated in 1984 by Ketcham [186] and broadcast by Florian [187] in a 1986 newsletter article to the conservation community. In 1991, Gilberg and Brokerhof [188] wrote: "In the absence of a systematic study of the time-mortality relationship for the major museum pests, it is difficult to establish appropriate treatment procedures for the disinfestation of museum objects."

What was clearly needed was foundation work that would lay to rest the key pest questions hampering day to day practitioners charged with the care of cultural property who wanted to change fumigation practice and in the process of which didn't want to do anything ethically wrong or functionally useless. Those people were calling the CCI at a rate of a couple hundred a year for advice.

The goal of paper one was to establish a large body of efficacy data for species that can be considered pests of collections, which included insects attacking display objects of agricultural villages, fine arts in its many forms, furniture, textiles, natural history specimens, etc. The need was to reduce controversy stemming from uncertainty about both the efficacy of thermal methods and the method needed for them to be successful. Then current recommendations, assumptions about efficacy in adopting thermal treatment methods for quarantine and records of extermination protocols were tested against the data (see paper one figures 2a, 2b and 4).

Plotting data for inspection is a valid methodology enhanced by clearly showing the largest possible set of information to the reader for their study[1]. Concentrating on graphical exposition of data was chosen since the design of experiments summarized in the sources did not lend itself to modern expectations for statistical investigation (com-

[1]See Tufte [189] on visual display of data and works by J. Tukey on exploratory data analysis

monly probit analysis). This problem with applying statistics to previous reports has also been documented in Fields for his similar work on reviewing thermal efficacy against grain pests [190]. Discussion of the impact of data biases on creating general recommendation for thermal control were addressed in paper one.

"What about the eggs" was a common question posed to the the author from the conservation community as people had a concern they were able to survive low temperature and are difficult to find. The limited mortality data presented to the conservation community by that date by Florian [187] was for insect eggs of five species: *Trogoderma granarium*, *Attagenus pellio*, *Stegobium paniceum*, *Tineola bisselliella*, *Anthrenus verbasci* and one species at multiple temperatures *Dermestes maculatus* (see figure 5.2).

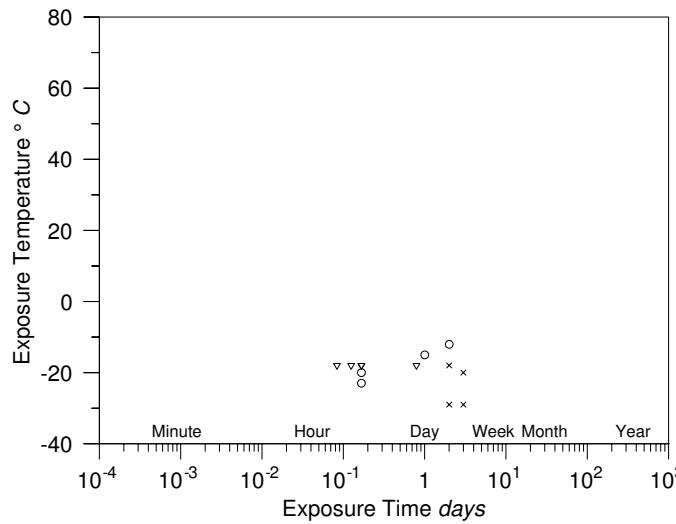


Figure 5.2: Data for mortality of eggs for five insect species (triangles), all stages for one species (circles) and reported treatments (crosses) listed in Florian [187].

To answer the queries paper one (Strang [67]) plots five divisions of insect development (figure 5) which indicated that while the larval

phase insects were possibly most able to withstand cold, there was not a great difference that would favour one stage over another within a general recommendation. The intermittent data for stages and species was pointed out through an extensive appendix summarizing the published values open to all to re-evaluate around specific situations. However, the aggregate data was compact enough to support manageable recommendations based on temperature and duration of exposure.

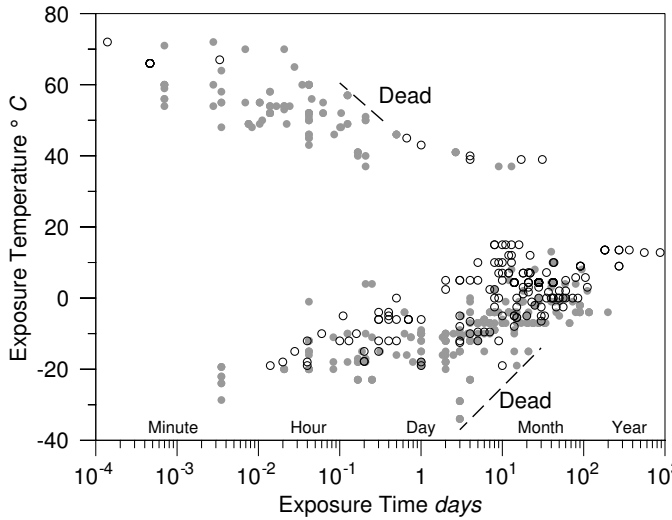


Figure 5.3: 100% mortality data from Fields [190] (183 points, black circles) plotted over 100% mortality data from Strang [67] (415 points, grey dots)

The review published by Fields [190] in the same year collated low and high temperature mortality data for 16 species of stored product pests damaging to Canadian grain production. The low temperature 100% mortality data are plotted here in figure 5.3 comparing its distribution to 46 species listed in paper one.

The selection for species to include in these two papers overlapped with 10 species as museum pest risk includes potential harbouring of grain pests through herbarium holdings and historic village oper-

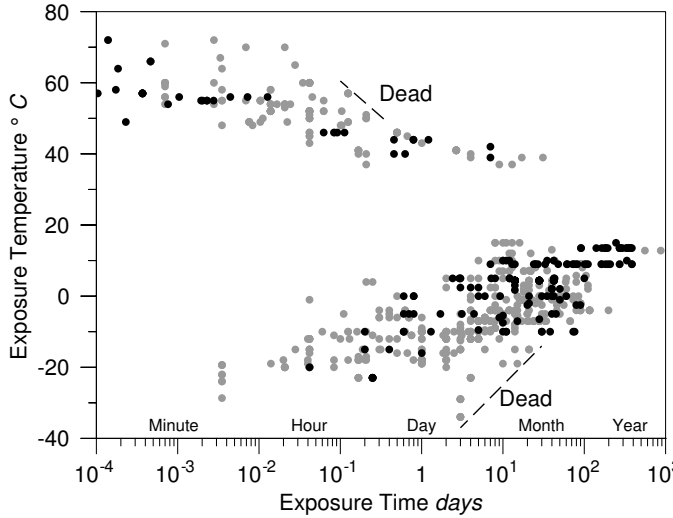


Figure 5.4: Reported 99% to 95% mortality data from Fields [190] and Strang [67](157 points, black) plotted over merged 100% mortality data from Strang [67] and Fields [190] (grey).

ations. Dermestids commonly found as museum skin and hair pests, *Attagenus piceus* (now *A. unicolor*), *Trogoderma tarsale* and *Anthrenus verbasci* are also known to go through their life cycle consuming predominantly carbohydrate feeds [191].

The combined plot in figure 5.3 does not extend the region covered by efficacy data reported in either paper so variability in pest response to cold and heat was well represented by either paper despite the authors' selection process behind the inclusion or exclusion of species. As discussed earlier on mould (page 131) examining larger numbers of species increases the guarantee of general efficacy for the purpose of helping groups of clients with diverse pest hazards.

Agglomeration also reduces data biases of individually limited experimental conditions by tiling the field with experiments. There is a subsequent greater variety of conditions and species across a large num-

ber of experimenter's works with which reveal or resolve outstanding problems. Any severe outliers can then be examined.

One wants to see low survivorship data close to but not exceeding the edge of full mortality data, as this informs the periodicity of data capture was not so great as to create exaggerated wait time. A few 'hops' in data, where full mortality is reported followed then by low survivorship at slightly longer exposure time do exist in a few reports on experiments, and so the low survivorship distribution also lets us examine this for its impact on certainty of the general advice.

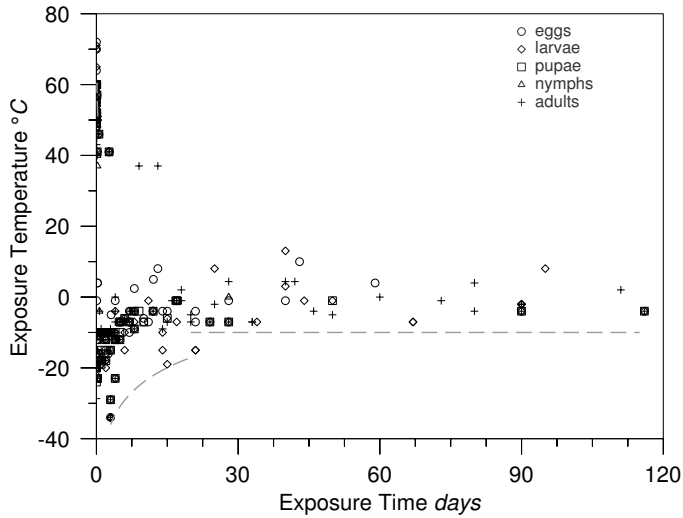


Figure 5.5: Thermal mortality (linear time axis) from Strang [67]. Curved dashed line highlights possible supercooling values and the long horizontal tail above $-10\,^{\circ}C$. Dense point distribution upward from $-20\,^{\circ}C$ shows where majority of low temperature control is obtained for museum pest insects. Relative rapidity of elevated temperature control is evident.

Discussions starting with "cold won't kill the pests" cannot bear up to the evidence in figure 5.3, but neither will isolated failure to control such as a case of diapausing *Cis bilamellatus* larvae in a mycology specimen whose adults were subsequently killed at $-20\,^{\circ}C$ (Moore [192])

eliminate general confidence in the method given the weight of evidence to the contrary for effective control of many other and more problematic species.

Uncertainty is perversely reinstated when any information is used to create a confident sounding 'magic number' solution, like "$-20\,^{\circ}C$ for 48 hours" as concise binary value recommendations are promulgated more widely than the judgements on source data behind them. When novel situations arise (different temperature, tighter deadline) there should be concern that the 'magic number' can fail and precautions taken. My argument was that with enough information in front of their eyes, people can see how to correct and make a process work despite such hurdles. For example: "Our old donated freezer is only working at $-17\,^{\circ}C$, how long should I leave the objects in?" Use figure 5.3 to work out the answer.

To test confidence in the data inspection method, figure 4 and table 4 in paper one showed documented failures to control by low temperature. As a further illustration, the range of low survival in experiments (99% mortality to 95% mortality) reported in Fields [190] is plotted here in figure 5.4 along with those from paper one. This distribution reinforced the need for chest freezer temperatures rather than cool (heavily air conditioned room) or refrigeration ($-4\,^{\circ}C$) temperature to ensure efficacy in reasonable time even though these latter situations provide some control of harms through non-lethal effects or eventual high mortality (several months). By $-15\,^{\circ}C$ reported survival appears restricted to a day at most.

The selection of species and volume of data reportable as museum pests in paper one better covers the region where chest freezers operate below $-15\,^{\circ}C$, while many stored crop pest experiments used temperatures found in storage bins during winter. The surviving populations (right hand side black points in figure 5.4) are deliberately acclimated insects [190]. These could represent responses by pests of material collected in cool seasonal temperatures but are less likely in materials stored in heated spaces independent of the winter months.

The lower edges indicated in figures 5.3 and 5.4 (dashed lines) from 3

days to 3 weeks for cold exposure incorporates sparsely distributed evidence of mortality. These marginal points were referenced by species in Strang [67] figure 2c. Figure 5.5's linear time axis better illustrates both the sharp curvature in the time / temperature mortality relationship at lower temperatures and the long horizontal tail above $-10\,^{\circ}C$, which is discussed below in the context of 'double freeze' proposals and the large horizontal displacement of few marginal points indicating full mortality at the lowest temperatures.

For these low hanging points several possibilities exist: they are reported supercooling points (paper one, figure 2c marked *Camponotus herculeanus*); over-runs in time when pulling samples that determine fatality; or stand-alone successful treatments (*Cryptotermes brevis*, *Gastrallus sp.*) which may already be extended 'just to make sure'. The lack of nearby survivor data argues efficacy within the boundary of these points (paper one figures 3 and 4).

Supercooling points for numerous insects have been determined and cover a wide range from $-5\,^{\circ}C$ to $-54\,^{\circ}C$ [193] and are plotted in figure 5.6.

The two categories of insect response Sømme defined are "freezing-tolerant" (body fluids freeze and recover) and "freezing-susceptible / intolerant" [194]. Other authors use the variant term 'freeze-avoidant' for this latter category. Sømme excluded values from reports using suspect methodologies to measure supercooling. He also notes the tabulated points are without standard deviations, which represent the variation within species to put off freezing, and the different rates of cooling used by experimenters also affects the supercooling point.

Despite the implication of the term, freezing tolerant species are not impervious to cold. "Freezing tolerance is a relative term, since survival in many species decreases with both decreasing temperature and time subjected to the frozen state." [194] This is the trend clearly illustrated by paper one and favours extending a single cooling cycle. "Most species are considered as freezing-tolerant if they survive freezing at temperatures corresponding to their SCP, or lower." Sømme notes these temperatures are comparatively high, with some excep-

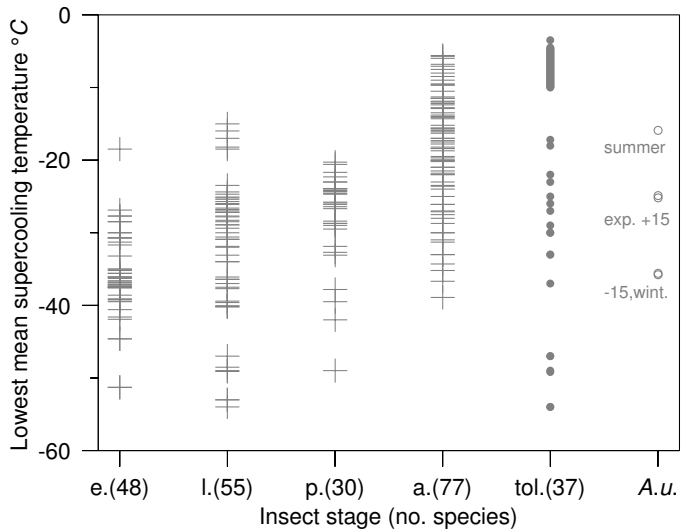


Figure 5.6: Supercooling points for winter surviving freezing-intolerant insects (denoted by +). The supercooling point represents the lowest temperature achieved before freezing of body fluids. Only one species *Camponotus herculeanus* (−28.7 °*C*) was listed in Strang 1992 [67], other species plotted as + not implicated in damaging cultural properties. Freezing-tolerant insect supercooling points depicted as solid circles, aggregated stages. *A.u.* shows *Attagenus unicolor* supercooling with differing acclimation. Data from Sømme 1982 [194], Ring 1982 [195] and Hou et al. [196].

tions mainly in the region of −4 °*C* to −10 °*C* (solid grey line in figure 5.6). These insects would be proofed to cold once frozen, so they supercool at these relatively warm temperatures, sufficient protection to get themselves ready during autumn.

The supercooling point (SCP) is more important to those insects which cannot accommodate freezing and recover (plotted as + in figure 5.6). The supercooling point "represents the lower limit of survival in freezing-intolerant species. The SCP is the temperature at which spontaneous freezing occurs during gradual cooling." [194] Eggs laid in exposed conditions and larvae without insulating snow cover need pro-

tection against climactic extreme, while adults can burrow deep into insulating cover are the interpretation Sømme provides for the observed trends. Low temperature survival is a probabilistic event within a climactic zone. High insect fecundity redresses the inevitable losses.

Hou, Fields and Galloway [196] sampled wild winter and indoor summer populations of *Attagenus unicolor* carpet beetle larvae, determined their supercooling points and low temperature mortality. Collected in winter at $-20\ ^{\circ}C$, samples were held at $-15\ ^{\circ}C$ and some acclimated to $15\ ^{\circ}C$ for a week. Larvae acclimated to $-15\ ^{\circ}C$ were exposed to $-25\ ^{\circ}C$ for up too a week, both the 5 day and 7 day exposures resulted in 100% mortality, while one and three day exposures gave 20% and 90% mortality. Figure 5.6 plots average supercooling points that were measured from $-35.9\ ^{\circ}C$ (-30.3 to $-39.0\ ^{\circ}C$) for winter larvae, and $-15.9\ ^{\circ}C$ (-9.8 to $-21.2\ ^{\circ}C$). They also report cold injury increasing with length of cold exposure above the supercooling point. These results indicate that cold exposure in freezer temperatures can control even 'cold hardened' *A. unicolor* and shows that the supercooling point is not the lowest point which must be achieved for complete mortality to occur provided time of exposure is adequate. The supercooling point is simply the lowest temperature which need be sought, and for stored product insects this commonly falls between $-10\ ^{\circ}C$ and $-25\ ^{\circ}C$ [197].

In their study of the low temperature mortality of *Ephestia kühniella*, Andreadis et al. [198] show that despite determining supercooling points of $-23.3\ ^{\circ}C$ for pupae, $-21.6\ ^{\circ}C$ for adults, $-19.5\ ^{\circ}C$ for late instar larvae and $-16.1\ ^{\circ}C$ for early instar larvae, these were not significant at altering the complete mortality induced to all stages including eggs by exposure to $-12.5\ ^{\circ}C$ for two hours in what they call 'prefreezing' mortality.

These studies show significant to complete mortality occurs well above supercooling points, and is certainly the effect illustrated by the distribution of mortality in figure 5.5. Brokerhof et al. [199] studied the cold tolerance of *Tineola bisselliella* eggs finding the relationship proposed on an Arrhenius model between temperature of exposure and

time could predict mortality. The linearity shown by the log plot of aggregate pest cold mortality (figure 5.3) also confirms this trend.

A key field study was that by Solomon and Adamson [200] who observed winter insect survival and the climate mitigating effect of different building constructions and the containers within them which commonly provided 2 °*C* to 5 °*C* higher temperatures than in the building proper. This study is the closest one to examining pest survival in the 'uncontrolled' environment of historic villages, and was undertaken in a climate zone where the mean daily winter minimum is between 0 °*C* and 7 °*C* , and the lowest events did not exceed −10 °*C* . The mix of long survival until mortality for this temperature band is clearly visible in figure 5.5.

Florian wrote as late as 1997:

> "Unfortunately, there is so much variation in the insects themselves, their ability to respond to environmental changes and the methods and parameters of the research that it seems to be beyond our ability to use the published information logically" [201]

In 1992 paper one argued quite the opposite: with enough trees one can clearly see the forest.

Do I need to freeze twice?

Another common question was "do I need to freeze twice". This recommendation was re-initiated without presenting any efficacy data on museum pests by Florian [187] who recommended "immediately repeat the freeze thaw cycle" in her articles based on the concept of 'breaking down' supercooling ability. It has become a persistent meme.

There was one piece of museum literature that suggested repeat exposure to cold, Rice's 1969 article [202] in which an 18 °*F* , 50 °*F* , 18 °*F* "temperature shock treatment" was briefly described without citation of implementation or efficacy data other than "kills the moth and beetle eggs and larvae". However, in the course of preparing paper one, repeated cooling was not always found to have the great efficacy

that was supposed in the museum community that read Florian's articles, nor was it warranted with the lower temperatures now universally available as discussed in the section above.

The volume of single treatment efficacy data presented in paper one showed little need for double treatment given the low temperatures of modern freezers. Ultimately Florian conceded repeat freezing was not necessary in 'Heritage Eaters' [201] yet misquoted paper one with:

> "As a result of these below −20 °*C* temperatures, Strang (1992) suggests the use of −30 °*C* in chest freezers, but stated that if this cannot be reached then repeated freeze/ thaw cycles are recommended."

The actual statement from paper one did not specify an extreme of −30 °*C* and is worded thus:

> " Repeated exposure was first incorporated in a general recommendation for the disinfecting of wool and fur goods by Howard (1896), for combating household pests by Back (1923), for the preservation of museum textile collections by Rice (1968), and most recently by Florian (1986). Repeated exposure may require additional handling of the infested goods, however, it would be a useful procedure in combating these three species if one cannot use a lower temperature that achieves 100% mortality in a single exposure." [67]

It is worth reviewing all these early author's work in detail so as to become familiar with their texts and data. It is from this familiarity one can properly judge the necessity on Rice and Florian's pronounced requirement to 'freeze twice'. The texts properly reveal what was tried, and significantly, what was not, and the effect of the temperature / time relationship becomes clearer.

The citations on repeat treatments all used relatively warm temperatures compared to modern freezers. Both −8 °*C* which was achiev-

able by mechanical means in 1896 [203] and $-10\,^{\circ}C$ in 1923 [4] had reports of greater efficacy in repeated exposure than just holding at the selfsame temperatures (paper one, Table 3, endnotes 166, 167, 168).

The incomplete mortality of Khapra beetle reported by Voelkel in 1924 [204] (paper one, endnote 72) from experiments at $-10\,^{\circ}C$ and $-16\,^{\circ}C$ did not recommended repeat freezing at $-10\,^{\circ}C$ as fully efficacious, whereas simply holding once at $-16\,^{\circ}C$ greatly improved the kill. Any argument that the 'exposure was not long enough' stands equally for failure of single and repeated freezing.

The work by Solomon and Adamson [200] was reviewed and they were unable to lower cold adaptation below $-15\,^{\circ}C$ for five species including a major moth and cockroach pests. So, as one progressed below $-10\,^{\circ}C$ past $-16\,^{\circ}C$ the early literature reviewed for paper one indicated single exposure to kill was sufficient, as recommended initially for museums by Leechman [3] in the late 1920's.

In 1914, Runner [205] examined the damaging cigarette beetle *Lasioderma serricorne*. Through a series of repeated experiments (over thirty) near $14\,^{\circ}F$ [$-10\,^{\circ}C$] with single exposures of larvae, pupae and adults for five days and eggs in more than one day[2] he determined it could be completely controlled. Larvae were noted as most resistant.

Runner did perform a single experiment that demands inspection:

> "The alternation of a low temperature with a comparatively high temperature is apparently more effective on the tobacco beetle than is a single exposure to cold. During the course of cold-storage investigations at Richmond, Va., in 1914, two lots of badly infested smoking tobacco were put in cold storage for 2 days at temperatures ranging from 14° to $16\,^{\circ}F$. Lot A was not removed from the storage room, whereas at the end of 24 hours lot B was removed and kept in a warm room for 24 hours, then put

[2]He also describes current work with packaging,cool storage, light trapping as preventive measures; winter cold, boric acid, vacuum, gas and vapour fumigants, steam heat, ultraviolet and X-rays as treatments.

> back in cold storage for a further period of 24 hours. On March 22, 2 days after treatment, both lots were examined and no live stages of the beetle were found in lot B. In lot A about 90 per cent of the different stages were dead. The tobacco used in the experiments was kept until August 28, 1914, and upon examination lot A was found heavily infested whereas lot B was uninfested." [205]

Runner had determined 24 hours as the threshold for 100% efficacy at 14 °*F* for eggs of this species and in practical tests on infested boxes of 100 cigarettes and five day single exposure was indicated at 14 °*F* for complete control in up to 20 pounds of tobacco [205]. A full bale of tobacco was also successfully run for 28 days at 14 °*F* [3]. So it would have been useful to know the unreported volumes of the 'lots' A and B to determine the likely effect of mass. The cold treatments of just two days in the freezer total in either experiment are significantly shorter than the successful five and 28 day runs at the same temperature. Runner's experiments were along the bottom of the long survival tail in figure 5.5 and "For short exposures it was found that results depended largely upon the insulation afforded by wrapping". He also described several mitigations for condensation problems (which double exposure risks twice).

The Chief Entomologist for the United States, L.O. Howard had reported to other entomologists in 1896 of the search for temperatures to prevent damage, not specifically for inducing mortality of damaging insects [203]. The beginnings of study into use of cold came from questions of efficacy and economic concern from a company specialized in cold storage of agricultural products. They desired to know the temperatures sufficient for cold storage of woollen and fur objects, having already invested in systems running at 32 °*F* to 40 °*F* for eggs and fruit, and 12 °*F* to 20 °*F* for butter and poultry. Howard could

[3] Tobacco bale mass is not a standard measure, but likely in the order of 75 pounds (34 kg) for a "farm bale" to 450 pounds (204 kg) for a "unitized bale". [206]

only respond at the time "not more that 40 °*F* would in all probability keep any of the insects concerned in an inactive condition."

Further correspondence with other storage firms had shown Howard "that many companies engaged in this business have not considered it worth while to inform themselves on this important point [of necessary temperature], but have, in their desire to 'make a sure thing of it,' kept this class of goods systematically at a most unnecessarily low temperature, and have thus practically thrown away large sums of money."

Howard's response was to solicit results of experiments on pests of woollens through correspondence and collaboration with "Dr. Albert M. Read, manager of the storage warehouse department of the American Security and Trust Company of Washington". This company was then a young charter bank (1889) with significant storage and safe deposit operations and a novel "women's department" [207].

> "THE COMMON CLOTHES MOTH (*Tinea bisselliella*.—*Eggs*.—Recently laid eggs of this species were sent Dr. Read May 2 and were immediately placed at a temperature of 37 °*F*. June 16 (the temperature in the interim having varied from 34° to 40°) they were taken out for examination and kept for twenty-four hours at a temperature of 78°. No change could be seen, and they were placed back in cold room, where they have since remained without hatching, at an average temperature of about 34°." [203]

This section inferred a double cooling cycle but does not prove requirement to kill eggs as no efficacy was determined after the first low temperature exposure. 37 °*F* is 3 °*C*. Note the second cooling was observed to only keep the eggs from hatching.

> "*Adult*.—Experiments upon adults are necessarily more or less unsatisfactory, but here is one of interest. One small bundle of rugs (4 feet long and 1 foot in diameter) out of a large consignment which was found to be swarming with

> moths was saved from the general cleaning and heating, was rolled lightly in burlap, and placed in test room at a temperature of 62 °*F* . June 21, at 4 p.m., the brine was turned on. June 22, 10 a.m., temperature 32°, nearly all the moths were dead, those alive being at the middle of the bundle. June 24, temperature 40°, very few were still alive, and those were inactive. June 25, temperature 31°, all were dead." [203]

As well as reporting the usual use of heat to disinfest carpets, and longer survival of the most insulated insects, a single exposure at its lowest 31 °*F* (−1 °*C*) for around three days duration was considered sufficient for adults[4]. No numbers of individuals used were reported.

> "*Larvæ*.—None of the experiments made showed that the larvæ subjected to a continuous low temperature, even reaching 18°, will die, although larvæ kept at from 28° to 18° for a time, then revived by warmth, and then restored to the cold temperature almost invariably died. In fact the survival at a *continuous* low temperature is shown by the following experiment:
>
> June 18, 13 larvæ were dropped in a bit of woolen goods and placed in cold room at a temperature of 31 °*F* . June 29, 29° to 33°. July 11, 28°. Self-registering thermometer showed 18° lowest temperature. All larvæ apparently dead. Five taken out and kept in warm room. Two moved in fifteen minutes, one in thirty-five minutes, and the fourth in seventy minutes. No. 5 showed no signs of life at this time as was watched no longer.
>
> Larvæ with corduroy were kept for many days under observation; at temperatures of 37°, 39°, 40°, and 42° were absolutely motionless; at 44°, 45°, 47° and 48° were moving very slightly. Forty-eight degrees was the highest tem-

[4] 28 °*F* is −2 °*C* , 18 °*F* is −8 °*C* .

> perature reached, and between April 24 and June 15 there had been no attack whatsoever on the goods. On the latter date all larvæ were removed to warm room, when 20 out of 50 revived.
>
> A parallel experiment on uncovered larvæ showed practically the same result." [203]

This was a directed experiment to determine the effect of 18 °*F* (−8 °*C*) on larval mortality and the strongest evidence for necessity of repeated low temperature exposure with the low refrigeration temperatures available at that time. However a properly reported experiment for the double exposure was not given while the single exposure was with very few individuals. The real significance of this piece of work was establishing threshold to movement and concomitant lack of feeding, critical for returning goods to owners without new damage and using a cost effective environment to achieve this goal.

> "THE BLACK CARPET BEETLE (*Attagenus piceus*).—*Adult*.—The beetle was found to move at 47° and was motionless at 42°.
>
> *Larvæ*.—Larvæ of this species, which is one of the principal household insects in the South, replacing there Anthrenus scrophulariæ, were tested both with bits of carpet and in corn meal in which they were found. At 38°, 39°, 40°, and 44 °*F* they were motionless. At 45° those with meal were motionless, but one of those with cloth was seen to move its legs and head slightly. At 47° and 48° both lots moved, though very sluggishly.
>
> Of those kept with cloth at degrees varying from 38° to 48° from May 6 to June 15 none revived after a 'long time' in a warm room, from which D. Read made a marginal note, 'Don't seem to stand long-continued cold as well as moth larvæ.' With those in the meal, however, the case was different. They were maintained from May 2 to June

> 29 at a temperature ranging from 29° to 48°. On the latter date they were removed to a warm room and only a few revived after 75 minutes, but next day all were active." [203]

There was no report of the volume of corn meal providing insulation and buffering or reporting of numbers of individuals. The lowest temperature used, 29 $°F$, is only $-2\,°C$.

Other experiments on *Dermestes vulpinus* larvae, *Tenebrio obscurus* larvae, *Trogoderma tarsale* pupae and adults looked at constraining motion with temperature. Howard concludes: "it will be perfectly safe to keep materials infested by any of the insects mentioned above during he summer months at a temperature of from 40° to 42 $°F$, and that the average cold-storage company, if my information as to the customary temperatures be correct, has been wasting in the neighbourhood of 20° of cold." [203].

So the work by Read and Howard clearly did not aim at disinfestation, but solely to minimize cost of safe storage of disinfested goods and protect storage companies from claims against them. Mortality was a useful outcome, but clearly not a certainty with the temperatures then in service.

> "The economic entomologist is always interested to know in cases like this what the actual saving will be in dollars and cents, but in this case it is impossible to say. It is practically impossible to estimate a definite cost for each degree of refrigeration, on account of the differences in machines, in insulation of rooms, in cost of coal at different points, and more particularly on account of the increase of cost in periods of excessive summer heat. It is plain, however, that in every such establishment every degree of temperature below that of the outside air requires a definite expenditure of coal, and, therefore, a saving of 20° of actual temperature is a saving indeed." [203]

In this approach to managing pest risk a 'vector' was applied to advice:

'only increasing cold to this point is better', despite the inability to calculate actual savings due to obfuscating variances. Howard's statement may have stemmed not from complete inability to acquire required information, but the general lack of readily collated data from the prototypical HVAC professionals of the day.

Current sustainability exercises put pressure on calculating these missing costs for collections relying on cooled storage and again question the benefits. Howard's problem continues to this day until 'smart monitoring' of building systems give the requisite information. Only then can a cost benefit model be constructed for that portion of collections buildings which are special climates for preserving against pests and other losses in values (chemical deterioration). The benefit calculation will require equivalent documentation of the saved cost of chronic pest problems and losses to collections.

From Fernald's discussion to this presentation: "Mr. Howard suggested that in view of the increase of the expense of this treatment the lower the temperature be maintained, if previous disinfection be given articles it would doubtless be possible to keep them with safety through the summer at a temperature of 50 °*F* . He suggested steaming, as a preliminary disinfection, wherever practicable." This also shows the intention was clearly not disinfestation with cold, rather that steam heat was used "in Boston by certain storage companies". No comments were made on whether to use single or repeated exposure at low temperature as a disinfestation method. Howard's own summary in his annual report [208] confirms the goal: "the exact degree of temperature at which household insects and insects affecting woolen goods, furs, stored foods, etc., will remain inactive, was definitely ascertained and reported.... The results of this investigation indicated the possibility of a very considerable saving to cold-storage companies and consequent possible reduction in the charges for storing goods through the summer months."

The summary of 40 °*F* for preventive storage was repeated in Marlatt's contribution on moths to the 1896 'Principle Household Insects' volume [209] designed for educating the American householder or ento-

mologists who consulted them.

It is Back who in 1923 expanded the authority of this early work for general readership in a U.S.D.A. Farmer's Bulletin as follows:

> "A number of years ago a manager of a large storage warehouse company in Washington, D. C., conducted certain experiments at the instance of the Chief of the Bureau of Entomology, with the result that it was found that larvæ of the webbing clothes moth and of the black carpet beetle can withstand for a long time a temperature of 18 °*F* . It has been discovered that it is not so much the cold that kills. It is the sudden change from a cold to a warmer temperature and back to a cold temperature that most quickly results fatally. Thus it was learned that if articles infested with clothes moths were refrigerated at 18 °*F* for several days, then suddenly exposed for a short time to 50 °*F* , and then returned to 18 °*F* , and finally held permanently at about 40 °*F* all moth life in them would be killed.
>
> If cold storage aims at the destruction of clothes moths in articles intrusted to them, as well as the protection from injury of these articles during the period of storage, it is recommended that articles be exposed to two or three changes of temperature as noted above before they are placed permanently at 40° to 42 °*F* . The maintenance of a temperature lower than 40° to 42 °*F* is needless and a wasteful expense." [4]

From this quote one can see Rice's 1969 amplifying re-statement of it in his 18 °*F* , 50 °*F* , 18 °*F* exposure[5] guide as "shock treatment" [202]. Back is properly warning consumers of the survival of healthy moth larvae at these temperatures if the objects were not first treated before undertaking investment in commercial fur storage as it was operating at the time. "Thus well grown larvæ of the webbing clothes moth in

[5] 18 °*F* is −8 °*C* , 40 °*F* is 4.4 °*C* , 50 °*F* is 10 °*C* .

fur and wool were held in commercial cold storage at a temperature said to fluctuate between 24° and 48 °*F* , but held mostly at about 40 °*F* , and were found by the writer to be alive after storage for 6, 8, 10, 11, and 12 months." [4].

It is of interest that Back also states: "While larvæ refrigerated for 10 to 12 months matured, as above stated, into moths, a large percentage, though active soon after removal from storage, died after being subjected to warmer temperature." This indicates marginal rather than full survival with a single long exposure despite some contrary evidence and statement that cold-warm-cold was the killer.

If the first exposure is sub-lethal, a supposition which is prerequisite for stipulating a second pass, the documented cases of sub-lethal first exposure **increasing** the survival of the second colder exposure (continued acclimation) must be considered. These were cases of 0 °*C* exposures of up to two hours allowing "prevention of cold-shock injury" to survive subsequent −10 °*C* exposure (flies, beetles, bugs) [210].

Again, 0 °*C* to −10 °*C* exposure was not generally efficacious in short time as ultimately shown by the aggregated mortality data underlined horizontally in figure 5.5 and it is this greater 'uncertainty' in the region of −10 °*C*
which influences the 'double freeze' efficacy test results.

It was not inconsequential to resolve the necessity of the 'double freezing' meme in the conservation community. Having a federal body (CCI) issue a recommendation which unnecessarily doubles the labour and increases the handling hazards to all materials undergoing low temperature disinfestation would be unconscionable when the literature review (paper one) showed efficacy was evidently assured through a single treatment with modern freezer temperatures. When temperatures were marginal for extirpation there was some work that indicated repeated exposures were somewhat efficacious which indicates probabilistic (ice nucleation) or degenerative (metabolic drain, accumulated harms) mechanisms.

Most significantly, the recommended temperature stated in paper one:

'below $-20\ ^{\circ}C$', was a common enough value for affordable household chest freezers which were accessible to the majority of institutions seeking CCI's advice, not a more expensive industrial device capable of $-30\ ^{\circ}C$ or lower. The assembled efficacy data in paper one assured kill by extending time as much as dropping temperature — not unlike application of concentration-time (CT) curves for fumigants. However, $-30\ ^{\circ}C$ has since been adopted in larger institutions using walk-in freezers designed for this lower set point on the grounds they shorten disinfestation time through increased thermal gradient and fan induced air movement, thus providing an increased level of certainty or more rapid turnaround in institutions where there are significant volumes to manage[6].

Contra-indications to continuing to go even lower than $-30\ ^{\circ}C$ and especially $-40\ ^{\circ}C$ are machine cost (capital, maintenance, operation) and the increased risk presented from differentials in thermal contraction in susceptible objects which had been noted by Michalski in a report [211] [212] assessing risk with cold storage temperatures for composite objects. The confluence of these issues was addressed by the author (Strang) in CCI Notes 3/3 (1997) [213], a widely disseminated guide on low temperature control of insect pests in museums.

[6]Chaining probabilities of repeat treatment needs brief discussion to reveal the panacea. When a practitioner feels a treatment is only say 95% effective so treats twice, then imagined survival is $0.05(0.05N)$ for the double treatment. The panacea derives from faulty assumption by the practitioner that infestation (sample) population N is small enough nothing survives. For larger noticeable larvae and adults the low number may be true if material was inspected and little found. However the cryptic output of four females, say four hundred eggs, gives 20 survivors after treatment one, and one survivor after second treatment. People were worried about eggs more than other stages, voicing the erroneous suspicion that eggs were superior in survival rather than just present in larger number. Repeats *per se* are arguably never wholly effective as they *a priori* assume faulty efficacy and furthermore the aggregated loads treated over time L must be pooled, giving $L(0.05(0.05N))$ as the number of survivors potentially introduced to the collection. Ensuring efficacy is key, repetition halves throughput.

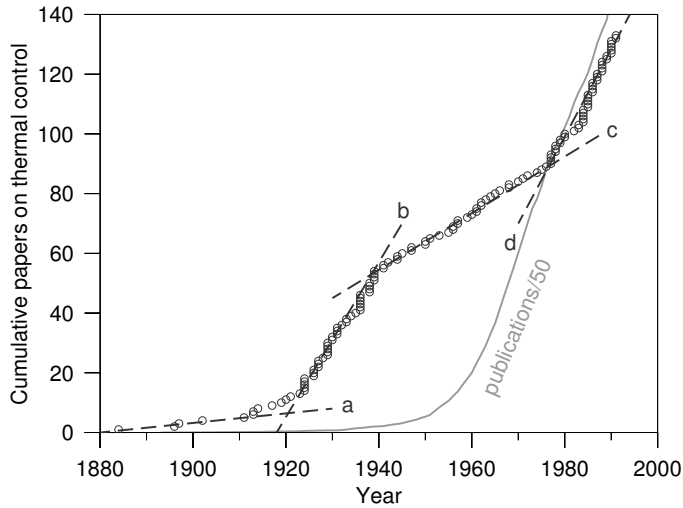


Figure 5.7: Cumulative publications on thermal control of insects cited by Strang [67] (open circles). Lines a-d define trends in publication rate: 'a' USDA interest in pest control, establishment of national quarantine; 'b' WW1 and postwar growth of commodity handling; 'c' WW2 and competing postwar increase in fumigant and pesticide use; 'd' 1970's oil crisis, IPM adoption, restricting and avoiding fumigants and pesticides. Line marked 'publications/50' shows the scaled trend in growth of nearly 13,000 publications on stored product pests.

Trend of interest in thermal methods

Plotting cumulative publication dates for papers on thermal control cited in paper one (figure 5.7) shows long shifts of interest (rates of publication) in thermal control through the 1800's and 1900's which map to historic events: (a) Crop disasters, introduced blights, and ultimately political recognition of the harm from imported species fostered national quarantine policy, national agricultural research stations, land grant universities, and increased status of federal economic entomological work in the U.S.A. [2] and Canada. (b) The outcome of publicly funded research around World War I and accelerating ex-

amination of pest problems increased understanding of organisms. (c) By World War II, agriculture had coupled chemical innovations (fumigants, insecticides, fungicides) with widespread application technologies to handle pest problems in war materiel. (d) Recognition of problems with fumigant residues and resistance foster a renewed interest in thermal control for quarantine, combined with growing application for museum collections.

Comparing a large sample of publications on stored product pests shows the difference in publication rate from other topics within the discipline. Papers on thermal control in recent time are possibly 2% of the total production ('publications/50') and clearly a much smaller fraction from 1940 to 1970[7].

As early as 1896 the use of thermal control was considered readily available and efficacious for **preventing moth damage in storage**, for Marlatt states:

> "A common method of protection followed by larger dealers in carpets and furs, etc. , is the use of cold storage for protection. In all large towns anyone can avail himself of this means by patronizing storage companies, and protection will be guaranteed. A temperature maintained at 40 °*F* is protective, but often a much lower temperature is maintained — down to 20 °*F* ." [209]

Note the described margin of 20 °*F* to establish confidence mentioned by Howard. For comparison: 40 °*F* is 4 °*C* and still a common refrigeration temperature, while 20 °*F* is only −7 °*C* .

Today, advice on using cold as a low cost and accessible method has been greatly improved with the spread of refrigeration technology, for in 1896 Howard states:

[7]The total publications trend data was extracted from an Agriculture & Agri-Food Canada scientist-compiled database of papers of interest containing about 13,000 citations provided to the author by Paul Fields.

> "That a certain degree of cold would result in inactivity on the part of these insects was a foregone conclusion, and as a result of the general understanding to this effect the first advertisements of cold-storage firms for furs and rugs met with an immediate response from the wealthier inhabitants of our larger cities .... So satisfactory has it proved that the writer, in addressing the Washington Club (an organization composed entirely of wealthy or well-to-do women) last winter, did not consider it worth while to mention any other remedy against clothes moths. Had he, however, been addressing an audience of housekeepers to whom a small sum of money should be an object, other remedies would have been mentioned." [203]

The complete context for control of clothes moth on fur was given by Marlatt [209] who also recommended beating of furs, combing out, and repeated through the storage season at two to four week intervals. Marlatt also recounts Howard's use of paper tape sealed tailor's pasteboard boxes to block insect access, as well as the use of "stout paper", tar roofing paper, or linen or cotton bags. For chemical control Marlatt recommended seasonal application of benzine or naphtha, or "a dilute solution of corrosive sublimate in alcohol made just strong enough not to leave a white stain"[8].

Prevention potential with marginal temperatures

In keeping with work on **prevention** rather than **eradication** the terms describing significant temperatures were recorded to demarcate other aspects of insect control in endnotes in paper one. To illustrate constraint of insect harm to collections through museum environmental control these can be divided into two groups, 'restricting damage' means no feeding on objects, 'restricting population' means reproductive success is becoming compromised despite possible feeding on objects (see table 5.1).

[8]Mercuric chloride, responsible in time for the darkening of many natural history

Restricting outright damage	**Restricting population**
immobile	egg hatching limit
chill coma	egg laying limit
cold torpor	population development limit
movement ceases	breeding limit
inactive	not maturing
feeding ceases	limit for copulation
growth ceases	flight ceases

Table 5.1: Classified descriptive terms for constraints to insects from references cited in Strang [67] with flight data from Cox et al. [214].

The stem and leaf plot in table 5.2 depicts number of species for which information represented by a paper one endnote containing details lies within the temperature increment on the stem. The debilitating temperatures have a distribution which instructs why air conditioned interiors cannot wholly prevent insects eating collections until at rather uncomfortable levels, but do reduce insect population growth.

Flying affects dispersal of infestation, pest mating success and parasite control strategies. Cox et al. [214]) investigated minimum temperatures for flight in nine stored product pests and two parasitoids. The moth species began to fly in the lowest temperatures between 12.5 °*C* and 15 °*C* , parasites at 17.5 °*C* and the beetles over the higher range from 17.5 °*C* to 27.5 °*C* . Dispersal and mating success span both categories and are marked by asterisk in table 5.2.

Figure 4.10 illustrates the consequence of these non-lethal restrictions for pest insects. The 'optimal' temperatures for development where consumption rates are fastest and reproduction success greatest sits above 20 °*C* to 25 °*C* . Lowering storage temperature has been used in time of infestation has capitalized on these restrictions to forestall harm while effecting control. Determining a common temperature amongst species' capabilities to exploit (say 15 °*C* or 10 °*C*) is some-

specimens and labels.

Restricting outright damage	°C	Restricting population
	−5	
59,103,134	**0**	
30, 34, 41, 44, 63, 71,110,125,132	**5**	
34, 53, 63, 71,110,114,125	**10**	71, 84,114
*46, 53, 71,110	**15**	21, 24, 30, 34, 53, 58*
*8	**20**	8, 12, 26, 34, 59, 63,120*
	25	8, 16, 63, 71, 75, 95,135*
	30	2, 59,135*
	35	30, 34
	40	24, 26
	45	71,135
	50	71,135,138

Table 5.2: Stem and leaf plot of temperatures debilitating to insects by species classified by restricting damage or reproductive potential. Leaves reference endnotes with pest data in paper one [67], asterisks mark ranges with minimum flight temperatures from Cox et al. [214].

what problematic, however cooler is certainly better at reducing both growth rate and harm.

Presupposing a variety of insects in the collection, elevating temperature norms from 20 °*C* to 25 °*C* may be more hazardous than from 25 °*C* to 30 °*C* as it takes the brakes off reproductive success, rate of growth and number of generations per year. As discussed in chapter 2 more larvae imply proportionally more damage per unit time.

Summation

As it stands this area of study can still benefit from efforts to obtain efficacy data for species, aimed towards minimizing treatment times or increasing confidence around undocumented species. A recent publication examining both efficacy and method for freezing museum textiles containing pests for which data did not exist can be read in Bergh et al. [215].

In paper one there was demonstrated however sufficient body of evidence in the literature on which to make longstanding general recommendations which have continued to prove convincing and efficacious.

Paper Two—on thermal methods

"The effect of thermal methods of pest control on museum collections" was written for the 3rd International Conference on Biodeterioration of Cultural Property (4–7 July, 1995, Bangkok, Thailand) to address issues about the use of thermal methods which had been raised as reasons to not employ thermal methods. Discussion of potential hazards in the absence of examined data was to be avoided.

Wilson and Wessel [128] evaluated concerns for low temperature storage of paper records to prevent chemical degradation, citing other authors work to argue ice crystals don't form in photographs and cellulose papers, concluding equilibration "at room temperature at a relative humidity of 25–30 percent, and hermetically sealed in an enclosure with a minimum of residual air left in the sealed enclosure" was a safe practice for low temperature exposure.

This issue of ice crystals and whether dry museum objects could be 'frozen safely' continued to emerge in questions from enquiries to this author through the early 1990's as interest in applying low temperature control methods increased.

In paper two, application of thermal control to cultural property was described and concerns on effects were navigated through: freezing and stiffening, melting and softening, chemical deterioration, physical deterioration of leathers, the temperature dependent efficiency of polyethylene vapour barrier, object moisture content change, dimensional change in wood and textiles, rate of change of moisture and temperature, moisture movement and condensation risk during treatment, and mould risk of treating and storing polyethylene bagged objects.

A graphic guide was also developed for estimating general thermal treatment time for thickness and type of objects and concomitant risk of moisture loss (see the paper's figure 4). This was used by the author to assist with requests on setting up treatment protocols around specific objects estimating total duration of treatments and risk from moisture content change.

A section on applying solar heat illustrated a low cost application for small institutions which was developed by the author at CCI initially to help kill pests of textiles in a rural historic house museum. These institutions needed simple and fast methods between seasonal opening and closing time and I had encountered one that did not have access to a sufficient freezer nor could it afford a pest control company visit so it built a heat chamber.

Photographs of the solar frame described and performance reported were presented at the conference but illustrations were not reproduced in the paper. For guides to these device's final forms see the appendix on page 389 and photographs of one application were reproduced in paper four.

Paper Three—on seeds (macromolecule vulnerability)

"Sensitivity of seeds in herbarium collections to storage conditions, and implications for thermal insect pest control methods" was written for the Society for the Preservation of Natural History Collections (SPNHC) herbarium workshop (Toronto 1995) publication [216]. The purpose was to examine the risk to seeds by heat disinfestation. Seeds are arguably the single most widespread living component in natural history museum collections (barring staff and pests). The key concept was to consider seed germination as a switch (on / off) which would indicate if storage and treatment conditions had been deleterious.

Seeds are designed for survival and propagation, so their continued viability can represent good macromolecular preservation. Seeds had also been held up as possible to damage by thermal control methods by Florian [187] with qualifiers like "complexity of freezing seeds and viability" and "drastic reduction of viability" unsupported by data. The questions around this aspect of herbarium operation clearly needed examination using as large a set of seed data to assess the risks.

This paper was written to address concerns about heat disinfestation in a way that would assist the herbarium community. Damage thresholds were established from reviews of agricultural practice with seed drying and storage where the interplay of humidity, moisture content and viability have long been subject to experimentation. Environment conditions for herbaria and general likelihood of seed survival were reviewed against this background, and projections of likely survival made.

Egenberg and Moe [217] had published a paper ascribing physical harm to herbarium specimens by thermal treatment and was subsequently fully examined and refuted by Shchepanek [218] [219] through experimentally examining both preparation environment and mounting practices. Herbarium research was by then moving beyond straightforward descriptive systematics based on physical characteristics.

Unlike other collections excepting agricultural produce and paper archives, microwaves had been examined as they suited the format of botanical samples. This literature was reviewed for its effects and suitability alongside convection heating. Toxic gas and controlled atmosphere fumigation impacts were also touched upon.

In the beginning stages of DNA recovery from specimens for extending systematic and evolution knowledge, relative sample size was a primary factor for whether to allow these tests to consume parts of specimens. Herbarium specimens, while numerous in the whole, are voucher of a particular time and place so their individual physical existence has great value. While the prospect at the time was the methods for DNA examination of collection-based specimens would improve (smaller sample, better recovery), a pending concern was that past treatments may have compromised the ability to use specimens. Also, considering using thermal treatment opened up the concern that it might degrade or prevent future DNA work. Herbarium material was initially seen as second best to fresh material but there was recognition of research potential within a rapidly improving field [220].

In the absence of information one can argue that 'changing horses' widens the possible harms by applying a method with different chemistry or physical effects. A countering argument is proposing incremental harm from repeated treatment being worse than change.

Discussions on macromolecular stability in this paper led to direct examination on the question of DNA recovery and sequencing by Kigawa et al. [154] who looked at a wide variety of fumigant and thermal methods then in use. This further led to the collaborative design of paper seven to examine protein response to the same suite of control methods. Examinations of dichlorvos's effects on DNA recovery as dichlorvos (DDVP) was a widely used in-cabinet fumigant was published by Espeland et al. [221] and further examination of heat on DNA by Ackery et al. [222] have helped fill in the picture of relative harm to DNA recovery by preservation methods, and so far, thermal methods and controlled atmospheres have proved to be least harmful.

Paper Four—on heat disinfestation

"Principles of heat disinfestation" was an invited topic by the "2001 A Pest Odyssey" conference (London, England) written to expand upon the the work presented in paper two. Of the thermal and CAF techniques, heat disinfestation presented the scariest sounding alternative to chemical fumigation to the conservation community which is inculcated in the need for tight environmental control standards unsurprisingly near those for human comfort. Thus, heat provides a convenient foil for testing the limits of the boundary between efficacy, effects, and economics. Heat is universally available, the quickest method of the three, and can be delivered in a variety of ways. Heat also has a long history for use against pests of goods, structures and agriculture.

The principles discussed walk the reader through the cumulative concepts of partial pressure, moisture content, sorption isotherm, enclosure and humidity buffering, rate of moisture and heat equilibrium, heat ageing and risk of damage, water activity and mould and condensate risk to educate on the means by which heat disinfestation can be applied without causing commonly voiced harms. The paper also summarized the efficacy information (paper one) for the convenience of the reader.

This paper also reports three case studies at institutions undertaken in cooperation with the author through the CCI: the development of an oven heating protocol for herbarium specimens brought in by visitors for comparative study at the Canadian Museum of Nature (Ottawa, Canada, undertaken by M. Shchepanek), an electric heat disinfestation of large and small pieces from a wood borer infested agricultural collection at the Albert County Museum (New Brunswick, Canada, undertaken by Alastair Fox and the museum's volunteers), and a solar disinfestation of textiles and other objects at the Royal Palace Museum (Luang Prabang, Laos, undertaken by Bonnie Baskin [223] with the museum's staff). These were included to show how successful low cost heat methods could be applied in differing situations with careful adhesion to the principles.

Paper Six—on the Isoperm model (thermal degradation)

"Temperature and humidity considerations for the preservation of organic collections — the isoperm revisited" was written as the first step in examining the concept of isoperm in light of more recent work on deterioration and its relevance to projecting losses with sustainability driven changes in environmental control, and resulting pressure on environmental set points for storage of cultural property. It also has future application to projection of loss in 'lifetime' from heat disinfestation (papers two and four).

The original isoperm equation [108] which was proposed only as a model, did not fully predict the data that was available at the time of formulation. However, conceptually people knew it was trending correctly (general–realistic), but the equation had to be further adjusted by application of significant power law factors to increased precision by both Sebera [224] and Michalski [225]. While this alteration quantifies a rough extent of the systematic deviation from data (assumed true) the changes could equally have been replaced by curve fitting alternate equations. Differences between model and data should be used to work forward and resolve them through execution of experiments and improved representation of the factors. Alterations to the equation should be formulated to progress understanding the underlying physical construct.

Paper six lays out an alternate isoperm model as a means to restart discussion for improving the concept and incorporate more recent data than that available to Sebera within a planned future work.

Paper Seven—on proteins and fumigants (macromolecule vulnerability)

"Investigation into effects of fumigants on proteinaceous components of museum objects (muscle, animal glue and silk) in comparison with other non-chemical pest eradicating measures" was undertaken from 2006 to determine measurable effects of fumigants on silk, glue and muscle proteins and gauge relative harms or change between pest control methods. Methyl bromide, methyl iodide, methyl bromide / ethylene oxide mixture, propylene oxide, sulfuryl fluoride, carbon dioxide, low oxygen, heat and cold were used to treat sample material under conditions identical to a single use on cultural property.

This paper continued to look for effects of agents selected for the paper by Kigawa et al. [154] which examined the harms posed to DNA recovery and synthesis. The purpose behind this effort came from recognition that, with the reduction and elimination of Methyl Bromide (MeBr) through the 1992 Copenhagen Amendment Annex E to the UNEP Montreal Protocol on Substances that Deplete the Ozone Layer [226] following the schedule laid out in Article 2H, after 2004 other reactive chemical fumigants might be promoted and chosen as replacements for use on cultural property in 'developed countries'.

Methyl bromide use on cultural property in Asia was widespread as it is a fumigant for both insects and mould and readily available for use for stored product and soil fumigation. Usage for domestic purposes in 128 designated 'developing countries' including China where an established baseline consumption of less than 0.3 kg per capita allows delayed compliance by ten years (Article 5 [226]). Developing countries signatory to the amendment are thus to phase out MeBr by 2015.

Information was needed on the possible historical harms from MeBr use and relative harms replacements might pose in order to guide good decision making in the interim and post ban periods.

The Canadian schedule to reduce use of methyl bromide was pro-

duction and consumption were capped in 1995, a 25% reduction by 1998, and 100% elimination of use by 2001 "excluding quantities used for quarantine and pre-shipment applications and quantities used for emergency and critical uses" [227]. In 1992 Canada had used 130 tonnes of methyl bromide in structural fumigation.

A measure of the UNEP schedule's impact on cultural property fumigation can be examined through the post-2004 agreed 'critical use' categories for extending MeBr application in agricultural production, and 64 documented cases of signatory country's 'non-compliance' (Article 8 [226]).

'Supplemental critical use' categories in 2005 for MeBr use on cultural properties were moved over to 'critical use' in 2006 (see table 5.3). Preservation of publications and archives was excluded as a legitimate category with "global essential-use exemption" in 2007. Categories for cultural property have not been listed as 'critical use' since 2008 [226].

The mass of one metric tonne corresponds to a volume of 12,500 cubic meters fumigated by MeBr at a the higher dose of 80 grams per cubic meter for control of insects as had been practised in Japan until cessation after 2004. Dosage is temperature dependent, and rates as low as 16 gram per cubic meter are used in agricultural quarantine applications [228] giving 62,500 cubic meters per tonne of MeBr. The three years of 'critical use' extension allowed four 'developed' countries somewhere between 275 thousand to 1.38 million cubic meters of MeBr fumigation on cultural property from 2005 through 2007.

The exclusions for methyl bromide use proved somewhat significant. In 2006, a Netherland's research report indicated methyl bromide usage was increasing for quarantine applications under ISPM 15 export treaty requirements on phytosanitation of wood packaging material (crates, pallets) to cope with "last minute pre-shipment treatment of loaded containers", resulting in excessive levels of fumigant as residues in the enclosed products. World increase in methyl bromide use to meet ISPM 15 was estimated from 11,000 tons in 2002 to 18,000 tons in 2004. The serious concern is that failure to adopt efficacious replacements (heat, sulfuryl fluoride) would undermine the reductions

Applicant	Use	Tonnes MeBr
2005		
Belgium	old buildings	1.15
	artefacts and structures	0.59
	old buildings	1.15
	churches, monuments and ships quarters	0.15
	antique structures and furniture	0.319
Germany	artefacts	0.25
Israel	artefacts	0.65
Italy	artefacts	5.225
2006		
Belgium	antique structures and furniture	0.199
	artefacts and structures	0.307
	churches, monuments, and ships' quarters	0.059
	old buildings	0.306
	old buildings	0.282
Germany	artefacts	0.1
Israel	artefacts and libraries	0.65
Italy	artefacts	5.225
	artefacts	0.275*
2007		
Italy	artefacts	5.000
2008		
	none	
2009		
	none	
Total		22.038

Table 5.3: Categories of agreed 'supplemental critical use' and 'critical use' [226] extending MeBr for fumigation of cultural properties past 2004. 'Critical use nomination' marked as *. Quantities in metric tonnes.

already gained in sectors outside those governed by quarantine and pre-shipment (QPS) exemptions [229].

While the North American museum community sought replacements for fumigants including methyl bromide and quickly adapted its crating practices to avoid the proscribed materials and incorporate certified treated wood in shipment of artworks and objects for exhibitions, the potential for methyl bromide exposure had not been eliminated due to allowance for QPS use.

Fumigants are generally used on cultural property to achieve laudable goals, the elimination of destructive pests capable of total consumption, reducing mechanical stability or severely marring aesthetic values. Yet, worldwide the quantities needed for cultural property are relatively small. Opposing indiscriminate use of fumigants are concerns of chemical interaction leading to deleterious changes, contamination by residues, application and regulatory costs, efficacy failures in non-standard materials and formats, and human exposure.

Fumigant use on protein based materials was an under-served area in studies specifically for museum materials so paper seven was undertaken to decrease uncertainty about interactions. The fumigants chosen for study were available for use in Japan and overlap fumigants available in more limited registration elsewhere including Canada. All have been used on cultural property to some degree[9] The alternatives of heat, cold and CAF (low oxygen, carbon dioxide) were also tested to provide necessary comparative information.

A novel contribution within this paper is the application of three thermal techniques in concert to reveal changes which can be related to specimen value (dimensional and molecular stability) in avian muscle. Differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and thermal microscopy (Tmic) each examine aspects of thermal response. DSC measures enthalpy change (heat absorbed or evolved), TGA reveals stability through measurement of mass loss with heating in an inert atmosphere, and Tmic directly records and analyzes motion induced by controlled temperature change. These signals can be correlated through the temperature programs run during the analysis and were demonstrated to repeatedly and with sensitivity detect changes induced by applied agents. Of protein structures, muscle is present in freeze dried and dehydrated specimens of natural history and anthropological collections and had not been previously

[9]Methyl iodide was recently removed in Japan (2010) by the proponent company due to a catastrophic blackening of silver maki-e objects (silver foil designs under urushi lacquer. R. Kigawa pers. comm.). Basic understanding of photographic chemistry was clearly absent in this decision to use MeI.

examined from a conservation perspective. Muscle also differs from structural proteins like collagen and keratin as it is highly contractile in vivo. This predisposition was considered useful to possibly enhance sensitivity of protein / fumigant interaction.

6 On problems posed by IPM

From the nose
Of the Great Buddha flew out
A swallow.

Matsuo Bashou (1644—1694),
Blyth [9]

Integrated pest management shares the same name in agriculture and museum practice with good reason. The recognition of "the control of insects by methods cultivation or farm practise" [230] and considerable subsequent research efforts developed a body of systematic knowledge that could assist crop yield before the advent of widespread reliance on pesticides. The Canadian Agri-Food Research Council succinctly defined IPM as "a decision-making process" merging sound economic and environmental requirements in the goal of suppressing food destroying pests [227].

Modern agricultural IPM utilizes contributory factors like controlling disease host plants, pest population models, monitoring pest population growth, tracking daily temperatures (degree days) to schedule control actions, sanitation guidelines etc. Economic concerns are addressed with measurable thresholds of harm to be weighed against control costs to maximize desired production goals (crop quantity, crop

quality, low pest contamination, low pesticide residue).

The term IPM was introduced to museums by Parker [231] in his seminal book on constructing a program to protect cultural property incorporating knowledge of the pests and response methods. Some of these aspects had been previously explored in volumes by Edwards et al. [232] for museums and later by Wellheiser [233] who concentrated on archives and libraries.

While there are strong parallels, the museum community cannot see things exactly in the way as other sectors where the product is for sale. They start from the premise that everything on the shelves is essentially precious, are unhappy with the prospect of any losses whatsoever and would likely be intolerant of minor annual depredations when they could do something unless cost was clearly prohibitive.

Unlike agriculture, the 'crop' in collection's care is largely nonrenewable so loss is terminal, damage can be expensive to restore, and items are 'time stamps' rather than 'time sensitive'. Cultural objects are physical information, voucher, iconic, illustrative, evocative, the focus of recorded stories and found collective or personal experiences. A museum's goals for retention are improving social values of its collections, an attitude which contributes to objects' survival in public trust.

Even with containment from the world at large, the sheer size and often cryptic nature of stored collections poses a greater challenge than routine quarantine of their incoming objects, however both quarantine and storage do have common conservation issues around the vulnerability of object materials to both pest and pest treatment, topics of papers two, three, four, six and seven of this volume. Organizing the greater effort of IPM to reduce pest hazards around the objects is the subject of of paper five. An overview of two branches of the IPM approach to protecting cultural property is shown in figure 6.1: mitigating exposure to risk through analysis of the object's situation, and the practicalities of coping with any present hazard.

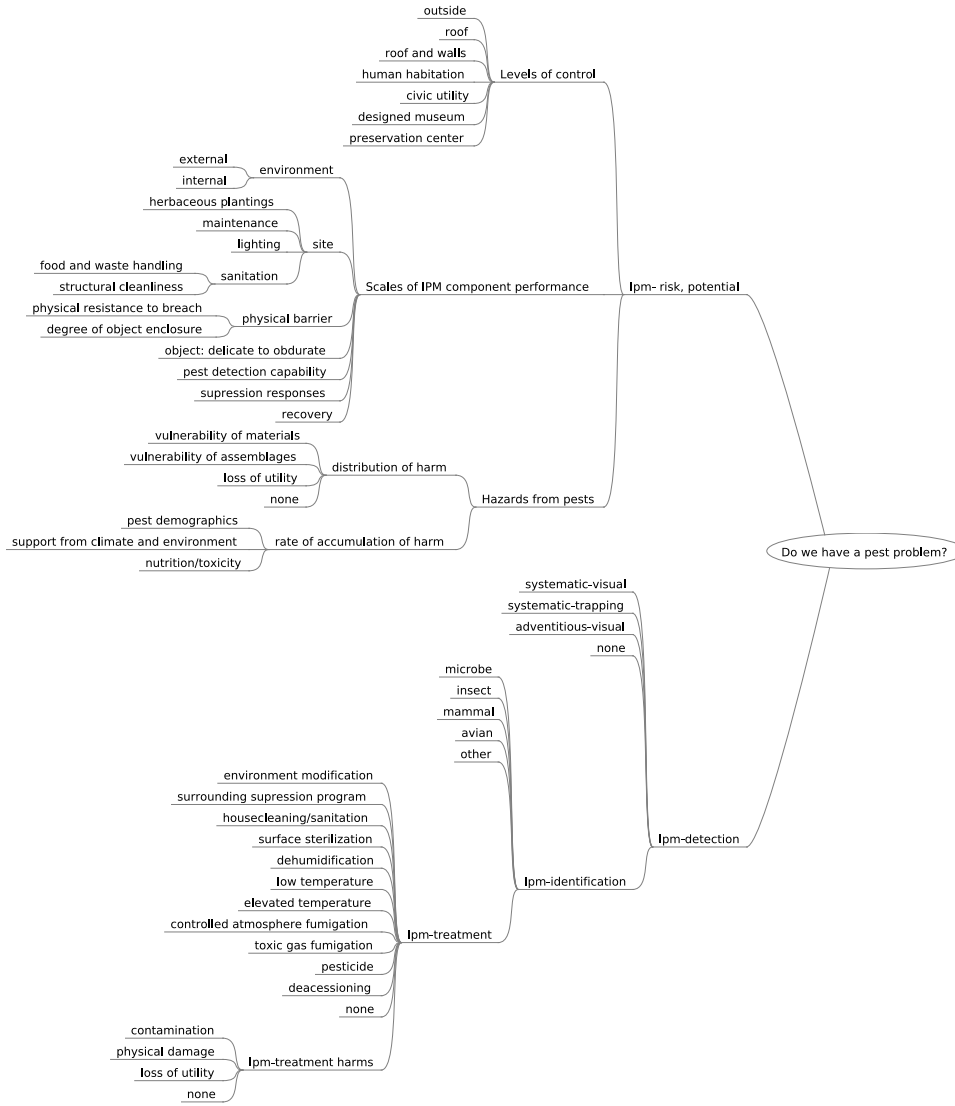


Figure 6.1: Two approaches to IPM: Upper branch is mitigating what is plausible (exposure to risk). Lower branch is combatting what is happening (exposed by detection).

Paper Five—on systematic IPM and its application

"Levels of IPM control: Matching conditions to performance and effort" was written for the 2005 Society for Preservation of Natural History Collections (SPNHC) conference "Realizing Standards" (Natural History Museum, London, England) to answer the question we were asked in our consultation with the large number of institutions which our two organizations serve: "How do I design a pest management programme for what I have to protect?"

Preventing and combatting pest losses depends on components which are either some form of passive physical barrier or an intervention from a decision. This paper predicates these components will have degrees or intensities that can be recognized to provide a useful level of protection measured against the unprotected state. Four object categories were named, obdurate, robust, soft, delicate, to model resistance to pests or vulnerability to pest harm.

For this paper we collated activities and infrastructure relating to IPM which were then categorized by themes and each theme sorted into scales of effectiveness. Levels of increasing physical barrier against pests were indicated by representative structures used to house cultural property. From this, the levels were turned into more detailed situations of site, building, fittings, procedures, deterioration challenges and prognosis. The scales of activities were applied to instruct on an IPM program for each situation. Improvements not requiring moving into a better structure were proposed (Plan B).

Not doing anything and exposure to maximum pest likelihood is the 'Level 0' state with maximum rate of deterioration nature can produce. Early in the levels, the emphasis is on reduction of loss by improving exclusion or protecting exposed items from accelerating factors, while later on more emphasis is placed on procedures to reduce pest introduction and spread inside larger structures.

The very act of erecting shelter or enclosure is the primary means to

reduce the rate and risk of pest attack. Otherwise we have to accept deterministic and stochastic loss from direct exposure to "Nature, red in tooth and claw"[1].

IPM for cultural property also has to work within a context and as a result can only impose so much. Vulnerable items outdoors may have to remain outdoors to serve their purpose, and ultimately face certain loss. The discussion is then how can we slow the demise. There are some differences to pest management that is applied to consumables where monetary value (profit) can be lost, but the product is continually replaced. The situation of object value being lost, but culturally replaced are exemplified by scheduled construction (Shinto temple) or restoration (Buddhist temple) or acceptance of loss (West coast totem poles). Finding means within cultural context and technical capacity at any level is the challenge for design of IPM programmes.

An early (1895) recorded discussion by economic entomologists as they drew from their personal experiences on solving problems with household dermestid pests captured some topics which remain current, especially to historic sites and small museums:

> "Mr. Fernald discussed the use against these insects of inflammable and explosive insecticides in connection with its bearing on insurance policies and was inclined on this latter account not to recommend them. He gave the method of controlling the carpet beetle followed with success by his wife, as follows: (1) Before bringing flowers into the house thoroughly shake them to dislodge the beetles. (2) Regularly collect and destroy the beetles which emerge and gather on the windows of the house during the months of March and April. (3) Carefully treat the carpets on the upper floors of the house, as the beetles commonly enter through the upper windows, and these carpets act as traps, getting the first and the bulk of the invasion.

[1] *In Memoriam*, A. Tennyson, 1849.

> Mr. Davis said his wife had been unsuccessful in the use of similar remedies." [234]

After playing the trump of relative hazard of fire versus pest (akin to that played by Mauduyt on Kuckahn) the focus turned to effective quarantine procedure[2] and argued a high return on sanitation activity. Knowledge of pest behaviour and key means of ingress, passively through open windows and actively by direct acquisition, are used in support of the argument. Failure is bluntly noted, but no evidence given as to whether it is actually due to the proposed procedures or their execution.

> "Mr. Rolf said that the work of the carpet beetle was much worse in the South than in the North, but he did not know the species. He used carbon bisulphide or cyanide gas, preferring the latter. If used with caution he thought neither of these substances dangerous, and their use was especially desirable in connection with herbariums.
>
> Mr. Linter said that he ordinarily recommended kerosene, which he thought more suitable than gasoline. Before laying new carpets all the grooves should be carefully filled with cement or plaster, and the carpets should be left loose at the borders to facilitate frequent investigation. The use of tarred paper was also advisable. He had found the following trap method valuable: Remove all woolens from rooms or closets and scatter about them bits of red flannel, which is a very attractive bait for the Anthrenus. The beetles thus attracted are afterwards collected and destroyed. Referring to Mr. Fernald's statement regarding the method of entrance of the beetles from flowers out of doors, he said that this is a common experience and that they commonly enter houses through the

[2]Including the earliest discovered literature source of the often oddly effected prohibition of live flowering plants in museums meme.

> upper windows and appear first in the carpets of the upper rooms." [234]

This discussion presents mapping of risk by geography through climate's influence on extent (South over North), and putting herbariums at the extreme (well past household structures) and hence requiring fumigation implies herbaria have a high likelihood of and vulnerability to infestation through their practices. The difficulties presented by convoluted collection spaces are reduced by a pervasive fumigant. Other points are: the relative hazard of pesticides, crevice harbourage elimination, design for easy repeat inspection, choice of good barrier film, bait preference and maximizing trap efficacy, procedures to avoid bringing in pests and pest behaviour to exploit in monitoring.

> "Mr. Fernald discussed the subject of the relation of color in wollens or carpets to infestation by the "buffalo moth," and said that it had been carefully investigated by his former assistant, Mr. Lounsbury, as to the attractiveness both of particular colors and different dyes to the beetles. The information was sought from various sources, including factories for the manufacture of carpets and rugs. The conclusion arrived at was that color is not an important factor—at least the beetles do not confine their attacks to particular colors, though showing a preference for the greens. He thought it more likely that the preference exhibited by the beetles in certain cases was due rather to the mordant employed.
>
> Mr. Howard said that the best remedy, and the one which he now always advised, was to abandon the use of carpets altogether." [234]

This discussion is significant as it alludes to experimental evidence given to dispel conclusions of 'preference by colour' place the observation more properly on a property behind the visual cue, the nutritive to not-outright-poisonous influence of mordants on insect choice.

> "Mr. Smith had used the method suggested by Mr. Davis and had also employed gasoline. He had not found anything in insurance policies against the use of this or like substances in small quantities, but he was always careful to urge the greatest caution in the use of inflammable substances. He gave, by request, certain experiences which he had had with the use of bisulphide of carbon in the National Museum, a rather serious explosion having in one instance occurred from the ignition of this substance by the heat from a steam radiator, while there was another equally startling case of the ignition of the substance in a large box, resulting from a spark having been struck off from a nail in fastening down the lid for the box in which the bisulphide had been placed. In the latter case the box exploded, and the … laborer was either thrown or had leaped a distance of some feet under the excitement of the moment.
>
> Mr. Howard asked Mr. Taylor, a visitor present, who is engaged in the manufacture of bisulphide of carbon, if he knew of any cases of accident from the use of this substance.
>
> Mr. Taylor replied that he knew of but one case of serious results, and that was where an explosion had resulted from a stroke of lightning. He was inclined to think that with ordinary precautions the danger was trifling. He said that the substance will ignite at 220 °*F* .
>
> Mr. Smith said that the radiator referred to by him was not nearly so hot as that." [234]

In discussion of financial and physical risk from current pesticides a practitioner and producer square off on incidents of safety without citation of chemical safety data. Neither party mentioned a dose rate recommended to kill pests nor carbon disulphide's wide explosive concentration limits which are from 1% to 50% by volume and its autoignition range from 80 °*C* to 120 °*C* [235] conserves plausibility of

the accounts as it includes the cited temperature of 220 °*F* (104 °*C*) and allows for a temperature below that of boiling water (superheated steam can be higher).

Explosions in museums aside, if the discussion of household pests seems somewhat mundane it is because the amplification by number of affected households (millions) and cumulative loss of property was not addressed. While humour is provided by the minuscule sample (wife versus wife) recited by experienced economic entomologists with research capacity, taking the full variance of expert approaches from this 'brainstorming' session and creating a scale in gradation of action to firstly reduce household pests and secondarily preserve woollen carpets and other wool items in homes gives:

> Remove all woollen carpets permanently.
> Emphasize sanitation of incoming objects as a primary control in simple structures.
> Remove refugia underneath carpets, fill crevices, barrier paper.
> Remove woollen carpets temporarily and substitute flannel (wool) traps.
> Dose woollens in kerosene to kill larvae.
> Prefer kerosene to gasoline.
> Emphasize fumigation of complex structures.
> Prefer cyanide to carbon bisulphide.

The historic conversation quoted above mentioned many possible elements for control of a simple pest in the rather low density storage of households. It has been mirrored many conversations since between experts and their consulters. Before we can project contributions of control as probabilities for outcome the relative ranking of IPM approaches in likely effectiveness is a practical step. The homeowner or museum staff will draw their own lines of economy and tolerance in making choices.

Structuring pest control information for access by relative effectiveness and complexity of assembled differences in one structure, and

physical size became the demonstration goal of paper five. An answer to Mumford and Norton's key question for the protection of stored products from pest depredation: "how to get from the present condition to an acceptable condition" [49] can be viewed across a poster crafted for the dissemination of paper five's IPM design process (figure 6.2) where the objects progress from outdoors with maximum exposure to deteriorating elements, towards the best conditions we can currently devise.

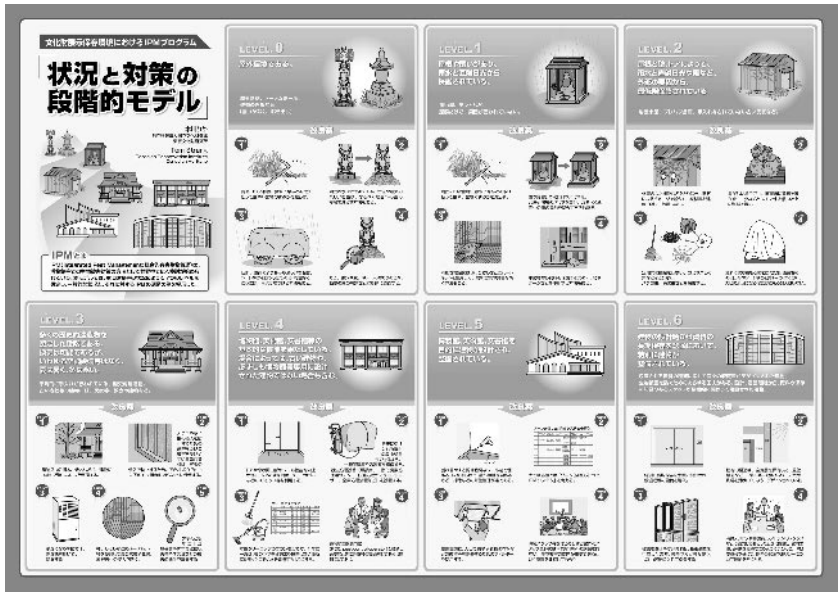


Figure 6.2: Japanese language poster illustrating the levels approach to IPM in a simplified manner using commonly recognizable situations. Key mitigating actions are depicted. Verso of the poster has the detailed version as presented in paper five's tables. R. Kigawa and T. Strang, National Research Institute for Cultural Properties, Tokyo, 2011.

7 Concluding Remarks and Future Work

The firefly:
As it dropped from a leaf
It suddenly flew away

Matsuo Bashou (1644—1694),
Blyth [9]

The preceding chapters have essayed into several key areas of work which are needed to support decisions by collection care professionals: the propensity for pest increase and infliction of harms; the balancing of beneficial response to pests against measurable reduction in object values deriving from the response; the role which collection environment plays in the support and control of fungal and insect pests; and where limits to pest activity can be established. Data for discussing mould growth limits around cultural property and have supported past recommendations for avoiding fungal problems was reviewed. This is an active area of concern for building sciences and a forward concern as we open up norms for environmental control around collections of cultural property. Building science will likely drive solutions toward resistant materials, but cultural collections must accept the sometimes quite vulnerable materials that were incorporated in both structure and housed collections.

Through the attached papers specific questions of concern were examined and a general synthesis of integrated pest management was proposed.

Paper one examined the efficacy of thermal treatment and found single exposure for a wide range of species can be applied confidently to control the main pests to collections Canadian cultural property. A general boundary from which to derive time / temperature solutions was proposed. This solution also applies to other geographic localities due to worldwide distribution of many collection pests. Reviewing a large volume of data is a valid method for creating general control recommendations despite some missing species or stages as it incorporates enough variance of the capability for survival expressed by the underlying biology (materials, enzymes, membranes, etc.) to project rational schemes for control.

Hazards to objects posed by thermal treatments were reviewed in papers two, three, four and seven. These were found to be low if simple principles were followed to restrict moisture movement. Macromolecular function was likely to be unimpaired (dormant seeds) implying DNA was likely undamaged by treatment. In normal mode of application thermal and controlled atmosphere treatments are less damaging than some of the most common fumigants applied to cultural property worldwide to date, both those which are outgoing and their possible replacements.

Paper six describes a new mathematical model for thermal deterioration of organic materials in terms of the adsorbed moisture. This provides an initial solution for comparing a concentration model of polymer degradation with the gas-surface interaction model represented by relative humidity. It was a necessary step toward further review of thermal degradation in particular the contribution of ongoing incremental harm in storage against that from additional short term treatments above ambient to control pests.

A proposal of ranked effectiveness for pest management features and activities within a scale of sheltering structures was laid out in paper five. This format provided a means to express action and attention

to physical detail where they are first likely to provide some significant return in reduction of pest harms. As a guide to IPM practices the paper also provided a fast assay of one's current situation to non-specialist caretakers of cultural property who might be asking what to do next.

The following topics for future work will improve our ability to provide estimates of pest and pest treatment risk to cultural property and guide decision making:

- Develop a formal decision support framework (tool) for relating the underpinning science models with the needs of caretakers of cultural property. This is a non-trivial task, the process of which simultaneously drives multiple areas of research and modelling. Initially a database can be designed which will allow accumulation of relevant elements, participatory development, testing and support ongoing consultation[1].

- Develop information on pest species population growth and concomitant environmental factors through literature review. This is essential prior to undertaking any study of live pest cultures to provide missing information. The result can be applied to determining the urgency of IPM responses. Intrinsic rate of increase can be applied to situations needing quarantine triage (risk model) when full quarantine cannot be obtained (threshold model).

- Develop information on the rate of damage posed by pest species. This can be applied to convey urgency, project losses and estimate value of forestalled harm which offsets investment in IPM activity, and better relate the hazard from pests to those caring for cultural properties.

[1]Discussion and prototype undertaken with Greg Paoli, Risk Sciences International.

- Develop demographic models for pest species to relate findings of trap and inspection cycles with predicting unobserved activity in collections. Demographic projection models could be combined with control models to inform of the periodicity over which efforts for redress can be projected to keep harm at inconsequential levels.

- Develop data and models for inspection efficacy, economic costs, trap and visual inspection correlation in collections[2]. Detection is a core activity of IPM which confirms species present, initiates response to present threat, and promises test of efficacy of current or changes to IPM programs. Examining the correlation of trap and inspection findings is needed for guiding future expectations from either method.

- Develop measures of efficacy of control for IPM practices considering the building in combination with other components[3] and measure contributions of efforts systematically treated in paper six. This is an exercise in constructing causal chains of pest activity and mitigation efforts protecting collections and measuring them in real situations.

- Critique existing mould-risk models currently used for building 'health' for any significant differences when protecting cultural property. As pointed out, sensitive materials which may have differing response time and surface vulnerability are not going to be covered by building research. Results from the literature review presented here can be compared to further experimental and site based studies[4].

- Continue to determine strength of hazard posed to objects by fumigants and their alternatives. This knowledge is applicable

[2]Publication on large scale natural history collection visual inspection in preparation with J. Jacobs

[3]Data collected and preliminary model developed, unpublished work with S. Ryder, R. Waller

[4]Work in progress with R. Kigawa

to constructing a decision model for choosing treatments. Continued development of scientific methods for this analysis which give direct measure of harms is desirable[5].

- Test isoperm models with matched isotherm and ageing data[6] with additional studies aimed at challenging isoperm models for their ability to match experimental results[7]. This work will further improve estimation of the extent of hazard posed to collections through the use of heat as a disinfestation method.

[5] In progress with R. Kigawa and G. Young

[6] A literature review has been completed and several models constructed for comparison.

[7] Work in progress with P. Bégin.

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Any errors and omissions that remain are my own. **T.J.K.S.**

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A review of published temperatures for the control of pest insects in museums

Paper 1

STRANG T.J.K. 1992. A REVIEW OF PUBLISHED TEMPERATURES FOR THE CONTROL OF PEST INSECTS IN MUSEUMS. COLLECTION FORUM, 8(2), PP. 41–67.

Errata

Page 59, endnote 8	'Development' typographical error as 'develpoment'
Page 61, endnote 52	*A. japonicus* Reitter, *A. canadensis* Casey, can be added to the synonym list.
Page 62, endnote 63	'not feeding at 8 °*C* ' typographical error as 'feeding at 8 °*C* '
Page 67, endnote 176	'Crisafulli' typographical error as 'Cristafulli'

A REVIEW OF PUBLISHED TEMPERATURES FOR THE CONTROL OF PEST INSECTS IN MUSEUMS

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Abstract.—Reported temperatures for the extermination and control of 46 museum insect pests are tabulated and graphed. Temperature and time of exposure found in publications recommending thermal control methods for museum use are tabulated for comparison to the mortality data from entomological literature. Miscellaneous control temperatures are also tabulated, providing information on chill-coma, feeding and developmental limits. A lethal boundary model is proposed as a provisional guide to thermal extermination of insect pests.

The use of thermal insect control techniques in museums and archives has been fostered by increased restrictions on, and costs of, fumigant and pesticide use. Thermal control methods are used when there is reticence to expose cultural property or museum personnel to proven or potentially deleterious chemical agents.

Adoption of thermal control techniques to replace pesticides is hampered by concerns that thermal techniques will fail to control insects. These concerns are due to the lack of available data on insect susceptibility to heat and cold, an awareness of some insects' capability to survive temperature extremes, a wariness of generalizations in literature, the need for justification of capital expenditure on new equipment, and suspected or known effects on artifacts and specimens.

In most of the recently published thermal control methods for museums, entomological literature is sparingly cited. Many of the earlier published recommendations were derived from experience with only a few species. Recommendations for controlling particular insect species have also been generalized in subsequent publications, so there is a danger of failure to control a species which was not included in the original recommendation.

This paper was written to address concerns rooted in the lack of comprehensive information on the thermal mortality limits of museum pest insects. Thermal mortality data are presented as a provisional guide for users of temperature extremes to control insects. The data are also provided for potential users of thermal insect control who require evidence of efficacy. Control methods from conservation and museology literature are reviewed and compared to an extensive source of entomological literature on temperature sensitivity of museum pest insects. The data on thermal limits to the insects are organized in the Appendix to this paper and provided as a basis for further study or individual need. This paper is restricted to a discussion of museum pest insects and excludes theorized and described effects on materials.

DATA

The food processing and storage industry has used thermal insect control methods for nearly a century (Mullen and Arbogast, 1984; Sheppard, 1984). This application has initiated many studies of temperatures lethal to insects as well as

Table 1. Fatal and limiting temperatures for museum pest insects.

Species	Temperatures that limit breeding & development (°C)	Lethal temperatures	
		Low temp. (°C)	High temp. (°C)
Coleoptera: Anobiidae			
Anobium punctatum (De Geer)[1]	30[2]	−16[3]	48[4]
Gastrallus sp.[5]		−29[6]	
Lasioderma serricorne (Fabricius)[7]	16[8]	−12[9]	49[10]
Stegobium paniceum (L.)[11]	17[12]	−18[13]	49[14]
Coleoptera: Bostrychidae			
Rhyzopertha dominica (Fab.)[15]	23[16]	−1[17]	
Coleoptera: Cerambycidae			
Hylotrupes bajulus (L.)[18]			56[19]
Coleoptera: Cucujidae			
Laemophloeus ferrugineus (Steph.)[20]	15[21]	−6[22]	
Oryzaephilus mercator (Fauvel)[23]	15[24]		
Oryzaephilus surinamensis (L.)[25]	17[26]	−18[27]	52[28]
Coleoptera: Curculionidae			
Sitophilus granarius (L.)[29]	2[30]	−18[31]	54[32]
Sitophilus oryzae (L.)[33]	5[34]	−18[35]	54[36]
Coleoptera: Dermestidae			
Anthrenus flavipes LeConte[37]		−18[38]	above 40[39]
Anthrenus museorum (L.)[40]	4[41]	below −20[42]	
Anthrenus scrophulariae (L.)[43]	4[44]		
Anthrenus verbasci (L.)[45]	14[46]	−20[47]	above 40[48]
Attagenus pellio (L.)[49]		−18[50]	52[51]
Attagenus unicolor (Brahm)[52]	10[53]	−24[54]	above 41[55]
Dermestes coarctatus Harold[56]			55[57]
Dermestes lardarius L.[58]	15[59]	below −2[60]	54[61]
Dermestes maculatus De G.[62]	8[63]	−23[64]	60[65]
Dermestes vorax Motschulsky[66]		−15[67]	
Reesa vespulae (Milliron)[68]		−20[69]	
Trogoderma granarium Everts[70]	15[71]	−19[72]	60[73]
Trogoderma versicolor (Creutzer)[74]	20[75]	below −2[76]	
Coleoptera: Lyctidae			
Lyctus africanus Lesne[77]			54[78]
Lyctus brunneus (Stephens)[79]			58[80]
Lyctus planicollis LeConte[81]			55[82]
Coleoptera: Ptinidae			
Ptinus tectus (Boieldieu)[83]	10[84]	below −8[85]	
Coleoptera: Tenebrionidae			
Tenebrio molitor (L.)[86]		−18[87]	52[88]
Tenebrio obscurus (Fab.)[89]		−18[90]	52[91]
Tribolium castaneum (Herbst)[92]		−10[93]	
Tribolium confusum Jacq. duVal[94]	21[95]	−20[96]	54[97]

Table 1. Continued.

Species	Temperatures that limit breeding & development (°C)	Lethal temperatures	
		Low temp. (°C)	High temp. (°C)
Hymenoptera: Formicidae			
Camponotus herculeanus L.[98]		−29[99]	
Camponotus obscuripes (I.)[100]		−10[101]	
Camponotus pennsylvanicus (De G.)[102]	0[103]		
Isoptera: Kalotermitidae			
Cryptotermes brevis (Walker)[104]		−34[105]	
Incisitermes minor (Hagen)[106]		−20[107]	51[108]
Lepidoptera: Tineidae			
Tineola bisselliella (Hummel)[109]	9[110]	−18[111]	49[112]
Lepidoptera: Pyralidae			
Anagasta kühniella (Zeller)[113]	8[114]	−18[115]	
Ephestia elutella Hübner[116]		−16[117]	64[118]
Plodia interpunctella (Hübner)[119]	18[120]	−17[121]	
Orthoptera: Blattellidae			
Blattella germanica (L.)[122]			45[123]
Orthoptera: Blattidae			
Blatta orientalis L.[124]	2[125]	−8[126]	46[127]
Periplaneta americana (L.)[128]		−15[129]	45[130]
Thysanura: Lepisimatidae			
Lepisma saccharina L.[131]	4[132]		37[133]
Thermobia domestica (Packard)[134]	22[135]	0[136]	55[137]

the economics and implementation of thermal control methods. Several authors have described utility to household sanitation. The major sources for finding papers with mortality data for this study were: Hinton (1945), Solomon and Adamson (1955), Mathlein (1961), Cornwell (1968), Story (1985), and Dawson (1987). The major sources for insect selection, nomenclature and authorship for this study were: Hinton (1945), Schrock (1988), Hickin (1985), Dillon and Dillon (1972) and Kingsolver (1988).

Table 1 is an index to larger sets of data from the entomological literature on the thermal limits of 46 species of insect pests which affect museums, galleries, and archives. The reference numbers correspond to notes in the Appendix. The values in Table 1 are only representative temperatures chosen from the full listing in the corresponding note. When known, the common names for each species are listed in boldface type in the Appendix. The Appendix can be scanned to find species with the desired common name. Note that identical common names are sometimes applied to more than one species listed in the Appendix.

Under the heading "Lethal temperatures," all values are for 100% mortality unless otherwise noted. When 100% mortality data were not available, the most extreme, albeit ineffective lethal temperatures for that insect are reported and marked as "above" or "below" that temperature. One would have to extend the

Table 2. High temperature control recommendations for extermination of insect pests.

Temperature (°C)	Time (hours)	Reference
49	4	Webster 1883, in Dean 1911[138]
52 to 66	—	Howard and Marlatt 1902[139]
60	—	Prümers 1905, in Rathgen 1924[140]
48 to 50	—	Dean 1911[138], 1913a[141]
52	—	Headlee, in Dean 1913a[141]
50 to 55	1 to 2	Goodwin 1914[142]
60	—	Holt 1917[143]
49 to 60	several	Back 1920[144]
52 to 60	8 to 10	Guyton 1926[145]
52 to 60		Back and Cotton 1926a[146]
60 to 70	24	Zacher 1927[147]
49	0.5	Clark 1928[148]
60	6	Gibson and Twinn 1929[149]
54	6 to 12	Leechman 1931[150]
77	5	Schlossberg, in Back and Cotton 1931[151]
60	4	Austen and McKenny Hughes 1932[152]
60 to 63	6	Cressman 1935[153]
77	4 to 5	O'Neill 1938[154]
54	12	Back 1947[155]
60	4	Wood 1956[156]
52 to 60	3 to 50	Forest Product Res. Lab. 1962[157]
49 to 54	10 to 12	Cotton 1963[158]
60 to 70	0.2	Cotton 1963[158]
49 to 55	12	Munro 1966[159]
60	12	Yonker 1985[160]
55	3	Parker 1987[161]
51	2 to 4	Forbes and Ebeling 1987[162]
49	0.5 to 6	Ebeling, Forbes and Ebeling 1989[163]
42	—	Watling 1989[164]
55	—	Anonymous 1990[165]

exposure or change the temperature in the indicated direction to achieve 100% mortality.

The values listed under "Temperatures that limit breeding and development" in Table 1 indicate temperatures that, while not necessarily eradicating an infestation, can prevent damage or eventually lead to decline of a population by interrupting breeding or feeding activity.

Note that values reported in Table 1 do not always represent control temperatures for all stages as, sometimes, only data for a few stages of the life cycle are available. Table 1 is used to index further data in the Appendix notes. Some of the values listed in the notes are contradictory. This is possibly due to unreported conditions such as strain variability, differing amounts of insulation that affect cooling rates, and humidity. The notes in the Appendix contain information on the insect stage, exposure time, mortality (only stated if not 100%) and the source of the information; the exposure time is usually the shortest exposure reported for 100% mortality. The information in the Appendix should be consulted before designing a thermal eradication temperature schedule for any specific insect.

Values reported in literature as general recommendations for control of an insect were not included in notes to Table 1 when there were no data or citation of an

Table 3. Low temperature control recommendations for extermination of insect pests.

Temperature (°C)	Time (hours)	Reference
−8, warm, −8	—	Read, cited in Howard 1896[166]
−10, warm, −10	—	Runner 1919[167]
−8, +10, −8	longer than 72	Back 1923[168]
−18	48	Back and Cotton 1926a[146]
below −18	12–24	Gibson and Twinn 1929[149]
below −18	longer than 24	Leechman 1931[149]
−18	—	Back and Cotton 1931[151]
below −6	720	Bovingdon 1933[169]
−11	204	Swingle 1938[170]
−18	—	Back 1947[155]
−8, +10, −8	—	Rice 1968[171]
−23	48	Remington, cited in Edelson 1978[172]
−10, −30	—	Toskina 1978[173]
−46	0.25	Appleby and Farris 1979[174]
−20	24	Arevad 1979[175]
−18	48	Crisafulli 1980[176]
−18	—	Moore 1983[177]
−40	24	Smith 1984[178]
−29	72	Nesheim 1985[179]
−18	96 to 120	Yonker 1985[160]
−20	48	Florian 1986[180], 1990[181]
−20	48	Norton 1986[182]
−20	0.5	Forbes and Ebeling 1986[183]
−35	72	Stewart 1988[184]
−25	72	Lawson 1988[185]
−20	336 to 504	Brokerhof 1989[186]
−20	168	Preiss 1990[187]
−20	40	Younghans-Butcher and Anderson 1990[188]
−20	48	Wilson 1990[189]

experiment. This was done to reveal lack of data for insects and reveal areas for research. When specific insects are reported to be exterminated by testing one of the general recommendations, the time and temperature data were included in notes to Table 1.

Tables 2 and 3 list thermal control methods in chronological order of their publication. Reference numbers refer to notes in the Appendix which give summaries of the techniques. Table 2 contains published recommendations for elevated temperature control, primarily for pests of museums, herbaria and archives, stored food products, furniture and structures. Table 3 contains the literature recommendations for low temperature control, primarily for pests of museum and archives. In Tables 2 and 3 some of the noted times refer to killing insects which were insulated within an infested object, while others note time required to kill uninsulated insects. The experimental apparatus is infrequently described in many of the sources.

Table 4 lists reported instances of failure to control insects when following recommended procedures. Some of the recommendations in Tables 2 and 3 are presented as minimum measures by the authors who, in this way, recognize the potential for failure, although very few discuss failure directly.

Table 4. Failure to control an insect by thermal methods.

Temperature (°C)	Time (hours)	Reference
−18	48	Stansfield 1985[190]
−18	24	Watling 1989[164]
−30	24	Brokerhof 1989[191]
−26	40	Brokerhof 1989[191]

Discussion

The data for 100% mortality found in the notes to Table 1 are shown in a plot of temperature against exposure time in Figure 1. Data for 46 species are shown; the upper cluster represents the conditions required to kill 26 insect species using heat, and the lower grouping shows exposure to low temperature required to kill 32 species. To aid comparison, Figure 1 is plotted in subsequent graphs and noted as 100% mortality in their keys.

As many of the researchers cited appear to have inspected their subjects at daily or longer intervals, it is likely that they have not always reported a minimum time of exposure to attain 100% mortality. This bias forces Figure 1 to be somewhat conservative. Similarly, any insulation or growth media in the experimental apparatus adds additional conservative bias by slowing the cooling rate and possibly allowing the insects time to increase their ability to survive. Rates of cooling are certainly different amongst the reviewed sources. However, in practice, cooling rates will never be uniform within mixed collections that may be subjected to low temperature control measures, and the aggregate data of Figure 1 represents this fact because of the unstandardized range of cooling rates of the experiments. Aggregation of many experiments over time also tends to reduce the effect of different responses by strains of any one species. For the purpose of recommending a general eradication technique, all these biases are beneficial.

A negative bias is the lack of data for some species, as is revealed by Table 1. Contributing to this is the occasional lack of experiments at the lower temperature commonly achieved by modern freezers. Illustrating these areas of missing information is one of the aims of this paper.

The shape of the lower cluster indicates that as temperature drops, less time is required to kill insects. The spread of this cluster illustrates the ability of many museum pests to survive lowered temperature for a considerable period of time.

In contrast, the high temperature cluster is much more tightly grouped, indicating that all stages of these insects have a lesser resistance to high temperatures than to low. At temperatures above 40°C, 100% mortality is achieved within a day for the cited species.

Figure 2a shows the recommended control methods (shown by solid horizontal lines) that have been published for eradication of insects using high temperature (Table 2) superimposed over the 100% mortality data from Figure 1. Figure 2b shows similar data from Table 3 superimposed on the low-temperature data from Figure 1. Note that the scales on the graphs vary in order to show the distribution of points more clearly. In both Figure 2a and 2b, to the right of the data cluster and overlying horizontal lines representing recommended exposures to kill insects,

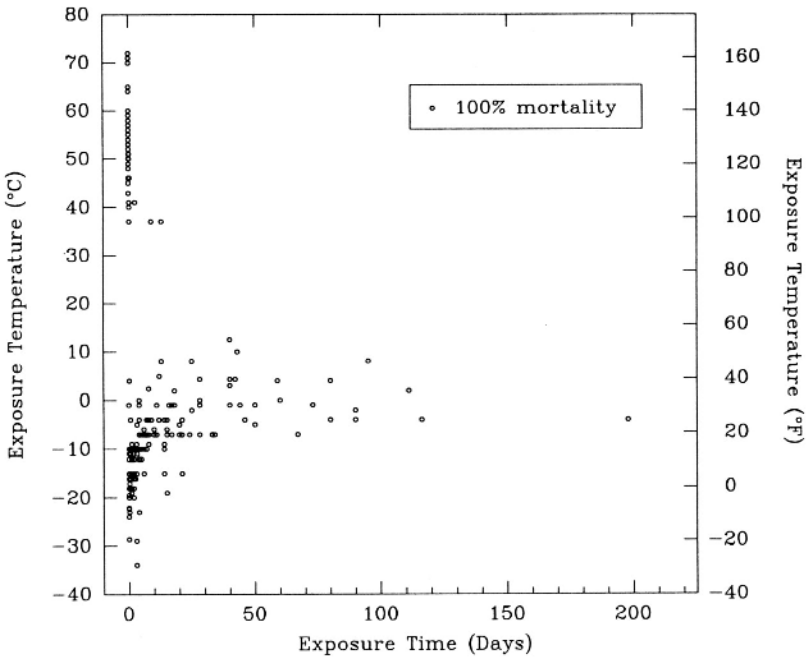

Figure 1. Thermal mortality of 46 museum pest insect species (Table 1).

a heavy solid line indicates what is described in this paper as the "lethal boundary." The lethal boundary is the approximate limit of the 100% mortality data.

The control methods shown in Figure 2a and 2b were generally developed from data from the entomology literature for a restricted number of species. It is, therefore, to be expected that the control methods bear some resemblance to the mortality data. Many of these recommended conditions, however, fall short of the lethal boundary in Figure 2b. This illustrates how failure to achieve complete eradication can result when such recommendations are extrapolated for use as a general preventive measure. A general method should embrace the mortality data of as many pest species as possible.

Another problem with the control methods is that they recommend fixed temperatures with no guideline to adapt to new coolants or other sources of variability, such as insulating effects of artifacts or the mechanical performance of refrigeration systems. The lethal boundary model facilitates adaptation to different temperatures.

The lethal boundaries of the data clusters marked by heavy lines in Figure 2a and 2b can serve as a provisional guide to thermal eradication of museum pest insects. Exposing infested material to temperature-time regimes that exceed these lethal boundaries should eradicate the listed insects. Any planned thermal control exposure should also include additional time needed to cool or heat the object.

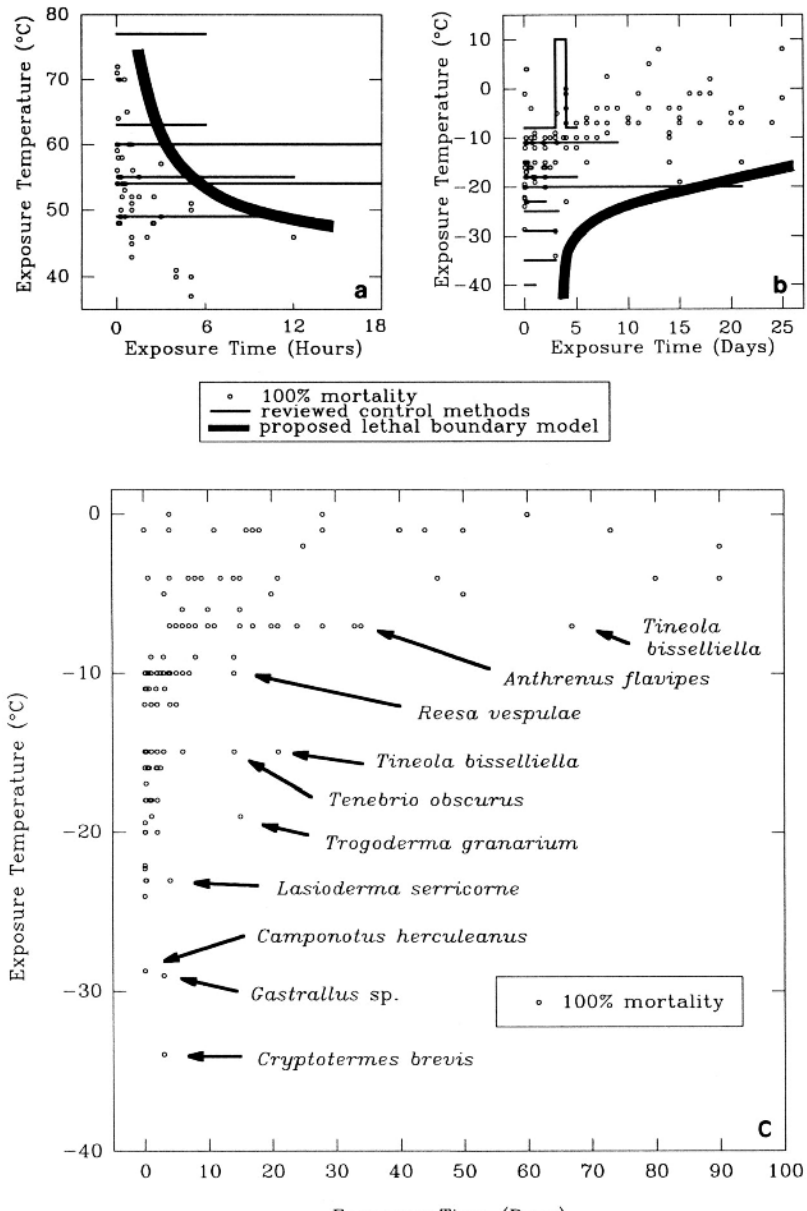

Figure 2. a. Reviewed thermal control recommendations: high temperature exposures (Table 2). b. Reviewed thermal control recommendations: low temperature exposures (Table 3). c. Species mortality data that defines the low temperature lethal boundary.

When the infesting insect is unknown, the lethal boundary model can provide a minimum recommendation that is already known to control many species.

Figure 2c shows points that define the low temperature lethal boundary labelled with species names. In general, the lower temperature points are successful treatments while the higher temperature points are efficacy data. *Cryptotermes brevis*[105] (Stewart, 1988[184]) and *Gastrallus* sp.[6] (Edelson, 1978[172]; Nesheim, 1985[179]) mark successful treatments of books in blast freezers and do not represent a minimum required exposure on unprotected insects. *Camponotus herculeanus*[99] notes a super-cooling point, the minimum temperature that conditioned insects sustained without freezing (Sømme, 1964). The point labelled *Lasioderma serricorne*[9] is an experimentally derived treatment schedule for tobacco products that ensured killing this species (Tenhet *et al.*, 1957). *Trogoderma granarium*[72] marks the exposure required to kill 400 to 500 larvae with no protective insulation (Mathlein, 1961). *Tenebrio obscurus*[90] labels the exposure required to kill larvae (Cotton and St. George, 1929). The points labelled *Tineola bisselliella*[111] are exposures required to kill larvae (Back and Cotton, 1927). *Reesa vespulae*[69] notes the exposure required to kill larvae (Mehl, 1975). *Anthrenus flavipes*[38] marks the exposure required to kill larvae (Back and Cotton, 1926a).

Threshold temperatures that limit breeding and development of insects are noted in the second column of Table 1. These temperatures support such general recommendations as cooling objects to 10°C to stop larval feeding (Story, 1985) and are the basis of economic use of cold storage in the fur industry (Howard, 1896, 1897). Some of these limiting temperatures can be used to slow the rate of damage until the insects can be eradicated, for example, by chilling a room with air-conditioning. Such use of these temperatures may increase the insects' hardiness to cold, and most of the insects would usually revive on warming.

There is concern as to whether or not museum pest insects can adapt to and thus survive temperatures recommended for low and high temperature control. Solomon and Adamson (1955) relate increased resistance to cold elicited by non-lethal exposure in *Tineola bisselliella, Tenebrioides mauritanicus, Blattella germanica, Blatta orientalis* and *Sitophilus oryzae.* The reported increases in tolerance, however, do not exceed several degrees below non-acclimated controls and are included in the data graphed in Figure 1. In the work of Solomon and Adamson, the minimum reported exposure temperature was −15°C. Figure 1 shows longer survival at −15°C than at lower temperatures that are easily achieved by modern refrigeration. The adaptive responses reported in Solomon and Adamson appear to be minor when compared to the low temperature survival of insects that are not museum pests (−20° to −50°C, Storey and Storey, 1983).

While few of the experiments reviewed in this paper were specifically designed to reveal acclimation, there are no examples of museum pest insects exhibiting a high degree of either freeze tolerant or freeze avoidant behaviours that would prevent their death below −20°C, with the exception of *C. herculeanus*[99]. There is no evidence for the ability for museum pest insects to adapt to temperatures higher than 50° to 60°C (Evans, 1986).

The majority of the low temperature data collated in this paper are for single periods of exposure to a low temperature. Leechman (1931) appears to have been the first to recommend this control of insect pests in museums. However, there are reports for three insect species describing the results of repeated exposure to

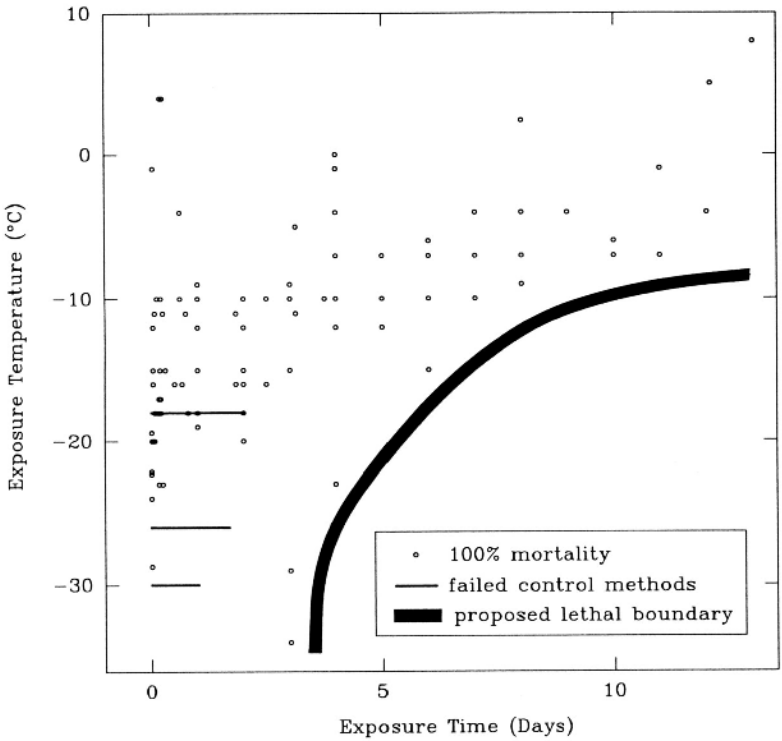

Figure 3. Reviewed thermal control recommendations: failure to control (Table 4).

regimes that did not cause 100% mortality with one exposure. In these experiments increased mortality or complete extermination during the subsequent exposures were noted: *Tineola bisselliella* (A. M. Read, cited in Howard, 1896[111,166]), *Lasioderma serricorne* (Runner, 1919[9,167]), and *Trogoderma granarium* (Voelkel, 1924[72]). Repeated exposure was first incorporated in a general recommendation for the disinfecting of wool and fur goods by Howard (1896), for combating household pests by Back (1923), for the preservation of museum textile collections by Rice (1968), and most recently by Florian (1986). Repeated exposure may require additional handling of the infested goods, however, it would be a useful procedure in combating these three species if one cannot use a lower temperature that achieves 100% mortality in a single exposure.

Reports of failure to control by low and high temperature exposure rarely appear in the literature discussing thermal control methods (see Table 4), but this cannot be taken as proof of efficacy. Figure 3 compares reported failures to the thermal mortality data. In all instances, exposure times fell short of the lethal boundaries proposed in this paper. The insects which these treatments failed to control include *Tineola bisselliella, Stegobium paniceum, Trogoderma granarium, Lasioderma*

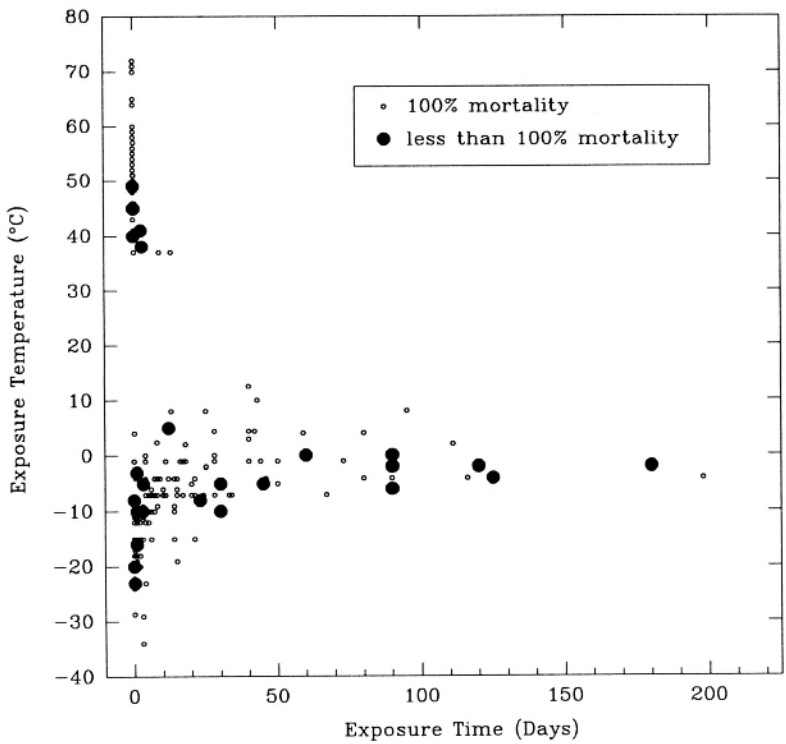

Figure 4. Distribution of less than 100% mortality data for museum pest insect species.

serricorne and *Anthrenus* species[164,190,191]. In actual museum applications, reinfestation could wrongly be attributed to inadequate exposure; therefore, rigor in treatment methodology, post treatment investigation, and publication are necessary.

Figure 4 shows the distribution of thermal exposures which have been reported as resulting in less than 100% mortality in insect populations. This incorporates the data noted by the words "above" and "below" in Table 1 and in the Appendix. The upper cluster indicates that a provisional threshold for high temperature eradication lies above 50°C. The lower cluster emphasises the need for temperatures below −10°C and certainly below −20°C when relatively short exposures are required.

Comparing Figures 3 and 4 indicates that a conservative approximation of the lethal boundary is required for treating infested objects. The incursion into the region below −20°C by control failures (Fig. 3) and less than 100% mortality data (Figure 4) show that, even below −20°C, several days exposure will be required.

A method to account for thermal insulation of objects is also necessary and can be empirically determined by temperature-time measurements of test objects in

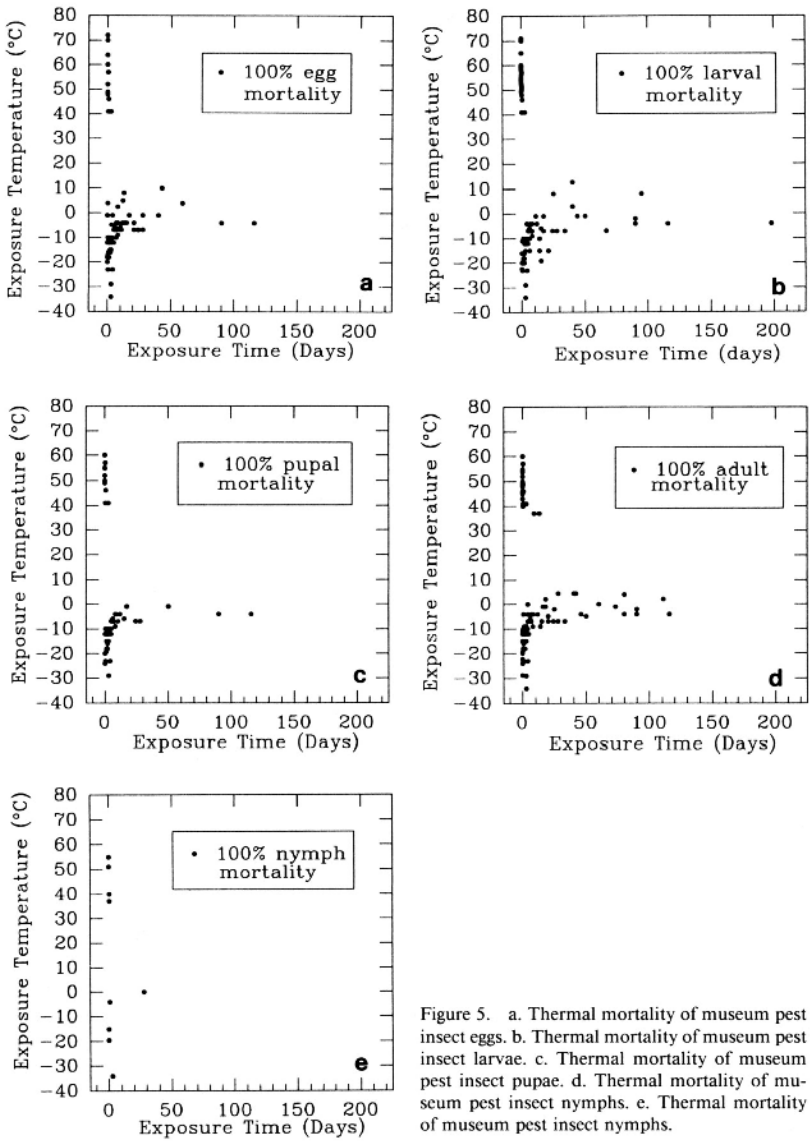

Figure 5. a. Thermal mortality of museum pest insect eggs. b. Thermal mortality of museum pest insect larvae. c. Thermal mortality of museum pest insect pupae. d. Thermal mortality of museum pest insect nymphs. e. Thermal mortality of museum pest insect nymphs.

the cooling or heating system, or calculated when physical constants are known for the materials.

The data were also grouped by developmental stage and plotted in Figure 5a to 5e. In aggregate, larvae are somewhat better adapted than other stages to survive

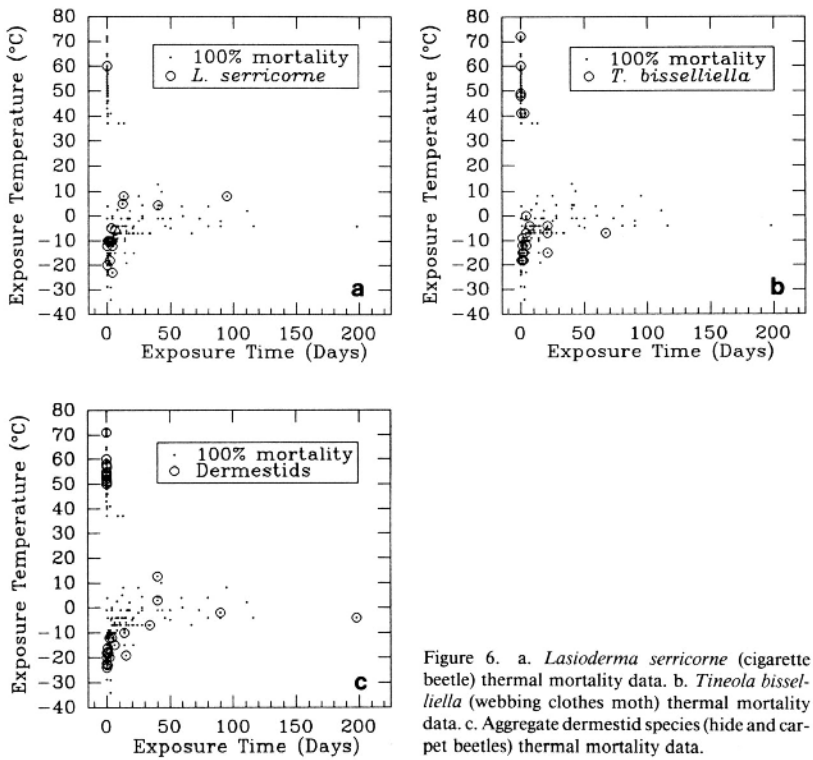

Figure 6. a. *Lasioderma serricorne* (cigarette beetle) thermal mortality data. b. *Tineola bisselliella* (webbing clothes moth) thermal mortality data. c. Aggregate dermestid species (hide and carpet beetles) thermal mortality data.

temperatures in the range of −10° to −20°C (Fig. 5b). The larval stage is often the most damaging. It is encouraging to note that eggs (Fig. 5a) are generally less able to survive than larvae, since eggs are often harder to detect due to their small size, lack of motion and cryptic placement. Pupae exhibit temperature tolerances similar to eggs (Fig. 5c).

When the specific pest insect is identified, and if sufficient mortality data exist, a tailored thermal control method can be proposed. Figure 6a and 6b show the 100% mortality data for two common museum pests superimposed on the general 100% mortality data from Figure 1. The cluster in Figure 6a illustrates that *Lasioderma serricorne* is more susceptible to low temperature mortality than the lethal boundary of the aggregate data would indicate. *Lasioderma serricorne* can be controlled by warmer temperatures or shorter exposures than those proposed by the lethal boundary (cf. the recommendation of Crisafulli, 1980[176]). This is in contrast to the cluster in Figure 6b for *Tineola bisselliella* and Figure 6c for dermestid species, both of which contribute to the lethal boundary in the aggregate low temperature data.

Conclusion

Data accumulated over the last century show that low and high temperature control of insect pests can be very effective. Extending the data on the thermal limits of the listed insects would increase confidence for eradicating infestations of any one species; however, researchers must be mindful of population and strain variability, must investigate the potential of the population to acclimate, and must include systematic identification of the examined species. Investigation and publishing on pest insects not listed here is also encouraged. Cooperation among interested parties with systematists, stored product pest laboratories, extension entomologists and cryobiologists is productive. Similarly, continued documenting and publishing of successful and failed control attempts is important to the museum community.

The lethal boundary model is offered as a provisional guide for lethal exposure where the right boundaries of the two data clusters as delineated in Figure 2a and 2b describe the minimum time and temperature for thermal control. The thermal mortality data are provided as a guide to set recommendations for the thermal eradication of insect pests in museums. Increased exposure time to compensate for the insulating properties of infested materials should be made when determining the length of exposure.

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Appendix

The following notes give detailed information on insect mortality data in Table 1, and annotate references in Tables 2, 3, and 4.

Entries on insect mortality use the following format: Insect stage, temperature in Celsius, relative humidity (if stated), exposure time, mortality (only noted if not 100%); further data in this format, source. The first entry in each note is the source for temperatures cited in Table 1. Temperatures that were converted from Fahrenheit to Celsius or reported as decimal fractions have been rounded to the nearest degree.

1. *Anobium punctatum* (De Geer). **Furniture beetle, common furniture beetle, woodworm, house-borer.** Previously *A. striatum* (Olivier) and *A. domesticum* (Geoffroy).
2. Adult female egg laying capability destroyed, 30°C, several days (Toskina, 1978).
3. Larvae, −16° to −17°C, 48 hours (Parfentiev, 1947).
   Larvae, −5° to −30°C, 3 months outdoor exposure (Toskina, 1978).
4. Larvae, 48°C, 150 minutes; 54°C, 30 minutes; 58°C, 20 minutes (Becker and Loebe, 1961).
   Larvae, 54°C, 1 minute; 50°C, 16 minutes; 49°C, 32 minutes (Cymorek, 1971).
   Eggs, 34°C (Toskina, 1978).
5. *Gastrallus* sp. **Unidentified anobiid.** C. L. Remington, cited in Nesheim (1985).
6. All stages, −23°C, 6 hours, 99% mortality, −29°C for 72 hours was the adopted treatment for books (Remington, cited in: Rasie, 1977; Nesheim, 1985).
7. *Lasioderma serricorne* (Fabricius). **Cigarette beetle.**
8. Feeding stopped, 16° to 18°C (Tenhet *et al.,* 1957).
   Adults inactive below 18°C (Runner, 1919).
   Eggs and young larvae non-viable in prolonged storage, 10° to 16°C (Crumb and Chamberlin, 1934).
   Minimum for population develpoment, 22°C (Howe, 1965).

9. Eggs, −12°C, 1 hour; adults, 4.4°C, 40 days (Strong, 1936).
   Adults, pupae, larvae, −11° to −12°C, 4 days; −10° to −9°C, 4 days; eggs, −10°C, 24 hours (Runner, 1919).
   All stages, rapid alternation of temperature, −9° to −10°C, 48 hours, room temperature for 24 hours, −9° to −10°C, 24 hours (Runner, 1919).
   All stages, −5° to −10°C, 3 days; −3° to −6°C, 6 days (Skalov, 1931).
   Eggs, −12°C, 1 hour; −10°C, 3 hours; larvae, −10°C, 60 hours; pupae, −12°C, 1 hour; −10°C, 3 hours; adults, −12°C, 1 hour; −10°C, 5 hours (Swingle, 1938).
   Larvae and adults dead after three months between +10° and −2°C (Mansbridge, 1936).
   All stages, −23°C, 4 days, in tobacco products; eggs, 8°C, 13 days; larvae, 8°C, 95 days (Tenhet *et al.*, 1957).
   Eggs, 5°C, 290 hours; −5°C, 75 hours; −20°C, more than 1 hour, all the preceding cause 95% mortality (Mullen and Arbogast, 1979).
   Larvae, pupae, adults, −18°C, 48 hours, treating herbarium material (Crisafulli, 1980).
10. All stages, 47° to 49°C (Goodwin, 1914).
    All stages, 54° to 60°C, 1 hour (Runner, 1919).
    All stages, 63°C air temperature in infested library, 6 hours (Cressman, 1935).
11. *Stegobium paniceum* (L.). **Drugstore, bread, or biscuit beetle.** Previously *Sitodrepa panicea* L.
12. Minimum for population development, 17°C (Howe, 1965).
13. Eggs, −18°C for 4 hours (Billings, personal communication in Florian, 1986).
    Larvae and adults, three months between +10° and −2°C (Mansbridge, 1936).
    Eggs, −20°C for 2 hours; larvae, pupae and adults, −20°C, 30 minutes (Gilberg and Brokerhof, 1991).
14. All stages, 47° to 49°C, not affected by humidity (Goodwin, 1914).
15. *Rhyzopertha dominica* (Fab.). **Lesser grain borer.**
16. Minimum for population development, 23°C (Howe, 1965).
17. Adults, conditioned at 16° to 13°C, −1°C, 18 days (Mathlein, 1961).
    Adults, 4.4°C, six weeks (David *et al.*, 1977).
18. *Hylotrupes bajulus* (L.). **Old house borer, house longhorn beetle.**
19. Larvae, 56°C, 1 minute; 52°C, 20 minutes (Cymorek, 1971).
    Larvae, 52°C, 150 minutes; 56°C, 65 minutes; 60°C, 50 minutes (Becker and Loebe, 1961).
20. *Laemophloeus ferrugineus* (Steph.). **Red rust grain beetle.**
21. Adult breeding limit, 15°C (Mathlein, 1961).
22. Adults, 0°C, 60 days; −5°C, 30 days; −7°C, 20 days (Mathlein, 1961).
23. *Oryzaephilus mercator* (Fauvel). **Merchant beetle, merchant grain beetle.**
24. Egg hatching limit, 15°C; larval development incomplete, 40°C (Howe, 1956).
25. *Oryzaephilus surinamensis* (L.). **Saw-toothed grain beetle.**
26. Lower limit for larval, pupal and adult development, 17°C (Mathlein, 1961).
    Upper limit for larval development, 40°C (Howe, 1956).
27. All stages, −18°C, 1 day; −7°C, 1 week (Back and Cotton, 1926b).
    Adults, −7°C, 15 days; −5°C, 20 days; −2°C, 25 days (Mathlein, 1961).
28. All stages, 52°C, 1 hour (Back and Cotton, 1926b).
    Larvae, pupae, adults, 45°C (Goodwin, 1914).
29. *Sitophilus granarius* (L.). **Granary weevil.** Previously *Calandra granaria* L.
30. Adults, chill-coma temperature is 2°C when acclimated at 15°C, chill-coma temperature is 5°C when acclimated at 27°C (Evans, 1977b).
    Eggs not laid above 34°C (Back and Cotton, 1924).
    Minimum for population development, 15°C (Howe, 1965).
31. Eggs, −1°C, 28 days; larvae, −1°C, 44 days; adults, −18°C, 5 hours; −15°C, 7.5 hours; −9° to −7°C, 14 days; −7° to −4°C, 33 days; −4° to −1°C, 46 days; −1° to 2°C, 73 days; 2° to 4°C, 111 days (Back and Cotton, 1924).
    Eggs 4°C, 59 days; −1°C, 40 days; −4°C, 15 days; −6°C, 10 days; larvae and pupae, −1°C, 50 days; −4°C, 30 days; −6°C, 15 days; adults, −4°C, 80 days; −7°C, 33 days (Mathlein, 1961).
32. Adults, 54°C, 0.5 hours; 49°C, 3 hours; 35° to 37°C, 13 days (Back and Cotton, 1924).
33. *Sitophilus oryzae* (L.) **Rice weevil.** Previously *Calandra oryzae* L.
34. Adults, chill-coma temperature is 5°C when acclimated at 15°C, chill-coma temperature is 8°C when acclimated at 27°C (Evans, 1977a).

Eggs not laid below 13°C or above 35°C (Birch, 1953).
Eggs not laid above 34°C (Back and Cotton, 1924).
Minimum for population development, 17°C (Howe, 1965).

35. Eggs, −1°C, 4 days; larvae, −1°C, 11 days; adults, −18°C, 4 hours; −15°C, 4.5 hours; −9° to −7°C, 3 days; −7° to −4°C, 6 days; −4° to −1°C, 8 days; −1° to 2°C, 16 days; 2° to 4°C, 18 days; 4° to 7°C, 80 days (Back and Cotton, 1924).
Adults, 4.4°C, 4 weeks (David *et al.*, 1977).
Eggs, −8.5° to −10°C, 90 hours; −4° to −6°C, 12 days; adults, −4° to −6°C, 4 days; −8.5° to −10°C, 15 hours (Ushatinskaia, 1950).
36. Adults, 54°C, 0.5 hours; 49°C, 3 hours; 35° to 37°C, 9 days (Back and Cotton, 1924).
All stages, 27°C increasing over 64 hours to 41°C (Kenaga and Fletcher, 1942).
Adults, 48°C, several minutes; 46°C, 12 hours (Dean, 1913b).
37. *Anthrenus flavipes* LeConte. **Furniture carpet beetle.** Previously *Anthrenus vorax* (Waterh.), *Anthrenus fasciatus* Herbst.
38. All stages, −18°C, 1 day; eggs, larvae and adults, −15° to −18°C, 1 day; larvae, −12° to −9°C, 2 days; −7° to −4°C, 34 days; adults, −12° to −9°C, 4 days (Back and Cotton, 1926a).
Adults and larvae survive −2°C all winter (Herfs, 1936).
39. Larvae, 40°C; pupae, 40°C, 40% RH; pupae, 40°C, 50% to 60% RH, 80% mortality (Herfs, 1936).
40. *Anthrenus museorum* (L.). **Museum beetle.**
41. Store skins at 4°C to prevent damage (Clark, 1929).
42. First instar larvae, adults, −20°C, 1 hour; eggs survived −20°C, 6 hours (Arevad, 1979).
Larvae survived −20°C, 2 hours (Arevad, 1974).
43. *Anthrenus scrophulariae* (L.). **Common carpet beetle, buffalo carpet beetle, buffalo moth, buffalo bug, old-fashioned carpet beetle, European carpet beetle.**
44. Storage to prevent damage, 4° to 6°C (Howard and Marlatt, 1902).
45. *Anthrenus verbasci* (L.). **Varied carpet beetle, buffalo carpet beetle.**
46. Cold torpor, 14°C (Harrison, 1944).
47. Eggs, −20°C, 2 hours, some survived; pupae, −20°C, 30 minutes; adults, −20°C, 30 minutes (Arevad, 1979).
Larvae, −20°C, 1 hour (Arevad, 1974).
Eggs, −18°C, 2 hours (Billings, personal communication in Florian, 1986).
Larvae survived after three months between +10° and −2°C (Mansbridge, 1936).
48. Heat torpor and death, above 40°C (Harrison, 1944).
49. *Attagenus pellio* (L.). **Black carpet beetle, furrier's beetle.**
50. Eggs, −18°C for 4 hours (Billings, personal communication in Florian, 1986).
51. Eggs, larvae, 52°C, 20 minutes (Zacher, 1927).
52. *Attagenus unicolor* (Brahm). **Black carpet beetle.** Previously *Attagenus megatoma* (F.) and *Attagenus piceus* (Olivier).
53. Feeding ceases, 10°C (Yamada, 1939).
Adult and larval motion stopped, 6° to 7°C (Read, cited in Howard, 1896).
No eggs laid at 13°C (Griswold and Greenwald, 1941).
Larval growth ceases and pupation shortened, 15°C (Baker, 1982).
54. Larvae, −22°C, several minutes; pupae and adults, −24°C, several minutes (Salt, 1936).
Larvae, 3° to 9°C, 40 days (Read, cited in Howard, 1896).
Larvae, −4° to −1°C, 198 days (Back and Cotton, 1926a).
55. Adults, 90% mortality, 27°C increasing over 64 hours to 41°C, less fatal to immature stages (Kenaga and Fletcher, 1942).
56. *Dermestes coarctatus* Harold.
57. Larvae, pupae, adults, 50°C, 1 hour; 55°C, 15 minutes (Yokoyama, 1927).
58. *Dermestes lardarius* L., **Larder beetle, bacon beetle.**
59. Lower limit for pupal development, 15°C; no eggs laid above 30°C (Coombs, 1978; Jacob and Fleming, 1980).
Lower limit for copulation, 16°C (Kreyenberg, 1929), 15°C (Coombs, 1978).
Adults, chill-coma, −3°C, not killed with 24 hours exposure (Kreyenberg, 1929).
60. Larvae dead and adults survived after three months between +10° and −2°C (Mansbridge, 1936).
Larvae, 12°C, 40 days (Coombs, 1978).

61. All stages, 54° to 57°C, 3 hours (Tessier, 1941).
Eggs, larvae, 52°C, 20 minutes (Zacher, 1927).
62. *Dermestes maculatus* De G., **Hide beetle, leather beetle, tallow beetle.** Previously *Dermestes vulpinus* (Fabricius).
63. Larvae motionless at 4°C, feeding at 8°C, (Read, cited in Howard, 1896).
Lower limit for copulation, 16°C (Kreyenberg, 1929).
Minimum for population development, 20°C (Howe, 1965).
64. All stages, −23°C, 4 hours; −12°C, 48 hours (Ketcham, 1984). Larvae and adults dead after three months between +10° and −2°C (Mansbridge, 1936).
65. All stages, 60°C, 1 hour (Kimura and Takakura, 1919).
Eggs, larvae, pupae, adults, 45°C, 50% mortality, respectively, at 3 hours, 45 minutes, 4 hours, 3 hours (Rosenthal, 1938).
Eggs, larvae, 52°C, 20 minutes (Zacher, 1927).
Dermestes vulpinus (Fab.) destroyed by treating books at 52°C, (T. J. Headlee in discussion, Dean, 1913a).
66. *Dermestes vorax* Motschulsky.
67. Larvae, −15°C, six days (Dawson, 1984).
68. *Reesa vespulae* (Milliron). **Carpet beetle.**
69. Larvae, −20°C, 2 days; −10°C, 2 weeks (Mehl, 1975).
Larvae, −20°C, 1 hour (Arevad, 1974).
70. *Trogoderma granarium* Everts. **Khapra beetle.**
71. Larvae inactive, 6.5°C, feeding minimum, 15°C (Mathlein, 1961).
Larvae and egg development halted, 5°C (Zacher, 1927).
Larvae inactive, 8° to 10°C; adults inactive, 10°C; male fertility destroyed, −8°C, 30 hours; adult male, lower copulation limit 10°C, upper copulation limit 42°C (Voelkel, 1924).
Minimum for population development, 24°C (Howe, 1965).
Minimum for breeding between 20° and 25°C (Mathlein, 1961).
Larvae and egg development halted, 48°C (Zacher, 1927).
72. Larvae, −19°C, 15 days; −10°C, 30 days, 97.5% mortality; −6°C, 90 days, 23% mortality; −2°C, 180 days, 44.7% mortality (Mathlein, 1961).
Eggs, −18°C, 19 hours (Billings, personal communication in Florian, 1986).
Larvae, 4th instar most cold tolerant, −10°C, 50% mortality, 25 hours (Zacher, 1938).
Larvae, −10°C, 72 hours, 11% mortality; repeated fast cooling to −10°C, 25 hours, 73% mortality; compared with −16°C, 98% mortality, 24 hours; adults, −16°C, 16 hours, 100% mortality (Voelkel, 1924).
Larvae alive after three months between +10° and −2°C (Mansbridge, 1936).
73. Larvae, 50°C, 5 hours; 54°C, 20 minutes; 60°C, 4 minutes (Husain and Bhasin, 1921).
Mason (1924) states that 50°C allowed growth and also "at the anomalous temperature of 56°C."
Larvae, 50° to 51°C, 5 hours; 52°C, 1.5 hours; 53°C, 0.5 hours; 54°C, 20 minutes; 55°C, 10 minutes; 58°C, 5 minutes; 71° to 77°C, 1 minute; 82° to 100°C, 0.5 minutes (Zacher, 1927).
74. *Trogoderma versicolor* (Creutzer).
75. Development slowed at 20°C (Hadaway, cited in Solomon and Adamson, 1955).
76. Larvae alive after three months between +10° and −2°C (Mansbridge, 1936).
77. *Lyctus africanus* Lesne.
78. Larvae, 59°C, 1 minute; 54°C, 24 minutes (Cymorek, 1971).
79. *Lyctus brunneus* (Stephens). **Powderpost beetle.**
80. Larvae, 48°C, 145 minutes; 54°C, 35 minutes; 58°C, 20 minutes (Becker and Loebe, 1961).
Larvae, 49° to 65°C, 40 minutes, infested wood blocks and structures (Ebeling *et al.,* 1989).
Larvae, 56°C, 1 minute; 54°C, 20 minutes (Cymorek, 1971).
81. *Lyctus planicollis* LeConte. **Flat-necked powder post beetle, southern Lyctus beetle.**
82. Larvae, 55°C, 90 minutes in steam kiln; 38°C not effective in killing larvae after several days; 49°C dry heat not effective (Snyder and St. George, 1924).
83. *Ptinus tectus* (Boieldieu). **Australian spider beetle.**
84. Minimum for population development, 10°C (Howe, 1965).
85. Adults, −8°C, recover after short exposure (Hickin, 1985).
Larvae, −2°C, 90 days; −5°C, 50 days; conditioned 60 days at 0°C then exposed to −5°C for

45 days, 50% mortality; adults, −5°C, 30 days, 70% mortality; 0°C, 90 days, 77% mortality (Mathlein, 1961).

86. *Tenebrio molitor* (L.). **Yellow mealworm.**
87. Eggs, −1°C, 1 hour; larvae, −18°C, 24 hours; adults, −12°C, 24 hours (Cotton and St. George, 1929).
88. All stages, 52°C, 1 hour (Cotton and St. George, 1929).
89. *Tenebrio obscurus* (Fab.). **Dark mealworm.**
90. Eggs, −1°C, 1 hour; larvae, −18°C, 24 hours; −15°C, 14 days; pupae, −15°C, 24 hours; adults, −12°C, 24 hours (Cotton and St. George, 1929).
91. All stages, 52°C, 1 hour (Cotton and St. George, 1929).
92. *Tribolium castaneum* (Herbst). **Red flour beetle.**
93. All stages, −1°C, 17 days; −4°C, 8 days; −7°C, 5 days; −10°C, 1 day (Cotton, 1950).
94. *Tribolium confusum* Jacq. duVal. **Confused flour beetle.**
95. Minimum for population development, 21°C (Howe, 1965).
96. Adults, −18.5° to −19.4°C, 5 minutes (Forbes and Ebeling, 1986).
    Adults, −15°C, 1 hour (Knipling and Sullivan, 1957).
    Eggs, −17°C, 5 hours; 4°C, 6 hours (Adler, 1960).
    All stages, −1°C, 17 days; −4°C, 12 days; −7°C, 5 days; −10°C, 1 day (Cotton, 1950).
97. Adults, 46°C, 123 minutes; 54°C, 4 minutes (Forbes and Ebeling, 1987).
    Larvae, 49°C, 15 minutes (Dean, 1911).
    All stages, 46°C, 12 hours (Dean, 1913b).
98. *Camponotus herculeanus* L., **Carpenter ant.**
99. Workers, conditioned 12 weeks at 0°C, −28.7°C supercooling point; conditioned 2 weeks at 20°C, −22°C supercooling point (Sømme, 1964).
100. *Camponotus obscuripes* (I.).
101. Workers, males, −10°C, 3 days (Tanno, 1962).
102. *Camponotus pennsylvanicus* (De G.). **Black carpenter ant.**
103. Adults immobile below 0°C, gained glycerol in 6 days at 0° to 5°C, lost glycerol in 3 days at 20° to 25°C (Dubach *et al.*, 1959).
104. *Cryptotermes brevis* (Walker). **West Indian drywood termite.**
105. All stages, −34°C, 3 days (Stewart, 1988).
106. *Incisitermes minor* (Hagen). **Western drywood termite.**
107. Nymphs and alates, 5 minutes, −18.5° to 19.4°C (Forbes and Ebeling, 1986).
108. Nymphs, 51°C, 1 hour (Forbes and Ebeling, 1987).
109. *Tineola bisselliella* (Hummel). **Webbing clothes moth, clothes moth.**
110. Larval feeding ceases, 9°C; larval movement ceases, 4° to 6°C (Read, cited in Howard, 1896). Store at 4° to 6°C to prevent feeding. Developed larvae can survive one year at 4°C (Back and Cotton, 1927).
    Adults inactive below 13°C (Clark, 1928).
111. All stages, −18°C, 1 day (Back and Cotton, 1926a).
    Eggs, −18° to −15°C, 1 day; −15° to −12°C, 2 days; −12° to −9°C, 4 days; −7° to −4°C, 21 days; −4° to −1°C, 21 days (Back and Cotton, 1927).
    Larvae, −18° to −15°C, 2 days; −15° to −12°C, 21 days; −7° to −4°C, 67 days; −4° to −1°C, greater than 125 days (Back and Cotton, 1927).
    Adults, −18° to −15°C, 1 day; −15° to −12°C, 1 day; −12° to −9°C, 1 day; −9° to −7°C, 1 day; −7° to −4°C, 4 days; −4° to −1°C, 7 days (Back and Cotton, 1927).
    Adults, 0° to 4°C, 4 days; larvae survived −8°C, 23 days; larvae all died when cooled to −8°C, warmed to room temperature then returned to −8°C (Read, cited in Howard, 1896).
    Eggs, −18°C, 3 hours (Billings, personal communication in Florian, 1986).
    Larvae survived after three months between +10° and −2°C (Mansbridge, 1936).
    Eggs, 48°C, 12 minutes; 72°C, 4 minutes (Titschacks, 1922 in Rathgen, 1924).
112. All stages, 49°C, 11 minutes; 60°C water, immediately (Back, 1923).
    Adults and eggs, 100% mortality, larvae 90% mortality, 27°C increasing to 41°C over 64 hours (Kenaga and Fletcher, 1942).
    All stages, 70% RH, 41°C, 4 hours (Rawle, 1951).
    Eggs, 21°C, 1.5 hours of direct sunlight; adults, 21°C, several minutes, no measurement of the surface temperature given (Clark, 1928).

113. *Anagasta kühniella* (Zeller). **Mediterranean flour moth.** Also seen as *A. kuehniella,* and *A. kuhniella.* Previously *Ephestia kühniella.*
114. Adult, egg laying and breeding limits, 8°C; egg hatching limit, 10°C (Mathlein, 1961).
115. Eggs, conditioned at 0° to 4°C for 3 days prior to exposure, −18°C, 1 day; −10°C, 7 days; −7°C, 10 days; 10°C, 43 days; larvae, −19°C, 1 day; −10°C, 6 days; −7°C, 17 days; pupae, −19°C, 1 day; −10°C, 5 days (Mathlein, 1961).
Eggs, −4°C, 14 days; −7°C, 11 days; −11°C, 75 hours; −16°C, 60 hours; larvae, −4°C, 7 days; −7°C, 8 days; −11°C, 18 hours; pupae, −4°C, 9 days, −7°C, 10 days; −11°C, 44 hours; −16°C, 44 hours; adults, −11°C, 2 hours (Bovingdon, 1933).
All stages, −4°C, 116 days; −7°C, 24 days; −10°C, 7 days; −12°C, 4 days; −15°C, 3 days; −18°C, 1 day (Cotton, 1950).
116. *Ephestia elutella* Hübner. **Cacao moth, warehouse moth, cocoa moth.**
117. Eggs, −4°C, 7 days; −7°C, 7 days; −11°C, 18 hours; −16°C, 12 hours; larvae, −4°C, 4 days; −11°C, 6 hours; −16°C, 1 hour (Bovingdon, 1933).
118. Eggs, 70°C, 30 minutes; larvae and pupae, 70°C, 10 minutes (Noyes, 1930).
Larvae, 64°C, 5 minutes (Mokrzecki, 1930).
119. *Plodia interpunctella* (Hübner). **Indian meal moth.**
120. Minimum for population development, 18°C (Howe, 1965).
121. Eggs, −17°C, 4 hours; 4°C, 5 hours (Adler, 1960).
Eggs, 2.4°C, 192 hours (Cline, 1970).
Larvae, 8°C, 25 days (Stratil and Reichmuth, 1984).
All stages, −4°C, 90 days; −7°C, 28 days; −9°C, 8 days; −12°C, 5 days (Cotton, 1950).
122. *Blattella germanica* (L.). **German cockroach, steamfly.**
123. Adults, 45°C at 0% RH, 1 hour; 43°C at 90% RH, 1 hour (Gunn and Notley, 1936).
Adult males, 46°C, 1 hour (Forbes and Ebeling, 1987).
124. *Blatta orientalis* L. **Oriental cockroach, black beetle.**
125. Nymphs and adults, acclimated at 14° to 17°C, chill-coma at 2°C; acclimated at 30°C, chill-coma at 7.5°C (Mellanby, 1939).
126. Nymphs and adults, −4° to −8°C, 15 hours, acclimated at 15°C and 30°C (Mellanby, 1939).
127. Adults, 46°C at 0% RH, 1 hour; 43°C at 90% RH, 1 hour (Gunn and Notley, 1936).
Adults, 40°C, 4 hours, independent of humidity (Gunn, 1933).
128. *Periplaneta americana* (L.). **American cockroach.**
129. Nymphs and adults, −15°C, 1 hour (Knipling and Sullivan, 1957).
130. Adults, 45°C at 0% RH, 42°C at 90% RH, 1 hour (Gunn and Notley, 1936).
Adults, 99% mortality, 27°C increasing to 41°C over 64 hours, less fatal to immature stages (Kenaga and Fletcher, 1942).
131. *Lepisma saccharina* L., **Silverfish, fish-moth.**
132. Cold torpor, 4°C (Zacher, 1927).
133. Nymphs, 37° to 40°C, independent of humidity; adults and nymphs, greater than 32°C, a few hours (Sweetman, 1939).
134. *Thermobia domestica* (Packard). **Firebrat.**
135. No eggs laid above 42°C and below 29°C at 76% RH. Eggs do not hatch below 22°C or above 48°C, independent of humidity;
Nymphs do not mature below 22°C or above 47°C, independent of humidity (Sweetman, 1938).
Nymphs immobile below 0°C (Sweetman, 1938).
136. Nymphs, 0°C, 4 weeks (Sweetman, 1938).
137. Nymphs, adults, 55°C, 5 minutes (Sweetman, 1938).
138. Dean (1911) cited work of Webster in 1883 for eradication of *Sitotroga cerealella* (Angoumois grain moth) infestation. Heated a mill to 49°C for 4 hours to kill pests. Reported no ill effect on germination of grain after 8 hour exposure to 66°C.
139. Howard and Marlatt (1902) gave a general recommendation for destruction of "most" insects by exposure to 52° to 66°C. They also recommended the protection of goods by storage at 4° to 7°C.
140. Rathgen (1924) cited work by Prümers (1905) on the destruction of pests of wood and paper by heating at 60° to 70°C. Clothes moth pests were destroyed by "safe and inexpensive" use of 60°C heat. Rathgen (1924) also cites Titschacks' (1922) use of heat to kill *Tineola bisselliella* eggs, 48°C, 12 minutes; 72°C, 4 minutes.

141. Dean (1913a) used heat in grain mills. Approximately 18 hours exposure, heating to 46° to 54°C was effective in killing insect pests. Heating to 66°C for 30 hours did not damage wooden machinery. In discussion following Dean's paper, T. J. Headlee related the use of 52°C heat to kill *Dermestes vulpinus* (F.) in books.
142. Goodwin (1914) gave a general recommendation to eliminate cereal pests, 50° to 55°C for 1 to 2 hours. Revival of insects after several days of inactivity was noticed after sub-lethal heating.
143. Holt (1917) described good housekeeping practice. Used 60°C heat to disinfest dried foods. Used a damp towel and a hot iron to steam and kill carpet moths, with two further applications at weekly intervals to kill insects missed by the process.
144. Back (1920) recommended killing psocids (book lice) with 49° to 60°C heat for several hours.
145. Guyton (1926) describes superheating houses. Exposure to 52° to 60°C for 8 to 10 hours to get penetration, especially in stuffed furniture. This recommendation was given for *Attagenus unicolor* and *Anthrenus scrophulariae.*
146. Back and Cotton (1926a) described clothes moths, carpet beetles, psocids and tobacco beetles as common furniture pests, the first two being the more damaging. Life cycle, food preference, optimal temperatures for development and control measures discussed. Notes use of vacuum, dry cleaning, heat, cold, and gas fumigation to kill pests in furniture. 52° to 60°C recommended. Cites use of heat to exterminate bedbugs and flour mill pests. States "cold storage is excellent for either preventing injury or in actually killing the insects" then discusses use of cold weather to kill pests. Notes −15° to −18°C kills clothes moth and furniture carpet beetle stages in one to two days.
147. Zacher (1927) described the use of heat to combat insects. *Liposcellis divinatorius* (book louse), 50° to 60°C dry heat. *Dermestes lardarius, D. vulpinus, Attagenus piceus, A. pellio,* larvae and eggs, 52°C dry heat for 20 minutes; 67°C hot water for 5 seconds.
Gave a recommendation of 60° to 70°C for 24 hours to kill *Stegobium panicea.*
148. Clark (1928) reviewed control methods, fumigants, and mothproofing in the textile industry. Cited control temperatures: moths, all stages, 49°C, 11 minutes; some dermestids, all stages, 49°C, 30 minutes, but noted that higher temperatures are required to kill other dermestids; eggs and larvae, 60°C water, 5 seconds.
149. Gibson and Twinn (1929) discussed heating and cooling buildings. Heat, 49°C for several hours. Heat upholstered furniture, 54° to 60°C, more than 6 hours. Open building for 12 to 24 hours when temperature goes below −18°C. General methods recommended for *Plodia interpunctella, Ptinus, Dermestes* and Anobiid species. *Camponotus pennsylvanicus* infestation treated with hot water.
150. Leechman (1931) suggested low temperature control in museums. Recommended less than −18°C for 24 hours. Leechman also recommended high temperature control using 54°C for 6 to 12 hours while cautioning about possible damage to artifacts.
151. Back and Cotton (1931) reported work of Schlossberg stating that external air must be 74° to 77°C for 5 hours to kill clothes moths in stuffed furniture. Several hours exposure to −18°C also recommended.
152. Austen and McKenny Hughes (1932) recommended 60°C for 3 to 4 hours to disinfest upholstered furniture and cited Back (1923), Back and Cotton (1931). Recommended use of cold storage during warm seasons to prevent damage to goods.
153. Cressman (1935) reported the heating of a library to 60°C to 63°C for 6 hours to kill a *Lasioderma serricorne* infestation, without disrupting the use of the building. Gas burners used with electric fans to ensure even heating of the space. No living insects found when the library was inspected 37 days later. Wood furniture, sheepskin and buckram bindings were not considered injured in any way.
154. O'Neill (1938) recommended the use of 77°C air temperature to heat herbarium plant bundles to 60°C for 4 to 6 hours. Dermestids, weevils and cockroaches killed.
155. Back (1947) recommended one to two days exposure to −18°C to kill moths. Heating for a "short time" to 54°C said to kill all stages. Mentioned superheating of houses for 12 hours to kill clothes moths, carpet beetles and bedbugs.
156. Wood (1956) reviewed heat treatments to eradicate book infesting insects. Psocids, "bookworm" and *Tineola bisselliella* mentioned, 60°C for 4 hours.
157. Forest Product Research Laboratory (1962) published a kiln schedule for heat sterilization of timber against *Lyctus* infestation. Temperatures from 52° to 60°C and relative humidities

between 60% and 100% are related to timber thickness and equilibrium moisture content. *Anobium punctatum* and species of Bostrychidae were also killed by this schedule. Cellulose, paint, and turpentine varnish surface finishes were not affected below 55°C and 80% RH. Wax finishes were affected at all temperatures in the schedule.

158. Cotton (1963) recommended temperatures of 49° to 54°C for 10 to 12 hours to kill insect pests in mill structures. Grain and grain products were heated to 60° or 70°C for 5 to 10 minutes to kill pests.
159. Munro (1966) related the use of heat in mills, 49° to 55°C, 10 to 12 hours.
160. Yonker (1985) gave general recommendations for *Lasioderma serricorne,* 60°C, 12 hours; −18°C, 4 to 5 days.
161. Parker (1987) noted use of heating to 60° to 63°C for 6 hours to disinfest structures. Recommended a 54°C oven for 3 hours with a water source to maintain moisture content for disinfesting books or botanical specimens. Noted it is easier to kill insects by heat than cold.
162. Forbes and Ebeling (1987) described heat treatments of building mock-ups and reported mortality data for several insect species. *Blattella germanica* (German cockroach), *Tribolium confusum* (flour beetle), *Incisitermes minor* (drywood termite), *Iridomyrmex humilis* (Argentine ant), and *Ctenocephalides felis* (cat flea). Also reported the treatment of a house infested with *Cryptotermes brevis* (drywood termite).
163. Ebeling, Forbes and Ebeling (1989) treated historic buildings for a powderpost beetle infestation. The heating required 3 to 6 hours and was stopped after maintaining 49°C for 30 minutes at thermocouples placed throughout the structure.
164. Watling (1989) recommended using a 40° to 42°C drying cabinet to kill mycophagous insects during fungal collection preparation. Watling also reported the herbarium practise of using −18°C for 24 hours to exterminate herbarium pests and cited a failure to control *Ceracis cucculatus* (tree-fungus beetle), *Trogoderma granarium, Stegobium paniceum* and *Liposceles bostrychophilus* by this method.
165. Anonymous (1990) note stated that temperature above 55°C kills wood destroying insects.
166. Howard (1896) described experiments by commercial firms using cold storage for fur and woollens (0° to 4°C) and their need to optimize the temperature for reasons of economy. Moth infested goods were normally treated with a "general cleaning and heating". Howard reported the work of A. M. Read on *Tineola bisselliella, Attagenus unicolor* and *Dermestes maculatus,* to find optimal storage temperature that would inhibit feeding. 10°C was reported as the feeding threshold although movement was still seen at several degrees lower. Read was the first to report that *Tineola bisselliella* larvae were killed by cooling to −8°C, warming and return to the cold. In contrast, continuous storage at −8°C for 23 days did not kill all the larvae. Temperatures below −8°C were not used in the experiments.
167. Runner (1919) used alternating temperatures to kill a *Lasioderma serricorne* infestation in tobacco; −10°C, 48 hours, warm for 24 hours, −10°C for 24 hours. A control experiment with infested tobacco held at −10°C had survivors.
168. Back (1923) recommended refrigeration for control of webbing clothes moth and black carpet beetle larvae, −8°C for "several days," brought up to 10°C for a "short time" then returned to −8°C with a final long term storage temperature of 4°C. The quick change in temperature and repeated cooling was credited with the killing effect since long term survival at −8°C was demonstrated. This procedure was first published by Howard (1896).
169. Bovingdon (1933) investigated the temperature and time for killing *Anagasta* (Ephestia) *kühniella* in bales of tobacco. Bovingdon noted that labour was the major cost of the process. Thermocouples were recommended to tell when a low core temperature was achieved.
170. Swingle (1938) treated *Lasioderma serricorne* infested tobacco hogsheads and bales, −11°C, 9 days.
171. Rice (1968) described the moth eradication method originally proposed by Reid (Howard, 1896[166]) and suggested its use on textile collections.
172. Edelson (1978) reported that Remington normally used −23°C for 48 hours to kill insects. Rasie (1977) reported Remington's control method, −23°C, 6 hours, 99% mortality. In practice, books were cooled to −29°C for 72 hours to kill *Gastrallus* sp. (Nesheim, 1985).
173. Toskina (1978) described a successful treatment for *Anobium punctatum* infested icons by exposure to ambient winter conditions for 3 months. Temperatures averaged −10°C with two cold periods of several days duration, reaching −20°C and −30°C.

174. Appleby and Farris (1979) used −46°C to kill lepidoptera larvae before freeze drying.
175. Arevad (1979) recommended −20°C for 1 day to control *Anthrenus verbasci* and *Anthrenus museorum*.
176. Cristafulli (1980) recommended exterminating *L. serricorne* in herbarium collections with −18°C for 48 hours, as was done at the Royal Botanic Gardens at Kew. Other institutions used temperatures as low as −40°C. See Watling (1989[164]).
177. Moore (1983) suggested using a deep freeze on wood objects, −18°C or lower for several days.
178. Smith (1984) gave a general recommendation of −40°C to ensure mortality and states 24 hour exposure is sufficient.
179. Nesheim (1985) described a blast-freezer treatment, −29°C for 72 hours to control *Gastrallus* sp. in a 37,000 volume rare book collection. Nesheim reported that Remington recommended −29°C for 72 hours to treat books.
180. Florian (1986) recommended −20°C for 48 hours to kill insect pests in museums.
181. Florian (1990) cited Florian (1986). Stated that control failures occur when the recommended temperature of −20°C for 48 hours was not adhered to.
182. Norton (1986) mentioned the use of −20°C for 48 hours to control clothes moths.
183. Forbes and Ebeling (1986) reported that *Incisitermes minor* (drywood termite) infestations were controlled with spot applications of liquid nitrogen. Wall sections were cooled to −20°C in 75 minutes. In controlled experiments the termites were killed by a 5 minute exposure to −20°C.
184. Stewart (1988) exterminated a *Cryptotermes brevis* (West Indian drywood termite) infestation of books with −35°C for 72 hours.
185. Lawson (1988) described a 1983 treatment of books to kill an unidentified insect, −25°C for 78 hours. A three year follow-up examination showed no further insect activity.
186. Brokerhof (1989) reported on the State Museum for Natural History in Leyden, the Netherlands' control method for pests of stuffed animals, −20°C, 2 to 3 weeks.
187. Preiss (1990) reported a dermestid infestation of woollen tapestries treated by exposure to −20°C for 9 days. Preiss recommended a minimum exposure of 7 days to ensure an effective treatment.
188. Younghans-Butcher and Anderson (1990) cited Florian (1986), −20°C for 40 (sic) hours.
189. Wilson (1990) cited Florian (1986), −20°C for 48 hours.
190. Stansfield (1985) cited failure to control *Niptus hololeucus* (golden spider beetle) and *Tineola bisselliella* by exposure to −18°C for 48 hours.
191. Brokerhof (1989) reported the failure of the State Museum for Natural History in Leyden's treatment for *Lasioderma serricorne* (Herbarium beetle), −30°C for 24 hours. Failure was attributed to insulation by material surrounding the insects. Brokerhof also reported the Herbarium in Utrecht's use of −26°C, 40 hours to control *Anthrenus* species sometimes failed to kill larvae and eggs.

The effect of thermal methods of pest control on museum collections

Paper 2

STRANG, THOMAS J.K. THE EFFECT OF THERMAL METHODS OF PEST CONTROL ON MUSEUM COLLECTIONS. PP. 199–212 IN *3rd International Conference on Biodeterioration of Cultural Property, 4–7 July, 1995, Bangkok, Thailand: Preprints.* BANGKOK: ORGANIZING COMMITTEE OF ICBCP–3, 1995.

Errata

Since publication of this paper the author has discovered that contributions to mould risk while cotton textiles are in transport was first laid out by Armstead and Harland in 1923 [164]. They describe two methods of inducing unexpected mould: Thermal differential across packaged fabric when initial moisture content was below that required for mould growth and subsequently conveyed in sealed tins. Failed seals and subsequent container leakage allowing moisture infiltration as the second mode of harm.

This paper utilized the work of Hazeu and Hueck [165] who discussed the mould in transport problem within the context of more recent packaging materials (post-WWII).

The Effect of Thermal Methods of Pest Control on Museum Collections

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Abstract

This paper reviews the efficacy and risks from using thermal control methods for the protection of cultural property. Thermal methods are attractive as they leave no residues, are inexpensive, and applicable to many scales of problem. For many organic materials and assemblies, the risks from thermal techniques are eliminated by the simple act of enclosing objects in a vapour barrier prior to treatment. The magnitude of the risks and possible mitigation procedures for common materials are discussed. A procedure developed for applying solar heat for insect extermination in textiles is given as an illustration.

INTRODUCTION

The use of heat or cold to control insects underwent a period of rapid development prior to 1940, but was then superseded by the use of chemical pest-control methods. Over the past decade, interest in thermal methods of pest control has been rekindled due to a reluctance to expose collections to harmful chemicals, and the need to find alternatives to restricted fumigants and pesticides.

There are a number of factors that make the use of thermal methods of pest control attractive to the museum community. Availability and affordability are key issues, especially as many of the museums with the worst pest-control problems are in less affluent areas of the world. Thermal methods of pest control can be carried out using natural conditions, or widespread technologies which provide heat or cold. Cost for the application of thermal methods, which can be measured in terms of equipment, labour and time, is generally low; even so, institutions with little money but access to a labour pool can minimize equipment costs and use more labour-intensive thermal methods to achieve their goals.

However, two major issues continue to arise concerning the use of thermal methods in museums. The first is efficacy; the effectiveness of heat and cooling has been addressed elsewhere but will be briefly reviewed below. The second deals with the effects of high and low temperatures on museum objects. While these methods do pose risks to some types of materials, these risks can be managed with many types of objects. This paper will examine some of the potential threats posed to museum objects, and assess their severity for different types of objects.

EFFICACY OF THERMAL TECHNIQUES FOR ERADICATING INSECTS

The thermal response of insects has been investigated by economic entomologists throughout this century, and is widely applied in pest-management programs for agriculture. While there are some collection pests for which we might wish further knowledge, a functional description of thermal limits for museum insect pests is available (Strang, 1992). Figure 1 summarizes the thermal limits for 46 species of museum and stored product pests. To the right of the solid lines are zones in which no pest insect is reported to have survived, and are thus conservative recommendations for treatment (Strang, 1992). Points to the right of the dashes line generally represent insects reported as eradicated while within objects.

These published treatments show that temperatures of 55°C to 60°C will kill pests in a relatively short period of time, between 1 to 8 hours (books, buildings). The time required at low temperature is more dependant on the temperature used. Convenient chest freezer temperatures between -20°C to -40°C generally require under one week's exposure to be efficacious (Strang, 1992).

RISK TO MUSEUM OBJECTS FROM THE USE OF THERMAL TECHNIQUES

Thermal techniques are being used widely at present for pest control in a variety of applications, both in the museum field and elsewhere. A summary of some of the applications is given in Table 1.

Table 1. Some applications of thermal control methods currently in use.

Thermal Control Method	Temperature	Material undergoing Treatment
Mechanical refrigeration	below -18°C	ethnographic skin and fur objects, animal study skins, herbarium sheets, books, furniture, textiles, archeological textiles, water-saturated artifacts awaiting freeze drying
Outdoor temperatures (cold climates)	winter, generally less than -20°C	herbarium storage, general museum storage, furniture, bedding, granaries
Hot water	60°C	washing clothes (delousing), seed and plant spraying (anti-fungal and insect)
Convection	60°C	herbarium sheets, wood sculpture, marquetry, Boulle, wax and shellac finished furniture, stuffed furniture, seeds (grain)
Heated structures	60°C (target temperature)	libraries, herbaria, historic houses, households, granaries

In spite of this extensive usage, these techniques cannot be used carelessly, as they do pose risks to certain museum objects. This paper will assess some of these risks, attempt to identify vulnerable materials, and suggest ways of minimizing the risk where possible. The risk factors that will be considered are: stiffening of materials at low temperatures, melting of materials, accelerated chemical deterioration at high temperatures, physical deterioration at high temperatures, changes in moisture content, dimensional changes due to heating and cooling in wood, dimensional changes in textiles, and mould risk associated with bagged objects.

LOW-TEMPERATURE EFFECTS - FREEZING AND STIFFENING

Although the term 'freezing' is often used to describe low-temperature pest control, in fact ice does not form in a porous organic object such as wood (Nanassy, 1978) unless it has a very high moisture content (flood-damaged, saturated).

However, polymeric materials do become stiffer and more brittle at low

temperatures. The thermal response of coating is well characterized. Drying oil films have a glassy behaviour below -30°C and a glassy /rubbery transition between -30°C and 0°C. Acrylics used in most paint formulations are glassy below 0°C and are leathery between 0°C and 50°C (Michalski, 1991). This led to the recommendation against the low-temperature treatment of oil and acrylic paintings on canvas due to the increased brittleness in the image layer; these brittle layers may not fracture on their own, but will be vulnerable to external physical force, such as a shock. If the risks associated with cold temperature can be minimized by ensuring, for example, safe handling, then cold temperatures can be a viable method of pest control. Resin varnishes and glue have transitions higher than acrylic and are already glassy at room temperature and median humidities. Therefore, assembles with glued joints are of less concern than paint layers (Michalski, 1991).

HIGH-TEMPERATURE EFFECTS - MELTING AND SOFTENING

Melting of materials, waxes and resins in particular, is an obvious risk when using elevated temperatures. In restoration, this softening is commonly used in a controlled manner to consolidate cupped paintings. Commercial firms using heat to kill insects in marquetry and Boulle furniture do not report damage to shellac and waxed surfaces (Anonymous, 1990). However, one may wish to exclude materials that have melting ranges beginning near 60°C. Resin varnishes and glue become rubbery by 60°C (Michalski, 1991), so some caution is advised, but generally this should not pose problems for glued assemblies.

CHEMICAL DETERIORATION

Many chemical reactions proceed more quickly at high temperatures. Studies on poor-quality paper indicate that the rate of deterioration approximately doubles for every 5°C rise in temperature during the first and most rapid stage of its deterioration (Michalski, 1991). This means that high temperatures will shorten the useful 'lifetime' of an artifact, and conversely low temperatures will extend this lifetime.

Low temperatures are commonly used for the storage of unstable materials (e.g. colour photographic negatives). Thus low-temperature pest-control methods will not only kill pests, but will slightly extend the lifetime of chemically unstable materials. Elevated temperature methods, however, present a dilemma, as they will kill insects but also temporarily accelerate chemical deterioration. If heat deteriorates objects, can one use it ethically?

Let us consider an example. Using the rule of thumb that chemical rates double every 5°C, estimates of 'lifetimes' for an artifact that will deteriorate chemically in 500 years at 20°C are: 64 days lost (0.00035 lifetimes) for 6-hours exposure at 60°C, and 0.03 days gained for 7 days of -20°C exposure. If the lifetime is only 50 years at 20°C (e.g. poor paper) a 6-hour heat treatment uses 0.0035 lifetimes. Therefore short-term thermal treatments have a negligible effect on the chemical longevity of these objects.

PHYSICAL DETERIORATION AT HIGH TEMPERATURE - LEATHER

Studies carried out on the deterioration of leather have relevance to high-temperature treatment of this material. Irreversible dimensional change in collagen molecules above a temperature threshold (shrinkage temperature, T_s) seriously distorts skin objects. The thermostability of collagen in water relates to the state of deterioration of the object (Young, 1990). Figure 2 shows temperature for maximum denaturation of collagen against equilibrium relative humidity (Kopp *et al.*, 1989, Komanowski, 1991). The curve indicates that fresh and tanned collagen at less than 90% RH tolerates temperature well above 60°C without distortion.

However, problems could arise with deteriorated collagen in ethnographic objects since their T_s's at saturation can be much lower (Figure 2, Young, 1990). Until equivalent curves for deteriorated materials are characterized, it is not advisable to subject collagenous material to heat treatment unless its T_s at saturation is above the treatment temperature.

VAPOUR AND INSECT BARRIER - POLYETHYLENE BAGS

Any discussion on moisture in objects involves a discussion of bagging the artifacts. This section defines what is intended by the terminology of a 'bagged' artifact in this paper, and the material involved.

Gary Thompson (1964) determined the minimum ratio (buffering capacity) of wood to air to prevent loss of equilibrium moisture content (EMC) in the wood to be 1 kg of wood to 1 cubic metre of air. With less wood than this, humidity induces a new EMC. More wood than this enforces an equilibrium RH in the package based on the EMC. Adding even more buffer simply reduces the already minimal EMC change. The use of the term 'bagged' in this paper implies this last state.

Low density polyethylene (LDPE) comes as a clear or pigmented, inexpensive, heat sealable, moisture barrier film. LDPE has a melting point above 100°C and its brittle temperature is below -50°C (Andrews and Dawson, 1986). These properties combine to make it an ideal barrier film for either thermal treatment. Moisture permeability increases with heat and is directly proportional to thickness (see Figure 4).

While polyethylene can be penetrated by some insects, Highland (1984) rated 5 mil (125 micron) polyethylene as fair, and 10 mil as good for insect resistance. Five-year trials with woollens stored in kraft-polyethylene laminate showed only unsealed materials to be affected by mould and insects (Bry *et al.*, 1972). Artifact bagging can be used with confidence that effort is not being wasted.

Since folds and seams are the major route of infiltration by penetrating insects (Newton, 1988), the seams are ideally closed with a wide heat-seal (1 cm) and trimmed flush to eliminate crevices. Taped seals will not last as long as heat seals but can be used. Include an RH indicator strip inside the bag for monitoring and have the staff member initial and date the strip for quality control.

THE EFFECT OF TEMPERATURE CHANGES ON MOISTURE CONTENT

If an organic object is heated sufficiently without being first placed in an enclosure, its moisture content will drop, and eventually it will become desiccated. Clearly, this is a situation to be avoided. However, heating a bagged object will only result in a small change in moisture content (and a change in RH within the enclosure), and the system will equilibrate rapidly.

When available, sorption isotherms, such as those shown in Figure 3, can be used to predict the maximum RH change in an enclosed package. Figure 3 shows that a bagged sample of wool which is heated from 35°C to 58°C will undergo an increase in relative humidity from 50% to just under 60%. Similarly, Richard (1991) has expressed the relationship for wood as:

$$RH_{final} = RH_{initial} + 0.35(T_{final} - T_{initial}).$$

Sorption isotherms are created in an essentially infinite amount of air, starting from desiccation or saturation. They are laboratory extremes that define boundaries. In practice, objects ratchet back and forth within the adsorption and

desorption curves and changes are less than predictions from these curves.

Figure 3 also illustrates that if packages of wool and cotton are heated the same amount, there will be a small difference between the final RH for the two packages. If these two materials are combined in the same package, there will be a minor adjustment of final equilibrium content (EMC) in the lesser mass of the two materials. In fact, given the similarity in the shape of most isotherms for organic materials, this small adjustment will be insignificant in most cases.

DIMENSIONAL CHANGES IN WOOD

The previous section illustrates the co-dependence of temperature and moisture in hygroscopic materials. This section will examine the contribution of the thermal and moisture effects to the dimensional changes, and assess the risk this poses to objects.

The coefficient of thermal expansion for wood in its tangential direction (most reactive) ranges from 3.9 to 8.1 x 10^{-5} per °C (Forest Products Laboratory, 1980). Therefore, a 40°C shift in temperature will result in a 0.3% swelling in this direction. This is not enough to cause fracture in constrained glassy polymers (e.g. paint on wood), as their elastic limit is between 1% and 3% (Michalski, 1991).

For bagged artifacts, the total amount of moisture within the bag remains constant, and so the EMC of the wooden components changes very little (Richard, 1991). As a result, thermal expansion dominates in these situations, and again the amount of physical movement is generally too low to cause damage to sound artifacts.

For unbagged wooden materials, however, the movement of moisture into or out of the object dominates the dimensional changes. The moisture coefficient for the tangential direction ranges from 2.0 to 4.5 x 10^{-3} per % EMC (Richard 1991-given that 1% EMC = 5.9% RH). This indicates that a 1% change in EMC will result in a dimensional change approximately 60 times greater than that caused by a 1°C temperature change.

Let us re-examine the case of an unbagged wooden object undergoing a 40°C temperature increase. Using the equation above (Richard, 1991) this temperature rise will result in a 2% decrease in the EMC of the wood, causing 0.9% shrinkage in the tangential direction. This is approaching the elastic limit of

glassy polymers, which indicates that caution should be exercised with assemblies such as painted wood. This is one reason for the bagging of artifacts before thermal treatments.

DIMENSIONAL CHANGES IN TEXTILES

Textiles are frequently considered for thermal treatments, but temperature and humidity fluctuations generally pose little risk to fabrics. As Michalski states:

> "Constrained textiles show very little tension change between 75% RH and 0% RH, because of crimp in the yarns. Textile can shrink dangerously in the region 75%-100% RH, especially above 90% RH" (Michalski, 1993b).

However, this is not generally a concern for unconstrained textiles such as clothing or carpets.

RATE OF CHANGE - MOISTURE AND TEMPERATURE

The calculations of change in dimension which have been considered in this paper are assuming equilibrium conditions, that is they assume that the object has equilibrated at its new temperature and moisture conditions. However, objects do not respond to changes in conditions instantaneously.

Figure 4 plots half-times for hygrometric response against thickness for wood and cotton, bare and when coated with paint or enclosed in polyethylene film (Michalski, 1993b; Crank, 1960). Curves for polyethylene bagged objects are given at -20°C and 60°C, as well as three thickness at 20°C. Coating or bagging postpones changes in an object's EMC and allows more time to relax induced stresses.

A half-time is commonly between one-third to one-fifth of the time required for re-establishing equilibrium, so Figure 4 depicts states that are half way through the change in magnitude, but 70% to 80% away from completion in time.

The points in Figure 4 plot half-times for thermal response ($\pm$ 40°C to 60°C from ambient) in differing thicknesses of wood, cotton, herbarium sheets, books, porous whale bone, wall sections, bales of cotton, wool and tobacco.

Figure 4 shows that materials without any moisture barrier (cotton) may exhibit less than ten times separation between heat and moisture half-times (i.e. vertical

separation between cotton and points plotted in Figure 4). Wrapping with polyethylene separates heat and moisture response by 1,000 times for heating, or 100,000 times for cooling. For example, consider heating a 10 mm wooden panel wrapped in 6 mil polyethylene to 60°C; Figure 4 indicates that the temperature half-time would be reached in about 6 minutes and temperature equilibrium would be reached within about 30 minutes, while the hygroscopic half-time is about 20 days. Therefore, a 6-hour heating cycle should provide sufficiently high temperature within the wood to kill insects, yet will result in minimal moisture change in the wood. This is another major reason for using a vapour barrier around an object during thermal treatments.

MOVEMENT OF MOISTURE IN ENCLOSURES DURING TREATMENT

When a piece of wood is sealed in a fitted bag and subjected to a 40°C rise, the increase in the bagged air's capacity for water vapour is not enough to lower the EMC of the contents. Moisture loss ceases, the object moves very little, and any small change is well inside the elastic limit (safe) (Michalski, 1991; Richard, 1991).

Slow leakage of moisture via perforations or permeation can pose a risk over the long term (Thompson, 1964). During thermal treatments, permeation can be discounted provided the bag is physically intact, since the insects are dead well before a significant amount of water permeates through the barrier, even for very thin contents (Figure 4). Post-treatment storage of disinfested, polyethylene bagged objects can be considered for at least one year in humid climates and possibly more, provided the bag is thick (6 mil, or doubled up thinner films) and the object sealed when at an EMC providing less than 65% RH (see 'Bagged Objects and Mould Risks' below for caveats). This is an important strategy when reinfestation is a risk in collection storage.

Condensation is observed inside bags of water-saturated objects placed in freezers, but the author has never observed it in objects acclimatised to median RH's. Even an empty bag scavenges the moisture on the polythene surface when cooled to -40°C. On removal, all condensation occurs on the outside of the bag. This is another major reason to bag objects.

Within heat treatments, there is no condensation until the warm bag enters cooler air or touches a cool surface (hand, table). Condensation forms away from the object, inside the cooler periphery of the bag and disappears once the object cools. One could mitigate against condensation with a layer of tissue

paper, but it is probably unnecessary with careful handling.

BAGGED OBJECTS AND MOULDS RISK

Resistance of the conservation community to sealing artifacts in polyethylene bags is usually related to the perception that this increases risk of moulds. Based on work with goods shipped from tropical ports in polyethylene bags, Hueck (1965) warned textile conservators against bagging objects for storage. However, in the same document, and commonly overlooked in the argument, Hueck stated that if one is trying to combat insect infestation, bags are extremely useful and may take priority since one can mitigate the conditions that give rise to mould. One can reduce moisture contents of materials prior to bagging, or bag when annual cycles allow.

Hazeu and Hueck (1966) measured the movement of moisture inside containers packed with wool and cotton under a thermal gradient. Their predictive curve is plotted in Figure 5 on the same graph as the risk to the contents from mould. Mould risk is expressed as time that elapses before growth is visible on nutrient material held at the indicated humidity (Michalski, 1993a). The mould risk lines are valid for the range of 25°C to 40°C. Outside this range mould growth is slower than indicated, or RH must be higher.

Consider this situation: a textile at equilibrium with 60% RH (I) is sealed in a bag and placed against the wall that is 5°C cooler than the 25°C room. Trace up the 60% RH line and intersect the two curves marked 5°C (warm and cool sides). The warm portion drops to 52% RH (W) and the cool side rises to 67% RH (C). The cool side has a mould risk in about one year. The same package risks mould in under one month with a 10°C thermal gradient. If bagged at equilibrium with 40% RH, the textile would not risk mould with a 15°C gradient. The curves are conservative since Hazeu and Hueck's measurements at 15°C match the 10°C predictive line reproduced in Figure 5. Note that trends to both desiccation and saturation occur in different areas of the package.

Mouldy objects in bags are achieved by the following means:

1) Bag at equilibrium RH (ERH) above 65% and maintain long enough for mould to initiate (see Figure 5).
2) Bag at ERH less than 65 % but subsequently store at elevated temperature, inducing an ERH above 65% (see Figure 3).
3) Bag at ERH less than 65% but store with a thermal gradient significant

enough to induce RH above 65% in part of the bag (see Figure 5).

4) Bag at ERH less than 65% but store in higher RH air that eventually permeates the bag (see Figure 4).

Avoid these situations and the risk of mould is minimal.

APPLICATION - THERMAL TREATMENT USING SOLAR HEAT

The use of solar energy to achieve high temperature pest control is of particular interest to museums with minimal resources. The author conducted experiments with wool carpet to demonstrate applicability of solar heating for insect extermination. Maximizing solar gain is used to decrease soil pests (Katan and DeVay, 1991). Sunning kills textile-damaging insects (Clark, 1928) but risks fading, contamination, and reinfestation.

Surfaces exposed to the sun rise in temperature until heat gain matches heat loss. Yamasaki and Blaga (1976) demonstrated the maximum rise for black PVC panels in still air was limited to 44°C above ambient temperature. The exposures were made under a clear sky at 45°C north longitude. Black colour reduced reflective losses and efficiently converted radiant energy to heat (94%). Insulating the shaded side reduced radiation loss.

Figure 6 shows the temperature profile through a 1 cm thick hooked wool rug sealed in black 6 mil polyethylene to conserve moisture, maximize solar heat gain, and eliminate photo-induced fading. An envelope of clear polyethylene around the black plastic formed a greenhouse to reduce wind cooling. The package rested horizontally on a mesh 10 cm off the ground to reduce conductive loss. This configuration achieved a 50°C rise over ambient throughout midday. In this evaluation, no shade-side insulation was used and the temperature difference across the carpet reached 20°C. Insulation raises the shade-side temperature, reduces moisture partitioning, and treatment time. After exposure, the bag was left sealed until the contents cooled to ambient temperature before opening.

The exposure to kill textile pests at different temperature was obtained from data reported in Strang (1992). A minimum exposure of one hour would be needed to eliminate textile pests in the illustrated example. This technique gives anyone with minimal resources access to effective heat treatment for infested textiles. The total cost of materials was $25.00 Canadian.

CONCLUSION

Thermal control methods can be used selectively, but on a large proportion of general museum collections without undue fear of damage. Thermal control is efficacious and does not leave residues on objects. The methods are available to many institutions without resource to fumigation chambers and its scale of use ranges from individual items to entire structures. Used intelligently, the required bagging can be retained afterwards to adequately protect collections against many agents of deterioration (abrasion, smoke, water, insects, contaminants, incorrect humidity) so benefits accrue over a longer term.

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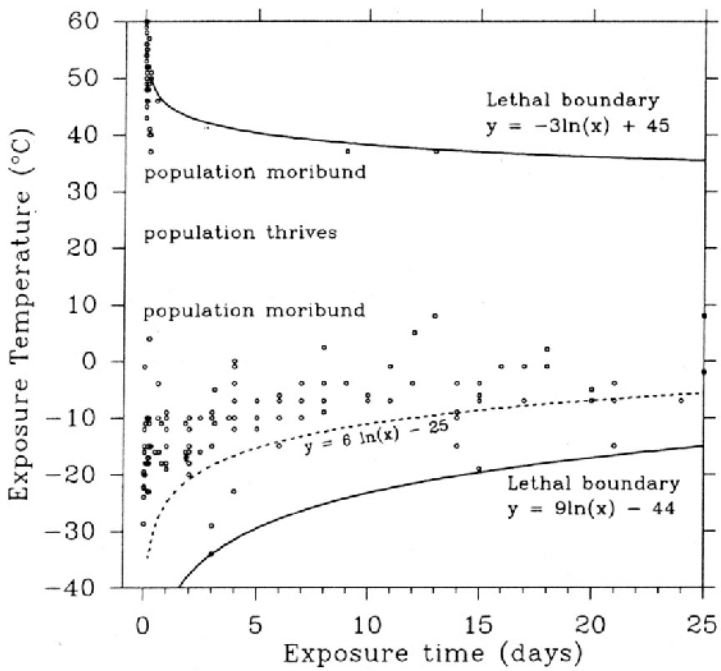

Figure 1. Time to effect 100% mortality on insect pests of collections. After Strang (1992), 46 species.

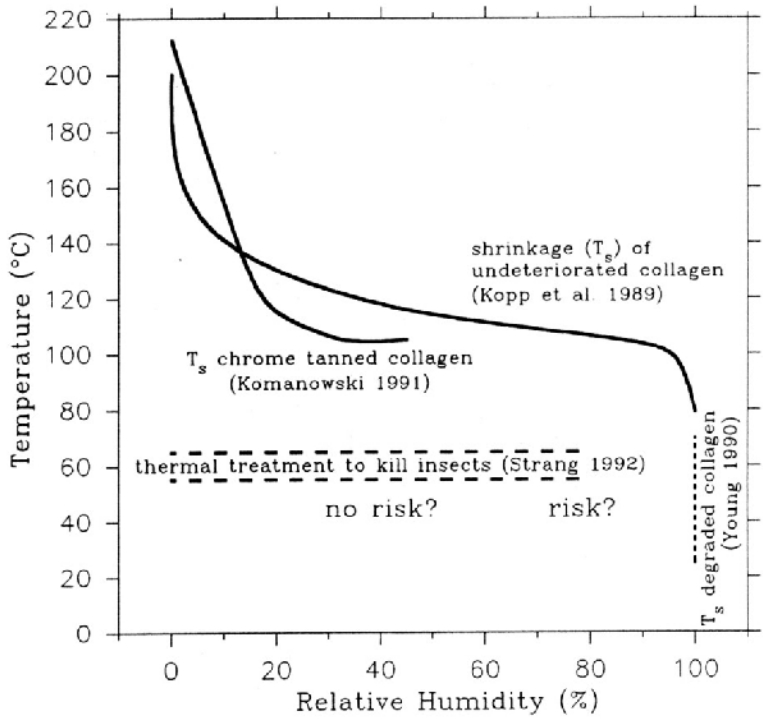

Figure 2. Maximum denaturation temperature of collagen at different relative humidities.

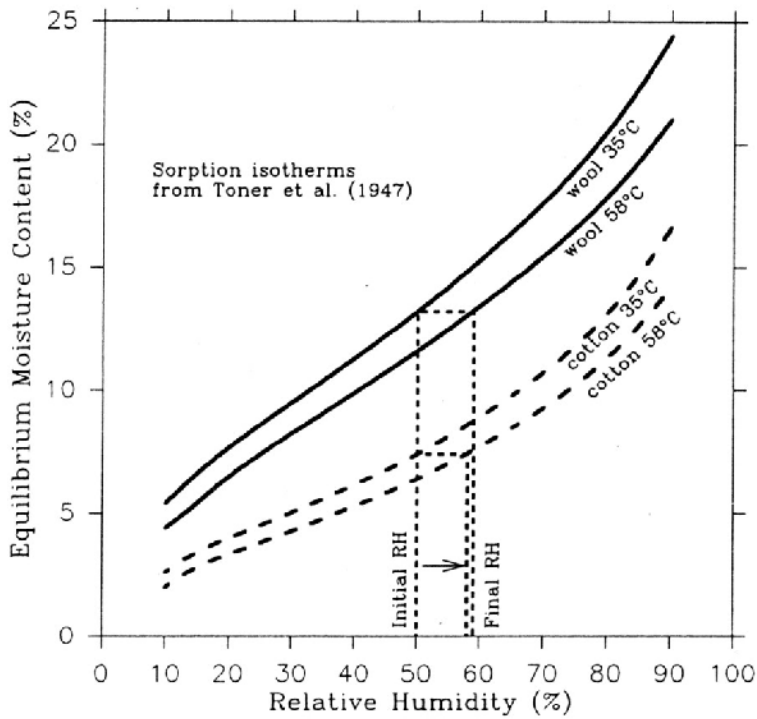

Figure 3. Humidity change around bagged objects subjected to a rise in temperature. EMC held constant by bag.

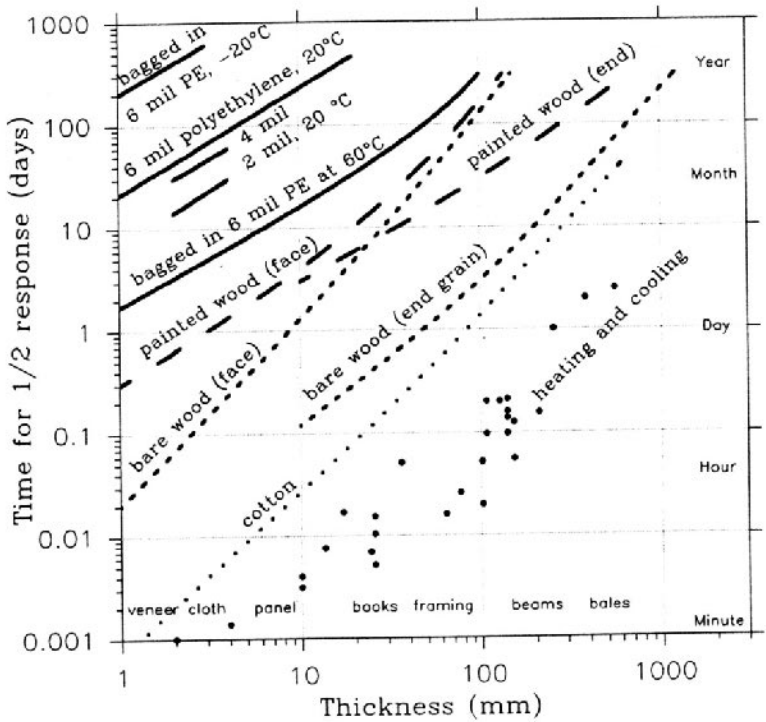

Figure 4. Comparison of response half-time for EMC (lines) and Temperature (points). EMC curves: Michalski (1993b), Crank (1960). Thermal half-time points: references from Strang (1992) and measurements by author.

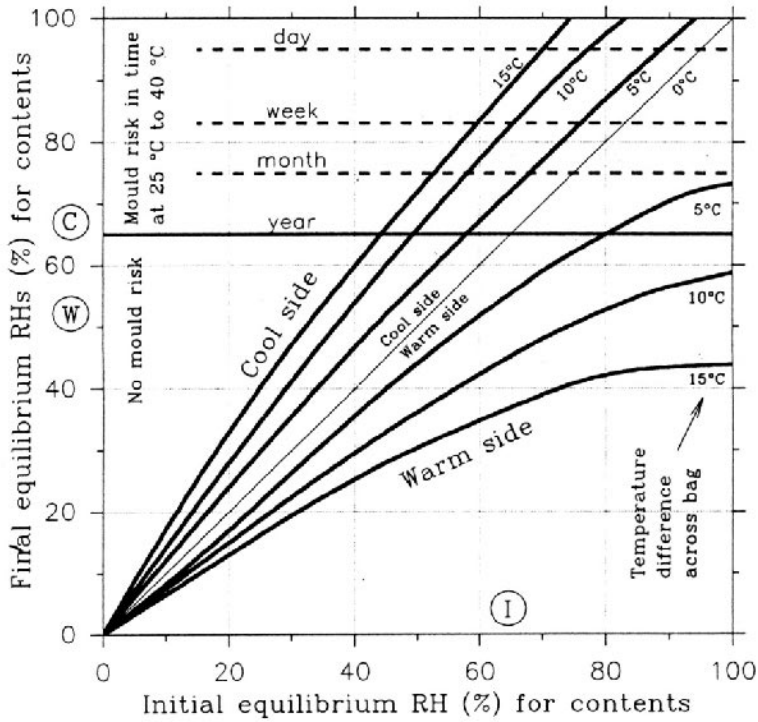

Figure 5. Expected psychrometic behaviour of bagged textile in a thermal gradient, and mould risk. Curves from Hazeu and Hueck (1966), Michalski (1993a).

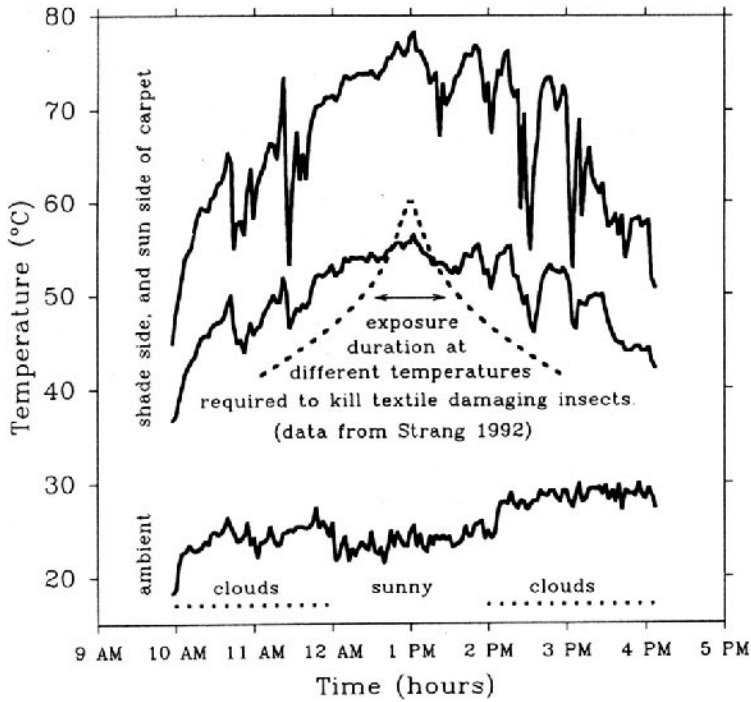

Figure 6. Solar heating of textiles and insect mortality. Thermal profile through bagged, 1 cm wool carpet with no shade-side insulation. Carried out by author in Ottawa, during the month of August, 1994.

Sensitivity of seeds in herbarium collections to storage conditions, and implications for thermal insect pest control methods

Paper 3

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Errata

CHAPTER 4

Sensitivity of Seeds in Herbarium Collections to Storage Conditions, and Implications for Thermal Insect Pest Control Methods

TOM J.K. STRANG

Abstract.—Throughout this century, herbarium staff have increasingly used convection heating, refrigeration, and microwaving for the control of insect pests. Emphasis within the resulting literature has been placed either on the ability of the methods to control pests, or on concerns about the effect of the treatment on herbarium materials. In order to critique thermal pest control methods, damage thresholds for collections have to be established. To compensate for the lack of defined damage thresholds in the botanical literature, mortality data for seeds of dried vascular plant specimens, drawn largely from the agricultural literature, are used here as an early indicator of material damage to herbarium specimens in general. Since thermal treatments are merely an extension of the storage environment, out of the same data it is possible to extract ideal storage conditions that are based on measured performance. Given the potential for loss of seed viability due to normal herbarium practices and natural longevity, the additional risks to seed viability posed by thermal pest control methods are considered to be minor compared to the certain ravages by insect pests.

INTRODUCTION

Herbarium staff, as with all museum professionals, are ethically bound to consider the effects of any pest control methods on collections so that they do not reduce the collection's research potential in efforts to save it from a highly destructive agent such as insects. Conversely, potential for losses to parts of the collection must be balanced against the overall good gained from a treatment that protects the entire collection. This paper puts this ethical requirement for thermal pest control in perspective with the available knowledge on seed viability. Herbaria have the interesting twist that they are likely to be the only living collection in many natural history museums because of the seeds or spores attached to, or cultures associated with, the specimens. A seed's complex chemistry makes it more broadly susceptible to damaging agents than any one macromolecule, and because the seeds may be viable, one can measure changes in their viability as a threshold indicator of potential deterioration and damage to other tissues.

Botanical collections have, in the past, been sampled for viable seed (Harrington, 1972). With vascular plant collections, this allows researchers to entertain the prospect of germinating some seeds from the collection to perpetuate a species, or to extend botanical knowledge (Hill, 1983). Womersley (1981) states that germination from seed is the best approach to the study of seedlings and floral development. With the exception of fungal collections, herbaria are not primary sources of living material. They are, however, a potentially valuable source of material for macromolecular studies, and so pest control techniques must certainly respect this potential use of the collections.

Within the botanical literature, seed death and physical damage have been cited as an inhibiting caveat to the use of some methods of thermal pest control (Hill, 1983; Forman and Bridson, 1989; Stansfield, 1989; Egenberg and Moe, 1991; Gunn, 1994). These assertions seem to contradict those to be found in other disciplines. The agricultural literature, for instance, contains many references to conditions affecting seed viability that can be applied to the herbarium context.

By treating seeds as dosimeters that log cumulative damage to the collections, this paper will seek to determine if any general,

mixed group of herbarium specimens will survive either high or low temperature control aimed at eliminating insects, and if thermal techniques are marginalized by an overwhelming adverse effect on the treated specimens.

In considering the adverse effect on the specimens I will distinguish between deterioration and damage. Deterioration is often described chemically (e.g., loss of degree of polymerization in organic molecules) and is incremental and unavoidable although we may modify its rate. Damage represents actual harm to specimen integrity, and so utility. The description of damage is specimen-dependant; however, for purposes of this discussion, it refers to the loss of taxonomically important characters. The scale of damage to botanical material will range from the loss of macroscopic features to the loss of intact DNA. Examining seed mortality will show if this range of damage is occurring, since damage at macroscopic, microscopic, or molecular levels will surely contribute to seed senescence and death.

HISTORICAL BACKGROUND

Thermal treatments, among the so-called new or alternative methods in use today, have actually been used successfully for a longer time than the more familiar chemicals found on or around herbarium specimens: mercuric chloride, naphthalene, paradichlorobenzene, lauryl pentachlorophenate, etc. Table 1 gives a very brief history of thermal pest control applications to natural history collections. In the first four decades of the twentieth century, before the advent of modern fumigants and pesticides, heating greenhouses and entire grain mills was recognized by millers and their insurers, and by some botanists, as the most efficacious and cost effective method (Dean, 1911; Back, 1920; Cressman, 1935; O'Neill, 1938) . There are mills that still operate using heat disinfestation. The argument restricting renewed expansion of this scheme revolves not around efficacy, but around the required capital investment, as compared to the continuing low immediate cost of fumigant use.

Attention has returned to the use of thermal pest control methods in collections because many favoured pesticides and fumigants

TABLE 1. Brief summary of publications referring to thermal control of insects in natural history collections.

AUTHOR	YEAR	COMMENTS
Kuckahn	1771	recommended heating bird specimens to kill insects
Howard	1896	described disinfesting fur with –8°C storage
Dean	1911	expanded on other work from 1883 and reported no effect on germination of grain exposed in a mill heated to 66°C over eight hours
Bovingdon	1933	killed *Lasioderma serricorne* in cigars and bales of tobacco with –6°C
Cressman	1935	used gas burners and electric fans to disinfest a library
O'Neill	1938	wrote on the outfitting of herbarium cabinets to heat treat their contents to 60–70°C within four to five hours
Crisafulli	1980	recommended –18°C to kill *L. serricorne* in herbarium collections
Watling	1989	recommended 42°C heat to kill mycophagous insects before accessioning the fungi; also warned of –18°C having failed to kill four species of insect
Miller and Rajer	1994	used low winter temperatures in 1985 to chill a herbarium below –18°C

have been restricted by regulatory changes and thus removed from the hands of collections staff. Thermal methods are attractive because they involve no toxins or toxic residues, are largely available to anyone, and need not depend on an expensive or governmentally regulated infrastructure. By applying the principles of thermal control, large quantities of material can be preserved at low unit cost and on short notice. Strang (1992) provides a comprehensive treatment of the efficacy and history of thermal insect pest control.

Within the botanical literature, articles on microwave heating provide the most discussion on a thermal treatment in the herbarium context so they will be reviewed here. The effect of microwaves on insects has been documented since the 1920s and work with them performed by agriculturalists since the 1940s (Nelson and Stetson, 1974). This work concentrated on finding whether there was an appropriate microwave frequency to affect pests which minimised damage from heating to the surrounding commodity,

and on trying to determine whether efficacy was due to more than general heating. At 2450 MHz frequencies there was no differential heating; both insect and commodity needed to be heated above 60°C to kill the pests, a condition identical to convection heating. At lower frequencies (1 to 50 MHz), microwaves did create the differential heating effect for some insects and commodities, but it was not universal. While some researchers had noted the ability of microwaves to kill pests without affecting grain germination, provided the moisture contents were low, general adoption of microwaves was prevented by energy costs that exceeded the cost of conventional fumigation by a factor of five (Nelson, 1967). When microwaves became readily available during the 1980s in the form of rapid cooking devices (2450 MHz), botanists and other collection professionals naturally tried these machines for pest control and drying specimens.

Hall (1981) advocated microwaves as a fast method to kill insects which alleviated pressures created by the need to quickly associate suspect material with clean holdings. No adverse effects were mentioned, so insect damage to the entire collection obviously took priority over any particular loss to the dry specimen, and the practice was used for a year prior to Hall's publication. Hardin (1981) treated all accessions with microwaves. With a microwave unit right in the collection, he also treated the entire collection annually, taking one hour per cabinet.

Clearly there have been situations in which botanists have desired the dramatic effects of microwaves on a succulent specimen. "The material is 'done' when it has a flaccid, water-soaked appearance. It can then be arranged on a newspaper and pressed in the usual way..." (Fuller and Barbe, 1981). However, Baker et al. (1985) described the damage threshold: "discoloration and singeing of the spines", and sticking to absorbent towels, which they also tell how to avoid.

Other microwave users started noting their concerns by indicating damage thresholds for their collections from microwave treatments: Hill (1983) demonstrated damaging loss of seed viability on old specimens. Philbrick (1984) echos the seed concern, and postulates macromolecule and fine morphological deterioration. Bacci et al. (1985) demonstrated that morphology visible in

a light microscope and specimen colour were preserved adequately after microwaving, but ultrastructure was adversely affected compared to room temperature drying. Jacquin-Dubreuil et al. (1989) demonstrated that relevant morphology and alkaloids were preserved through microwave drying. Arens and Traverse (1989) demonstrated no additional loss of pollen or spores by microwaving after standard drying practice, but much higher losses in fresh material to microwaving when compared to air drying. Pyle and Adams (1989) found damage to grass material after three minutes of microwaving, but did not try dry samples, or 60°C convection heat. Diprose et al. (1984) noted that germination actually increased in some seed that was heated by microwaves but cited losses in other tests.

In the end, botanists working on herbarium collections independently rediscovered what the agriculturalists had reported in previous decades about microwave treatment: microwave heating is far less controllable than convection heating and so it is easy to overheat and damage tissues.

I am concerned about the differences between the conclusions drawn in herbarium literature and those found in agricultural literature concerning the effects on seeds of convection heating and cooling (often called freezing) used for the control of insect pests. Because herbarium staff have raised seed viability as a reason for not using thermal methods, I will devote much of this paper to focusing on factors affecting seed viability.

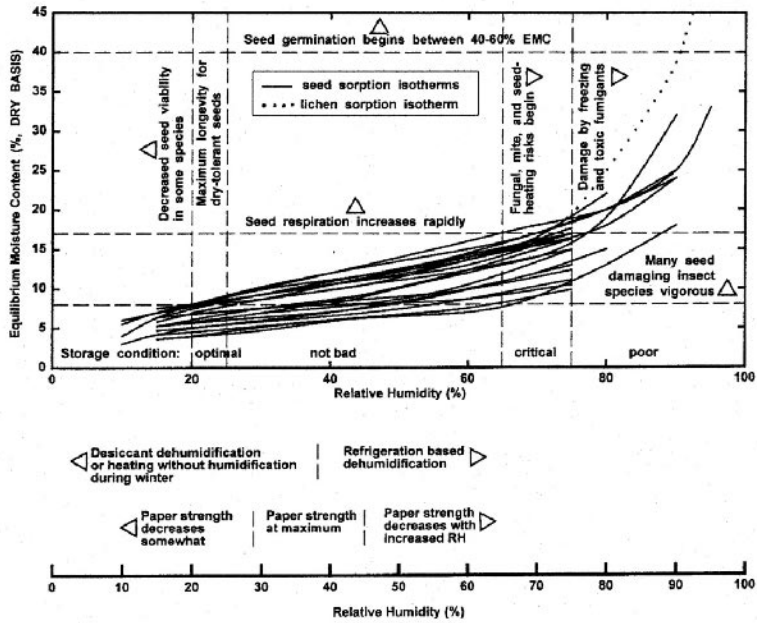
EFFECT OF HERBARIUM PRACTICES ON SEED VIABILITY

Because thermal treatments are merely an extension of the storage environment, it is first necessary to consider whether herbarium practices damage seed viability, our allegorical figure for a collection's physical survival.

Developmental Stage of the Seed When Collected

It must be recognised that within a herbarium collection, the plants may not have been collected at the correct time to ensure seed viability. If they were already dry on the plant, seeds may

FIGURE 1. Damage thresholds for seeds in herbarium storage. Equilibrium moisture content (EMC) is mapped to corresponding relative humidity by sorption isotherms. Sorption isotherms from Harrington (1972), Blum (1973), and Iglesias and Cherife (1982). Seed damage thresholds from Howe (1965), Harrington (1972), and Priestley (1986). Paper threshold from Brandon (1980). Humidification system threshold from Harriman (1990).



store reasonably well in herbarium conditions. Seeds that are wet (e.g., found in fruit or not quite mature) must dry to equilibrium below 65% relative humidity (RH), otherwise they will succumb to fungal attack and respiration heating (Fig. 1). After fertilization, seeds pass through several named stages: zygote, embryo (often in liquid endosperm), ovule (early, late), seed (immature, ripening, mature, senescent, dead). The following benchmarks of survival are generalized in Harrington's review (1972). The late ovule stage is the earliest stage at which seeds normally survive when separated from the parent plant. Immature seeds may germinate on sowing when they are fresh but will die if they are dried out. The immature stage has a maximum storage life rated in

hours or a few days. Maturity, for some seeds, occurs when they reach their maximum dry weight. Other seeds mature their embryos or lose dormancy during a later drying phase. Most mature seeds can be dried and stored.

Dryness in Storage

Whether a seed is on the plant or stored separately, its longevity (and demonstrably the longevity of all organic matter) is related to moisture content. Moisture content is mapped to corresponding RH by sorption isotherms (Fig. 1). Strang (1995) outlines the relevance of sorption isotherms to thermal treatments on common collection materials within tight enclosures. Appropriate humidity norms for general museum collections and the underlying technical reasons are discussed in Michalski (1993).

For optimal, long-term storage in moisture proof enclosures, seed packagers strive for a dry-weight equilibrium moisture content (EMC) that matches the 20–25% RH range (Harrington, 1972). The measurement of moisture content in seeds has traditionally been on a wet basis, whereas many scientific disciplines routinely use dry basis. For this paper, moisture contents have been translated to dry basis, although the differences at low EMCs are fairly small.

Below 20% RH, Harrington (1972) described the autooxidative phenomenon to be mildly deleterious. Priestley (1986) proposes an alternate mechanism for lower germination around imbibitional stresses with examples of seed unaffected by extreme dryness. Whatever the cause, there are measured losses in viability at RHs below 20% for some seeds.

Above 25% RH seed deteriorates faster from chemical processes, although the 25% to 65% RH range is not overly detrimental to viable dried seed held over the short term (Owen, 1956). Above 65% RH, the probability of mould increases: three months near 70% RH, two weeks near 80% RH, and a couple of days at over 90% RH (Michalski, 1993).

To an extent, dry storage of seed restricts insect activity (Fig. 1). While there are a few seed-destroying insects that still thrive on very dry seed (e.g., *Trogoderma granarium* Herts, *Callosobruchus*

spp.), many species become moribund on dry seed, that is seed at equilibrium with less than 30% RH (Howe, 1965).

Of course, herbarium specimens are more than just seeds, and low RH does not necessarily protect the specimens from all pests, although it is now often suggested as a means of control (Lull and Moore, this volume). Bridson and Forman (1992) mention environmental conditions for herbarium storage, but only as a contributory element to pest control and "staff efficiency". Unfortunately, their suggested 20° to 23°C, 40 to 60% RH regime is not likely to greatly affect pests (see Howe, 1965; and Fig. 1).

At this point, I have to depart from the narrow seed allegory and discuss the connections to wider issues in the context of humidity norms for herbarium storage. Since herbaria use paper mounting sheets and envelopes, a parallel issue is paper strength or brittleness. Brandon (1980) summarized strength losses in burst and tensile tests performed below 30% and above 50% RH (Fig. 1, lower graph). Fold endurance rises with humidity until 70% to 90% RH. Maintaining humidity below 30% would not contribute to preserving paper from the stress of improper handling.

Reducing RH does slow chemical deterioration (measured as strength loss) and paper lifetime is doubled by a drop in storage RH from 50% to 30% (Michalski, 1993). This is in contrast to Bridson and Forman's (1992) ideal conditions of "20–23°C at ± [sic] 55% humidity." If one wishes to extend the material lifetime of a collection, specifying as low an RH as is feasible appears to be the justifiable and quantifiable specification, not artificially holding 55% RH.

How does changing humidity affect the assemblies of plant and paper we call mounted specimens? To get a sense of the effect, while moisture content of seed increases with increased RH of the seed store, fluctuations in seed moisture content are moderated by the seed coat, surrounding paper media such as envelopes and sheets, and the closed cases. The response time of different species' seeds exposed to altered humidity range from one day to eight weeks at room temperature (Owen, 1956). The measured time to equilibrium doubled with a 10°C drop in temperature (Whitehead and Gastler, 1946–7). The effect of any surrounding storage

materials will be to further slow any shift in equilibrium. This is important to remember if one is concerned about a short duration swing in humidity, either in the herbarium environment, or during a thermal or controlled atmosphere pest eradication treatment. For a larger treatment of moderating humidity effects during thermal treatment, see Strang (1995).

Egenberg and Moe (1991) demonstrate damage to adhesive-dot mounted *Primula* sp. cycled between 95% and 15% RH. These conditions are called normal by the authors. However, in contrast to their conclusions, this range of humidity cycling does not occur with specimens treated for pests at either low or high temperatures (as defined in Strang, 1992) when the specimens are bagged at median relative humidities (Strang, 1995). Michalski (1993) demonstrates why less than 25% RH and greater than 75% RH are better termed extremes when discussing the humidity response of organic materials.

To obtain building-wide, room, or case humidity below 40% RH at human comfort temperature, one is usually required to use desiccant dehumidification, while control above 40% RH is possible using more conventional refrigerant systems (Fig. 1; Harriman, 1990). Note that in temperate climates one can achieve low RHs in winter months by heating without humidification. Humidification of the collection space much higher than 30% RH during winter heating months is not really justified for botanical collection preservation.

For maximum extension of specimen longevity when humidities are uncontrollably high, one should apply local solutions such as placing dried specimens with desiccants in sealed enclosures. Sufficiently dried material in a tight enclosure can remain unaffected by external high humidities for years (Michalski, 1994; Strang, 1995).

Drying Temperature and Method

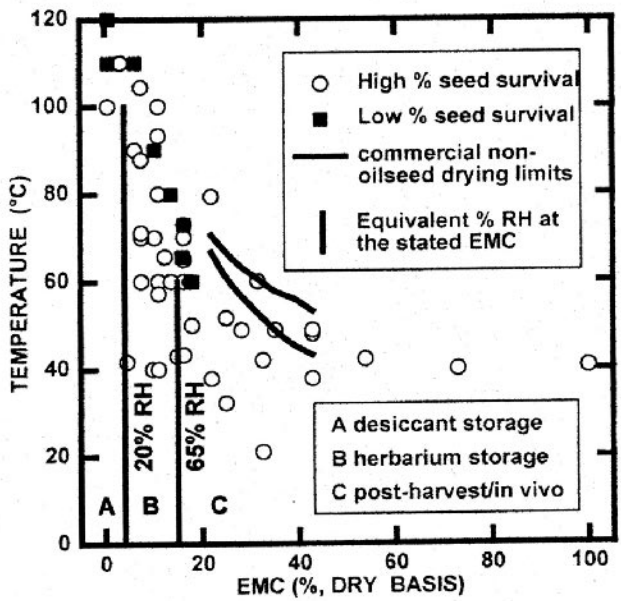
While terminal moisture content of seed is the primary factor in prolonging viability, drying methods will also affect the result. Air drying in the sun can expose objects to temperatures 20°C to 40°C higher than ambient (Yamasaki and Blaga, 1976). Absorption of infrared radiation, especially by dark objects, and the insulating

ability of stagnant air easily creates temperatures of 50°C to 60°C. These principles were used to advantage in the design of a solar plant drier (Sinnot, 1983), and for eliminating textile pests (Strang, 1995). Mechanically-assisted seed drying with fans relies on the ambient humidity being lower than that over the seed. Under damp conditions, seed may not dry fast enough to protect it from losses caused by fungal attack or partial germination.

Safe maximum temperatures for drying newly harvested crop seeds with heated air are 45°C for grain, beets, and grasses, and 35°C for vegetable seed (Harrington, 1972). These temperatures match those selected for use in herbarium drying cabinets to reduce specimen browning. Drying too fast leads to cracking of the seed coat as it shrinks over the damper core of the seed, but prolonged heating at the higher EMC also damages viability (Harrington, 1972). Dry seed can withstand higher temperatures. Figure 2 plots the relationship between EMC and maximum safe drying temperature from data in reviews by Harrington (1972) and Owen (1956). A boundary is created by the intersection of low and high percentage germination data. Not surprisingly, commercial recommendations delineate the boundary for safe exposure at higher moisture contents.

Very dry seed survives temperatures near 100°C for short periods. This fact is exploited by systems used in grain mills that kill insect pests by passing seed through heated enclosures. Restricting the length of thermal exposure is not as critical as maintaining a low moisture content, even in short-lived seed (Rocha, 1959). Standard herbarium practice for drying damp plants and their attached seeds uses fan-blown air at 45°C. While this may be too high for some fresh seeds, it lies within the commercial norm for others (Fig. 2). It appears that elevating temperatures of herbarium specimens to 55-60°C to kill insects (Strang, 1992) would not pose a significant risk to germination of dried viable seed. It might be wise to limit thermal treatments to specimens that are acclimated to 50% RH or less at room temperature, which would allow a margin of safety. Heat treating damp specimens to kill insects should be carried out only after first drying them down. However, if the specimens have been held for a prolonged time in elevated humidity (such as herbaria in the tropics), the damage

FIGURE 2. Heat damage to seed. Drying temperatures plotted against equilibrium moisture content (EMC). Data from Owen (1956) and Harrington (1972). Relative humidities at 20% and 65% are plotted vertically from their equivalent EMC (based on sorption isotherms in Fig. 1) to enclose a zone that represents optimal to fair herbarium storage (marked B). Overly dry storage is marked A, and post-harvest/in vivo moisture levels are marked C. A damage threshold is created by the intersection of low and high percentage germination data, which continues into commercial seed drying specifications at higher moisture contents.



from moisture-mediated deterioration may well have occurred and this restriction will prove unnecessary. Since the RH over the seed and other organic matter in a vapour barrier enclosure increases as the temperature rises, treatment of specimens that are acclimated to 65% RH at room temperature might at first glance be at risk of a mould outbreak. This risk is actually small. These samples might reach 80% RH during heating, but the time for mould response at 80% RH is long (10 days), and the treatments are very short (a few hours). Also, at 55–60°C, many of the moulds, with the exception of thermophiles, are unable to function

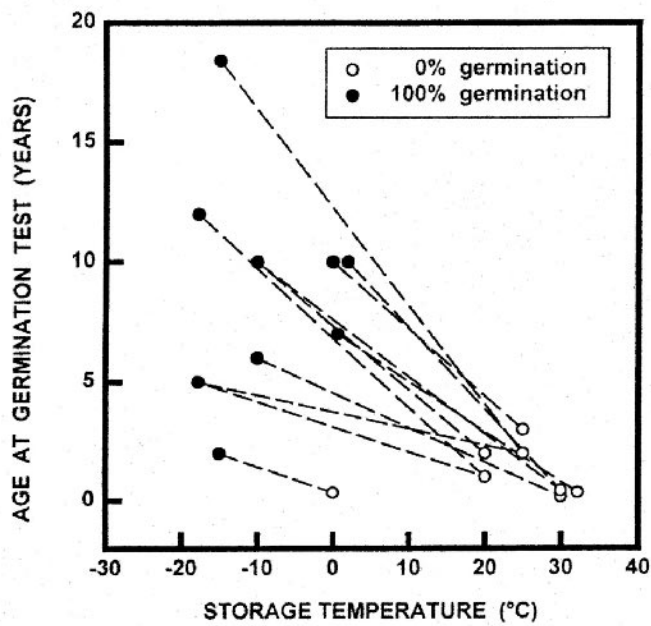
(Michalski, 1993). See Strang (1995) for a longer discussion on mould and condensation risk during thermal treatments and how to avoid it.

As a historical note, in addition to drying, brief immersion of seed in water near 55°C was a well-developed technique to eliminate fungal damage prior to planting with little change in germination, as were hot water sprays on living plants (Bourcart, 1926).

Low Storage Temperatures

Seeds, like other organic tissues, have a storage lifetime that doubles roughly with a 5°C drop in temperature. Harrington (1972) points out that this rate is known for seeds tested between 0°C to 50°C but there is little data outside these limits. Figure 3 shows the effect of storage temperature on seed viability. These experiments may be carried out either in a refrigerated container at

FIGURE 3. Effect of storage temperature on viability of seeds stored at the same equilibrium moisture content. Each line represents seeds of one species. Data from Owen (1956).



constant relative humidity, or hermetically sealed and then chilled. In the latter case, the seed moisture content rises a little and equilibrium RH drops.

Seed that is dried to less than 14% EMC can be safely stored at temperatures below freezing. Damage (loss of viability) is only slight near 20% EMC (Harrington, 1972). 20% EMC is roughly the fibre saturation point of many wood xylem cells. The often-raised issue of water freezing and damaging organic matter during low temperature treatment receives no support from nuclear magnetic resonance studies which show no freezing activity between 0°C and –30°C in organic matter with EMCs less than 25% (Pichel, 1965; Toledo et al., 1968; Nanassy, 1978).

By the mid 1900s, researchers concluded that while there was significant improvement of viability in seeds that tolerate drying when stored between 20% and 30% RH, and at temperatures near 0°C, the lowering of either temperature or humidity was good enough for agronomic purposes (Owen, 1956). This pragmatic choice reduced the need to use temperatures much below 0°C. After all, why look for something better than good enough? Where commercial pressures are not as relevant, temperatures near –15°C to –20°C are used to preserve seed, and liquid nitrogen (–196°C) is also employed (Priestley, 1986).

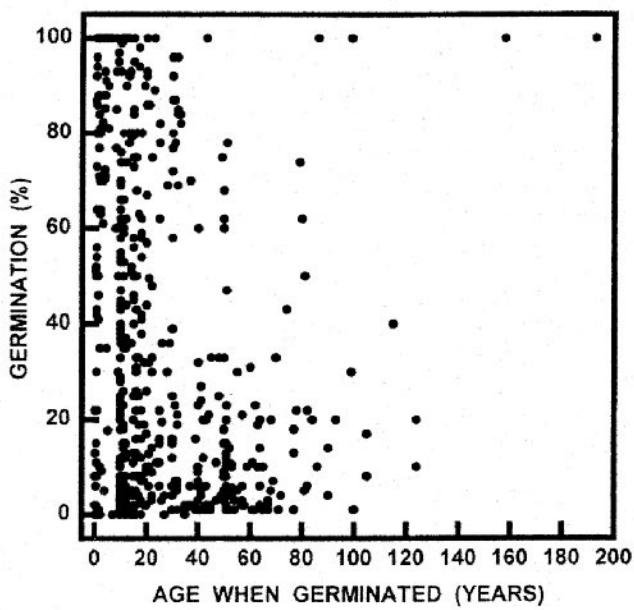
Pyle and Adams (1989) recovered comparable DNA fragments from fresh plant material and samples stored for five months at –20°C, 4°C, and 42°C. Low temperature pest control is not likely to affect DNA recovery.

Natural Seed Longevity

The published longevity of seeds stored indoors are plotted in Figure 4. Long-lived seeds, retaining viability for more than 10 years at ambient conditions, are often characterised by dryness at maturity (under 4% EMC) and a hard seed coat that requires abrasion prior to germination. The range in viability of these seeds spans the time that many herbarium collections have existed, from decades to centuries — longer in the case of some dated archaeological recoveries.

Even if collected at an appropriate stage, some seeds cannot be saved for more than a short time. Harrington (1972) lists this varia-

FIGURE 4. Percent germination over time of a mixed collection of 584 species of seed stored indoors in botanical or laboratory collections. Data from Owen (1956), Harrington (1972), and Priestley (1986).



tion in viability by plant species. The list of poor survivors is dominated by aquatics, nut trees, and tropical species. Seed senescence in these species occurs between 2 weeks and 5 years. Other seeds are very short lived as they do not tolerate any drying, even once mature.

Factors that contribute to lower germination of seeds include stresses on the mother plant (Harrington, 1972); size less than 1 mm, and study field conditions (Priestley, 1986); and unknown temperature optima ranging from 0.5°C to 50°C (Mayer and Poljakoff-Mayber, 1963).

Of the 584 species stored indoors and tabulated by Harrington (1972), 128 survived less than five years. Only five species are listed as being damaged by temperatures under 0–10°C. Sixty-two species are listed as being intolerant to drying, i.e., they are viviparous. From this alone, one must expect less than three-quarters of species in a mixed collection to contain viable seed. The germination

trend in Figure 4 is not encouraging for old collections, but establishes a reasonable probability that some of the holdings in herbaria are yet viable. Therefore, botanists questioning potential effects of treatments on seed viability have some reason to be concerned.

Impact of Fumigants on Seed Viability

Controlled atmospheres are used to kill insect pests by creating either low levels of oxygen (0.1%) or high concentrations of CO_2 (>60%) (Annis, 1986). Both of these conditions contribute to seed dormancy (Harrington, 1972). Experiments on seed storage in these cover gasses showed them to be beneficial to neutral in extending seed life (Owen, 1956). Either gas must be applied for a minimum of three weeks at room temperatures (20–30°C) to ensure efficacy against seed boring insects (Annis, 1986). Efficacy is rather temperature sensitive, and higher temperatures are preferred.

Somatic cell abberations have been noted in germinated seed that had been stored at room temperature in air, carbon dioxide or nitrogen, or heat treated along the boundary area shown in Figure 2 (Owen, 1956). Chromosome errors increase with seed age, but are reduced with cool, dry storage. These changes were not considered to be serious for commercial ventures, but are possibly of interest to more specific investigations (Harrington, 1972). These errors will have occurred in aging specimens under normal herbarium conditions.

Toxic gas fumigants are not used on high moisture content seed as the seed is more likely to succumb to the fumigant (Fig. 1). A dry herbarium collection would not be as susceptible. Naphthalene has reduced germination of some seeds but not others over trials of one year, and herbicide vapours decreased seed germination (Owen, 1956).

CONCLUSIONS ON THE RISKS TO SEEDS FROM THERMAL CONTROL TREATMENTS

The vulnerabilities of seeds cited in this paper demonstrate that seeds susceptible to damage from thermal pest control methods are likely to have succumbed to standard herbarium processing

and storage anyway. With the exception of treatment in microwaves, most viable dried seeds will survive the necessary pest control temperatures under controlled application. Microwave heating is far less controllable than convection heating; overheating is easy and so microwaving is often fatal to seed. Convection heating without tight containment of the sample to maintain moisture certainly desiccates material, causing damage. Likewise, unprotected samples in freezers face an unnecessary mould risk in the event of mechanical failure. The only published description of damage to a specimen on a herbarium sheet (Egenberg and Moe, 1991) is actually limited to extreme humidity change, not temperature. Such humidity change does not occur in thermal treatments of bagged material. *Thermal treatments should always be carried out in vapour barrier enclosures.*

Forman and Bridson (1989) make no mention of convection heating, yet it clearly avoids the majority of problems associated with microwaving. Convection heating has been used longer than any other thermal method to prepare herbarium specimens for storage. Convection heating is incapable of elevating specimens above the controlled-supply air temperature, and readily disinfests blocks of specimens for use by researchers in an hour (Strang and Shchepanek, 1995). A few sheets are done in minutes.

The following observations are offered to assist those debating the use of thermal pest control in herbarium collections:

- Practical experience shows no damage to herbarium collections in moisture barrier enclosures when low temperature is used for pest control, and chemical deterioration is actually slowed for the duration of the treatment. Refrigeration, including temperatures below 0°C, usually prolongs seed viability, especially shorter-lived varieties (Fig. 3). Low temperature control of insect pests is possible on all seeds that are tolerant to drying. Researchers looking at macromolecules (including enzymes and DNA) generally prefer low temperature control to elevated temperature; they routinely use low temperatures to store their materials.
- Available data indicate that properly dried viable seeds can withstand the convection oven temperatures used to kill insect pests (Fig. 2). Treatment times can be very short if the material

is properly organized (Strang and Shchepanek, 1995). The material undergoes no significant change in dimension or moisture content if tightly bagged (Strang, 1995). Counter to Stansfield's (1989) criticism, proper technique avoids damage to objects and specimens during heat treatments.

The loss of specimen longevity due to increased oxidation of cellulosics during a one hour heat treatment at 60°C every 10 years in perpetuity is 0.15% (S. Michalski, CCI, pers. comm.). Thus, heat treatments can be used sporadically when the need arises without too great a concern for reducing specimen longevity. More precisely, the rate of loss due to pests (if measured) can be compared to the projected loss due to the pest control treatment.

- While some authors have demonstrated benefits, microwave heating is not favoured as a pest control method as it is harder to control the peak temperature, metallic inclusions introduce fire hazards, and chamber sizes are often too small to accommodate standard herbarium sheets.
- Properly dried viable seed will likely withstand the low and high temperatures necessary to ensure insect mortality. For seeds that withstand drying, humidity is a dominant factor in seed longevity. If preservation of seed is an objective, herbarium staff should look to their environmental norms to maximize seed longevity and insure the specimen is within these norms prior to thermal treatment. Drier storage conditions also increase the lifetime of plant and mount materials, and slow some insect pests (Fig. 1). Those seeds that do not tolerate drying will already be dead in herbaria unless special procedures were taken to preserve viability at the time of collection.
- Eventual species-specific seed senescence (Fig. 4) suggests that if herbarium specimens are to be used as a seed source, this should be done sooner rather than later.

In conclusion, the risks of using thermal insect pest control methods for herbarium samples are minor compared to the certain ravages by insect pests.

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Principles of heat disinfestation

Paper 4

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Errata

Figure 1 was repeated in publication as figure 10. Intended figure was:

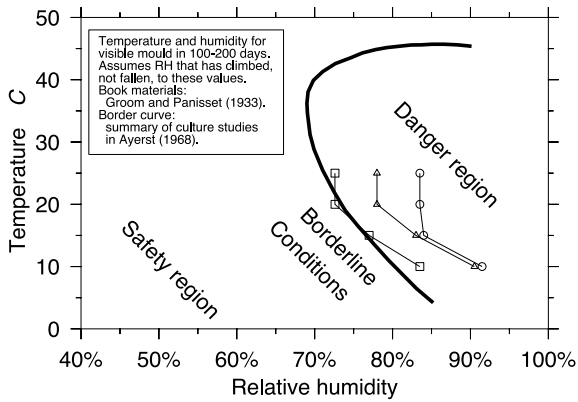

Figure 10 The effect of temperature and humidity for the growth of a mould (redrawn from Michalski, 1993a)

CHAPTER EIGHTEEN

PRINCIPLES OF HEAT DISINFESTATION

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ABSTRACT

Heating is an effective way to eliminate insect pests from collections. Relatively short exposures are needed to assure efficacy, so the utility of heat is relatively quick compared to other methods, and the universal susceptibility of insects. The ability to scale from small to large volumes of affected objects, and availability worldwide, largely without encumbrance by patent, royalty, and regulatory approval, also make heat a valuable addition to the tools we require to prevent loss of cultural property. The deleterious effects of heat treatment are quantified so relative risk can be discussed. The magnitude of protection conferred by a vapour resistant enclosure during treatment is illustrated along with examination of mould risk. Heat disinfestation has been used for centuries, both within and outside the context of cultural property, and remains a valuable tool, augmenting our ability to save property from loss to insect pests.

KEYWORDS

Heat, thermal, insect, disinfestation, collections, enclosure, ageing, mould, risk

INTRODUCTION

The choice of thermal disinfestation over alternatives is best made if its principles are well understood. This paper reviews key concepts from which the argument for heat disinfestation is built. Sections examine the effects on the target organisms and the target objects when viewed as both material and assemblage. Much of this summary is based on the author's previous publications on thermal control and extended to explanations and examples derived since that time.

To date, heat has been mostly employed when alternatives are deprecated, either due to efficacy, cost, timeliness, availability, or scale. Part of this deprecation comes from due caution fostered in the conservation profession as the course of minimal intervention. However, the argument for use of heat requires understanding of concurrent events within the atmosphere and materials being treated, which are not generally taught. This paper is meant to assist in following this argument, and show how the delivery method described within greatly reduces the magnitude of the potential effects on objects, compared to the commonly perceived threat.

FIRST PRINCIPLES

This section presents physical concepts, which are fundamental to understanding heat disinfestation. An attempt has been made to place them in step-wise fashion towards comprehending the dynamics of heating objects within vapour resistant enclosures for the purpose of killing insect pests. Some basic comprehension of scientific principles is presumed, but key areas are dealt with at length.

Partial pressure

The total pressure of any atmosphere is the sum of all pressures contributed by its gas and vapour components. The contribution of each component is termed a partial pressure. Partial pressure is directly related to temperature. If you raise the temperature of water in an enclosure, the partial pressure of water vapour increases and if you lower the temperature, the partial pressure drops.

Near absolute zero (–273.15°C), vapour pressure is practically non-existent and matter is essentially in a solid state. At boiling point, the partial pressure of a substance (saturation vapour pressure) is the same as the surrounding atmospheric pressure, and given the right conditions of leakage could fully replace the atmosphere in a restrictive container through dilution (Figure 1). Saturation vapour pressure is a limit. The atmosphere over a bowl of water will not support a partial pressure of water greater than x, where x is the saturation vapour pressure for water at the temperature of the system. Any excess vapour will condense.

An atmosphere can have component vapours at less than their saturation pressure, depending on availability. The quantity of vapour present in the system is moderated by events other than temperature. Temperature simply sets the maximum for the portion of gas present. This relationship for water is fully illustrated in a psychrometric table (Anon. and Mackintosh, 1985).

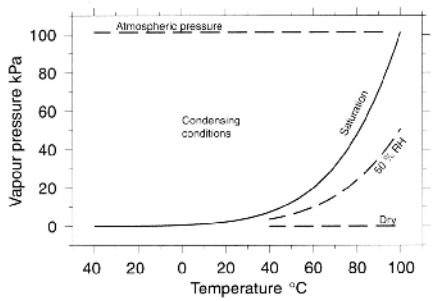

Figure 1 Saturation vapour pressure of water against temperature. Data is from Weast (1972–3)

Humidity may be qualified as relative or absolute humidity. Absolute humidity is the mass of water vapour per unit mass of dry air. Relative humidity (RH) is the ratio of the measured vapour (partial) pressure of water to its saturation vapour pressure at a known temperature. A value of 0.5 RH or 50% RH means that there is only half as much water vapour measured as pressure in an atmosphere as there could be for a given temperature (Figure 1).

In the simple case when water vapour is at a higher partial pressure in one part of a system, water vapour will migrate to the area of the system with the lower partial pressure until equilibrium is reached. To get there, it will migrate by convection, diffusion, or permeation.

If an area of lower temperature exists within a system, convective mixing of air results in an averaging of air temperature, but lowered saturation vapour pressure for the cooled air and hence higher RH.

When a system contains organic matter and a temperature gradient the dynamic is less simple. Vapour permeates through a material barrier between two voids (wall), and vapour within the material equilibrates with the outside world. One way to calculate the potential for motion is by multiplying the RHs (expressed as a fraction) by the associated saturation vapour pressure of water, to get the partial pressures in regions of differing temperature (Latta and Beach, 1964). When these pressures differ, water vapour moves.

In an open system, a portion of an organic barrier can become saturated by permeating water vapour if its temperature prescribes an internal saturation vapour pressure lower than the partial pressure of water in the air supply. Further vapour movement into the barrier condenses until the material saturates. This is a mechanism that damages buildings, and is combated by properly installing a vapour barrier to choke off the supply of water before it enters the wall. Other mechanisms are described in Michalski (1996).

The other available control is insulating or otherwise preventing temperature differences within a system, so that the saturation vapour pressure of the water remains higher than its partial pressure throughout the system (Latta and Beach, 1964). With the exception of insulating heat chambers to save on fuel cost, or backing a solar bag, we need to encourage unobstructed heat flow within the system to effect safe treatment. We use vapour barriers extensively in thermal pest control to resist moisture flow.

Summary: Temperature limits the maximum amount of water vapour that can be in any atmosphere. This limit is unaffected by any other gaseous component. Differing partial pressure (representing concentration gradient) provides the motive force for moisture movement in materials undergoing thermal change. Sufficient temperature change or differential in a system can result in condensation of water vapour, but only when there is a sufficient supply of water. Vapour barriers are used to significantly reduce the rate of moisture movement by eliminating convection and diffusion flow, and slowing permeation.

Moisture content

The previous section ended with moisture concerns. Moisture is used in the sense of water that associates intimately into the molecular structure of materials and subsequently fills capillaries. The standard concept is one of the water first grouping at charged sites, and as more water associates, it layers on top of these initial water molecules and penetrates holes between polymer molecules, ending with water filling pores, or solution of the substance (van den Berg and Bruin, 1981).

Moisture content (MC) on a dry basis is calculated as the ratio of mass of substance containing water minus its dry weight, divided by the dry weight of the substance. Given as a percentage, MC is the weight proportion due to water content. One-inch lumber stored outdoors undercover in a temperate climate will vary by 3% to 5% annually. Depending on the species, the MC will vary from a minimum of 11% to a maximum of 18%. Wood that is stored indoors has a similar annual cycle, but ranges between 6% to 14% depending on species (Baxter *et al.*, 1951).

Unlike vapour and humidity, saturation is more difficult to define with moisture content. It is generally a matter of definition either when the free space around molecules in a solid is filled with water, or when all large-scale pores are also filled. Dryness is often defined by lack of mass change under vacuum, or heating.

Equilibrium is another way of saying wait a long time for all measurable change to stop. The equilibrium moisture content (EMC) of a material is in balance with the equilibrium relative humidity (ERH) in the atmosphere bathing the solid.

Volume change of organic matter correlates with moisture content associated with molecular structures, or thermal effects. When the volume change is unequal in directions relative to the orientation of molecules or

cellular structure, the response is called anisotropic. Wood is an example of anisotropy, as most changes in dimension occur in the tangential direction to the grain rather than along it.

Summary: Organic solids absorb and release significant amounts of associated water in response to the water vapour present in the surrounding atmosphere. The dimensions of organic solids are altered by changes in moisture content proportional to the volume of water transferred, but often expressed in an anisotropic (asymmetrical) manner.

Sorption isotherm

Sorption isotherms were developed to quantify the relationship between atmospheric moisture surrounding a substance, and the moisture contained within the substance. Isotherm means the sorption is measured at a constant temperature. Determination of a sorption isotherm uses an essentially infinite source of conditioned atmosphere relative to a rather small sample, to facilitate equilibrium. A full description of numerous methods is given in Gál (1975).

The sorption isotherm is affected by the moisture history of a material. If we start with wet material and place it into a series of drying atmospheres, we can measure the desorption or the loss of water toward the equilibrium state. If we start with a dry material, we can measure adsorption in moist atmospheres.

The equilibrium states of these two approaches are commonly not identical. Desorption isotherms typically have higher EMCs than the adsorption isotherm. This property is called hysteresis – the separation of two isotherms for the same material at the same temperature. The hysteresis in cotton can be 1–2% for a region of 20–80% RH. Two blocks of material brought to equilibrium in the same humidity, one by adsorption and one by desorption, can sit nearby for years and not drift to a common moisture content because there is no difference in vapour pressure exhibited over the two samples (Urquhart, 1960).

In practice, when adjusting to humidity changes in the middle range, the isotherm of a material mimics the general shape of the outside curves, but values are somewhere within the laboratory curves (Urquhart, 1960). Published curves are an outer boundary, and the current EMC of a material depends on its history of exposure. We will prevent large EMC shifts during heat disinfestation so hysteresis can be safely ignored.

When sorption isotherms for a material are compared for several temperatures they show a trend (Figure 2). The higher temperature isotherm exhibits lower moisture content for the same RH. Simply stated, more heat in the system creates increased molecular motion and the moisture increasingly favours the vapour phase over sorption onto solids. As the temperature rises, a higher vapour pressure of water is needed to hold the moisture

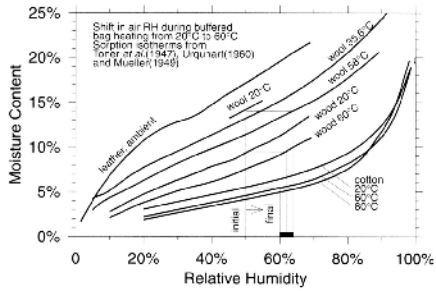

Figure 2 Humidity change with temperature in enclosures. Data is from Toner *et al.* (1947), Urquhart (1960), Mueller (1949)

content steady. This will be accomplished naturally by enclosure. The 80°C cotton curve shows a crossover effect noted in other materials (Urquhart, 1960). This convergent trend is helpful in limiting a rise in RH in treatments that run too hot.

Summary: Sorption isotherms are experimental extremes to plot boundaries of moisture content against RH. The equilibrium moisture content depends on the history of exposure to humidity change, but sorption isotherms give us boundaries of the possible values. As EMC changes are limited, hysteresis can be ignored. The rise of RH in an enclosure is roughly predicted from a family of sorption isotherms.

Enclosure and humidity buffering for dimensional stability

The sorption isotherm represents EMC imposed by ERH in infinite supply with unrestrained time and at constant temperature. Thermal control inverts this so that RH imposes EMC by enclosures, which create conditions of restrained vapour supply. The remaining differences, caused by changing temperature for short periods of time, are examined in the next subsection.

Thermal control for pest eradication uses enclosed systems to its advantage. A sealed bag around an object contains a relatively small volume of air compared to the volume of the object, and is largely leak-free, except for a slow permeation of gas and vapour through the bag wall. This creates a situation where the moisture content of the enclosed material influences the humidity within the enclosure, rather than the moisture content being driven by an effectively infinite source of atmospheric water. This effect is commonly called 'humidity buffering'.

For museum displays, Thompson (1964) determined the minimum ratio (buffering capacity) to control RH change from thermal cycling to be 1 kg of wood to 1 m^3 of air, in a swing of 20°C from 15°C to 35°C. Adding even more buffer simply reinforced the already minimized RH change and broadens control through a wider temperature swing. The use of the term 'bagged' or 'enclosed' in this paper implies this latter state.

When heated without a vapour barrier, the moisture content of organic material will drop as water desorbs. When heated inside an enclosure (marked 'initial' in Figure 2), a small amount of desorbed water will elevate the RH (partial pressure) to the RH equivalent (marked 'final' in Figure 2) to the original EMC on the high temperature sorption isotherm. Without motive force, moisture transfer stalls and desiccation does not proceed. At 20°C and 50% RH, 1 m^3 of air contains 7.4 g of water vapour. At 60°C and 63% RH (example plotted on Figure 2), 1 m^3 of air contains 91.4 g of water (Anon. and Mackintosh, 1985). The difference between these concentrations (84 g), is the required contribution of desorbed moisture if the objects in a bag are to buffer the free space and retain a constant EMC.

The density of seasoned Canadian wood species ranges from 250 kg/m^3 to 750 kg/m^3 (Baxter *et al.*, 1951). At 10% EMC there is potentially 25–75 kg of water available for exchange in 1 m^3 of wood. When about half of the volume is air in cell voids, only some 42 g of this water would need to vapourize to rebalance the EMC at 60°C. This represents the situation of tightly bagged timber.

Examples from Figure 2: For a wood object sitting in 1 m^3 of air at equilibrium with 50% RH, heated from 20°C to 60°C, the wood needs to contribute 84 g of water to forestall EMC change. One kilogram of wood at 10% EMC (100 g water) would stand to lose about 80% of its water, desiccating the object. Twenty kilograms of wood would lose 4%, similar to maximum annual fluctuations. Eighty kilograms would lose 1% EMC. A drop of 1% EMC is equivalent to a 5–10% reduction in RH of the common materials shown in Figure 3. The ASHRAE guidelines (Anon. and Parsons, 1999) give ± 5% RH as a rating of 'no risk of mechanical damage to most artefacts and paintings' (type AA) and ± 10%RH as a rating of 'small risk of mechanical damage to high vulnerability artefacts' (type A).

From this, the recommended minimum packing for self-buffering heat treatments should be greater than 100 kg/m^3, which is still less than half the volume of a bag with the lightest of common woods. As the density of wood can exceed many hundred kg/m^3, there is wide scope for safely enclosing various shaped objects with bags while being reasonably conformal. Obviously, minimizing air volume is beneficial through conformal bagging, or adding exchangeable water, by added dunnage in the form of cotton sheet over-wraps. For a full treatment of how buffering can stabilize EMC in tight or leaky structures, see Michalski (1994).

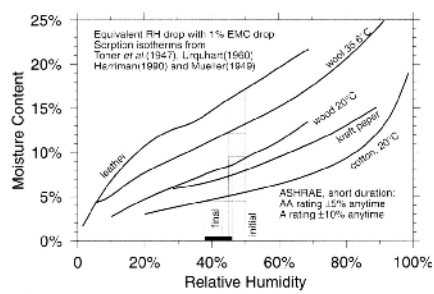

Figure 3 Equivalent RH drop for a 1% EMC drop. Data is from Toner *et al.* (1947), Urquhart (1960), Mueller (1949) and Harriman (1990)

The coefficient of thermal expansion for wood in its tangential (most reactive) direction ranges from 3.9×10^{-5} to 8.1×10^{-5} per °C (USDA, 1987). A 40°C shift in temperature would result in a 0.3% swelling in the tangential direction. This is not enough to cause fracture in constrained glassy polymers such as most paint on wood, as their elastic limits are between 1% and 3% elongation at break (Michalski, 1991). Therefore, in itself, heat used to disinfest is incapable of damaging constrained assemblages through the effect of expansion, but other factors need to be considered.

For bagged artefacts, the total amount of moisture within the bag remains constant and the EMC of components changes very little (Richard, 1991). As a result, thermal expansion dominates in these situations and the resulting physical movement is too low to cause damage to sound artefacts.

However, for unbagged wooden materials, the loss and gain of moisture dominates dimensional change. The moisture coefficient for wood in the tangential direction ranges from 2.0×10^{-5} to 4.5×10^{-5} % EMC change, and 1% EMC equates to 5.9% RH (Richard, 1991). Using median values, a 1% EMC change will be about 60 times the dimensional change caused by 1°C. Using the equation by Richard (1991), which is valid for a wood buffered enclosure with minimal air space:

$$RH_{final} = RH_{initial} + 0.35\ (T_{final} - T_{initial})$$

If an unbagged wooden object were subjected to a 40°C temperature increase it would experience a 2% decrease in EMC even when kept at the same RH (see Figure 2), causing a 0.9% shrinkage in the tangential direction. This is approaching the elastic limit of glassy polymers (Michalski, 1991), which indicates that caution should be exercised with assemblies such as painted wood. Bagging artefacts before heat treatment circumvents this problem (Strang, 1995).

A beneficial trend comes from the thermal expansion. While some moisture is lost to vapour in the bag at higher temperature and causes minor shrinkage, thermal expansion counteracts this dimensional change. Through the heating/cooling cycle in an enclosure, minor moisture loss is balanced by thermal expansion and further reduces strain on joints.

The vapour barrier of choice is 150 µm (6 mil) low-density polyethylene. This film is either clear or pigmented,

is heat-sealable, widely available, and inexpensive. With a melting point above 100°C and a brittle temperature below −50°C (Andrews and Dawson, 1986), low-density polyethylene is an ideal barrier film for thermal treatments. Moisture permeability increases with heat and is directly proportional to thickness (Figure 4).

While polyethylene can be penetrated by some insects, Highland (1984) rated 125 µm (5 mil) polyethylene as fair, and 250 µm (10 mil) as good for insect resistance. Five-year trials with woollens stored in kraft-polyethylene laminate showed only unsealed materials to be affected by mould and insects (Bry *et al.*, 1972). Artefact bagging can be used with confidence that effort is not being wasted (see below on mould risk).

As folds and seams are the major route of infiltration by penetrating insects (Newton, 1998), seams should ideally be closed with a wide heat seal (1 cm) and trimmed flush to eliminate crevices. Taped seals or rolled and clipped seals will not fare as well in the long term, but may be used. A humidity indicator strip should be dated and placed inside the bag for monitoring long-term storage. Heat disinfestation uses the enclosure to quarantine, retain moisture balance, divide collections into manageable units, and direct heat to where it is needed. The solar bagging application (Strang, 1995; see below) extends the enclosure to become the heat source for carrying out the treatment and protection from environmental disturbance. Polyethylene bags on storage shelves are generally no more combustible than the organic objects they protect. In practice, the Canadian Conservation Institute (CCI) has found that polyethylene enclosures absorb significant amounts of infrared radiation from localized fires, prevents widespread sprinkler and smoke damage, and lowers the overall level of contamination. Even when shrivelled onto objects, the film has often been easily removable.

Summary: The primary function of a vapour resistant enclosure during heat treatment is to restrain moisture loss in the object. With conformal bagging, but not obsessively so, the minor equilibrium moisture content change will result in insignificant dimensional change with little risk of damage. There are currently studies underway to systematically observe any effects on collections being treated. Fast reacting dunnage can reduce drying of thin elements. Thermal expansion counteracts minor loss of moisture during heating. Polyethylene is a good enclosure due to ease of sealing, widespread availability, low cost, long-term stability, and advantages in long-term collection preservation, which offset the labour of bagging.

Rates of moisture and heat equilibration

Restricting dimensional change with vapour barrier enclosures is sufficient to protect objects from damage they would experience without the bag. An examination of the process with time and relative rates of change in heat and moisture content provides information leading to establishing effective treatment schedules.

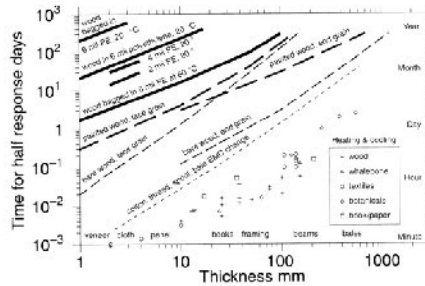

Figure 4 Time for half response of the relative moisture content and heat movement to occur. Data is from Strang, 1995

The curves in Figure 4 represent the time needed fo half of the total EMC change to occur. Wood which i bare, painted, and bagged, can be modelled as infinite sheet exposed on two sides (Michalski, 1993b; Crank, 1975), an the cotton data comes from measurements on threads spools and bales (Crank, 1960).

The time for half hygrometric response was chosen as i coincides with the more rapid and linear portion of th exponential decay curves, which fit equilibration data. T roughly calculate the time for completion, multiply th half response time by a factor of three (88% complete) t five (97% complete).

The examples were chosen to show the resistance c different barriers to moisture movement: diffusion throug the boundary layer of air (no bag), permeation through paint layer, and permeation through a sealed polyethylen bag. Within the range of thickness considered for woo and cotton, the rate of response is primarily determined b the coating or bag. At greater thicknesses (right hand sid of Figure 4), the diffusion characteristics of the materi inside the coating or bag dominate.

The −20°C and 60°C curves for polyethylene bagge wood illustrate the effect of temperature on barri permeation. The contribution of film thickness is als illustrated, calculated from the data in Pauly (1989).

The heating of materials is also plotted in Figure where the points represent experimental findings. Woo samples include bagged veneers, structural walls an massive timbers. Books range from a slim volume to fu depth on a packed library shelf. Textiles range from carpe to bolts. Botanicals range from a few herbarium sheets, full cabinet shelf, to bales of tobacco. Cancellou whalebone represents the most insulating form of bon These examples were extracted from the literature c heat/cold treatment or developed by the author complete cases similar to the ones encountered collections.

The significance of the curve and point distribution that heat (and cold, as it is the reverse flow of the sam case) moves faster in and out of materials than moisture room temperature, even for end grain or fibre exposed

air with no other barrier. However, for very thin objects at elevated temperature, there is a risk of moisture moving almost as fast as heat, so a vapour barrier must be used. An existing paint film would suffice for short treatments of thicker objects, however, a simple inexpensive polyethylene bag is superior and has many advantages over existing surface films at the elevated treatment temperature, and reduces the chance of surface effects.

The overall advantage of bagging objects for heat treatment is a thousand times delay of hygrometric half time relative to the half time for heat (vertical separation of lines and points, Figure 4). The necessary multiplication of exposure time by five to get full penetration of heat is still inconsequential in comparison, even as it approaches moisture response times for the unprotected cotton.

The question of how moisture content changes with mixed materials is of great interest in the food industry (Gál, 1975). The resultant EMC of a finely divided mixture (food) is practically calculated as a mass-proportional mean of the isotherm differences (van den Berg and Bruin, 1981). A parallel concern is safety of multi-material objects with divergent sorption isotherms during a bagged heat treatment. The materials will attempt to independently adjust the EMC, as shown in the multiple final paths in Figure 2. In practice, a new equilibrium RH is struck, based on the proportion of the materials. The relatively parallel and straight middle portion of sorption isotherms mitigates the effect of mixing materials, as the difference in RH between materials is kept small.

As well as surface moisture leaving to perform the buffering effect, moisture will also move within the object. Any difference in temperature through an object will result in a parallel EMC gradient. The major risk to the object is the initial requirement to buffer the enclosed air space, and mitigation of this risk has been described. As the heat flows into the object, desorbing moisture will elevate humidity in cellular voids and fibre gaps towards a new equilibrium vapour pressure. As the external vapour pressure is already high (buffered air in the bag) there is nowhere for moisture to go except towards the cooler core in the direction of heat flow. This moisture would then be adsorbed. However, sorption requires the evolution of heat, which augments the externally provided heating wave. The coupling of simultaneous moisture and heat transfer 'waves' is described in Crank (1975). What is useful for the topic of this paper is that significant amounts of the moisture in motion will not have anywhere to go to cause significant stress to the object during the course of heating and cooling. The voids cannot take on enough vapour. Moisture will in large remain bound to the object, performing its role contributing to dimensional stability.

Once the object is at an even temperature, the moisture gradient should seek equilibrium, but we generally initiate cooling at this point which reverses the gradients, and moisture will now migrate from the enclosed air onto the object's surface and the matter will take on vapour from its cooling voids. As the movement of moisture in a material is slower when it is dry than when it is moist, the regain will not be symmetrical with time. Some minor hysteresis lowering of EMC may also contribute to the resultant surface EMC, leaving this zone slightly dryer than its initial state. This is where dunnage is effective in protecting finer elements from drying.

Any losses, for example permeation through the bag, seal leakage, or dumping condensation upon opening the bag, will also lower the final EMC, but not at a level that causes undue strain.

Condensation forms on cooling when the object is far enough from the bag wall so that the dew point is inside the bag. Heat will flow out of the object and also continue into its centre if a gradient was still in effect when heat was turned off. As the surface cools, it will adsorb moisture from both the air and the warmer core, reversing the trend established during heating.

The only way to reduce this small but unavoidable 'sloshing' effect of moisture movement within the object is to optimize heating to the fastest rate possible without elevating the temperature beyond what is needed to kill insects. The potential for movement is restricted by lack of time to reach equilibrium. Slowed cooling by insulating the bag for the cooling phase will not help.

During moisture adsorption a small amount of heat given off by the newly sorbed water moderates the rate of uptake. Full thermodynamic treatment of changes during heating and cooling is complicated by this simultaneous heat and moisture transfer problem. The above description is intended to give the general outline of events, which are also moderated to the point of insignificance for the welfare of the object.

Removal of the bag at the end of active heating, before cooling, results in direct loss of moisture to the atmosphere from both the bag air and the warm object. This would be bad for thin objects, but thicker and painted or gilded objects would 'dry' slowly compared to heat loss and might not suffer unduly.

Leaving the bag on will increase the condensation damage risk, but if the object in the bag is protected or supported, direct contact is avoided and no solution effects would occur. Cotton over-wraps, which cool early and quickly, also absorb vapour and prevent condensation, as well as buffering thin components of objects earlier during heating (Strang, 1999a).

Summary: Time to equilibrium has a principle role to play in heat disinfestation. Slow equilibration favours stability during brief changes in surrounding conditions. Fast equilibration requires some mitigation to prevent unwanted dimensional change, most of which is provided by moisture retention in a polyethylene bag, where heat equilibrates several orders of magnitude faster than moisture. Internal moisture transfer is also limited to comparatively slow mechanisms. Rapid responding dunnage buffers any thin members from moisture loss

during the early stages of heat treatment. The condensation risk is strong on cooling, but mitigated by object heat, moisture scavenging cotton over-wraps, and careful object support.

Heat ageing and the risk of damage

Many chemical reactions proceed more rapidly with elevated temperature. Studies on paper, film and magnetic tape binder indicate that the rate of deterioration doubles with increments in temperature of 5°C during the first and most rapid stage of its deterioration (Michalski, 2000). This means elevated temperatures will shorten useful 'lifetime'.

Figure 5 shows the extent of this effect. The inset graph shows the net lowering of expected lifetime of paper objects to 98.6% by an eight-hour heat treatment carried out in perpetuity, every ten years. This is equivalent to the exposure which disinfests entire frame-construction buildings or library stacks. If we expect paper to last at least a century, a single eight-hour exposure will incur something on the order of 0.1% loss of expected lifetime. An hour or so exposure needed for unrolled carpets in the solar bagging application described below, will incur even less deterioration. This cost can be borne when the alternative is destruction by pests.

Figure 6 illustrates how heat affects paper strength. While enduring sharp folding under tension equates to extreme treatment of an object, the comparative data is useful to illustrate how little the paper strength is affected at 60°C when thermal ageing is of short duration. Heat treatment of books would approach eight hours only if one were attempting to heat an entire shelving stack as a unit.

The deterioration of leather increases risk of shrinkage even at temperatures below room conditions when moisture is applied. Irreversible dimensional change in collagen molecules above a threshold temperature (shrinkage temperature, T_s) seriously distorts skin objects. The thermostability of collagen in water relates to the state of deterioration of the object (Young, 1990). Figure 7 shows the temperature for maximum denaturation of collagen against RH (Kopp *et al.*, 1989; Komanowsky,

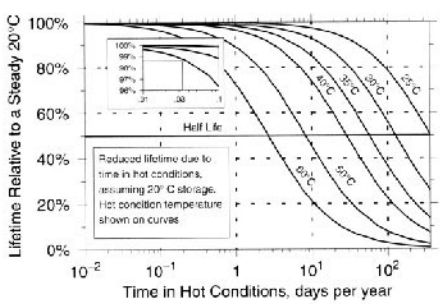

Figure 5 Time in hot conditions greater than 20°C. Data is from Michalski (2000)

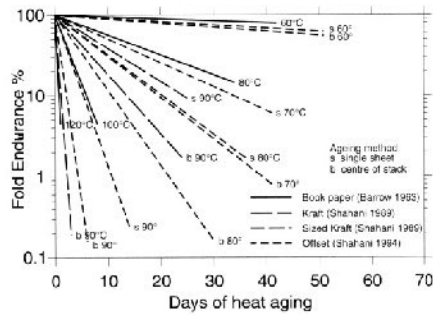

Figure 6 Paper fold endurance after heat ageing. Data is from Shahani (1994), Shahani *et al.* (1989) and Barrow (1963)

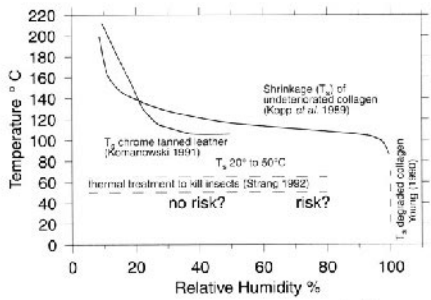

Figure 7 Maximum denaturation temperature of collagen at different relative humidities (Strang, 1995). Data is from Komanowsky (1991), Young (1990) and Kopp *et al.* (1989).

1991). The curve indicates that fresh and tanned collage at less than 90% RH tolerates temperatures well abov 60°C without distortion.

However, problems could arise with deteriorate collagen in ethnographic objects since their shrinkag temperature at saturation can be much lower. Unt equivalent curves for deteriorated materials a characterized it is not advisable to subject collagenot material to heat treatment unless its T_s at saturation above the treatment temperature (Strang, 1995). This poi can be determined by microscopic analysis (Young, 1990

The author performed limited differential scannin calorimetry (DSC) work in determining the T_s deteriorated collagen under conditions less than saturatio and the results are encouraging. However, the denaturatio temperature in the region of 50–70% was above th treatment protocol, and so full characterization is sti needed to ensure low overall risk. Thompson's investigatio of heat treatment of leather with T_s near 50°C arrived at similar conclusion (Thompson, 1995). If the material already damp this might be a case for mild desiccatio prior to heat treatment to ensure stability.

At a physical level, melting and softening of waxes, resins and adhesives are a commonly expressed concern when elevating the temperature of objects. Heat above 60°C is commonly used in restoration treatments in a controlled manner to consolidate cupped paintings. Commercial firms use heat to kill insects in buildings and objects as inherently sensitive as Boulle furniture. They do not report damage to shellac and waxed surfaces (Anon., 1990).

Of course, we would not treat objects with materials having melting ranges near 60°C. Resin varnishes and glue become rubbery by 60°C (Michalski, 1991), so caution is advised, but generally this should not pose problems for glued assemblies as the necessary mechanical strain to disrupt joints is not applied in bagged and heated objects.

Summary: The chemical effects of ageing are small enough to allow a discussion of the expenditure of object lifetime for heat disinfestation, as much as we spend on colour by choosing to exhibit under lights, and on lifetime by storing in ambient temperature rather than in cooled rooms.

Water activity, mould risk and condensate distribution

Since moisture movement and its concentration, compounded by the perceived risks from vapour barrier bags is a common concern to those contemplating thermal pest control, some way to estimate subsequent risk by mould is needed. This is extended to storage scenarios simply because bags have a continued use as quarantines before and after heat treatment of collections, certainly until the space is free of pests, and beyond. The microbiological equivalent to relative humidity is the value called water activity (a_w). This term was coined in the food preservation literature 50 years ago to correlate observations on microbial growth to the contribution by water in systems under observation. Water activity is correlated to the ability of water to engage in chemical and biological processes. While study of water activity and microbial processes is complicated by variations and detail of interactions (van den Berg and Bruin, 1981), overall limits are well enough established to provide a useful guide.

The non-ideal (real life) behaviour of water vapour at ambient temperature and pressures is termed fugacity, and is at most 0.2% different from ideal (van den Berg and Bruin, 1981). With allowances for this small difference, water activity is essentially equal to the ratio of measured partial pressure of water to its saturation vapour pressure at a given temperature, and is thus identical to RH expressed as a fraction. Microbiological risk can then be mapped to equilibrium with a system's atmosphere.

The dependence of mould on water activity is summarized in Figure 8. The curve predicts potential for mould growth when humidity (water activity) is known. Higher humidity equates to shorter periods of time before recognizable growth, hence more acute risk occurs. The data in Figure 8 is from one important study on three substrates: dried grass, linseed cake and bone meal,

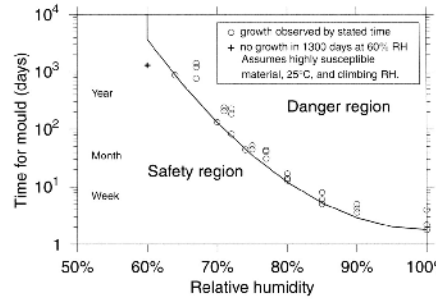

Figure 8 Time for mould growth against relative humidity (Michalski, 1993a). Data is from Snow *et al.* (1944)

representing the most susceptible ethnographic or contaminated objects. The relation between microbial growth and moisture content is a consequence of water activity. We cannot equate growth on one material with potential for growth on another through equivalence in moisture content. We must always refer to the sorption isotherms in order to project risk to other materials, otherwise the prediction is falsely alarmist for mould risk at humidities below 65%.

It is mould and bacterial growth that translates to damage through digestion, or staining. A short time at elevated humidity restricts this potential for damage, so even when heat treatment creates conditions for higher humidity in the bag, mould is not an issue. This is due to the relatively short duration of the resorption phase for mould growth initiation, and the distribution of any condensate on the bag film is well away from the warmer surfaces of the enclosed object (Figure 9). In fact, breaking spore dormancy, only to quickly return to adverse humidity, is beneficial.

The effect of temperature on the need of a mould for moisture is shown in Figure 10, with short curves for old parchment, starched cotton and goatskin in order of increasing sensitivity to mould at lower humidity. The outer boundary is summarized from 50 years of industrial microbiological effort, where moisture content is the key

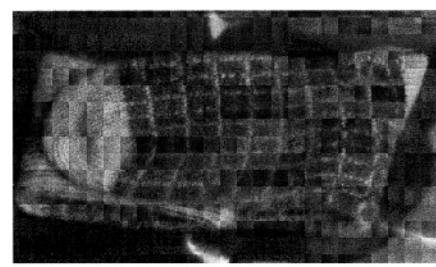

Figure 9 Wool socks at 60°C. Condensate in the bag stays away from the object during cooling

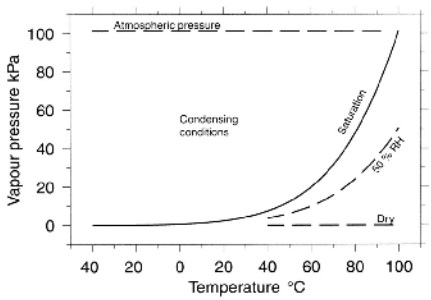

Figure 10 The effect of temperature and humidity for the growth of a mould (Michalski, 1993a)

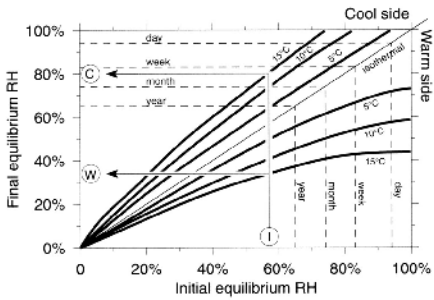

Figure 11 Calculated psychrometric behaviour of bagged wool in a thermal gradient, and mould risk (Strang, 1992). Data is from Hazeu and Hueck (1966) and Michalski (1993a).

for the preservation of goods. Bacteria require greater water activity than moulds. Both high and low temperatures put a strain on organisms in the form of greater dependence on high humidity in order to sustain life. The lesson from this curve is that common moulds, capable of destroying objects, are going to need very high humidities indeed to sustain growth during heat treatment.

Figure 11 shows the effect of equilibrium thermal gradients on moisture distribution in bagged wool (Hazeu and Hueck, 1966) and is similar to cotton. This effect was studied to understand mould risk during ship hold transport of polyethylene bagged materials. Bagged textile, initially at equilibrium with 58% RH (marked I) subjected to a 15°C differential, will drop to 35% RH on the warm side, and climb to 80% RH on the cooler side with a mould risk of a couple of weeks (Strang, 1995).

There are four ways to make an object mouldy in a bag:

- bag at equilibrium RH (ERH) above 65% and maintain long enough for mould to grow (Figure 8)
- bag at an ERH less than 65% but subsequently store at elevated temperature inducing an ERH above 65% (Figure 2)
- bag at ERH less than 65% but store with a thermal gradient significant enough to induce RH above 65% in part of the bag (Figure 11)
- bag at ERH less than 65% but store in air at a higher RH that eventually permeates the bag (Figure 4)

Avoid these situations and the risk of mould is minimal (Strang, 1995).

Summary: The potential for mould growth during thermal pest eradication can be predicted by the RH (equivalent to water activity) of the atmosphere relative to the enclosed materials, irrespective of the materials' moisture contents. Given the short duration of heat treatment, damage by mould is unlikely. Precautions against mould are stated for long-term storage in the bags. Temperature gradients inside the bag must be avoided during long-term storage due to increased mould risk. Examples of risky locations are deep shelves against exterior walls, and bagged or tarpaulined objects resting on concrete floors at grade.

EFFICACY OF HEAT DISINFESTATION

In pest control, efficacy is a euphemism for 'ability to kill'. Since the 1900s, efficacy has been a primary requirement for licensing any pesticide, and more recently that it does so without significant side effects. The author performed a literature review of thermal mortality limits to insect populations to establish a solid demonstration of efficacy (Strang, 1992). Fields (1992) published a similar study focusing on agricultural pest control. The summary of thermal mortality data is given in Figure 12 covering 46 species in total, 26 of which are represented in the heat data. The lines show recommended treatment schedules of reasonable duration to ensure efficacy.

The author reviewed the effect of heat treatment on seed viability (Strang, 1999c). Seeds were chosen as a model system, since germination after treatment indicates little chemical or physical effect on a complex living system, unlike the simple and nearly monotonic systems most conservators worry about. Temperature, humidity,

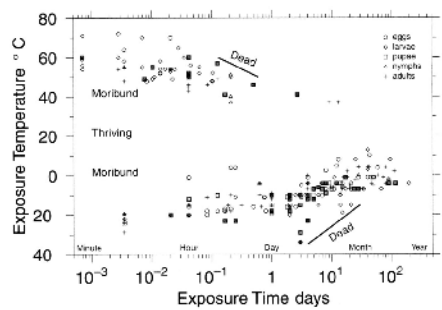

Figure 12 A plot of temperature against time for the mortality of insects (Strang, 1992)

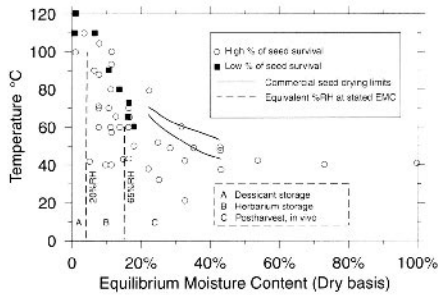

Figure 13 Mortality of seeds correlated to storage temperature, RH and EMC (Strang, 1999c)

and moisture content for optimum seed storage is a well-studied area in agriculture and their recommendations have extensive foundation in annual practice.

By using EMC/RH conversion through the sorption isotherms, seed viability against EMC can be related to viability against RH in storage. Combining viability with temperature and EMC/RH, Figure 13 shows that seeds can undergo heat treatment at 60°C without significant effect on germination up to 60% RH. The effect of low moisture content in reducing damage during heat treatment is clearly seen. For full treatment of thermal control in the herbarium context, see Strang (1999c).

Applications of thermal disinfestation

In the end it all comes down to application. If a technique is too damaging, complicated, expensive or awkward to employ it will rarely be of value. The principles behind thermal treatments in an efficacious and safe manner are a foundation for developing an application. Application also balances cost, timeliness and availability. All the methods described below have been applied to relieving cultural property of their infestations. The problem lies in the details of implementation.

Demonstration

The simplest demonstration of heating an anisotropic material is to construct a longitudinal grain strip of wood veneer, fused to a cross-grain strip of the same veneer by double-sided adhesive tape. Placed in a polyethylene bag and heated to 60°C with an oven or hair dryer, the strip exhibits very minor curl towards the long grain side, indicative of greater cross-grain thermal expansion. Place the strip in a convection oven, and heat it to 60°C and the strip quickly exhibits extensive curl to the cross-grain side, indicative of massive moisture content loss in both sides and anisotropic response. Figure 14 shows the effect of a 2 L bag around 5 g of wood prepared in the described manner, heated to 60°C for 20 minutes. This is a graphic example of the forces we control with a vapour barrier during thermal treatment; the same forces we know to be responsible for damage to our collections in uncontrolled extreme storage environments.

Solar heating

The author encountered several clients in his advisory role at the CCI who had few resources with which to disinfest

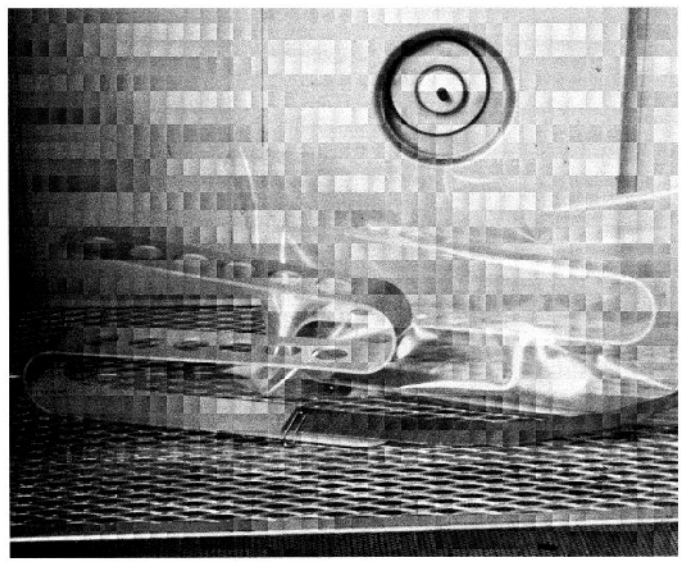

Figure 14 Demonstration of the bag effect during heating to 60°C

textile collections. Clark (1928) demonstrated that sunning textiles killed textile pests. However, exposing dyed fabrics to high light levels and other threats is less acceptable in the museum context. The following system was developed by the author for this more discerning audience, and has been extended by others to wooden objects of the order of 5 cm or less in thickness (Strang, 1995; Strang, 1999a).

Bag a relatively thin object wrapped in cotton in black polyethylene, or place a thin black, well-washed cloth under a clear polyethylene film around the object. A rolled and clipped closure is sufficient if heat sealing is not possible. The bagged object is then placed in a clear plastic surrounding 'greenhouse' to retain heated air outside the black bag and reduce wind cooling. The three following strategies reduce the temperature differential through the objects being treated and the risk of moisture rise on the cooler shade side (as illustrated in Figure 11):

- warm air from the sunny side of the greenhouse is moved to the shady side by mechanical pumping or blowing
- the shady side of the black bag is thermally insulated
- a tubular black skirt is used to absorb heat and conduct it up the shade side

Heating from both sides is superior to an insulated shade side as it speeds treatment and more quickly reduces the thermal gradient.

A black object can exhibit a skin temperature rise of 40°C (Yamasaki and Blaga, 1976), which, on a sunny day in temperate Ottawa, brings the bag to a rapidly lethal 60°C from May to October. This coincides nicely with the opening and closing of seasonal museums which often have resource problems. The black bag protects against light fading and contaminants, as well as the issues detailed in the above sections. A cotton overwrap between the black polyethylene and the object rapidly delivers initial humidity to the bagged air on heating to protect fine structures, and scavenges moisture quickly on cooling to reduce condensation risks. The equivalent of ten pillowcases per m^3 of air should suffice.

This process, detailed in Strang (1999a) was used extensively in field trials between November 1999 and March 2000 by Baskin at the Luang Prabang Museum, in Laos (Figure 15). Heavily infested and damaged shell and glass inlayed lacquered and gilded Buddha figures, as well as fur and fabric items were treated. A solar powered fan was used to blow warm air round to the backside of the black bag. No damage from treatment, condensation or dampness in the cotton wrappings was seen on opening 24–39 hours after the treatment. No sign of infestation was visible after a year (B. Baskin, pers. comm.).

Brokerhof carried out solar heat disinfestations of gilded iconostasis elements in a variety of heat-gathering configurations (Brokerhof, 1998). An L-shaped clear-fronted greenhouse lined with black and insulated from the ground was chosen as the more efficient of the systems tried. The components had been tightly wrapped in black polyethylene, and bag surface temperatures had commonly approached 80°C. Normalized to initial EMC, changes after treatment ranged from +3% to −5% and narrowed over two days from +1% to −3% with an average new EMC, which was 1% lower than initial EMC. Despite the large EMC change in some of the examples, no dimensional change was measured across existing cracks. This indicated that the EMC shift, if as large as was measured, was very shallow as predicted above. Mechanical damage to very tenuously bound surface fragments was noted as equivalent to other handling procedures. No

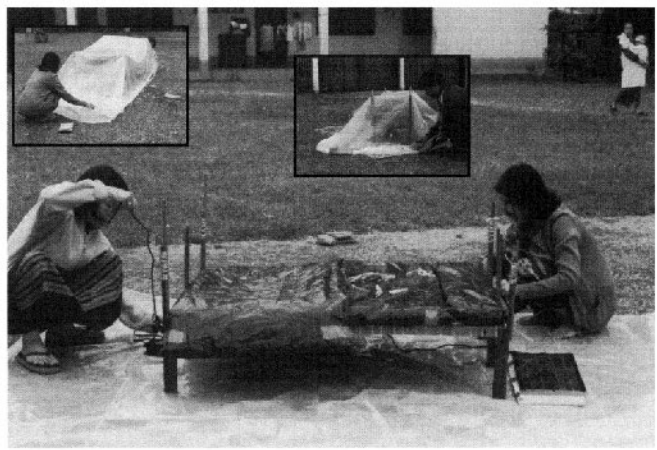

Figure 15 Solar disinfestation system being used to disinfest textiles at the Luang Prabang Museum. Photograph by Baskin (1999)

buffering overwraps had been employed to protect these fine elements from rapid early-treatment EMC shift, or pressure from the bags.

Pearson and his students built a trial solar disinfestation oven, measuring 1 m × 0.5 m² with glass double-glazing and a black lining. Black-bagged objects were set on a rack to allow isothermal heating. Vented with a thermostatically controlled fan operating at 12 V, the chamber maintained a temperature of 58°C to 63°C for three hours, and successfully treated up to 10 kg of black-bagged wood (Strang *et al.*, 2000).

Summary: Maximizing solar gain is not the prime objective of this technique, and temperatures high enough to heat the object without soaring past 60°C are sufficient. High skin temperatures prompt surface desiccation and push the bag humidity to unacceptable levels. Ventilation of the outer envelope moderates the inner envelope, and wrapping with cotton moderates surface EMC change and condensation risk. The author's intention for the solar technique was to allow fast and assured pest control to those who have no other choice. However, it need not be considered a last ditch risky method when used with care and understanding of the underlying principles.

Convection heated enclosure

Plant specimens drying at 45°C are at the low end of the lethal boundary. However, an additional situation was proposed by M. Shchepanek of the Canadian Museum of Nature, which was whether it would be possible to heat disinfest material arriving with visiting researchers. The material is generally unmounted, and not likely to go into the permanent collection. Such material does present significant risk of introducing pests, and the social pressures are often one of quick response to the request when a professional colleague appears plant in hand.

The specimens are commonly pressed in folded newspaper, so they can be safely stacked to a thickness of a centimetre between modified herbarium press cardboard. The cardboard acts as both hypocaust and radiator, quickly delivering heat to the centre portion of the specimens (Figure 16).

Heated in a convection oven at 60°C for one hour is sufficient to eliminate pests. No other technique could respond as quickly, with as little risk of insect survival (Strang and Shchepanek, 1995). The specimens were unbagged as additional drying was not a concern. The role of thermal pest control in herbaria has been extensively reviewed by the author (Figure 13; Strang 1999c), as well as its integration into wider IPM strategies (Strang, 1999b).

An insulated plywood box with heat supplied by an internal heater or an external supply can disinfest large or many objects in one treatment. This method was applied to an entire farm equipment collection that was being devastated by woodboring beetles at the Albert County

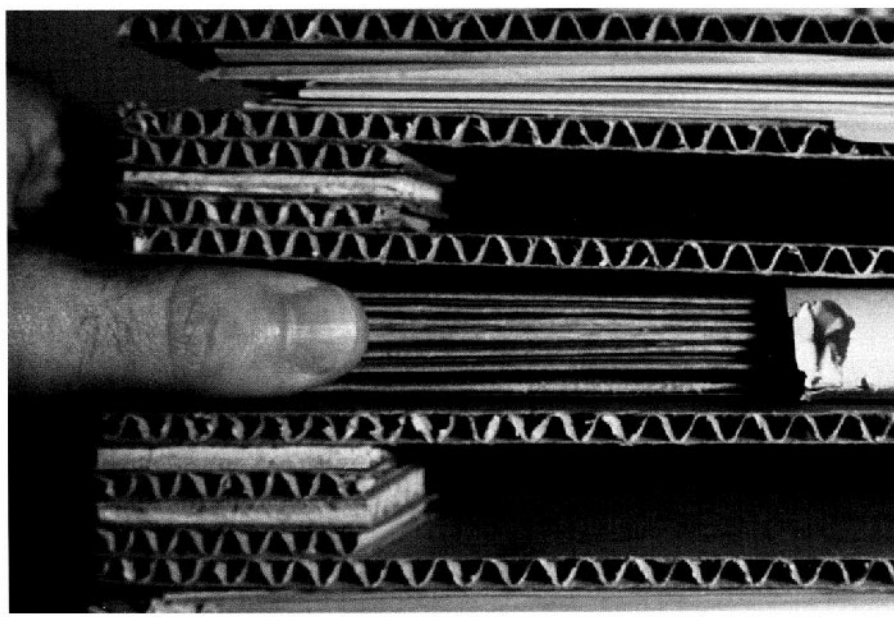

Figure 16 Convection heating herbarium specimens to kill pests, rule-of-thumb for ventilation gap and specimen stack height (Strang and Shchepanek, 1995)

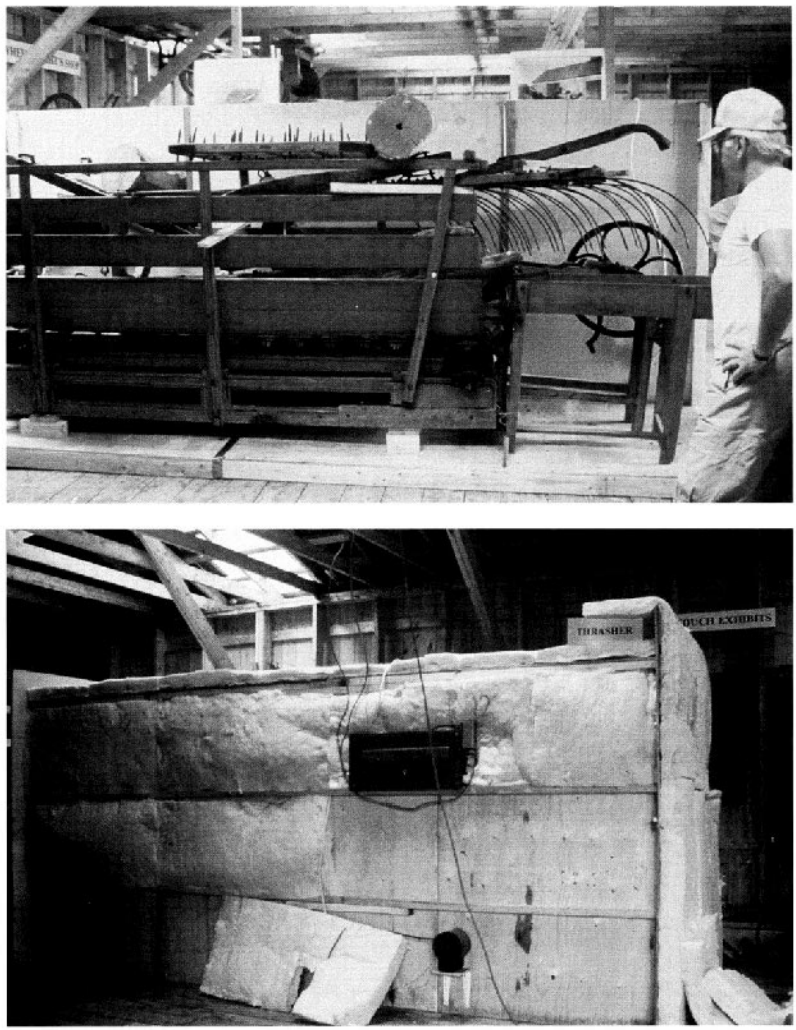

Figure 17 Heat chamber disinfestation of farm machinery. Photograph by Fox (1993)

Historical Society in New Brunswick. A 14 × 4 × 6 foot plywood box with glass-fibre insulation was heated to over 60°C with two 2500 W and 240 V electric heaters, under thermostatic control (Figure 17). A squirrel cage blower ensured air mixing, especially under the raised objects. Temperature measurement within carefully sized blocks of hardwood gave an indication of treatment completion when matched to the largest dimensions of the objects in the chamber.

The system's total expenditure was approximately Canadian $300, carried out by Alastair Fox and society members with initial guidance from the author. Several loads were treated for seven hours each and the infestation eliminated (Fox, 1993). The treatment relied on chamber walls, and the large buffering capacity of the timber objects in recirculated air to keep EMC loss minimal. Bagging, or bagging with cotton over-wraps, is advisable for thinner objects mixed in with larger timbers given the longer treatment time needed for the thicker pieces.

This method, with analysis of effects and efficacy, was carried out by A. Xavier-Rowe and colleagues at English Heritage on treated timber objects associated with

Broadsworth Hall (Xavier-Rowe *et al.*, 2000). In addition, a commercial humidity controlled heat disinfestation chamber is used commercially for heating objects in Europe (Nicholson and Von Rottberg 1996).

Convection heated building

The final and most daunting treatment scale is bagging a building or large outdoor sculpture. The exterior bag reduces reliance on wall insulation and vapour barrier properties, speeds heating and blocks access to the target being heated. Brought to technical pinnacle in the early 1900s for disinfesting granary and milling operations, heat has been employed at building scale throughout the last century. These include:

- heating by hot water radiators scaled to the task (Dean, 1913)
- portable coal-fired furnaces with telescopic pipes to deliver heat to upper stories (Hartnak, 1943)
- portable kerosene fired space heaters (Hartnak, 1943)
- propane-fired heaters with flexible insulating ducts (Forbes and Ebeling, 1987; Nicholson and Von Rottberg, 1996)

These have all been used to eliminate pests from structures and their contents. The treatment time is roughly a working day (can be estimated from Figure 4), with additional time to prepare the site by selective content removal or thermal protection. Tarping the building to allow heating from the exterior wall, thermally insulating interior ground surfaces to avoid cooling and moisture effects, and reversal of all preparations should be taken into account.

While the method can be prone to under-heating portions of the building in contact with the earth, careful setup, monitoring and heat delivery reduces this risk. When woodboring infestation is present in upper reaches, the technique can be very effective. Heat has been applied to fractions of buildings, such as a library within a civic building (Cressman, 1935), leaving other areas largely unaffected by the process. Buildings undergoing heat treatment can be entered for brief periods (Ebeling, pers. comm.) but it is not advisable, as heat stress is a certain risk if any delay is encountered.

CONCLUSION

Temperatures greater than 60°C are used to flatten cupped paintings, set adhesives on textiles, or bake sticky binders onto magnetic tape for one last play. Reasons for using heat therefore run from aesthetic correction, through structural reintegration, ending in salvage from oblivion. The use of heat to control pests in cultural objects is in no way less ethical than these treatments mentioned above.

Pests continually graze the aesthetic surface of our cultural patrimony, leaving ugly scars. Pests undermine the structure, and if uncontested, will reduce the value of the object. Imagine collections exposed in a forest, and then consider the beneficial effect of a roof and walls. Artificial ageing could equally mean the prolongation of an object's lifetime in the face of the ravages of unchecked nature.

As far as the author knows, the first well-recorded use of heat to disinfest objects for collections is that reported by Kuckahn in 1771 (Kuckahn, 1771). In these communications, Kuckahn details a procedure that ensures the correct temperature for disinfestation of bird mounts, without risk of damage to the feathers. He tested sacrificial feathers in a cooling wood-fired oven until no damage was perceived and then he placed the specimen inside.

> *Baking is not only useful in fresh preservations, but will also be of very great service to old ones, destroying the eggs of insects; and it should be a constant practice once in two or three years, to bake them over again, and to have the cases fresh washed, as above, which would not only preserve collections from decay much longer, but also keep them sweet.*
> (Kuckahn 1771)

Since that time, heat has been applied to seeds prior to planting for fungal control, to kill insects in carpets and furniture, and it has also been used to disinfest houses, granaries, mill structures and libraries. Heat has also protected cultural property, especially in institutions with a very limited budget, lacking electricity, or much pressed by time and volume.

Thermal disinfestation treatment has been introduced to the world many times and it has experienced periods of attention in written records. Ultimately, disinfestation of objects by heat or any other pest control treatment becomes an act of intervention to be gauged relative to doing nothing and accepting the consequences. I would therefore encourage those whose job it is to preserve cultural property to understand the niche and principles of heat disinfestation.

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BIOGRAPHY

Tom Strang is a research scientist with the Canadian Conservation Institute (CCI) in Ottawa, Canada. For the last decade he has investigated the efficacy and utility of thermal and controlled atmospheres to assist in their acceptance into the conservation community as routine methods of pest control to replace proscribed fumigants. He has also participated in conservation aspects of shipwrecks, historic site development, museum exhibits, natural history collections, and lead GPS survey and GIS work on high arctic fossil forests.

Levels of IPM control: Matching conditions to performance and effort

Paper 5

STRANG, T.J.K. AND R. KIGAWA. 2006. LEVELS OF IPM CONTROL: MATCHING CONDITIONS TO PERFORMANCE AND EFFORT. COLLECTION FORUM, 21(1–2):96–116.

Division of contribution

This paper was produced by inviting Dr. Kigawa to formally expand on discussions we held around the task of providing IPM knowledge to people who care for cultural properties in a way which would be recognizable and commensurate with their general situation. Both of us undertake research and training projects to provide guidance for controlling pests of cultural property at a national level (Canada, Japan) [34]. Scales and levels were jointly developed starting with details from work T. Strang had done to systematize IPM (Strang [58], Strang and Kigawa [8]) incorporating lessons from our gathered experiences working with institutions in our respective countries. T. Strang managed the submission and revisions.

Errata

LEVELS OF IPM CONTROL: MATCHING CONDITIONS TO PERFORMANCE AND EFFORT

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Abstract.—A scale in order of increasing improvement of pest control is presented to cover a wide range of situations from 'no resistance to pests' to 'comprehensive control'. Seven levels of IPM control are developed from this scale and for each level there are subsequently described appropriate remedial integrated pest management (IPM) solutions to the more significant vulnerabilities. These are intended to be a good starting point for IPM planning or instruction. Threshold 'Plan B' details have also been identified for each level, so the user can achieve the basics first and look to improve standards in the future. The levels provide an important benchmark for assessing long-term movements up, down or within the scale of standards. A prognosis is given for each level, forecasting the course of pest infestation and estimating rates of deterioration, which are discussed for obdurate, robust, soft and delicate materials. This provides a useful framework during collections surveying for classifying risks to collections from pest activities.

INTRODUCTION

The basic concepts and strategies of IPM for museums are well described in recent literature (Åkerlund et al. 1998, Kigawa 1999, Kingsley et al. 2001, Pinniger 2001, Strang 1999). Basic pest management can be rationalized around five stages of control: avoid, block, detect, respond and recover (CCI 1994, Strang 1999). Yet we have many questions attached to real situations such as: ''Our building's seals are far from tight,'' ''We don't have any money for IPM this year,'' ''We don't have enough staff for activities beyond basic running of the museum,'' ''It is sitting outside because it is really big.''

These questions arise from institutions with differing qualities of building, staffing levels and budgets. To respond to inquiries, we must characterize the background situation before offering a helpful strategy. The answers are not mechanistic, clear-cut, or without risk of failure.

This paper models a breadth of situations from outdoor exposure to the inside of a perfectly sealed container within a modern collection preservation building. Readers can estimate which level is closest to their situation and use the progression as a prototype for designing IPM strategies with the simple goal of establishing a 'generally good level of protection' for each situation.

IPM STRATEGIES

In developing an IPM workshop for collection managers, the authors wanted to establish a rough guide to IPM strategies that gave essential details. When people make changes to protect an object or collection, they should have assurance of what they will achieve or forestall. We called this approach 'Plan B' in jesting reference to the observation that we rarely get what we really want due to constraints such as time and money. When Plan B proves functional, other concerns can take the fore and Plan B becomes the operational norm. Plan B is tied to

performance expectations of the level in which it is described, and incorporates appropriate elements from the previous lower levels of control.

The authors have long advocated IPM as a layered approach as it creates greater resilience against single point failure when protecting collections. While some features will stand out as highly significant, others reduce pressures and lower risk through their filtering effects against pest attraction, colonization, and uncontrolled growth. Pests are generally defined as deleterious fungi, insects, rodents, and other adventitious annoyances.

The recent Natural History Museum (London, UK) initiative to zone for IPM purposes, recognizes that not all portions of the very large area of their urban museum are sensitive to pest attack, so they developed a tiered 'level of concern' designation for different sections of the building (A. Doyle pers. comm.). Subdividing into regions of appropriate behaviour and response avoids having to impose unnecessary regimes on staff that may never get near a sensitive collection. Focus can then be placed on collections that are most vulnerable. However, their proposal relies on IPM being applied overall to reduce internal threats to the more sensitive zones (NHM 2006). As a result, over 420 staff were trained in basic IPM principles and practices (D. Pinniger and P. Ackery pers. comm.). This 'building as gradient' approach is tacit acknowledgement that an old large building will never be free of pests, but equally it acknowledges that with some vigilance, people make a significant positive difference. This is a similar approach to the consultative work of the authors, adapting the spectrum of IPM tools and approaches to what is reasonable for people to accomplish in a spectrum of individual situations.

Another method is to propose an IPM standard commensurate with a general situation. Standards should by nature be achievable and flexible enough to allow solutions that will show measurable prevention of pest damage.

Pest management strategies sometimes fall foul of several fallacies. If you have no pests it is not necessarily due to the system in place; you may just be lucky so far (pragmatic fallacy). Natural fluctuations in insect numbers can lead to a belief that changes made in the system are having an effect on the pest population (regressive fallacy). Post hoc reasoning, that one change caused another, can lack direct evidence. All this argues for controlled experimental measures for each IPM proposal. The advice given often follows other studies such as food safety engineering, (Imholte 1984) or efficacy studies like using bags as barriers to pests (Bry et al., 1972). Advice is also given using 'common sense' (e.g., beating carpets because insect eggs are fragile) or cultural practice (e.g., tight construction of cedar chests block pests with the cedar oil acting as a mild repellent).

A recent example of IPM moving into the area of standards is the April 2003 change to the Japanese statute governing the sanitation and environmental health in public buildings over 3000 square meters of floor space. By default this will include national and most prefectural museums. It can be considered a standard that increases the priority of IPM in the annual operation of these public spaces containing valuable items. The statute was amended to include the following:

1. Inspect the buildings for pest resistance, plan countermeasures for addressing the weaknesses.
2. Monitoring for pests at least semi-annually (instead of just routinely applying

chemicals) and when finding pests, cope with them using appropriate countermeasures.
3. In addition to routine cleaning, do thorough cleaning throughout the facilities twice a year. This cleaning must be done to inhibit or discourage pest inhabitation and activities.

Development of the Levels of Control

Living organisms respond to environments and are selective, or at least tolerant of conditions around them. The first step was to create a scale that reflects increments in environment generally associated with heritage objects that are progressively more resistant to debilitating pest problems. Groups of IPM details within each level were then established from a non-existent to an ideal contribution. In setting a standard, threshold details (things you should not be without) have to be identified, so the user can achieve the basics first and the niceties later.

Establishing levels started with endpoint calibration: 'no resistance' and 'comprehensive control'. These are relatively easy to see and immediately get the scale going. Setting the relative position of intermediate levels was more difficult but was done based on the previous experience of the authors.

Physical Barriers

The sizes of openings that allow pests to infiltrate are a dominant characteristic of the level designations. Level 0 is completely outside (opening is infinite). By adding a roof or tarpaulin (level 1) there may be some ineffectual protection against most pests. By levels 2 and 3, decimetre to centimetre sized openings dominate and centimetre to millimetre sized openings are characteristic of levels 4 to 6, with 7 being a hermetic or clean-room ideal. The concept of enclosure spans from outdoors, through buildings to sealed vials.

Intervention

No building stays pest free if left unattended with no cleaning or maintenance. Improving just the passive features can temporarily raise a situation a level, but can fail if a situation is ignored for too long. Invoking higher level detection and response procedures may significantly raise an institution's preservation level following the maxim of early detection, early cure. However, when the porosity of the structure and fittings greatly adds to the labour cost through increased incidence of pests, the attempt to control by strictly human intervention may ultimately fail. Appropriate structural changes would have been the more germane choice.

With the exception of parthenogenic insect pests, most animals have need of sexual reproduction, or social structure for their success. This can be turned into a weakness, using pheromone lures, and removing or poisoning nests. Fungi, insects, and rodents need oxygen to survive, although some microbes and insects can survive short-term anaerobic environments. Anaerobic burial environments can effect very long preservation times for soft organics, with some microbial induced change. Time and experience will determine if we develop a similar attitude toward any changes from deliberate anoxic storage such as those seen by Kenjo (1980) or Griesser et al. (2004) when it is used for IPM followed by long term protective storage.

Appendices 1a and 1b contain the scales in order of increasing improvement of pest control elements. These scales were then developed into the levels of control described in detail in Appendices 2a–f.

Quantification of Deterioration

In order to develop prognoses for the levels of control (Appendix 2), we chose to discuss four classes of material listed below. However, it must be remembered that these classes are not exclusive to a pest, but degrees of a scale. For example, a rodent will chew anything if it wishes to maintain its teeth. Obviously, pests are most debilitating when they destroy outright (e.g. rodents shredding textiles, dermestids consuming specimens) or compromise the integrity of difficult to restore objects (e.g. structural pests in buildings, fine furniture, ornate carvings). But there is a significant amount of damage needed to get to this endpoint and a continuum from the first bite to the last burp. How much are pest effects forestalled by the situation or IPM practice in the control levels? We have ventured some qualitative estimates in Appendix 2, modelling from our experiences.

Obdurate Items

Many mineral, stone, metal, and ceramic objects are obdurate. While recognizing there are some soft rocks and friable ceramics, which may be stained or damaged in outdoor locations, this class is relatively hard and unattractive to pests.

An example is vegetation on stone. Dissolution of a cubic millimetre of mineral in pH 5, 25°C water ranges from 0.6 years for calcite to 3.4×10^7 years for quartz (Drever 1994). In trying to model rates, biological activity is recognized as accelerative; for example, the calcite dissolution rate increases tenfold with each 1 pH decrease (Drever 1994), so a 10 to 100 fold acceleration is easily possible from biological source acidity on susceptible minerals. However, these rates are rarely quantified in situ and biological films are sometimes considered decelerating if not benign. Ivy vines shelter surfaces, but also cause severe disruption to masonry structures in a century once their roots mature. Surface dwelling (epilithic) lichens may shelter details from weathering for nearly two centuries compared to uncolonised areas while penetrating (endolithic) lichen damages stone. However, applicable rate data is sparse (Schaffer 1932). Centuries of survival in the face of biodeterioration is not uncommon.

Robust Items

But what is the baseline for survival for robust items like wood posts, plank built objects and framing? Probably the oldest wood buildings on earth still exposed in their original state are in the Horyu-ji complex built outside Nara, Japan in the 8th Century (ICOMOS 1993). Revered within a relatively stable religious environment, these have survived the threats of fire, earthquake, and warfare that claimed many other such structures. Similar incidence of longevity is seen in the stave-churches of Norway. The reported fire risk in cultural institutions in Canada is greater than 1% per year, with average damage per fire exceeding $800,000 (P. Baril pers. comm.). So one could propose these elderly structures are exhibiting a rough tenfold survival over the norm to significant non-biodeterioration hazards.

Termite attack is one of the most aggressive wood pest scenarios. Termite destruction rate is not a simple estimate and their local distribution is most im-

portant in assessing hazard (Edwards and Mill 1986). Based on measurement of 83 milligrams of wood consumed per 1000 *Reticulitermes flavipes* individuals per day (Haverty 1976) an average colony of a quarter of a million individuals consumes 38 cubic centimetres per day (Edwards and Mill 1986). From U.S. state surveys on termite attacks in 1975 to1980, crawl spaces increased risk by a factor of two to six times, and increased the likelihood of supporting dry wood termite species (Edwards and Mill 1986). Buried construction waste is also a high risk factor for termite attack.

Two areas of concern arise, biodeterioration threat to mechanical properties of structural timbers, and hazard to aesthetic elements (e.g. surface carving). Many strength properties are roughly proportional to wood density. Aesthetic integrity will depend roughly on how the surviving matter approximates its original shape.

Definitive microscopic evidence of decay is only visible upward from 5% to 10% mass loss; prior to that it is termed 'early stage decay' (Wilcox 1977). Wood toughness to withstand shock loading is most sensitive to this region of early decay with 50% loss of toughness by one percent mass loss, and 60% to 85% toughness loss by ten percent mass loss. Commonly, wood exhibits 50% loss of mechanical property by two percent loss of mass (static bending, impact bending strength) while axial compression (pole load bearing strength) is roughly halved by a nine percent mass loss due to brown rot, and axial tension strength is roughly halved by a two percent mass loss. White rot is less severe than brown rot up to a rough factor of two (Wilcox 1977) due to the lessened effect on cellulose fibre by white rot.

Biodeterioration of outdoor exposed untreated timber species has been extensively measured in Australia. Decaying to 95% mass loss (defined as ''specimen life''), Mackensen et al. (2003) liberally defined service life as more than 60% to 75% loss of cross section (median specimen life compared to durability studies) for timber in ground contact and not infested with termites. While this is definition is counter to Wilcox's finding, Mackensen et al. are concerned with presence of wood waste on the forest floor (akin to a measure of survival of an object's form) not structural integrity under load. Lifespan for 76 species falls between seven and 373 years, with a median of 49 years, and average of 92 years. Temperature is a significant controlling factor, and very high rainfall prolonging lifetime through lumen saturation inhibition of fungal decay (Mackensen et al. 2003). From this picture we see that life beyond a century for exposed structural wood greatly depends on avoiding soil contact and maintenance of the sheltering roof, or burial in a waterlogged environment. For this reason we set the proposed biodeterioration survival of robust wood objects to be equivalent to the overall survival of the structure in which they are housed beyond the period of a century excepting wet-site archaeological materials.

Soft Items

Coarse natural fabrics (coir, hemp, bast), gourds, baskets and shelved books are easily attacked by aggressive insects like *Lasioderma serricorne.* Sheltered, their preservation is often better than loss to outdoor exposure (e.g., weeks for flower tissues, years for conifer needles). Wool fabrics and animal hides can be attacked by protein consuming pests. A flensed animal can be stripped to the bone by dermestid colonies in two to three hours (shrew), one to two days (opossum) or

five to ten days (horse) (J. Jacobs pers. comm.). Even indigestible synthetic fabrics are vulnerable as rodent nesting material.

Delicate Items

The previous category could be the final one, but a further designation of delicate was desired to include such objects as distinct hairs on tiny animal specimens, insect specimens, fine botanical specimens, fine natural fabrics, fusuma-e, and Nihon-ga style paintings on paper and silk. These become prey to clothes moth, dermestids, silverfish and cockroach grazing. Vulnerability is greatly enhanced when the fabric of the object is closely matched by the size of the pest's mouth, this category was set as a warning of high vulnerability.

CONCLUSIONS

The scales and levels approach to IPM presented here (Appendices 1, 2) enable an institution to embark on self-assessment. Examining the corresponding levels and 'Plan B' improvements make the concepts of IPM accessible in a more relevant way for a broad range of situations. The impact of the changes made, through examining incident data, can then be assessed against this standard.

Moving from the matching description to Plan B is a possible 'standard' for action, while moving from level to level is a 'standard' for progression as collection facilities upgrade through time.

A prognosis is given for each level forecasting the course of pest infestation. Measured rates are discussed in this paper and mentioned where possible in Appendices 1 and 2, and we hope more will be forthcoming from the risk assessment approach now under way in the collections care profession (Waller 2003).

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Appendix 1A. Progressive scales of IPM components.

Column headings are activities, and structure concerns that affect IPM in collection facilities.

Level and situation	Examples	Environment	Site	Object condition	Food waste	Lighting	Plants	Sanitation
[0] Outside	Totem pole, farm machine	Local climate and weather	No modification	Infested	Strewn throughout interior and around exterior	Ambient natural or city lighting	Nearby flowering plants and deadwood sources of pest insects	No cleaning except by natural weathering and wind
[1] Roof, tarp	Shrines, under eaves	Sheltered from rain and sun	Possible elevation, roof drainage		Consolidated in open containers		Encroaching foliage cut back (reduce moisture damage)	Dry sweeping raises dusts but may damage insects
[2] Roof and walls	Temples, sheds, barns	Sheltered from some windblown dirt and snow	Simple foundation drainage	Cleaned	Consolidated in lidded containers	Some interior lighting	Cut back encroaching trees (reduce root damage)	Clutter provides harbourage interfering with inspection
[3] Basic habitation	Historic homes, churches, temples	Protected from weather, may have winter heating	Subterranean foundation drainage	Sanitary	Hauled away weekly from exterior containers	Few lights mounted on exterior	Avoid cut wild flowers or inspect for insects before bringing indoors	Household vacuum and damp mop to capture dust and insects
[4] Commercial adapted	Civic archives, private gallery	Climate controlled by HVAC to eliminate extremes		Disinfected	Removed daily from interior, hauled away weekly from exterior lidded container	Mandated security lighting over doors	Restrictive policy includes inspection, treatment or ban of high risk (primarily local cut wild flowers)	Clutter localized into designated workrooms

Appendix 1A. Continued.

Column headings are activities, and structure concerns that affect IPM in collection facilities.

Level and situation	Examples	Environment	Site	Object condition	Food waste	Lighting	Plants	Sanitation
[5] Purpose built	Provincial and national museums from last century	Climate controlled by HVAC to year round human occupancy requirements	Site wide flood water drainage		Exterior compactor (rodent proofed)	Low pest attraction lights (UV poor) on exterior	Nearby exterior: only non-flowering plants. Interior: only greenhouse cut-flowers or healthy house plants in sterilized soil	Built-in vacuum system (bag room) isolates dust and captured insects
[6] Preservation designed	Collection preservation centres	Climate controlled by HVAC to debilitate pests, yet meets object needs	Designed to manage 100 year weather extremes		Well sealed interior garbage room (cooled) to control rodent and insect access	Attractive light draws insects from exterior walls and openings, light traps near entrance ways		HEPA vacuum (portable units or built in filtration)
[7] Ultimate		Optimal for all objects		Sterile	No food waste production		No plants that can be utilized by pests	Clean room air supply

Appendix 1B. Progressive scales of IPM components (continued).

Level	Physical barrier	Physical resistance	Object enclosures	Object shelving	Detection	Maintenance	Suppression response	Recovery
[0]	No barriers to pests	Intrinsic	Intrinsic	Objects on ground	No inspection	No maintenance	Predators, disease, weather	No recovery, no accounting of cost
[1]	Structure may encourage bird roosting			May sit on plinths, pallets	Annual visitation	Replace roofing, replace tarp	Residual pesticide, fumigant application to entire collection	
[2]	Perforations may allow rats, birds access	Building sheathing easily infiltrated	Cardboard boxes	Gravel, concrete slab	Adventitious observation during use	Repair structural failures as found	Tactical pesticide application	
[3]	Perforations may allow mice access, window and door screens block insect access	Sheathing gnawed by rodents and insects	Chests, fabric bags, jars, dressers, cupboards, gaping cabinets	Pantry shelves, sit on wood floor, carpet	Daily familiarity, inspections associated with incidence	Repair exterior seal failures as found	Low temperature, easy to obtain (control moisture risk, refrigerant leak hazard)	Thorough cleaning after infestation is treated to reset for future inspection program
[4]	Perforations may allow large insects access	Some mineral sheathing less prone to rodent or insect attack	Sealed wood cabinets, adopted commercial display cases. Insect resistant bags (polyethylene)	Sealed wood or metal racking elevating objects from floor	Periodic inspection of exterior and interior. Incoming objects quarantined and visually inspected	Repair interior seal failures and interior building fabric to support preservation needs including pest exclusion	Controlled atmosphere fumigation, increases volume (assume high pressure gas supply hazard)	Managerial analysis of pest control problems. Accounting of basic capital and contract costs

Appendix 1B. Continued.

Level	Physical barrier	Physical resistance	Object enclosures	Object shelving	Detection	Maintenance	Suppression response	Recovery
[5]	Perforations may allow small insects access	Mineral or metal sheathing impedes rodents and insects	Some tight metal cabinets, rest wood with loose seals	Metal racking elevating objects from sealed concrete floor	Systematic use of rodent and insect traps to map problem areas, vulnerable objects inspected	Improve exterior building fabric to support preservation needs	Elevated temperature treatment, increases throughput (controlled incremental thermal aging above natural rate)	Make physical improvements through capital planning (passive features)
[6]	Perimeter control blocks insects (perimeter corridor increases detection)	Near seamless sheathing is resistant to rodent or insect attack	All metal cabinets, tight seals. Compactor system allows total floor cleaning	Compactor shelving	Sensitive collections visually inspected annually	Replace aging components before failure		Make procedural improvements (active features). Accounting of all internal labour costs
[7]	Hermetic	Metal can	All metal cabinets, vials, hermetic seals	High density, robotic retrieval warehousing	All objects visually inspected annually			

Appendix 2A. Level 0—Outdoors with unbridled access by deleterious agents.

Common circumstance	Plan B
Examples: Building exterior, totem pole, public sculpture.	
Site: Outdoors, rural or urban, may be sheltered by trees, buildings, landforms. May be well or poorly drained. May be windswept or sheltered. Urban sites are likely public spaces, rural sites may be remote with little visitation.	Some environmental modification may be considered if site is clearly deleterious: e.g., cutting back encroaching growth that physically disrupts, shelters pests, induces higher moisture content through casting shade, clinging vines that disfigure, obscure, present fire risk etc.
Building: No exterior enclosure, fully exposed to year round weathering, object sitting directly on ground.	There is considerable preservation justification for moving objects under shelter. If that is not possible, in situ techniques should be considered. Use bird netting or sheet material closures if the object is open to weather and collecting detritus or housing animals (e.g., large machinery, derelict buildings). Angled rain-caps used where possible to reduce roosting and bird detritus inducing rot (e.g., on pole tops, exposed beam ends).
Portable fittings: None.	Separate rot-prone objects from the soil they are resting on, use gravel, paved surfaces, a fungicide/insecticide treated wood shoring, short concrete plinth, or a self-draining moisture barrier (metal sheet fixture) to: reduce ground contact, slow fungal attack, force exposure of termite tubes to easy detection.
Procedure: None. Abandoned to fate.	Routinely remove grime, soil pockets (foundation for rapid biological activity), and all surface growths: lichen, mould, moss etc. Examine for insect infestations, especially wood borers that can lead to structural collapse. Likely use of residual pesticides or fungicides when warranted. Water-sealing wood to reduce moisture absorption is most effective on smooth surface, minimally weathered new wood. Deteriorated surfaces allow easy paths for water into the interior, supporting systemic fungal attack. All surface treatments need maintenance coats as the surface weathers. Borate fungicide and insecticide treatments are susceptible to water elution, but migrate effectively with moisture. Preservative fungicides and insecticides may colour surfaces unduly, test first. Subterranean portions near soil surface can be excavated, approved fungicide applied and surface drainage improved as the fastest attack generally occurs here (just above the water table, still oxygenated). Thank people for their contribution when they detect problems.
Prognosis: Maximum algal, fungal, rodent, and insect attack. Chronic bird and bat roosting. Systemic effects by all pests attacking the materials to which they are adapted to use.	Restrained algal, fungal, rodent, insect attack, and bird roosting. Surface to systemic effects still expected due to high exposure to the elements, but lowered extent of damage through detection and remediation.
Expected deterioration: Noticeable effect or damage in one season, as fast as to a dead tree, mammal, insect, or leaf. Colonization of obdurate items by algae, moss, fungi and plants in a few years. Forestalled effects showing in a few years for robust items, and a few days for delicate items. Self-sheltered parts of object will retain features as in level 1 (below) but eventually fail.	Noticeable effect or damage in one season. Forestalled effects showing within a decade for robust items, few days for delicate items. Self-sheltering parts of object will retain features as in level 1 but eventually fail.

Appendix 2B. Level 1—Roof or tarp only.

Provides basic shelter from rain and overhead sun, either from an architectural element, applied covering or self-sheltering part of the exposed object. Include appropriate elements from previous Plan B.

Common circumstance	Plan B
Examples: Poor enclosure in wind-way, car-port, shed-roof, tarpaulin cover.	
Site: Outdoors, rural or urban, may be windswept or sheltered by trees, buildings, landforms. May be well or poorly drained.	Some environmental modification may be considered if it is clearly deleterious. (e.g. cutting back encroaching growth that shelters pests, induces higher moisture content through casting shade, clinging vine cover that disfigures.) Eliminate obvious nearby pest attractors such as open garbage containers. Ensure roof closure is capable of re-buffing maximum snow and wind load.
Building: A roof or tarpaulin overhead with no complete wall. Structure protects from direct rainfall, preventing extensive fungal attack and limits any mould-requiring boring insect attack. However, structure will attract nesting birds, rodents, insects seeking shelter. Does not stop rodent, bird or insect access.	Roof must extend over the object to protect against slanting rain. Encapsulating with tarpaulins must allow ridge ventilation to protect against prolonged entrapment of high humidity which avoids making an inverted cup when enclosed to the ground. Bird netting, or spikes used where possible to reduce roosting detritus on rest of structure or sheltered objects. Coordinate construction of enclosing wire screens or cages with physical protection needs. Treat timber in soil contact with fungicides.
Portable fittings: None, contents of enclosure resting directly on earth, gravel or semi buried.	Where possible, separate objects from soil or gravel surface with a short plinth, or insert a moisture barrier to reduce moisture from contact with soil. Ensure the barrier drains properly so as not to cause a local puddle against the object.
Procedure: No pest control procedures other than beneficial contributions of original construction (e.g. mineral shingles, paint). Little site sanitation other than through wind and weathering processes.	Consider improvements in level 0 Plan B.
Prognosis: Rodent or bird contamination in one year, structural insect attack in under ten years, surface mildew within ten years. Many deleterious pests can still have widespread access to sheltered objects.	Noticeable extension in lifetime of smaller dimension timbers with remedial fungicide treatment, or break with soil, especially rapid deteriorating species. Reduction in disfiguring animal nests and some wood boring insects. Elimination of most structural fungal attack due to low moisture content of sheltered objects. Surface mildew, moss, lichen, algae still present as a risk in humid environments.
Expected deterioration: Noticeable effect or damage in one season. Forestalled effects showing within a decade to century for robust items, several years for soft, months for delicate. Self-sheltering parts of object will retain features as in level 2.	Noticeable extension in lifetime of timbers with remedial fungicide treatment. Several years for soft, months for delicate. Self-sheltering parts of object will retain features as in level 2.

Appendix 2C. Level 2—Roof, walls, and loose fitting doors.

This level provides more complete shelter from the elements. Contents may have exposure to wind driven rain, oblique sun, excessive wind and windblown soil, snow, spores and seeds. Include appropriate elements from previous levels.

Common circumstance	Plan B
Examples: Poor to fair enclosure: outbuilding, shed, poorly maintained house.	
Site: Commonly rural, sometimes urban. Drainage may have been improved by small rise in elevation under or against foundations. Subterranean foundation leaky. Structure may be sound if roof has been maintained, otherwise structural damage expected.	Where possible, clearing of vegetation away from walls to reduce moisture damage and root jacking of foundations. Removal of nearby dead timber to lower local incidence of wood boring pests and dead-fall hazards to structure. Improve drainage if ponding of water against foundation or inside is seen after any rainfall.
Building: Walls, wood, porous cladding, basic doors with gaps, floor of rammed earth, planks, plywood, gravel, asphalt, or separate concrete pad. Will not stop determined burrowing or gnawing pests as structural materials and wall construction is easily compromised. Protects against wind driven precipitation, thus halting major fungal attack. Does not bar insects due to gaps in structure. May limit large rodent and bird ingress but gaps let small animals take advantage of building as shelter. May attract roosting and nesting birds into eaves and insects into the building fabric.	Bird netting eaves or wire caging openings where possible to reduce animal ingress and subsequent detritus. Coordinate construction of enclosure with physical protection needs. Improve or fix exterior sheathing if it has been compromised.
Portable fittings: Contents resting on hard floor can become damp from permeating ground moisture and support fungi.	Rudimentary shelving limits moisture transfer from ground. Shelving lowers chance encounters with some pests. If appropriate shelving is not available, at least use preservative treated pallets, or wood wrapped in plastic sheeting to raise objects from earth contact. Large heavy items sited off the ground, resting securely on concrete pads, or baulks of treated timber.
Procedure: Animal nests removed, grounds-keeping around building consists of annual to monthly cutting back grass and foliage.	Routine sweeping of interior space to eliminate wind blown detritus and spider nests. Immediate removal of wasp nests, bird nests. Use fabric (moisture permeable) tarpaulins as drapes over complex, hard to clean objects, to reduce dust accumulation, block flies from spotting surfaces, and allow moisture permeation (drying) after humid periods and constrain surface mould.
Prognosis: Expect fly specks, rodent invasion, insects grazing, or crawling over stored materials, especially in cluttered, static, unexamined areas. Water-staining and possible fungal attack after heavy rain with winds. Pests have free range, so all contents can be affected.	Reduction in disfiguring animal nests, early remediation of pest attack by removal or targeted pesticide use.
Expected deterioration: Forestalled effects showing within a century for robust objects, decade for soft and year for delicate.	Reduction in frequency of many insect attacks compared to lesser sheltered situations. Minimum structural microbial activity, and greatly reduced surface activity.

Appendix 2D. Level 3—Basic Habitation.

Human housing with reasonable protection from climate, and coarse control of the interior environment with basic heating or ventilation. Include appropriate elements from previous levels.

Common circumstance	Plan B
Examples: Fair enclosure: western housing into last century, public buildings like churches, palaces. Average maintained historic civic buildings, temples, and shrines.	
Site: Garden landscapes, walkways, lanes, streets. Drainage to open ditches, roadways, rudimentary sewer.	Limit growth of trees and shrubs against structure to protect vulnerable foundations against root-jacking.
Building: Reasonable attempt at full enclosure from bad weather to make a liveable building with some comfort through annual climate cycle. Gaps generally small if building has basic heating, but exterior cladding may allow determined or intermittent rodent access. Has single doors for egress, loose fitting sash windows, possibly no screens. Internal partition walls exhibit crevices along floor that can house insect life. Open fireplaces, flues, hypocausts, rough attics allow bird, rodent and insect access into structural voids. Some natural ventilation is possible to alter interior temperature or humidity, but there is no air conditioning system.	Use of screen doors and windows to reduce insect ingress and allow ventilation. Reducing structural gaps and spaces around habitually used openings (doors, windows) to half a centimetre to limit rodents. Ensure eaves trough has outflow pipes to carry water well away from foundations, reducing mould. Screen unused flues at roof level to block bird and insect access. Use heavy gauge plastic sheet 'soil covers' over enclosed earth-floor crawl spaces. Ensure good screened ventilation of this space to further reduce humidity, otherwise wood structural piles are prone to fungal and insect attack.
Portable fittings: Exhibited objects are inside the building as originally used (historic interior), but other objects are stored in closed rooms on shelves, within open or gaping boxes. Some contents may be in cabinets for security, but insect resistance of enclosures is generally poor.	Place vulnerable objects in well sealed display or storage cabinets (gaps less than 0.1 mm to 0.3 mm). Consider portable dehumidifiers to restrict humidity under 75% in short damp season (i.e., two months), and under 65% in year-round high humidity climates. Consider using polyethylene bag enclosures (enclosed during dry season), or fabric covers for soft items in storage to reduce pest incidence. Delicate items placed in lidded boxes or cabinets.
Procedure: Spring and fall cleaning, household vacuuming, dusting of exhibits may also occur when build up of dirt noticed.	Do not place things in underground levels if you cannot ensure good ventilation and flood control. Animal inspection of attic and basement areas for severe pest problems, these are often more open and fulfilling of pest's needs than the inhabited floors.
Prognosis: Multiple rooms can be affected, chronic outbreaks of paper and fabric pests could be supported. Storage in damp basements or attics are a retrograde choice.	Lessened chronic fly and dermestid problems with increased control over attic space. Lessened silverfish and mouse problems with increased control over basement and crawl spaces.
Expected deterioration: Forestalled effects equivalent to building lifetime for robust objects, decades to century for soft and years for delicate.	Lessened rodent, insect and fungal damage with increased building closure and routine sanitation activity.

Appendix 2E. Level 4—Commercial adapted.

Adapted civic structures built to handle large scale inhabitation, industrial process, project social status. Include appropriate elements from previous levels.	
Common circumstance	Plan B
Examples: Good enclosure: basic professional, commercial, or civic building adapted to museum archive or gallery use.	
Site: Drainage ensured close to foundation walls, but overall site may not yet be adapted to 100 year weather extreme, or is affected by adverse elements from neighbouring properties (strong attractors).	Consider flood hazard and rodent habitat reduction in site development planning.
Building: Commonly has a mineral exterior surface. Has multiple doors to stage egress to the exterior, a mudroom, or a divided entrance hall. Single layer of doors such as emergency exits are sealed tightly against pests with brush strips, rubber blades, rodent proof metal doors. Structure has HVAC system for air conditioning, heating, forced air movement.	Improve sealing of doors, windows, and other perforations, to prevent pest access. Interior partitions should be improved to limit rodent travel through reduced gaps under doors and screening accessible perforations.
Portable fittings: Exterior garbage bins or designed loading bay garbage collection area (bay is inside one exterior door, but has a well fitting inner door to cut it off from corridor). More extensive use of display cabinets, may not all be insect proof, but greatly lower incidence of insect infiltration. All collections on shelving, or palletized. May not have easy access throughout storeroom for pest inspections due to over-crowding. Hallways also used as overflow storage.	Create an enclosed space for quarantine of incoming goods, artefacts and for disinfestation treatments of new acquisitions. Obtain chest freezer, cool fumigation bubble or nitrogen treatment chamber and train several staff in proper and safe use complying with regulations. Include inspection needs in collection rehousing activities.
Procedures: Basic visual inspection of collection from familiarity through use, few traps used in areas with major exterior openings. Annual storage room sanitation limited to vacuuming, but only in corridor spaces, not under lower shelves. Gallery cleaning more frequent, but does not keep up with dust, litter, hair, etc. that is depositing in restricted spaces.	Annual cleaning reduce clutter, vacuum under shelving, view rarely accessed collections. Quarantine and eradicate pests before objects introduced to collections. With an established IPM program and low internal pest incidence, new collections are the highest risk for introducing infestation, along with used packaging and food service activities. Disposing garbage (especially foods) on a daily basis and immediately clean spills. Contract pest control operator (PCO) for public food areas. PCO activity in collection areas only if heavily infested and needing remedial action (baseboard sprays only, avoid area fumigation or pesticide application to objects). Trapping program to detect pests. With reasonably tight enclosure of the building trapping will tell more about what is going on in collections than what is crawling through the building that day.

Appendix 2E. Level 4—Continued.

Adapted civic structures built to handle large scale inhabitation, industrial process, project social status. Include appropriate elements from previous levels.	
Common circumstance	Plan B
Prognosis: Expect local outbreaks of pests, derived from importing pests with objects more than from building infiltrations, less chance of rodent damage, more from insects.	Reduction in chronic textile, fur and skin pests. Annual levels may be chronic but should become low in incidence and severity.
Expected deterioration: Forestalled effects equivalent to building for robust, century for soft, and decades for delicate.	Less frequent infestation by insects than previous level.

Appendix 2F. Level 5—Purpose built.

Designed as museum, gallery, or archive with increased planning that integrates policies and features to include pest control with control of other deteriorating agents. Include appropriate elements from previous levels.

Common circumstance	Plan B
Examples: Purposely designed as museum, archive, or gallery. Improved enclosure for preservation requirements, enhanced commercial construction.	
Site: Site planning includes perimeter control of neighbouring risks, through environmental modification (e.g., creation of buffer zones, controlled ponding of water and pruning of dense foliage to lower fire hazard.)	
Building: Designed with consideration for pest control such as fumigation room to support freezers, controlled atmosphere chamber and quarantine needs. Smooth flooring, coved junctions to walls for easy sanitation. Light coloured finishes and good lighting to assist detection. Pest resistant exterior wall materials and reduction of crevices in construction to lower HVAC losses and reduce wall moisture issues.	Crevices discovered to be housing insects are remedially caulked with appropriate sealant. Exterior window seals maintained promptly to exclude wall moisture risk, and improvements made in sealing of all exterior doors as flawed installation is discovered or materials fail. Improve HVAC filtration to "MERV 9" to eliminate mould spore and pollen transport via HVAC system.
Portable fittings: Intensive use of protective cabinets increases need for planned visual inspection. Many objects not regularly seen so there is a delay in finding outbreaks without deliberate inspection. Little consideration taken for cleaning underneath displays over the long term of a static gallery's life, high traffic brings accumulating littler, some of which can support pest life. Enclosed exhibits constructed to a level of tightness that excludes insects (0.1 mm to 0.3 mm). Possesses fumigation capability either as toxic gas, controlled atmosphere, or walk-in freezers (−25°C to −30°C) of sufficient size to handle routine volumes of artifacts.	Extensive gallery and modern exhibit techniques will have lots of pest hiding places adjacent to visitor traffic, so consider reducing this long term hazard through designed ease of access. Prompt removal of food garbage, which should all be in closed containers and emptied daily to reduce support for mice.

Appendix 2F. Level 5—Continued.

Designed as museum, gallery, or archive with increased planning that integrates policies and features to include pest control with control of other deteriorating agents. Include appropriate elements from previous levels.	
Common circumstance	Plan B
Procedure: Comprehensive trapping for insect detection with adhesive traps, bird proofing of structure. Will have commercial PCO for on-site restaurant. Permanent cleaning staff and security not trained in IPM concerns. All new acquisitions subject to quarantine, inspection, and pest eradication processes. International loans of objects must not include packaging that is in contravention of current import/export restrictions to limit the spread of wood pests, use only certified use wood (heat treated).	In larger institutions consider using a zoned IPM system to emphasize most vulnerable areas needing special precautions and protection against pests. Annual visual inspection of most sensitive and valuable objects. Give all permanent staff basic IPM training to sensitize them to pest problems and methods. Elevated degree of store room sanitation recognized as pest reduction activity. Annual cleaning of non-traffic areas including under-shelf spaces in storage rooms.
Prognosis: Sporadic outbreaks associated with non-collections areas and events. Older storage cabinets may continue to show higher incidence of infestation due to their porous structure, and pests living within monolith arrangements of cabinets.	Sporadic pest problems with new collections and returning loans.
Expected deterioration: Forestalled events equivalent for robust and soft objects, century for delicate.	Same as left or less frequency of sporadic issues due to early intervention and effective remediation.

Appendix 2G. Level 6—Preservation designed.

Collections facility with primary function of long term preservation. Provides excellent enclosure, with multiple-layers to intercept routine hazards and engineered to reduce calamities. Include appropriate elements from previous level.

Common circumstance	Plan B
Examples: Purpose-designed preservation enclosure; full spectrum of pest reducing features incorporated such as cool temperature herbarium collection building, refrigerated ethnographic fur storage room, extensive use of tightly sealed cabinetry for all collections.	
Site: Preparation conforms with need to fully manage expected 100 year weather extremes. Exterior plantings controlled, sanitary perimeter managed as Level 0, plan B. Use food processing plant techniques such as gravel borders on geo-textile to lower rodent pressure (see Imholte 1984). Manage exterior wall under protective eaves as Level 1 plan B.	
Building: Design process based on collection preservation needs. Construction phase monitored by people cognizant of collection needs. Perimeter corridor buffers storerooms. Poured concrete, slab/wall junctions sealed and maintained. Separate storage from high human occupancy operations. Floor sweep on interior doors restricts insect motion. Pipe and wiring chases minimize wall perforations, holes sealed with appropriate means to retain room to room quarantine. Built-in vacuum limits dust redeposition, or portable HEPA units used. Tightly sealed cabinets throughout. HVAC designed to eliminate particulate contaminants and reduce chemical pollutants if there is significant storage on open shelving lowers mould spore loading. Pest control facility near loading bay provides quarantine and treatment including sufficient room to store exhibit packaging. Cooled food waste and garbage storeroom.	Well filtered HVAC (MERV 13+) to eliminate particulate contaminants including dust mite faeces. Plan cool room storage to inhibit insect motion and lower chemical deterioration rate (e.g., rooms at 15 degrees C). Requires careful design and commitment to maintenance and energy use. Construction project managed with strict control of details such as vapour barriers due to high performance expectations of the building envelope. Structure and contents disinfested prior to occupation, requires coordination of pest control operations in collection move phase.

Appendix 2G. Level 6—Continued.

Collections facility with primary function of long term preservation. Provides excellent enclosure, with multiple-layers to intercept routine hazards and engineered to reduce calamities. Include appropriate elements from previous level.

Common circumstance	Plan B
Portable fittings: Light traps to draw insects out of loading bay. Bird curtains or shrouds connected to truck trailers block most pest access when doors are open. Appropriate system (−20 degrees C to −30 degrees C freezer, controlled atmosphere fumigation, heat chamber) for eradicating infestation of new acquisitions.	Cabinet integrity protected with annual inspection and maintenance plan. Near hermetic storage (e.g., film canisters) can be used for most valuable and vulnerable items in long term storage. All disinfested object sealed in pest resistant enclosures, possibly refrigerated, possibly with altered storage atmosphere. Walk-in storage freezers with redundant power supply used for routine pest control.
Procedure: Structural flaws promptly maintained, harbourage caulked. Routine trapping near openings of each room and vulnerable collections databased and mapped for long term analysis. Annual visual inspection of susceptible collections. For human comfort temperature storage: contents sanitized, sterilized, fumigated, cleaned before being hermetically sealed or deposited in tight pest resistant containers. Bagged, vials, boxed artifacts all placed in pest resistant cabinets. Visual inspections to confirm integrity of seals, and absence of pests on annual basis. For refrigerated storage: all contents prepared sealed against refrigeration failure and moisture movement, have recovery plan for mechanical failure. Train new staff in IPM policies and methods. Maintain work relationships through IPM committee and informal connections with staff who encounter pests (security, maintenance, food services).	
Prognosis: Few pest issues in storage environment, more found by floor trapping than cabinet visual inspection. Incidental pests in gallery spaces due to human traffic and food service.	Sporadic pest problem, mostly with new collections and returning loans.
Expected deterioration: Forestalled events equivalent to structure for robust to delicate objects. Long term object survival tied to cultural survival (available energy or interest remains).	

Temperature and humidity considerations for the preservation of organic collections — the isoperm revisited

Paper 6

STRANG, T.J.K AND D. GRATTAN. 2009. TEMPERATURE AND HUMIDITY CONSIDERATIONS FOR THE PRESERVATION OF ORGANIC COLLECTIONS — THE ISOPERM REVISITED. E-PRESERVATION SCIENCE, 6:122–128. E-ISSN 1581 9280

Division of contribution

Dr. Grattan, in the course of examining the scientific support for sustainability related claims in preventive conservation, extended an invitation to T. Strang to confirm the arithmetic derivation of a proposed isoperm equation from which Grattan had also extracted a useful form by the quadratic root approach. Strang's interest was allied, considering the relative cost from ambient temperature of net loss of 'object lifetime' through thermal treatments, for which Michalski incorporated greatly elevated temperature projections in presentation of 'time out of storage' in his CCI Technical Bulletin 23 *Guidelines for Humidity and Temperature for Canadian Archives*. Strang provided a modification of the equation of paper six to its present form, undertook extensive background literature review some of which was used to set the context for the mathematics in paper six and the remaining for subsequently planned papers. Strang drafted paper six, submitted the text with responses to reviewers mainly written by Strang with suggestions by Grattan.

Errata

Citation in text of Monleón et al. should have read: Monleón Pradas et al.

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FULL PAPER

TEMPERATURE AND HUMIDITY CONSIDERATIONS FOR THE PRESERVATION OF ORGANIC COLLECTIONS - THE ISOPERM REVISITED

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Since Sebera published his paper on Isoperms in 1994, much has changed. A significant amount of data has accumulated on the mechanism of paper degradation, more activation energies have been determined and there has been a convergence of values. Assumptions about the relationship between the relative humidity and the moisture content or the rate of degradation of paper need no longer be made as near complete theoretical descriptions are available. The method of modelling has therefore been revised and now incorporates the Arrhenius equation and the moisture sorption isotherm, which is best modelled by the Guggenheim-Anderson-deBoer (GAB) equation. This new method will allow direct experimental verification of the isoperm for cellulosic materials in museum collections. As the cost of energy usage for preservation has now become an important question, it is particularly critical to have access to more accurate isoperms.

1 Introduction

The following argument is based on the notion that it is the concentration of water in the cell wall of the paper fibres (where the chemical processes of deterioration actually occur) rather than the concentration of water vapour in the atmosphere (the RH), which has a direct impact on the rate of degradation of paper. In the conventional understanding of reaction kinetics it is concentration of reactant which controls rate of reaction, hence it would be surprising, if a parameter which is only indirectly related to reactant concentration i.e. RH had a simple direct controlling influence on rate of reaction – i.e. degradation. This assumption that moisture content - which expresses the water concentration in the cell wall - has a direct controlling influence has been used in CCI's approach to accelerated ageing for paper for some time now, and we have used constant moisture content rather than constant relative humidity at all elevated temperatures in our ageing protocols. We support this notion in two ways - one is that there is evidence of the direct relationship with moisture content in

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the work of Zou, Uesaka and Gurnagul[1]. Their data is plotted in Figure 1 below to demonstrate this relationship.

The second point is that even if some may consider that the evidence is indecisive on whether it is RH or moisture content which has a direct controlling influence on reaction rate - we should at the very least calculate the isoperms for both situations.

Sebera proposed the isoperm[2] as a quantitative tool for predicting "preservation outcome" as part of a greater preservation strategy for protecting collections of paper. His Isoperm plot is shown in Figure 2.

The isoperm is a line of constant permanence (or deterioration rate) on a graph of humidity versus temperature. The line that runs through the standard museum set point at 50% RH and 20ºC is arbitrarily set at unity, as the reference line, and other lines are established relative to this at half or double the permanence etc.

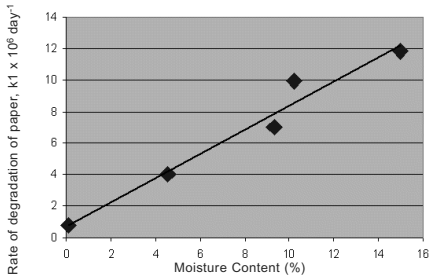

Figure 1: The rate of deterioration of paper versus moisture content Zou, Uesaka and Gurnagul data.[1]

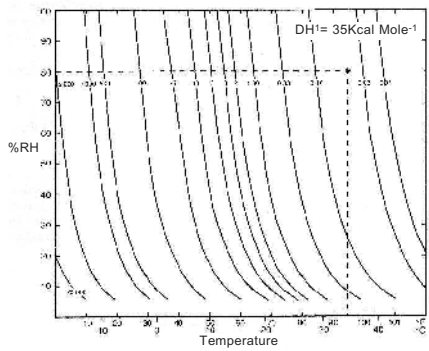

Figure 2: Sebera isoperm as a quantitative tool for predicting "preservation outcome".

Thus at a glance the impact of altering the conditions on degradation can be determined. This approach has been applied by others to paper and to other materials for which deterioration rates have been determined, such as cellulose acetate film stock (Riley, Image Permanence Institute - IPI[3]). All except the IPI method have assumed simple proportionality between degradation rate and relative humidity as did Sebera and thus all their predictions about rate must be open to question. The IPI method, unfortunately, remains somewhat opaque, as the derivation has not been published.

Sebera expresses the isoperm through this equation where:

$$\frac{P_2}{P_1} = \frac{r_1}{r_2} = \frac{RH_1}{RH_2} = \frac{MC_1}{MC_2} \qquad (1)$$

P is the symbol for *permanence*, the inverse of deterioration rate
r is the *deterioration rate*, a measurable rate of loss of a key property
RH is the *relative humidity* of storage or display
MC is the *moisture content* of the stored paper
subscript 1 represents the initial or reference state
subscript 2 represents a proposed state for comparison

For the following discussion, water concentration in units of weight of water per unit weight of substrate has been replaced by the percent moisture content (MC) which has the same units x100. This substitution was carried out for reasons of convenience and because moisture content is a better known and more easily accessible parameter.

$$[H_2O] \propto MC$$

For convenience and clarity in the equations the water activity Aw which is equivalent to %RH/100 is used rather than relative humidity RH, and Sebera's rate terms r_1, r_2 are substituted by the k_1 and k_2, the symbols normally employed to express rate in kinetic expressions such as the Arrhenius equation.

Grattan noted[4] that Sebera's assumption:

$$\frac{RH_1}{RH_2} = \frac{MC_1}{MC_2} \qquad (2)$$

is not consistent with the sorption isotherm, because it describes a simple linear relationship, whereas it is very well established that the relationship is an "S" shaped curve. Linearity is only roughly approximate in the middle of the moisture sorption isotherms that characterize most structural organic materials. There is significant non-linearity at the dry and damp ends where the greatest protection and maximum deterioration occur.

The relationship is more properly described by *MC = f (RH) or [H_2O] = f (A_w)*. Many equations

have been proposed to describe this function[5]. After a review of sorption isotherms for paper products and applicable models, Parker et al.[6] determined that the Guggenheim-Anderson-deBoer equation (GAB) was the most effective representation of paper moisture sorption. It is limited (less accurate) only where pore filling begins to dominate at a relative humidity in excess of 95%.

Real gains in preservation occur in cool dry conditions whereas the highest rate of loss is in a damp and warm environment. Modifying storage and display environments to extend object lifetime (to create what is often called a "stable environment'') yields a cost or a benefit accrued over time, that is related to the degree of deviation from the climatic norm. The isoperm thus needs to be recalculated in light of its potential influence in stipulating environmental standards for preservation, and particularly in balancing energy efficient building design with collections care. To do so will call on the best knowledge of paper permanence and challenge our lack of knowledge about thermal deterioration rates in many materials besides paper found in collections.

Zou et al.[1] reviewed the literature and showed experimental evidence to support a linear relationship between moisture content (n.b. not relative humidity) and a first order rate constant for the hydrolysis (or hydrolytic deterioration) reaction. So, for the isoperm model to estimate *permanence* (3) it must calculate a deterioration rate correlated to relative moisture contents of the reference state and the proposed state.

$$\frac{P_2}{P_1} = \frac{MC_1}{MC_2} \times \frac{k_1}{k_2} \qquad (3)$$

It is an equation which, interestingly, is in partial agreement with Sebera's equation. However, environmental controls are specified in terms of temperature and relative humidity. To resolve this problem two equations are substituted into the model:

$$\frac{P_2}{P_1} = \frac{GAB_1}{GAB_2} \times \frac{k_1}{k_2} \qquad (4)$$

The GAB equation to give moisture content:

$$M = \frac{M_o K C A_w}{(1 - KA_w)(1 - KA_w + CKA_w)} \qquad (5)$$

And the Arrhenius equation to provide *k*:

$$k = \mathcal{A} \exp \frac{-\mathcal{E}_a}{RT} \qquad (6)$$

Where:
T is temperature (°K)
ε_a activation energy (J/mol/°K)
A is the pre-exponential or frequency factor
R is the gas constant} 8.314 (J/mol/°K)

M is the *equilibrium moisture content*, dry basis
M_o is the *mono-layer moisture content*
K is the difference in state between pure liquid and upper layers
C is the difference in state between the mono-layer and upper layers
A_w is the *water activity*

The Arrhenius contribution k_1/k_2 expands as:

$$\frac{k_1}{k_2} = \frac{\mathcal{A}_1}{\mathcal{A}_2} \times \frac{\exp \frac{-\mathcal{E}_a}{RT_1}}{\exp \frac{-\mathcal{E}_a}{RT_2}} \qquad (7)$$

which can be represented as:

$$\frac{k_1}{k_2} = \frac{\mathcal{A}_1}{\mathcal{A}_2} \times \exp \frac{\mathcal{E}_a}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \qquad (8)$$

Pre-exponential factors (*A* values) are commonly considered as temperature independent and hence constant and thus could be cancelled. Even so, this constancy is always qualified as being for "small temperature" differences only, without "small" being properly characterized. From the original derivation of the Arrhenius model, *A* has been taken to represent the product of the number of activated molecules times the frequency of collision[7]. However, *A* is indicated to be mildly temperature sensitive[8] as:

$$\mathcal{A} = 10^3 N_A (r_a + r_b)^2 \left(\frac{8\pi kT}{\mu} \right)^{\frac{1}{2}} \qquad (9)$$

where r_a and r_b are the radii of two spherical reactants.

This relationship implies, by collision theory, that *A* is proportional to $\sqrt{T}$ but difficult to measure due to the "long extrapolation of the Arrhenius plot to $1/T = 0$".[8]

It is easy to dismiss the possibility of *A* having a temperature dependence, because it might be considered that the practical storage temperature range may not prove enough to change the ratio of A_1/A_2. However, the possibility exists that the *A* values are different. Zou et al.[9] redefine *A* as A_a which contains all the moisture related contributions to deterioration (see their section 2.1). As we are changing the moisture concentration, and there is a possibility $A_{1,2}$ could be determined with some precision[10] our model substitutes A_1/A_2 with GAB_1/GAB_2 to describe the influence of moisture in calculation of the isoperm.

Adding the Guggenheim, Anderson-deBoer (GAB) equation to relate relative humidity to moisture content gives the isoperm equation as: (10)
where the fixed parameters are:
P_1 the permanence, set as 1 "lifetime"

$$\frac{P_2}{P_1} = \frac{\frac{M_{o1}K_1C_1A_{w1}}{(1-K_1A_{w1})(1-K_1A_{w1}+C_1K_1A_{w1})}}{\frac{M_{o2}K_2C_2A_{w2}}{(1-K_2A_{w2})(1-K_2A_{w2}+C_2K_2A_{w2})}} \times \exp\frac{\mathcal{E}_a}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \quad (10)$$

$$\frac{P_2}{P_1} = \left(\frac{RH_1}{RH_2}\right)\left(\frac{T_1+460}{T_2+460}\right)^{10^{394}\Delta H^{\ddagger}\left(\frac{1}{T_2+460}-\frac{1}{T_1+460}\right)} \quad (11)$$

A_{w1} the water activity set to 0.50 (50% RH as p_o/p_i)
T_1 set to 293.15 °K (20 °C)
ε_a set to the activation energy of the material (J/mol/ °K)
R the gas constant, is 8.314 (J/mol/°K)
M_{o1} is the material's GAB monolayer moisture constant at 20 °C, 50% RH
K_1 is the material's pure liquid to upper-layer GAB parameter (20 °C, 50% RH)
C_1 is the material's monolayer to upper-layer GAB parameter (20 °C, 50% RH)

And solving for A_{w2} in each case with the variables:
T_2 set to the comparison temperature (°K)
M_{o2} from the GAB fit of the sorption isotherm at T_2
K_2 ditto
C_2 ditto
P_2 set to the desired 'lifetime multiplier"

The isoperms can be calculated by incrementing or decrementing the ratio P_2/P_1 (the lifetime multiplier) in integral units such as by two or three or by half etc. where P_1 is set to unity, and solving for A_{w2}. This humidity value is then checked against the GAB equation's limits of reasonable application: ($0 < A_{w2} > 0.95$), and plotted if it is within bounds. Once the search along the isotherm is exhausted we change to a new temperature T_2 and matching isotherm.

To carry out this work over a significant area, each material requires a family of sorption isotherms from 0.0 to 0.95 A_w, and deterioration rate data.

The newly proposed isoperm model is a function of the Arrhenius and GAB equation parameters:
A_{w2}=function(e_a,T_1,T_2,A_{w1},M_{o1},K_1,C_1,M_{o2},K_2,C_2,P_1,P_2)

As an example calculation, the reference point for permanence is P_2/P_1= 1 at T_1 = 20 °C and A_{w1} = 0.5 which requires:

$$GAB_1 = f(T_1, A_{w1}, M_{o1}, K_1, C_1)$$

where A_{w1} defines the point on the reference isotherm curve for T_1. The comparison point is defined as the series of positive fractions (isoperms) P_2/P_1 which lie on the isotherm:
$GAB_2 = f(T_2, M_{o2}, K_2, C_2)$
A_{w2} is the unknown to be calculated from a derivation of the revised isoperm equation (4) at the specified P_2/P_1. Any A_{w2} value outside the validity range ($0 < A_w > 0.95$) for the GAB_2 equation is discarded.

For comparison, Sebera's combined equation for the isoperm is (11) uses the Eyring term for which there is no data available instead of the Arrhenius relationship for which a significant amount of experimental data exists. To quote Sebera: "these equations can be evaluated algebraically to obtain a quantitative evaluation of permanence changes". (Note that Sebera's temperature is in Fahrenheit units).

2.1 Derivation of isoperms from Zou et al. paper degradation model

Isoperms can also be derived from Zou et al.'s model[1,9]. Using Zou et al.'s equation (12) directly builds on the Arrhenius data by partitioning the pre-exponential factor into several influences: oxidative reactions, water, and pH, and denoting this expansion as

$$\mathcal{A}_a = \mathcal{A}_{a0} + \mathcal{A}_{a2}[H_2O] + \mathcal{A}_{a5}[H^+][H_2O] \quad (12)$$

where:
A_{a0} is non-moisture, non acidity related degradation, 4.54 x10^9 day^{-1}
A_{a2} water concentration/moisture content related degradation, 2.83 x10^{12} day^{-1}
A_{a5} acidity related degradation, 9.85 x 10^{16} Lmol^{-1} day^{-1}

The relative importance of these is dealt with in Zou et al.[9] further reducing equation (12) to:

$$\mathcal{A}_a = \mathcal{A}_{a0} + \mathcal{A}'_{a2}[H_2O] \quad (13a)$$

where:

$$\mathcal{A}'_{a2} = \mathcal{A}_{a2} + \mathcal{A}_{a5}[H^+] \quad (13b)$$

If we substitute the GAB equation into the water concentration term [H_2O] of equation (13a), the resulting A_a factor can be interpreted in terms of water activity A_w (and thus RH) and allow predictions to be made for the effect of storage RH as originally intended by Sebera's isoperm model. The relationship so derived is thus consistent with current deterioration theory, based on tested Arrhenius principles, and on empirical data from well understood procedures.

It can be safely assumed that the non-moisture related, non hydrolytic pH influenced oxidation and

starting [H+] terms are equal for reference and comparison condition, they can be ignored and the resultant model becomes similar in form to new isoperm model proposed above in equation (10) as well as retaining most of the fractional A_w value (Zou et al.'s A_{a0} is 1000 times less than A_{a2}).

The permanence ratio is given in equation (14) which is a restatement of equation (4).

$$\frac{P_2}{P_1} = \frac{GAB_1}{GAB_2} \exp \frac{\mathcal{E}_a}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \quad (14)$$

As discussed by Zou et al.[9], the moisture driven hydrolysis reaction as described by A_{a2} is generally the greater contributor of the three A_a terms, and specifically so in alkaline conditions. We could then argue the other terms could be ignored outright. However there is a caveat by which we would expect the new model (14) to be an overestimate of permanence. This equation reflects the 'start condition' only, and does not integrate changes during ageing. In non-alkaline papers we expect pH shift during ageing, approximately one pH point or tenfold [H+] increase , which would decrease permanence in the moister comparison samples (P. Bégin, pers. com.).

The complete definition following from Zou et al.'s equation retaining the significant terms from equation (12) is presented in equation (15).

After reviewing the sources, we can modify either the Sebera or Zou et al. models in similar fashion to properly describe the isoperm.

2.2 Finding the solution to the Grattan-Strang model

To derive an equation for A_{w2} that can be calculated, we continue with equation (14) (see equations 16 to 18).

To ease manipulation we can symbolize the ratios of fixed values and other segments.

Where:
The *GAB* parameter ratio

$$\mathcal{S}_{1,2} = \frac{M_{o1} K_1 C_1}{M_{o2} K_2 C_2}$$

The GAB_1 denominator is
$gab_1=(1-K_1A_{w1})(1-K_1A_{w1}+C_1K_1A_{w1})$
The GAB_2 denominator is
$gab_2=(1-K_2A_{w2})(1-K_2A_{w2}+C_2K_2A_{w2})$

Applying the symbolic representation gives:

$$\frac{P_2}{P_1} = \mathcal{S}_{1,2} \times \frac{A_{w1} \times gab_2}{A_{w2} \times gab_1} \times arr_{1,2} \quad (19)$$

Rearrangement to put the two terms containing A_{w2} together gives:

$$\frac{A_{w2}}{gab_2} = \mathcal{S}_{1,2} \times \frac{A_{w1}}{gab_1} \times arr_{1,2} \times \frac{P_1}{P_2} \quad (20)$$

As they are all known quantities for the purpose of a single calculation, the right hand side can be reduced to a constant:

$$\mathcal{N} = \mathcal{S}_{1,2} \times \frac{A_{w1}}{gab_1} \times arr_{1,2} \times \frac{P_1}{P_2} \quad (21)$$

The full isoperm equation becomes:

$$\frac{A_{w2}}{gab_2} = \mathcal{N} \quad (22)$$

Rearranging:

$$0 = \frac{A_{w2}}{gab_2} - \mathcal{N} \quad (23)$$

$$0 = A_{w2} - \mathcal{N}\, gab_2 \quad (24)$$

Rearranging terms to solve for A_{w2} (see equations 25 to 31) and setting constants:

$$\alpha = K_2^2(1 - C_2)$$

$$\beta = (C_2K_2 - 2K_2 - 1/\mathcal{N})$$

$$\gamma = 1$$

Substituting α, β and γ reveals the quadratic:

$$0 = \alpha A_{w2}^2 + \beta A_{w2} + \gamma \quad (32)$$

Taking the roots of the quadratic yields:

$$A_{w2} = \frac{-\beta \pm \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha} \quad (33)$$

Back substitution of α, β and γ in equation (33) yields equation (34), providing a solution of the Isoperm in water activity units where water activity is equal to %RH/100 or the relative moisture vapour pressure. Below 50 °C the deviation of water activity from this definition is less than 0.2 % from actual measurements.[11,12]

3 Conclusion

The evidence supporting our approach to modelling the isoperm hinges on a linear relationship based on five data points in Zou et al.[1] At present this is only confirmed for 90 degree centigrade exposure. However, from a qualitative standpoint it is logical that the moisture in the cell wall (rather than in the air) will be rate determining. This being the case, it is necessary to examine the situation by employing a more likely relationship between moisture content and degradation. Our model corrects Sebera's simplifying assumption that $RH_1/RH_2=MC_1/MC_2$ and directly represents the measured concentration of water. And this is not just an academic question because current RH guidelines for museums and archives are based on Sebera's calculation. We need therefore to examine the impact of making a more likely assumption

$$\frac{P_2}{P_1} = \frac{\mathcal{A}_{0_1} + \mathcal{A}_{a2_1} GAB_1 + \mathcal{A}_{a5_1}[H^+]GAB_1}{\mathcal{A}_{0_2} + \mathcal{A}_{a2_2} GAB_2 + \mathcal{A}_{a5_2}[H^+]GAB_2} \times \exp\frac{\mathcal{E}_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (15)$$

$$\frac{P_2}{P_1} = \frac{\frac{M_{o1}K_1C_1A_{w1}}{(1-K_1A_{w1})(1-K_1A_{w1}+C_1K_1A_{w1})}}{\frac{M_{o2}K_2C_2A_{w2}}{(1-K_2A_{w2})(1-K_2A_{w2}+C_2K_2A_{w2})}} \times \exp\frac{\mathcal{E}_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (16)$$

$$\frac{P_2}{P_1} = \frac{M_{o1}K_1C_1}{M_{o2}K_2C_2} \times \frac{\frac{A_{w1}}{(1-K_1A_{w1})(1-K_1A_{w1}+C_1K_1A_{w1})}}{\frac{A_{w2}}{(1-K_2A_{w2})(1-K_2A_{w2}+C_2K_2A_{w2}}} \times \exp\frac{\mathcal{E}_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (17)$$

$$\frac{P_2}{P_1} = \frac{M_{o1}K_1C_1}{M_{o2}K_2C_2} \times \frac{A_{w1}(1-K_2A_{w2})(1-K_2A_{w2}+C_2K_2A_{w2})}{A_{w2}(1-K_1A_{w1})(1-K_1A_{w1}+C_1K_1A_{w1})} \times \exp\frac{\mathcal{E}_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (18)$$

$$0 = A_{w2} - \mathcal{N}(1-K_2A_{w2})(1-K_2A_{w2}+C_2K_2A_{w2}) \quad (25)$$

$$0 = A_{w2} + (-\mathcal{N} + K_2A_{w2}\mathcal{N})(1-K_2A_{w2}+C_2K_2A_{w2}) \quad (26)$$

$$0 = A_{w2} - \mathcal{N} + K_2A_{w2}\mathcal{N} - C_2K_2A_{w2}\mathcal{N} + K_2A_{w2}\mathcal{N} - K_2^2A_{w2}^2\mathcal{N} + C_2K_2^2A_{w2}^2\mathcal{N} \quad (27)$$

$$0 = A_{w2} - \mathcal{N} + K_2\mathcal{N}A_{w2} - C_2K_2\mathcal{N}A_{w2} + K_2\mathcal{N}A_{w2} - K_2^2\mathcal{N}A_{w2}^2 + C_2K_2^2\mathcal{N}A_{w2}^2 \quad (28)$$

$$0 = \underbrace{C_2K_2^2\mathcal{N}A_{w2}^2 - K_2^2\mathcal{N}A_{w2}^2} + \underbrace{K_2\mathcal{N}A_{w2} + K_2\mathcal{N}A_{w2} - C_2K_2\mathcal{N}A_{w2} + A_{w2}} - \mathcal{N} \quad (29)$$

$$0 = (C_2K_2^2\mathcal{N} - K_2^2\mathcal{N})A_{w2}^2 + (2K_2\mathcal{N} - C_2K_2\mathcal{N} + 1)A_{w2} - \mathcal{N} \quad (30)$$

$$0 = (-C_2K_2^2 + K_2^2)A_{w2}^2 + (-2K_2 + C_2K_2 - 1/\mathcal{N})A_{w2} + 1 \quad (31)$$

$$A_{w2} = \frac{-(C_2K_2 - 2K_2 - 1/\mathcal{N}) \pm \sqrt{(C_2K_2 - 2K_2 - 1/\mathcal{N})^2 - 4(K_2^2(1-C_2)) \times 1}}{2(K_2^2(1-C_2))} \quad (34)$$

on which to base the Isoperm and investigate the effect this would have on changes in permanence induced by temperature and RH change. If it makes little or no difference regardless of how we calculate the Isoperm - then the point becomes merely academic, but if the difference is substantial then it will become a priority to substantiate the work of Zou et al.

The recalculation of the isoperm concept requires detailed knowledge of two equations: the Arrhenius equation for modeling deterioration rate, and the Guggenheim-Anderson-deBoer (GAB) equation so moisture content can be translated into the relative humidity for specifying HVAC control.

The Arrhenius equation's applicability to rate studies is well discussed[8,1]. The most appropriate relation for describing moisture sorption for paper[6] and quite possibly other structural organic macromolecules is the GAB equation. The GAB has a strong basis in physical modelling and thermodynamic relationships to the point the GAB equation can be derived in thermodynamic terms as shown by Monleon et al.[13].

The materials for which conservation has the most data to resolve actual rates for the redefined isoperm equation are cellulosic paper (studies by CCI, PapriCan), and cellulose acetate film (studies by IPI). To properly use the proposed equation, both ageing and sorption isotherm studies on closely matched materials over a wide range of tempera-

ture and moisture content are required. This further limits the current pool of information.

The value of the isoperm concept is to make rational decisions on the long term storage environment of artifacts to minimize hydrolytic deterioration of key macromolecules. It can aid cost/benefit decisions by equating changes in humidity control to resultant lifetime extension especially if serious capital investment and energy consumption is being proposed. Based on the current isoperm model's predictions, it also provides a means to quantify the effects of proposed shifts from energy intensive climate control to more passive means for achieving energy conservation goals and this is particularly appropriate as sustainability of museum climate control becomes an ever more pressing issue as energy costs inevitably continue to rise. Lastly, as excessive heat is eschewed as an agent of deterioration, the isoperm is also tied to quantifying the effects of short term exposures such as heat and moisture used in treatment for re-shaping objects, and elevated temperature exposure (55 ºC) for insect extermination.

Because the isoperm has a central point to make in preventive conservation, it was important to redefine the isoperm model in terms of testable properties and come to a full understanding of the underlying assumptions, with the eventual goal of demonstrating its application through experimental results.

Unfortunately, we have been unable to find satisfactory GAB parameters for paper or any other material which is relevant to museum application. We have therefore initiated experimental work with a TGA Q5000 SA sorption analyzer. This machine generates GAB parameters directly over the temperature range of interest. Once we have a consistent set of data we plan to publish a follow-up paper with the revised Isoperms.

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Investigation into effects of fumigants on proteinaceous components of museum objects (muscle, animal glue and silk) in comparison with other non-chemical pest eradicating measures

Paper 7

KIGAWA, R., STRANG T., HAYAKAWA, N., YOSHIDA, N., KIMURA, H. AND G. YOUNG. 2011. INVESTIGATION INTO EFFECTS OF FUMIGANTS ON PROTEINACEOUS COMPONENTS OF MUSEUM OBJECTS (MUSCLE, ANIMAL GLUE AND SILK) IN COMPARISON WITH OTHER NON-CHEMICAL PEST ERADICATING MEASURES. STUDIES IN CONSERVATION, 56(191–215).

Division of contribution

Dr. Kigawa extended an invitation to T. Strang to collaborate on this work after discussions on the potential sensitivity of thermal analysis methods in detecting changes in protein conformation in materials not previously examined in conservation (largely any proteinaceous material other than collagen, parchment and leathers). A preliminary series of fumigated materials from Dr. Kigawa's work on DNA recovery was examined by Strang with DSC to establish protocols and confirm the potential for contribution. A second series of materials including the sequential concentrations and exposures was produced in discussion with Dr. Kigawa (this series was published in paper seven). The DSC work was carried out by Strang. Preliminary thermal microscopy was performed by Strang and final development of the method by Dr. Young (in discussions on refining sample conformation and mathematical analysis). A joint paper with Dr. Young on these methods is in preparation. TGA was carried out by Dr. Young. Graphic presentation of thermal analysis data was designed by Strang except the TGA running integral which was by Dr. Young. Introduction and discussion for the paper was co-written by Dr. Kigawa and T. Strang incorporating contributions of our co-authors on specific experiment related material and revisions after reviewer's comments. Dr. Kigawa managed the submission.

Errata

Investigation of Effects of Fumigants on Proteinaceous Components of Museum Objects (Muscle, Animal Glue and Silk) in Comparison with Other Non-chemical Pest Eradicating Measures

Rika Kigawa, Tom Strang, Noriko Hayakawa, Naoto Yoshida, Hiroshi Kimura and Gregory Young

Fumigant effects on protein-based materials were examined and compared with those of non-chemical pest-eradicating measures. The responses to six fumigants – methyl bromide, methyl iodide, ethylene oxide, methyl bromide/ethylene oxide mixture, propylene oxide and sulfuryl fluoride – were examined with two controlled atmospheres and a range of thermal treatments, using protein electrophoresis, Fourier transform infrared (FTIR) spectroscopy, differential scanning calorimetry (DSC), thermal microscopy (T_{mic}), thermal gravimetric analysis (TGA), amino acid analysis and X-ray fluorescence (XRF) spectrometry. A model soft-tissue protein, freeze-dried chicken muscle, was shown to be affected by some fumigants, especially methyl bromide, methyl iodide and sulfuryl fluoride (Vikane®). This is the first detailed evidence of chemical alterations of a protein material by fumigants under the common treatment conditions for museum use, especially showing a possibility of protein modification by purer grade sulfuryl fluoride whose definite mechanism of toxicity is still unknown. Residual bromine and iodine were clearly detected by XRF in the muscle specimen that had been fumigated with either methyl bromide or methyl iodide respectively, even after a single fumigation several years earlier. On the other hand, significant change in characteristics of animal glue and new and deteriorated silk textiles were not detected. However, residual bromine and occasionally iodine also were detected in the glue and silk samples fumigated by methyl bromide or methyl iodide several years earlier.

INTRODUCTION

Fumigation is an invasive and pervasive treatment for the preservation of cultural heritage so it warrants significant attention by those in the conservation community that require its use. Western countries have in the past used a significant number of fumigant chemicals which have been removed by loss of registration due to eventual recognition of toxicity and chronic effects, and increased cost of meeting health monitoring and disposal requirements. In some cases, recognition of adverse effects on museum objects, such as the risk of strong residual odor, have limited their use. There has also been an increased cultural repugnance to 'using chemicals', stemming from publications warning of pesticide overuse, and increased awareness and education on the health and environmental impacts of local chemical pollution and ozone layer destruction, which has helped the Western museum community shift towards controlled atmosphere and thermal control methods.

On the other hand, in some Asian countries where severe insect and mold damage are seen, due to the warm and humid monsoon climate, fumigants have been used unless visible or detectable damage by the chemicals is seen or demonstrated, as pest damage to the objects is considered more severe than putative invisible damage by fumigants. Methyl bromide is being reduced through the UNEP Montreal Protocol treaty Copenhagen

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amendment Annex E, as a controlled substance [1]. However, in some developing countries, methyl bromide is still in museum use until the complete phase-out of this chemical at the beginning of 2015. In Japan, methyl bromide was removed from museum use under Japan's obligation to the Montreal Protocol at the beginning of 2005. Methyl iodide, which was not covered by the international treaty, has not been used since 2010 partly due to adverse effects on objects such as silver, and large-scale fumigation has become rare in recent years. But ethylene oxide, propylene oxide and sulfuryl fluoride are still in use for some museum objects.

The loss of methyl bromide opens the market for replacement fumigants which are not likely to become listed as ozone depleters or greenhouse gases. As an example, sulfuryl fluoride, which has been available for decades in the USA for a variety of purposes including structural and cultural object fumigation, has now been registered for the first time in Canada (2008) for use on grain [2]. Sulfuryl fluoride has also been submitted for consideration for use under ISPM15 which governs control of wood pests in international shipments of wood [3]. ISPM15 has directly affected museum crating practice for international exhibitions.

Because of these situations and the history of fumigant use in Western countries, it is relevant to look into the fumigant effects on museum materials in comparison with non-chemical methods which are presently used in museum communities, to avoid future harm and to understand the historical practice in the past. There are citations describing observed alteration of objects by use of chemicals, such as changes in colors or odors, due to the use of methyl bromide [4, 5]. Damage can be easily and clearly defined as undesirable visible alteration of an object which lowers the aesthetic values of that object.

However, there is an important category of alteration to consider where significant changes cannot be observed with the human eye. Such 'invisible' changes are by definition not a problem for aesthetics but could severely affect chemical integrity, or the objects may retain undesirable residual components. The steps to determine the significance of such unseen changes are: discover them; determine their magnitude; and relate them to properties which are seen as valuable in the object.

One example of evidence of chemical change in museum specimens that is not observed by the human eye, is the adverse effect of some fumigants on the deoxyribonucleic acid (DNA) of natural history specimens [6]. The fumigants known as 'alkylating reagents', such as methyl bromide, methyl iodide, ethylene oxide and propylene oxide, make DNA molecules in natural specimens fragile and subsequent DNA analysis difficult; however, there is little visible sign of adverse effects on such specimens [6]. Since DNA analysis of natural history specimens has increasing importance in modern taxonomic studies, determining potential for damage by pest treatments to DNA molecules is a serious issue to consider when planning use of collection-based samples or controlling pest problems [6–9].

The example of fumigant-induced change to DNA prompted the evaluation of the effects on proteinaceous objects by pest control agents, as proteins are also major macromolecules of biological origin that have chemical bonds which are possibly attacked by some fumigants. There is some literature on the effects of fumigants on proteinaceous materials mentioning adverse effects such as mercaptan-like odors from objects like fur and leather where materials containing sulfur were fumigated with methyl bromide [4, 5]. Comprehensive analytical results of the effects of sulfuryl fluoride, commercial or purified (experimental) grade Vikane®, on various kinds of materials were reported [10–13]. According to these reports, commercial grade Vikane® in use at that time caused a drop in surface pH of leather due to impurities in the gas, but the experimental grade Vikane® did not show significant effects on proteinaceous objects. However, some changes to dyes analyzed by thin layer chromatography with the experimental grade Vikane® were reported [10, 12].

Although some of the literature [14] mentions possible chemical reactions of ethylene oxide on museum objects, there is little published experimental evidence to show clear chemical changes in proteinaceous museum objects by practical ethylene oxide treatments for pest eradication in the field of conservation.

On the other hand, it is well known from the medical literature that proteins in blood, hemoglobin, serum albumin etc. are chemically modified during human exposure to methyl bromide, ethylene oxide and propylene oxide and that elevation of hemoglobin or serum albumin adducts is observed [15–20]. Measurements of such adducts are adopted to determine levels of human exposure to some fumigants [19, 20]. Methyl iodide has been less used as a fumigant, but it has the potential to react with proteins too [21, 22]. Within agricultural literature the modification of wheat proteins such as gluten by methyl bromide [23, 24] and the possible interaction of sulfuryl fluoride with wheat proteins and food materials was reported [25, 26]. The

chemical changes by fumigants described in the literature are: alkylation; methylation (methyl bromide and methyl iodide) and hydroxyl alkylation (ethylene oxide and propylene oxide). Detailed effects of sulfuryl fluoride on protein species are still unknown, although the toxicity of the inorganic fluoride to the insect glycolysis pathway is suggested [27]. On the other hand, sulfuryl fluoride (Vikane®) had little adverse effect both on DNA molecules and subsequent DNA analysis [6, 28].

The aim of this study is to determine whether it is possible to detect chemical alteration of proteinaceous materials or any residual components when they are fumigated under typical fumigation schedules as commonly applied to museum objects, especially to evaluate the effects of currently available commercial grade Vikane®, as its purity is higher (99.8%) than that used in the previous studies [10–13] (labeled 'greater than 99%') , and to discuss the effects in comparison with those by currently used non-chemical methods.

MATERIALS AND TREATMENTS

Samples

There are many kinds of proteinaceous components found in museum collections, for example, muscles, furs, feathers, leathers in natural history specimens or ethnology collections; animal glue, casein and albumin used in paintings; wool and silk in textiles; and gelatin in photographic materials. In this research, different types of proteinaceous samples were chosen – muscle specimens, animal glue, and silk textiles (new and artificially deteriorated) – for analysis.

Muscle is the largest volume protein in freeze-dried mammalian natural history specimens and mummified remains, and supports the final specimen shape. Also, muscle specimen DNA was shown in previous work [6] to be severely damaged by some fumigants. Animal glue is a significant adhesive and art material binder. Silk is a very important element of textile and art collections in Asia and when in a deteriorated condition it is not readily separated from composite objects for fumigation. Animal glue and silk are the major proteinaceous components used in traditional Japanese paintings such as hanging scrolls. Many such paintings were fumigated with methyl bromide in the past and are occasionally fumigated with ethylene oxide.

Freeze-dried muscle: muscle of chicken *Gallus gallus* was freeze-dried at −40°C and 7.5×10^{-4} Pa for four days then cut into small pieces (approximately 500 mg each).

Animal glue pellets (Daio): both pellets and painted layers of glue on polyester sheets (approximately 100 g m^{-2}) were prepared as samples. Approximately 50 g of pellet glue and 20 × 20 cm pieces of glue sheet were subjected to each treatment.

Degummed white silk: silk textile number 2-1 for Japanese Standards Association JIS L 0803 tests was used. Pieces of approximately 0.94 × 0.5 m were subjected to each treatment.

Raw silk (Eginu): a raw silk textile roll (Nichohi) used for Japanese paintings was cut into pieces of approximately 0.55 × 0.5 m for each treatment.

Artificially degraded silk: raw silk artificially deteriorated by electron beam radiation and commonly used for restoration of old Japanese paintings was cut into approximately 0.1 × 0.2 m for each treatment.

Treatments

Treatment conditions are shown in Table 1. Some of the fumigants were applied at two levels of dosage: a lower concentration for killing insects and a higher concentration for killing molds or tolerant insect species. This was also carried out to observe concentration-dependent changes. Fumigation was performed in glass chambers of approximately 10 L in volume at 25°C. After fumigation, treated materials were degassed in fresh air, then kept at room temperature.

Non-chemical methods for killing insects were also applied. Low-temperature treatment of sample material in a plastic bag (in the case of freeze-dried muscle sample, in a 1.5 mL plastic vial with the lid closed) was at −30°C for 1 week in a freezer, followed by returning to room temperature. Heat treatment was at 40°C, 47°C, 55°C and 60°C with incremental elevation of temperature in the same manner for 24 hours in air incubators with samples contained in sealed plastic bags or, in the case of freeze-dried muscle samples, in 1.5 mL plastic vials with the lids closed. Containing the samples in the tightly closed plastic bags or vials kept the sample equilibrium moisture content almost constant through thermal treatments. Low oxygen treatment was performed with an oxygen scavenger RP system® (K type, Mitsubishi Gas Chemicals Co. Ltd.) in a bag of oxygen barrier film (Escal®) (Mitsubishi Gas Chemicals Company, Inc.) at 30°C for 3 weeks. Carbon dioxide treatment was performed with 60% vol/vol of carbon dioxide with approximately 8% vol/vol of remaining oxygen at 25°C for 2 weeks.

Control muscle samples were stored in 1.5 mL plastic tubes, and glue samples and silk textiles were stored

Table 1 *Treatment conditions*

Sample name	Treatments	Concentration	Time	Target
Control	Non treated control	–	–	–
MB 30	Methyl bromide	30 $g.m^{-3}$	24 hours	Insects
MB 80	Methyl bromide	80 $g.m^{-3}$	72 hours	Insects
MI 40	Methyl iodide	40 $g.m^{-3}$	24 hours	Insects
MI 100	Methyl iodide	100 $g.m^{-3}$	72 hours	Insects and fungi
ME 100	Methyl bromide 86%wt/ethylene oxide 14%wt	100 $g.m^{-3}$	48 hours	Insects and fungi
EO 200	Ethylene oxide 15% wt/HFC R-134a 85% wt	200 $g.m^{-3}$	48 hours	Insects and fungi
PO 48	Propylene oxide	48 $g.m^{-3}$	48 hours	Insects and fungi
SF 50	Sulfuryl fluoride (Vikane®)	50 $g.m^{-3}$	48 hours	Insects
SF 100	Sulfuryl fluoride (Vikane®)	100 $g.m^{-3}$	48 hours	Insects
LT –30°C	Low temperature at –30°C	–	1 week	Insects
HT 40°C	Heating at 40°C	–	24 hours	Insects
HT 47°C	Heating at 47°C	–	24 hours	Insects
HT 55°C	Heating at 55°C	–	24 hours	Insects
HT 60°C	Heating at 60°C	–	24 hours	Insects
$LowO_2$	Low oxygen at 30°C	<0.1% volume oxygen	3 weeks	Insects
CO_2	Carbon dioxide at 25°C	60% volume	2 weeks	Insects

Fumigation was carried out at approximately 25°C. The treatments were performed in June and July 2005.

in paper envelopes, all at room temperature under approximately 50% to 60% RH. Treated samples were also stored in the same manner before and after the treatments.

RESULTS FOR MUSCLE SPECIMEN

Denaturation of proteins in muscle specimens: Results from protein electrophoresis

Post treatment, the freeze-dried muscle specimen did not show any significant change in visual appearance. However, when soluble proteins were extracted for sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE), large fractions of soluble proteins were absent from treatments using methyl bromide (MB), methyl iodide (MI) and sulfuryl fluoride (SF), indicating possible alterations (Figure 1, soluble fraction). The change was more significant in samples treated with higher concentrations of these fumigants (MB 80, MI 100 and SF 100). The band of myosin protein (approximately 200 kDa) exhibited significant loss of soluble fraction, which was confirmed with western blot with myosin antibodies (data not shown).

Additionally, when residual pellet fractions of the samples were solubilized, greater amounts of proteins were observed in those pellets (Figure 1, insoluble fraction). In the lanes for methyl bromide/ethylene oxide mixed gas (ME 100), insoluble proteins are also obvious, probably owing to the large methyl bromide content of this fumigant (86% by weight). This suggests proteins had undergone denaturation and changes of chemical characteristics.

Modified amino acid of muscle specimen: Amino acid analysis

The electrophoresis results indicated treatments which altered the proteins, so untreated samples and those fumigated with methyl bromide, methyl iodide, sulfuryl fluoride, ethylene oxide and propylene oxide were selected for amino acid analysis. As a result of the quantitative analysis linked to liquid chromatography, two new distinct peaks of amino acid were found in the samples fumigated with methyl bromide and methyl iodide (Figure 2, arrows).

These two peaks were identified as 3-methylhistidine and alfa-amino-n-adipic acid by comparison of the retention time of each peak with those of 38 standard amino acids. A new peak of 3-methylhistidine strongly suggests the methylation of histidine residues by methyl bromide and methyl iodide. However, identification of one of the new peaks as alfa-amino-n-adipic acid was perplexing. Because identification of amino acids was based on retention time of each peak in comparison with a run of standard amino acid mixture, it is highly possible the standard amino acid mixture did not cover all the unusual methylated forms of amino acids. So the resulting identification from the retention time as alfa-amino-n-adipic acid could be different from the actual form of amino acid generated.

In contrast, there was not a very significant change

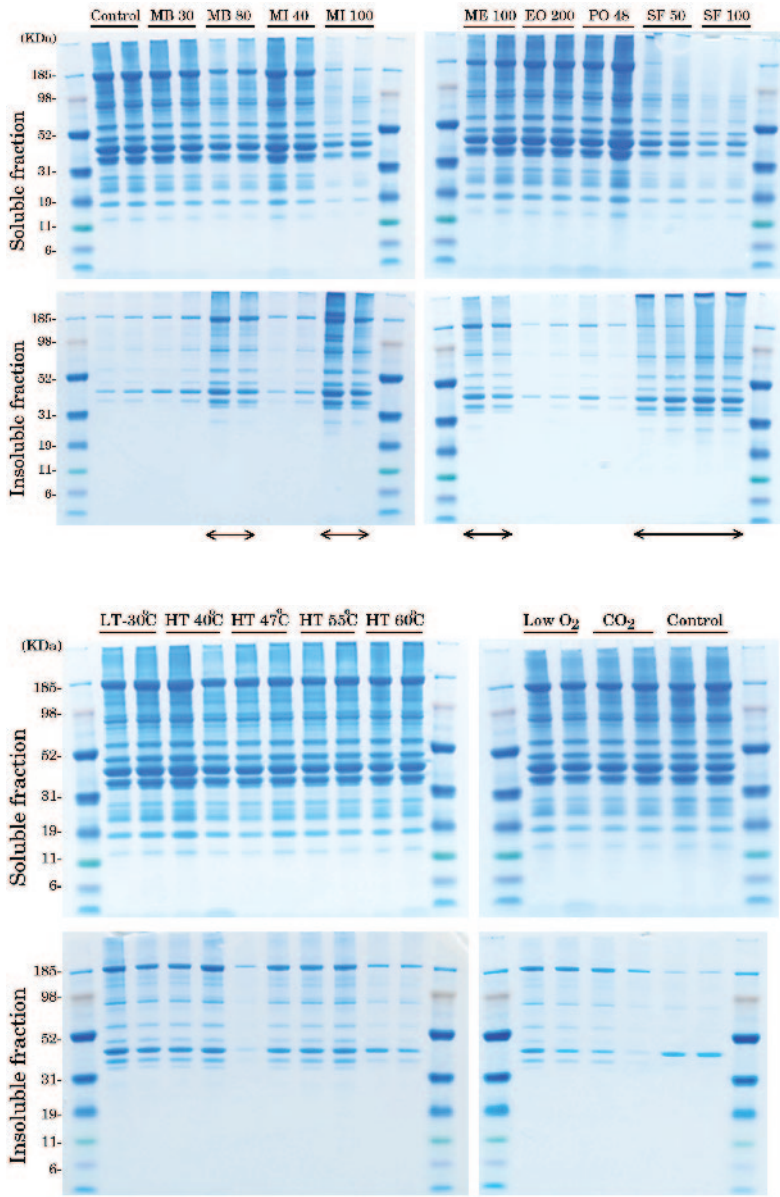

Figure 1 *Protein electrophoresis patterns of treated freeze-dried muscle samples. Arrows indicate the lanes where significant change was observed. Control: non-treated control; MB 30: methyl bromide, 30 g.m^{-3}; MB 80: methyl bromide, 80 g.m^{-3}; MI 40: methyl iodide, 40 g.m^{-3}; MI 100: methyl iodide, 100 g.m^{-3}; ME 100: methyl bromide 86% wt/ ethylene oxide 14% wt, 100 g.m^{-3}; EO 200: ethylene oxide 15% wt/HFC R-134a 85% wt, 200 g.m^{-3}; PO 48: propylene oxide, 48 g.m^{-3}; SF 50: sulfuryl fluoride (Vikane®), 50 g.m^{-3}; SF 100: sulfuryl fluoride (Vikane®), 100 g.m^{-3}; LT –30°C: low temperature treatment at –30°C; HT 40°C: heating at 40°C; HT 47°C: heating at 47°C; HT 55°C: heating at 55°C; HT 60°C: heating at 60°C; Low O_2: low oxygen treatment; CO_2: carbon dioxide treatment, 60% volume. Details of the treatment conditions are shown in Table 1.*

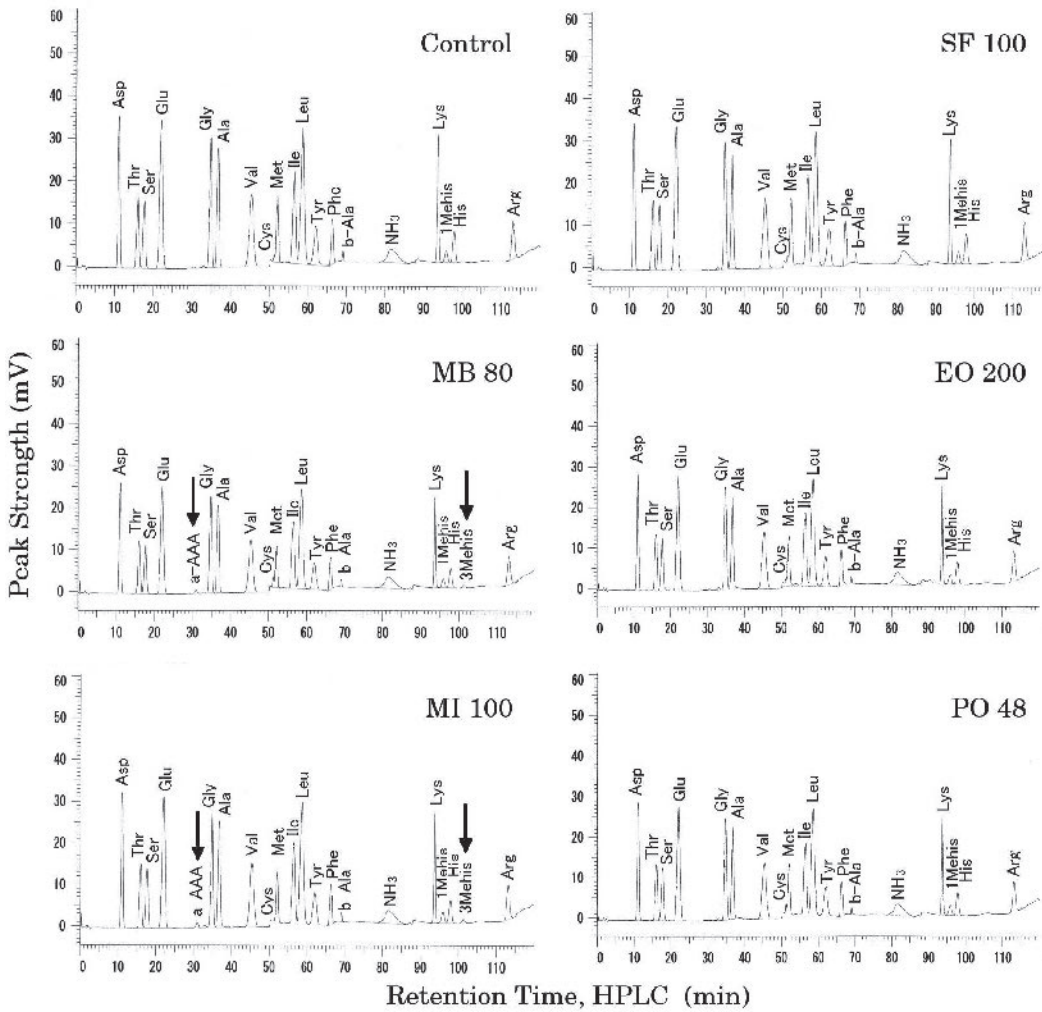

Figure 2 *Amino acid analysis of six muscle samples. Arrows indicate new peaks. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

of amino acid composition in the muscle samples fumigated with sulfuryl fluoride, ethylene oxide and propylene oxide. It is possible that these fumigants might not severely modify amino acids. However, there is a possibility that small new peaks may be hidden by strong peaks of major amino acids when their retention times are close.

Suggested modification of proteins of muscle specimen by sulfuryl fluoride: Results from FTIR

FTIR-ATR analysis was also performed with all the muscle samples. Large differences were not observed in the raw spectra (Figure 3a). However, subtraction from the control showed differences with sulfuryl fluoride-fumigated samples (Figure 3b) with two absorption

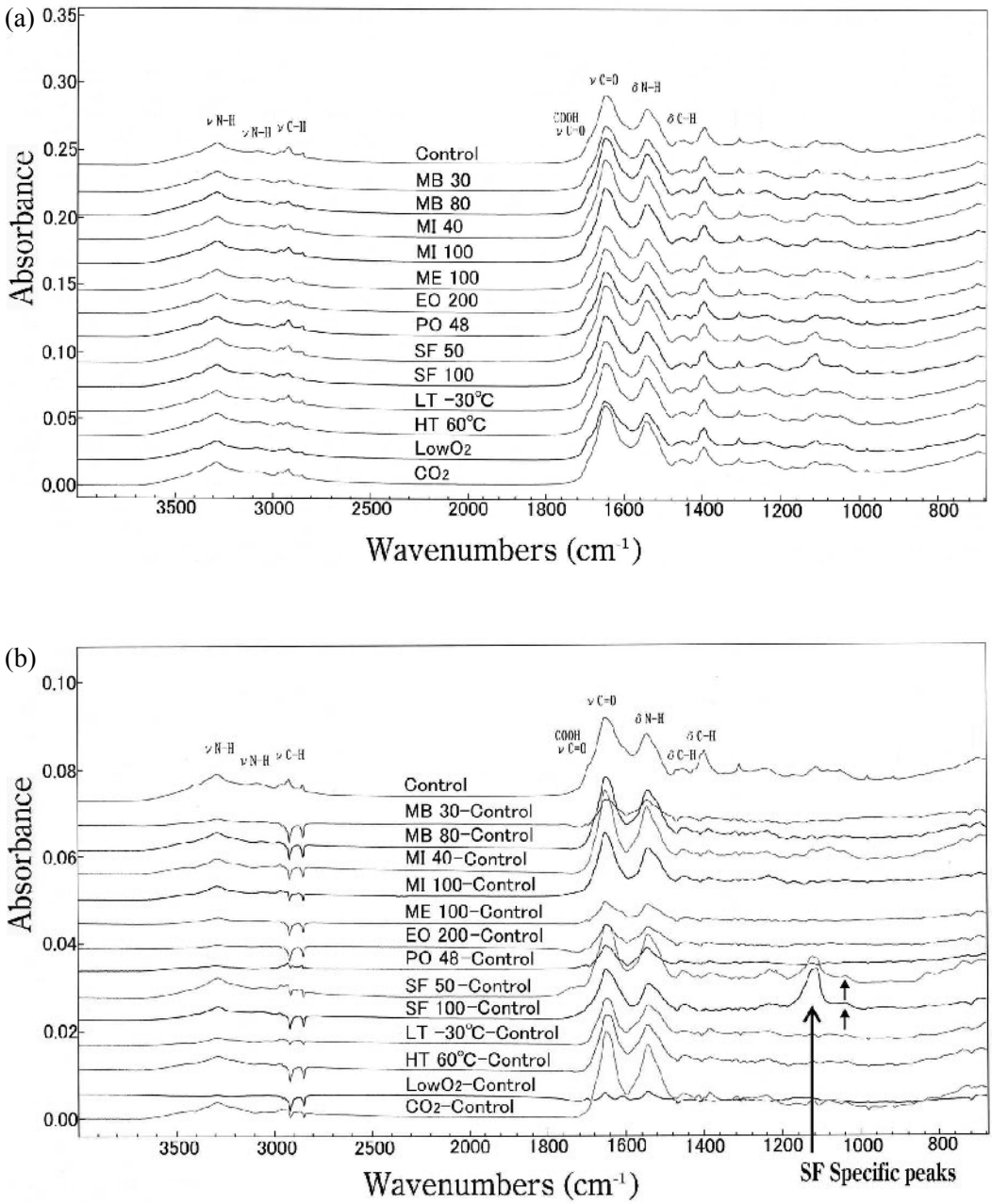

Figure 3 *(a) FTIR-ATR spectra of muscle samples and (b) subtraction patterns (arrows indicate specific peaks with sulfuryl fluoride (SF) fumigated samples). Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

peaks at about 1125 cm^{-1} and 1040 cm^{-1}. These are different from the positions of the typical absorption peaks for sulfuryl fluoride (SF) [29]. This could suggest the existence of the S=O bond, such as in R–$S(=O)_2$–OH (or metal) bonds [30, 31], which suggests a possibility that sulfuryl fluoride reacted with the proteins. Comparison of SF 50 (50 $g.m^{-3}$) and SF 100 (100 $g.m^{-3}$) in Figure 3b shows absorption at 1125 cm^{-1} was dose-dependent on the applied sulfuryl fluoride concentration.

This is the first evidence suggesting modification of a protein-based collection by fumigation with pure grade Vikane® (sulfuryl fluoride, greater than 99.8%).

Change in thermal decomposition of muscle proteins: Results from TGA in dry nitrogen

Thermal gravimetric analysis (TGA) was performed under dry nitrogen gas to measure thermal decompostion of the proteins (Figure 4). Statistically significant shifts from the control response can be seen for fumigants containing a high dose of methyl bromide (MB 80), methyl bromide/ethylene oxide mixed gas (ME 100), methyl iodide (MI 100) and sulfuryl fluoride (SF 50 and SF 100).

Increasing thermostability is clearly visible in progressive concentration-dependent shifts, as populations within many of the fumigated proteins volatilized at higher temperatures than the control. A significant increase in temperature was needed to elicit 50% mass loss for the high dose of sulfuryl fluoride (SF 100) with a response at 263°C compared to 251°C for the control (Figure 5). A second group of significant changes were seen for methyl bromide (MB 80), methyl iodide (MI 100), methyl bromide/ethylene oxide (ME 100) and the lower dose of sulfuryl fluoride (SF 50) with responses ranging from 252°C to 261°C.

There is marginal separation from the control for the low dose of methyl bromide (MB 30) and methyl iodide (MI 40) and none for ethylene oxide (EO 200), propylene oxide (PO 48), heat (HT 40°C, 47°C, 55°C and 60°C), low temperature (LT −30°C), carbon dioxide (CO_2) and low oxygen (Low O_2) treated samples (Figure 4).

These results are similar to the indications from electrophoresis for alteration of proteins. The shift to higher temperatures to achieve equivalent percentage of decomposition in TGA (Figure 5) indicates that MB, ME, MI and SF underwent conformal change or chemical modification conferring some thermal stability, as indicated by the higher thermal energy needed to volatilize components, and is commensurate with the greater proportion of insoluble fraction found in the electrophoresis of these samples.

Change in hydrothermal stability of muscle proteins: Results from differential scanning calorimetry (DSC) in aqueous suspension

Differential scanning calorimetry (DSC) of the samples showed differences between fumigants expressed by apparent shifts of endotherms or loss of endotherms (Figure 6). The chicken muscle used in this study has two main endotherms, that for myosin centered at 62°C and the other for actin centered at 77°C [32].

The methylating fumigants methyl bromide (MB), methyl iodide (MI) and the methyl bromide/ethylene oxide mixture (ME) all show much more significant losses of peaks and shifts in endotherms to lower temperatures (Figure 6). Progressive trends with the concentration of fumigant used are clearly visible. This supports the electrophoresis observations of severe alteration of the muscle protein with a single fumigation using methylating fumigants.

DSC of the sulfuryl fluoride fumigated samples (SF) also shows major flattening of endotherms and peak shift formation at 70°C where the control exhibits little endothermic activity (Figure 6). This represents a major shift in thermal stability of a large portion of the protein subunits. The magnitude of these stability changes reflects the results seen in the electrophoresis analysis.

The reduction in DSC endothermic response indicates the samples fumigated with MB, MI and SF had undergone conformal changes which left less myosin and actin structure to be altered during the DSC scan. This indicates a loss of original properties of the muscle by the fumigation treatment.

Ethylene oxide (EO) and propylene oxide (PO) samples showed similar lessening of response, with a minor shift in the actin peak to a lower temperature (75°C) and increase in endothermic response from 30°C to 55°C. However these changes are smaller than those by the other fumigants noted above (Figure 6).

The controlled atmosphere treatments (CO_2, Low O_2) showed lesser changes in their response with no peak shifts, but some flattening of the myosin peak.

The thermal treatment series using heat and cold, (labeled HT and LT by temperature) shows the 55°C and 60°C heat treatments exhibiting peak flattening and progressive shifts of the actin peak with the step between 55°C and 60°C having generated the most pronounced loss in both peaks.

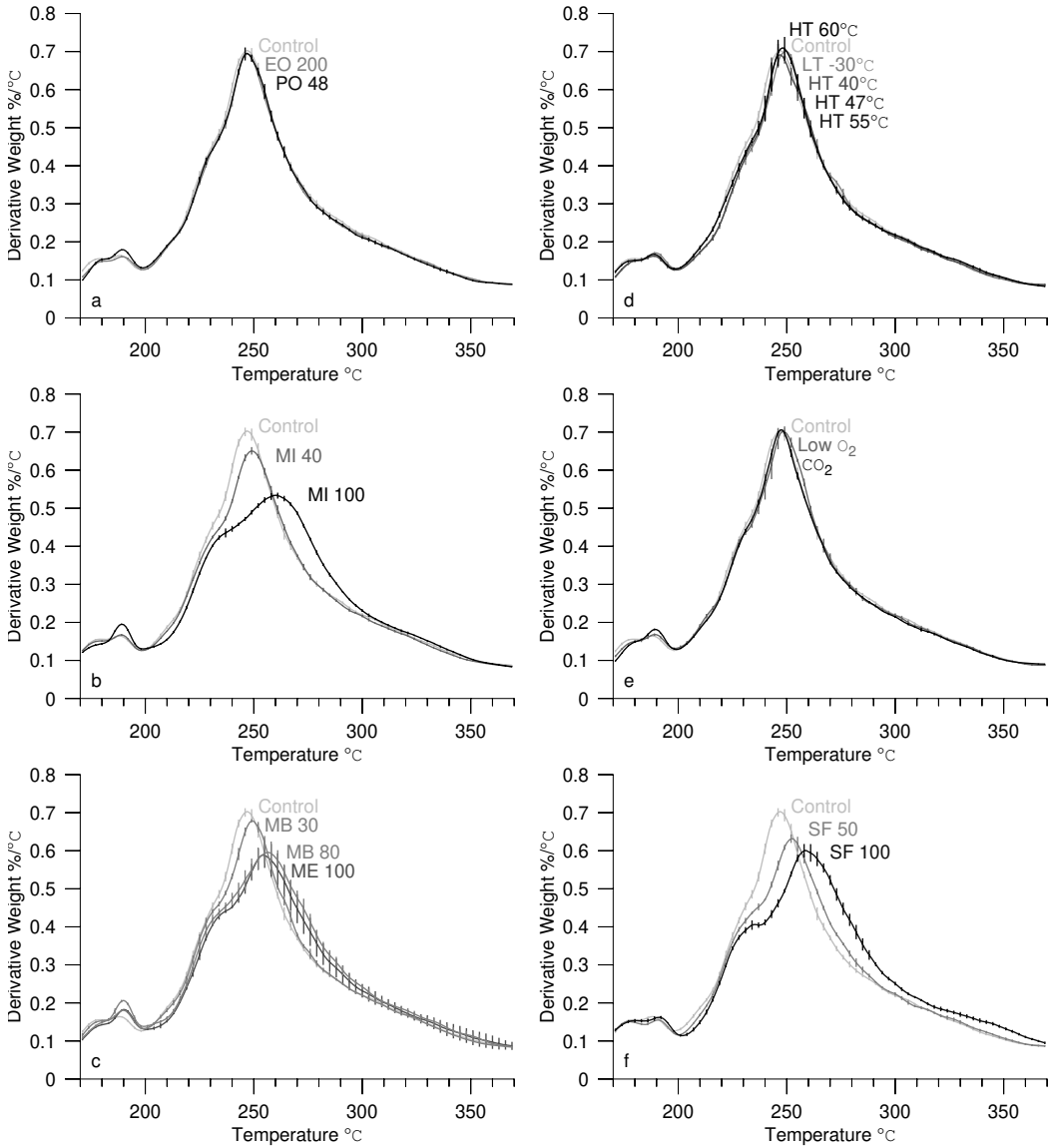

Figure 4 *TGA derivative weight % for treated muscle samples. Sample means shown as lines; bars are ± one sample standard deviation. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

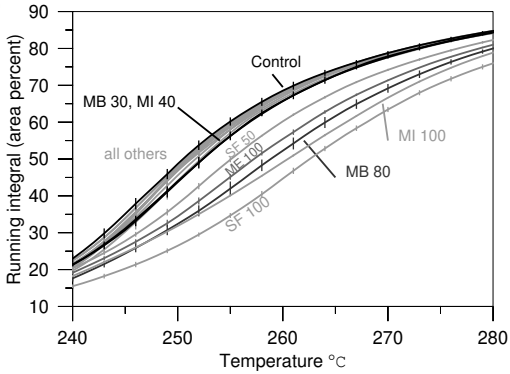

Figure 5 *TGA running integral (area %) of treated muscle samples. Bars are ± one standard deviation. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

The shape of the endotherms for EO, PO, CO_2, Low O_2, heat (HT) and low temperature (LT) all appear to express a similar pattern of progressive alteration from the control. The controlled atmosphere series had long exposures, 2 weeks and 3 weeks at 25°C and 30°C, respectively, compared to the control storage condition, which may contribute to the noted changes. DSC proved to be a sensitive tool to see differences in the subtle physical changes in muscle, which were not indicated by the electrophoresis, TGA, T_{mic} and FTIR-ATR results.

Thermal microscopy (T_{mic}) analysis of muscle specimen: Direct physical change in aqueous suspension

Thermal microscopy (T_{mic}) directly observes physical change by measuring the axial and lateral dimensions of the muscle fibers as they shrink in distilled water on a programmable hot stage. The results are shown in Figure 7. Tukey box plots of onset temperatures show statistically significant lowering of average onsets for axial shrinkage of ME 100, MB 80 and MI 100 samples, as well as significant lowering for ME 100, MB 80, MI 40, MI 100 and SF 100 in the lateral direction. Statistical significance (marked on graph margins) was determined by comparing treated group replicate measurements against those of the untreated control via a one-way analysis of variance (ANOVA) with SigmaStat version 3.0.1 (SPSS Inc., Somers, NY). The power of the analysis with $\alpha = 0.05$ was 1.000; the significant difference was determined at $P = <0.001$ and the multiple comparisons versus the control were performed using the Holm-Sidak method at the 0.05 level of significance.

The significant changes to minor axis onset temperatures (Figure 7) map to a region of increased endothermic response in DSC through the temperature range 25°C to 50°C. This indicates more protein structure is available for hydrothermal denaturation in this range after fumigation. EO 200 and PO 48 also show an increase in their endotherms in this region but with no significant change in onset.

Increased change in response to increased fumigant concentration for MB-, MI- and SF-fumigated samples is shown by T_{mic}, as well as by DSC and TGA.

X-ray fluorescence (XRF) measurement of muscle specimen: Detection of residual elements originating from fumigants

Under proper conditions, XRF can detect bromine originating from MB, iodine from MI and sulfur from SF. However, hydrogen, carbon, oxygen and fluorine are not detectable under any conditions by the instrument used in this study.

By XRF measurement with a tube voltage of 45 kV, peaks identified as bromine and iodine were clearly observed from freeze-dried muscle samples treated with MB 80 and MI 100, respectively (Figure 8). In addition, peak intensities showed no significant difference between the measurements under air and vacuum atmosphere of the sample chamber. From these results, it was suggested that bromine and iodine bind strongly to the muscle structure, and that they are not in a form which easily volatilizes. It is notable that the fumigations had been carried out more than 5 years before XRF measurement was performed and still such residual inorganic components existed in the specimen.

Measurement of an SF 100-treated sample with a tube voltage of 15 kV showed no significant difference in sulfur peak intensity with a non-treated sample (data not shown). This suggests that sulfur elements in the sample were of original proteins, not from SF 100 fumigation.

RESULTS FOR ANIMAL GLUE

Glue beads and the thin layer of glue on a polyester sheet did not show any difference by visual observation. Nor we did not see any difference when we extracted and dissolved the treated animal glue.

Results of electrophoresis of treated animal glue extracted from thin sheets are shown in Figure 9. There is no significant difference between samples. FTIR-ATR

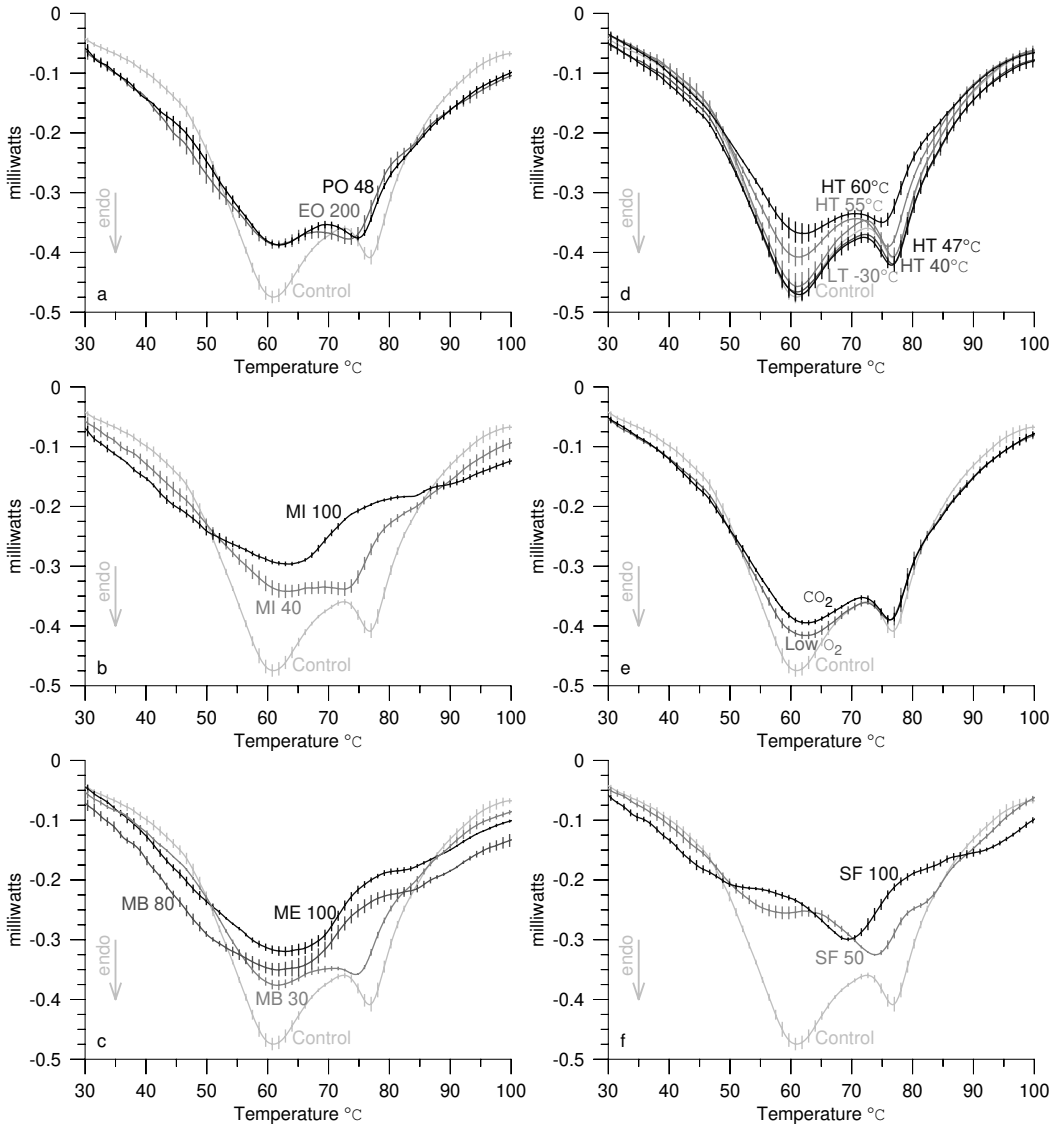

Figure 6 *DSC endotherms for treated muscle samples. Sample means shown as lines; bars are ± one sample standard deviation. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

spectra are shown in Figure 10. There was no significant change in the pattern of absorbance peaks (Figure 10). Subtraction patterns between samples were negligible (data not shown).

By XRF measurement with a tube voltage of 45 kV, strong bromine and weak but clear iodine peaks were observed from polyester sheet samples on which was painted animal glue treated with MB 80 and MI 100,

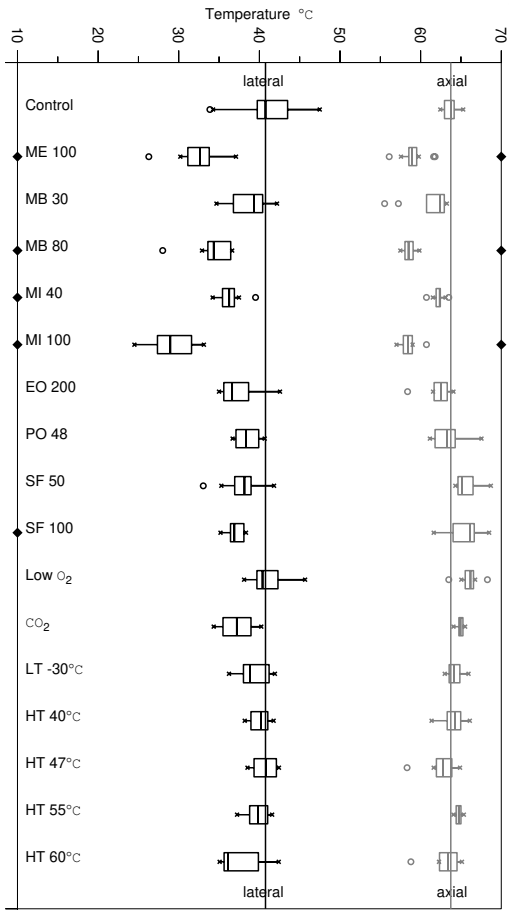

Figure 7 *Thermal microscopy, average onset temperatures of axial and lateral shrinkage of treated muscle samples. Whiskers are 1.5 interquartile range (IQR), open circles less than 3 × IQR, solid circles greater than 3 × IQR. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

respectively (Figure 11). At first, the bromine and iodine were not detected with a single layer of the glue-painted sheet, but they were detected with eight stacked sheets. These peaks' intensities showed no significant difference between the measurements under air and vacuum atmosphere, suggesting strong binding of bromine and iodine on the samples. It is not known from these results whether adsorption and/or bonding sites existed in the polyester or glue layers; however, since bromine was detected also from an MB 80-treated glue pellet sample (data not shown), it is suggested that bromine could bind to the glue itself. The fumigation had been done more than 5 years before and still such residual inorganic components existed in the materials.

Measurement of an SF 100-treated sample with a tube voltage of 15 kV showed no significant difference in sulfur peak intensity with a non-treated sample (data not shown). This suggests that detected sulfur elements were likely to be from the glue, not from SF 100 fumigation.

RESULTS FOR SILK TEXTILES

All the treated degummed silk, raw silk, and artificially deteriorated raw silk textiles did not show any visible difference. Tse and Dupont [33] reported that early deterioration of intact silk protein (fibroin) by light aging can be detected by HPLC and protein electrophoresis. Protein electrophoresis was adopted for this study, to use the low molecular weight band as an indication of early deterioration of fibroin of new silk textiles.

Silk proteins including a low molecular weight band (about 20 kDa) were observed in untreated new textile samples of both degummed silk and raw silk (Figure 12, left and middle columns, arrows). However, the low molecular weight band disappeared in artificially deteriorated silk used in conservation of Japanese paintings, which was produced by electron beam irradiation (Figure 12, right column). This shows that the low molecular weight band can serve as a good marker for deterioration of intact silk.

Treated and non-treated new degummed silk samples were analyzed by electrophoresis. There was no significant difference between the samples (Figure 13), and the low molecular band (about 20 kDa) can be seen in all the samples examined (Figure 13, arrow). The sericin protein of new raw silk was also examined as sericin is thought to protect fibroin fibers from damage. However, no significant difference between the samples was observed in the pattern of extracted sericin silk proteins (Figure 14). There was no significant change in the pattern of absorbance peaks of FTIR-ATR spectra of treated new degummed silk samples (Figure 15). Also no significant difference was observed by subtraction of spectra between the samples (data not shown). These results indicate that new silk fabric seems not to be seriously affected by the treatments used in this investigation.

To address the effects of fumigants on already deteriorated silk, FTIR-ATR analysis was performed

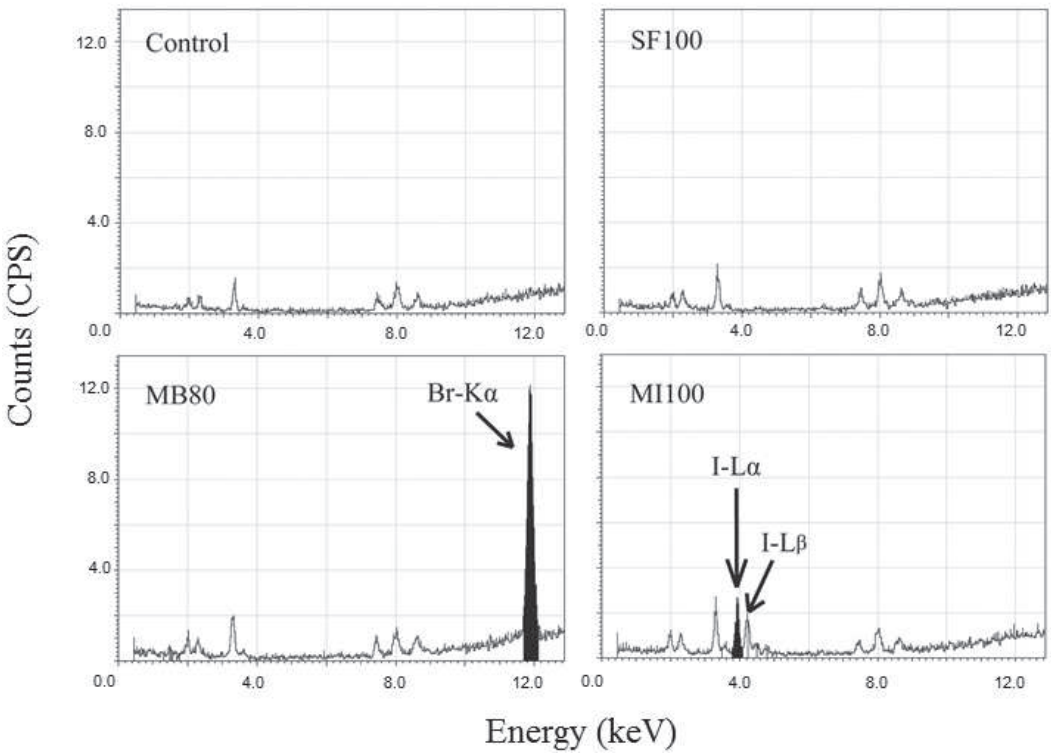

Figure 8 *X-ray fluorescence spectra of muscle specimens treated with fumigants. Measurement conditions: tube voltage 45 kV, tube current 28 μA and vacuum atmosphere. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

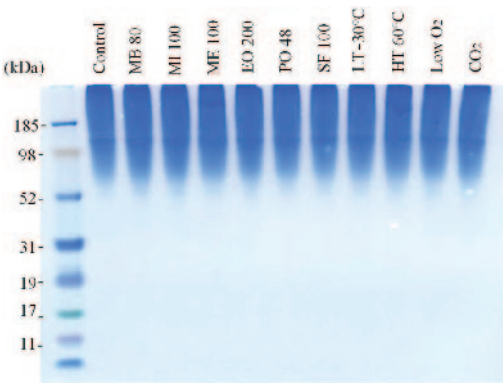

Figure 9 *Protein electrophoresis patterns of treated animal glue samples. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

with four samples of artificially deteriorated silk (Figure 16), as it was suspected that with artificially deteriorated silk the effects of chemicals might be stronger due to the deteriorated nature of the silk samples. In the case of deteriorated raw silk as a whole, the shapes of the absorbance curves are slightly different from those of new degummed silk (compare Figure 16 with Figure 15).

However, there was no significant difference between the treated deteriorated silk samples and the non-treated control. Subtraction analysis between the spectra was also carried out. The variation in repeated measurements of the non-treated control was bigger than the variation between the control and treated samples (data not shown).

XRF spectra of raw silk samples are shown in Figure 17. The bromine peak was clearly observed in the MB 80 treated sample. Bromine was also detected in degummed silk (data not shown). Moreover, peak intensities showed

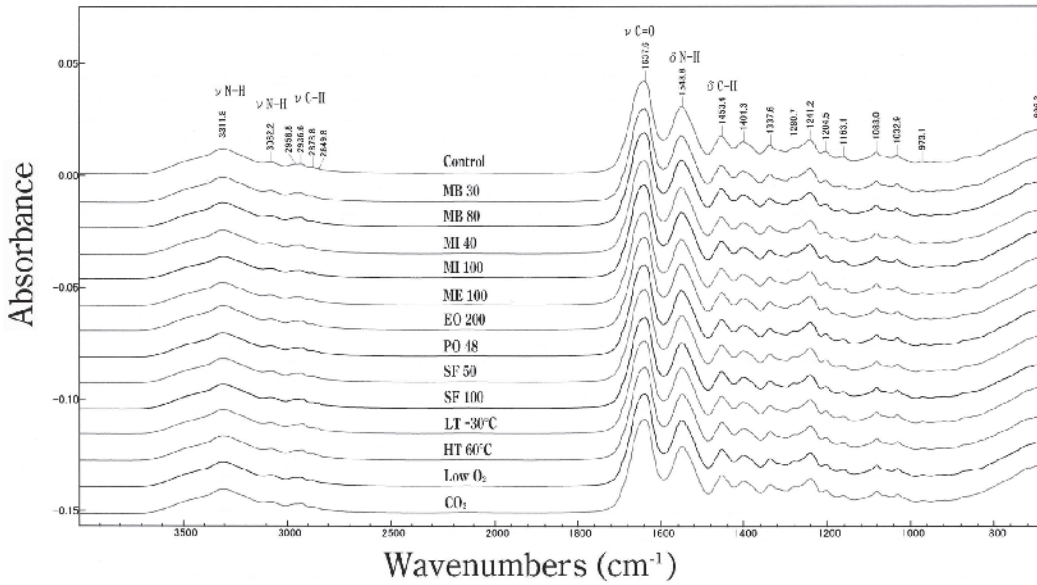

Figure 10 *FTIR-ATR spectra of treated animal glue samples. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

no significant difference between air and vacuum atmosphere, suggesting strong binding on silk. As in the case of glue sheets, bromine was not detected with single layered silk textile, but was detected with several layers (20 layers) of the silk textile. From the artificially deteriorated raw silk sample, bromine was not detected even when several layers were analyzed (data not shown). The fumigation had been performed more than 5 years before, but such residual inorganic components existed in the silk textiles. Iodine and treatment-specific sulfur peaks were not observed with any MI 100- and SF 100-treated silk samples.

DISCUSSION

Mechanism of alteration of muscle proteins by fumigants

Of the fumigants tested, methyl bromide (MB), methyl iodide (MI) and sulfuryl fluoride (SF) most affected the muscle specimen. A summary of the results is shown in Table 2. A possible mechanism for the alteration of muscle proteins by MB and MI would be by methylation. Amino acid analysis showed new peaks of possibly methylated amino acid groups from both MB- and MI-treated muscle proteins. Methylation is consistent with the indications from other research analyzing agricultural products [23, 24] and medical research showing human hemoglobin adducts from methylation by exposure to fumigants [15, 16, 19].

Alteration of freeze-dried muscle proteins by SF was also observed. Since SF had less effect on DNA in natural specimens compared with other fumigants [6, 28], SF has some advantage for use on natural specimens. SF use is increasing after the Montreal Protocol treaty ban of methyl bromide came into effect in developed countries in 2004, so elucidation of its action on protein molecules is an important topic.

Electrophoresis of the SF-treated muscle proteins showed denaturation of the major proteins. Large concentration-dependent peak reduction is also seen in DSC, which suggests comformational change of the proteins, and increased thermal stability of the proteins in TGA was observed. Subtraction of FTIR-ATR results of sulfuryl fluoride-fumigated muscle samples suggested modification of the muscle proteins. It might also suggest existence of S=O chemical bonds, such as $R–S(=O)_2$ –OH (or metal) bonds in the proteins.

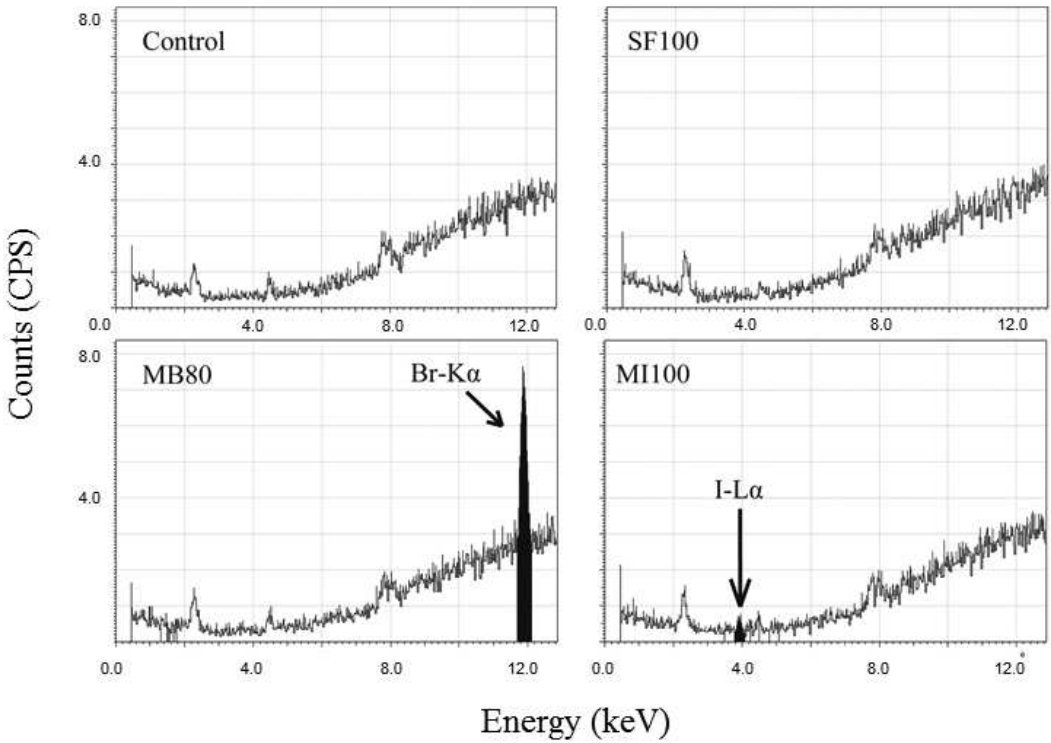

Figure 11 *X-ray fluorescence spectra of stacks of eight layers of animal glue-painted polyester sheets treated with fumigants. Measurement conditions: tube voltage 45 kV, tube current 28 μA and vacuum atmosphere. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

Meikle [25] used isotope-labeled SF (S^{35}) to demonstrate the distribution of reacted products in Graham flour and that the radioactive S^{35} was bound to the protein fraction. This suggests that SF might react with the muscle protein. However, as additionally generated peaks were not observed in the amino acid analysis in this study, the detail of such modification is not clear.

Ethylene oxide (EO) and propylene oxide (PO) showed no significant changes in electrophoresis, FTIR-ATR, amino acid and TGA analyses, but some myosin peak flattening in DSC. EO and PO also show human adducts through alkylation [18], but analogous modification to protein was not significant in this study. This low reactivity of EO and PO to the proteinaceous materials tested is surprising, as putative damage and alteration of protein-based materials by EO was believed by the museum community to occur. One possibility for the low reactivity might be the low moisture content present in the fumigated samples compared to *in vivo* studies of EO and PO exposures.

Residual components after fumigation

Residual chemical components on the objects are one of the major concerns of fumigation. By XRF measurement, bromine and iodine were clearly observed with freeze-dried muscle samples treated with methyl bromide and methyl iodide, respectively, more than 5 years earlier. As they were detected under vacuum condition, bromine and iodine elements were assumed to bind strongly to the muscle specimen, in a form which does not easily volatilize.

Likewise, bromine or iodine was also detected on the piles of several glue/polyethylene sheets, and residual bromine was detected with several layers of silk textiles and glue beads. In these cases, as iodine intensity was not

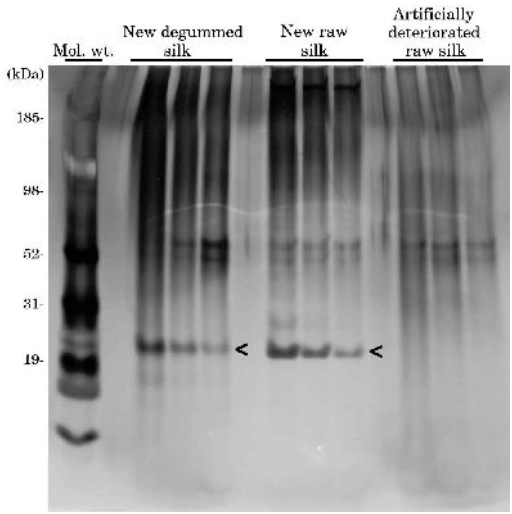

Figure 12 *Electrophoresis patterns of new (non-deteriorated) and deteriorated silk proteins. Each extract was diluted to 1/20, 1/50 and 1/100, then the same volumes of the diluted solutions were subjected to electrophoresis.*

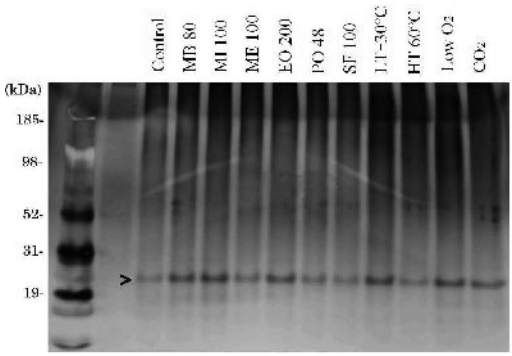

Figure 13 *Protein electrophoresis patterns of treated new degummed silk samples. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

as high as bromine with this analytical system, it is possible that iodine was below the detection limit of the analyzer.

As new covalent bond formation containing bromine or iodine was not detected by FTIR analysis in the fumigated samples, the residues are more likely to bind to the materials in a non-covalent manner. But details of the residual forms of bromine or iodine are unknown.

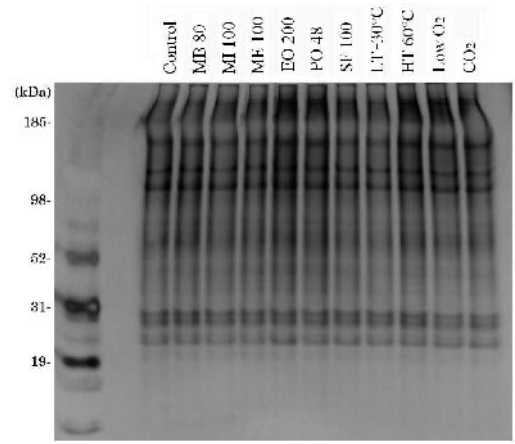

Figure 14 *Electrophoresis of sericin protein fraction of treated new raw silk samples. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

Such residual bromine was reported in XRF analyses of wooden statues or paintings which had been occasionally fumigated with methyl bromide many years before [34]. Mabuchi and Sano also reported residual bromine on the bulk of cellulose-based materials, such as paper and cotton textiles, which had been fumigated 2 years before the analysis [35].

Regarding toxicity of the fumigated materials, it cannot be stated that the materials are completely safe, as the exact chemical forms of such residues are unknown. So it remains a concern.

Interpretation of the changes caused by fumigation

Amino acid analysis and FTIR suggested that MB and MI caused methylation of the muscle proteins, and SF formed some covalent modification of the muscle proteins. Results of TGA indicate MB, MI and SF conferred the muscle proteins thermal stability and, from electrophoresis, the proteins were shown to be denatured by the fumigants. The results of DSC indicate the muscle protein samples fumigated with MB, MI and SF had undergone conformal changes that cause a loss of original properties of the muscle by the fumigation treatment. The change to muscle proteins could indicate similar trends seen in other research, where changes in collagen thermal stability map to aging or other

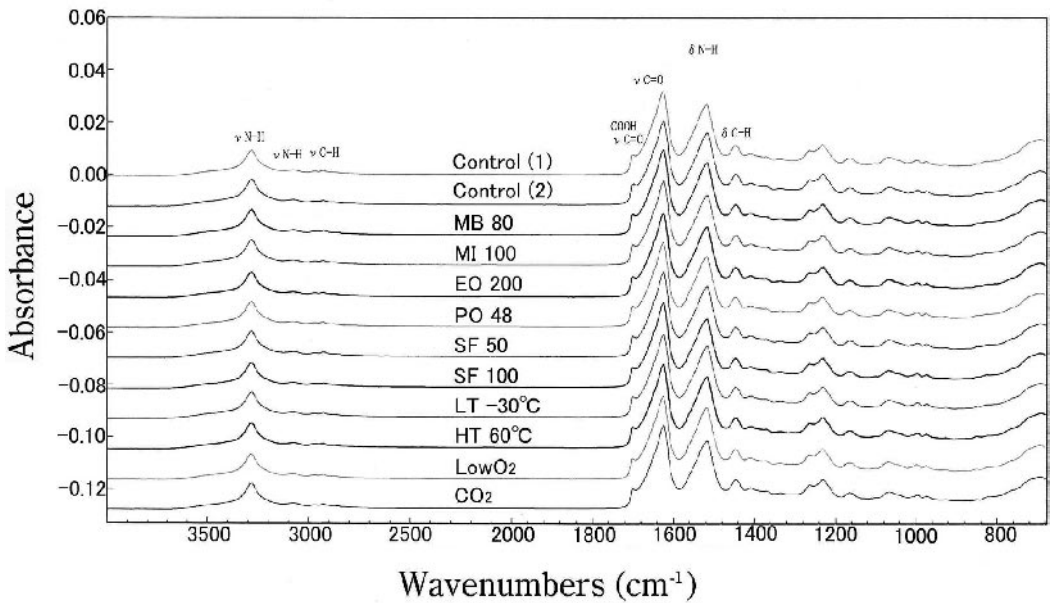

Figure 15 *FTIR-ATR spectra of treated new degummed silk samples. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

deterioration mechanisms [36, 37], so care is needed regarding the consequences of using the fumigants.

With XRF analysis, residual bromine or iodine was detected in the samples fumigated by MB or MI, respectively, even after more than 5 years had elapsed. Therefore, fumigation by MB, MI or SF would affect the results of future analytical studies, both in chemical characteristics of the specimen and in residual bromine or iodine originating from MB or MI fumigation. Thus records of historical treatments by fumigants are important if it is necessary to consider a possibility for future research and a possibility of unknown toxicity.

Discussion regarding effects by non-chemical treatments

As a whole, the non-chemical treatments examined in comparison with fumigant effects did not show very significant alterations on protein materials tested here. The results show minimal hazard will be posed by using controlled atmosphere fumigation (CAF) methods on chemically sensitive proteins such as the muscle used in this study.

Thermal exposure (low and elevated) did not affect electrophoresis, FTIR-ATR, T_{mic} and TGA results compared with the control. However, there was a sign of peak flattening in DSC progressing with higher temperature exposure, most evident at 60°C. The sign was more evident with incremental increase in the treatment temperature. Slight changes in DSC results were also seen with samples subjected to the 25°C, 2 weeks, CO_2 and 30°C, 3 weeks, low-oxygen controlled atmosphere protocols. Therefore, change in muscle protein detected by DSC might be caused by long duration of modestly higher temperature.

These changes suggested by DSC were subtle changes compared with the large changes by fumigants such as MB, MI and SF. But it can be said that 55°C is more appropriate than 60°C when considering treatment of heat-sensitive materials. These findings support current recommendations of heat-treating near 55°C, which optimizes efficacy against insect pests, as a relatively object-safe operation compared to fumigants, and low temperature exposure would show even less change. Set-points near 55°C have already been in use for over a decade by commercial operations heat-treating cultural property [38]. Furthermore, a similar temperature is

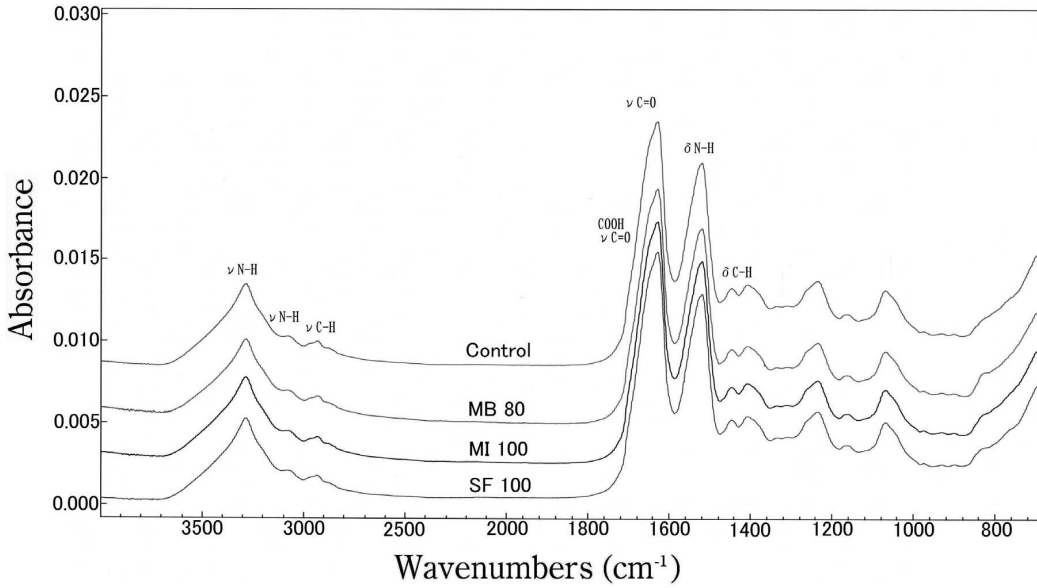

Figure 16 *FTIR-ATR spectra of treated artificially deteriorated raw silk samples. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

now incorporated in international phytosanitary heat-treatment protocols to meet ISPM 15 regulating the import of solid wood products [39], where heat-treated wood must achieve a core temperature of 56°C for 30 minutes, a stipulated protocol shorter than the 24 hour exposure adopted in this study.

Heating to kill insect pests damages systems critical to insect life such as epicuticule waxes and heat-sensitive enzymes. Most museum materials are in general quite dry compared to the same materials in living organisms and this, combined with short exposure to heat, are considered limits to significant changes by heat treatments.

Less reactivity of animal glue and silk textiles to fumigants

In contrast to the results with muscle specimens, significant effects were not observed for any treatments tested on animal glue and silks (both new and deteriorated). The results are consistent with the previous works by Baker et al. [10, 12], who tested photographic gelatin, hide glue and silk etc. with experimental grade Vikane® but did not observe changes. Differences in these protein structures are a likely explanation for their lowered reactivity to fumigants. Glue is highly altered collagen. Both collagen of glue and fibroin of silk are fibrous proteins adapted for a structural function to provide support, shape and external protection, while muscle is contractile soft tissue.

Animal glue is a very important proteinaceous component in museum objects. The protein could be deteriorated by light, UV radiation, desiccation etc. [40]. However, no very significant changes were observed in this study, probably because animal glues are subjected to heat, water and chemical reagents (lime, sulfates, etc.) in their production and are already highly denatured, and originally reactive chemical structures could already be changed to stable forms when they are supplied as glue products.

Silk is another important cultural material. Deterioration of silk can be caused by light [33, 41] and mechanical stress. However, no significant changes in silk were detected by molecular analysis, including a method to detect early signs of silk deterioration [33]. Silk proteins have a structural function to protect insect pupae from harm in cocoons. Sericin proteins are thought to protect fibroin fibers by coating the fibers.

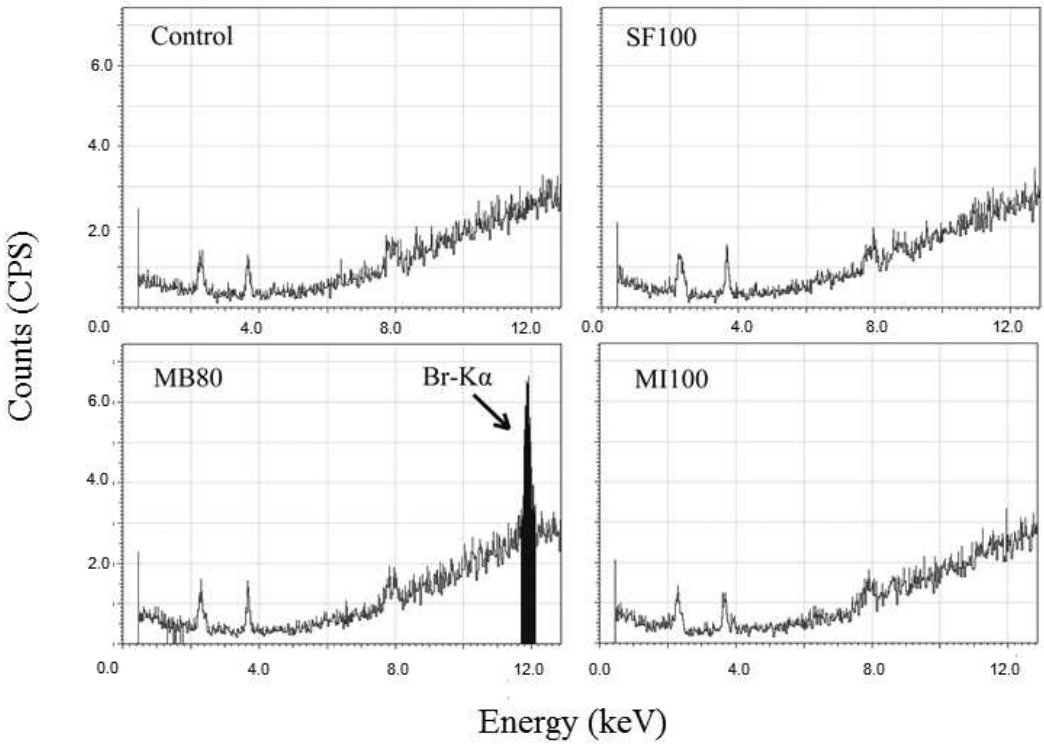

Figure 17 *X-ray fluorescence spectra of a stack of 20 layers of new raw silk textile treated with fumigants. Measurement conditions: tube voltage 45 kV, tube current 28 μA and vacuum atmosphere. Abbreviations as in Figure 1. Details of the treatment conditions are shown in Table 1.*

Table 2 *Summary of results*

Sample	Visual inspection	XRF	Electrophoresis	FTIR-ATR	Amino acid analysis	Thermal analysis:		
						TGA	DSC	T_{mic}
Freeze-dried muscle	No significant change	MB Br detected MI I detected	MB ++ MI ++ ME + SF ++	SF +	MB + MI + (ME was not analyzed)	MB ++ MI ++ ME ++ SF ++	MB ++ MI ++ ME ++ SF ++ EO + PO + HT 60°C +	MB ++ MI ++ ME ++ SF +
Animal glue (painted on polyethylene sheets or glue beads)	No significant change	MB Br detected MI I detected	No significant change	No significant change	(not tested)	(not tested)	(not tested)	(not tested)
Silk textiles (degummed and raw silk textiles)	No significant change	MB Br detected	No significant change	No significant change	(not tested)	(not tested)	(not tested)	(not tested)

+ = change; ++ = significant change

From this natural selection, these proteins might be more resistant to deteriorating agents.

As an example of the influence of a chemical on silk fibroin fiber, Kahn et al. [42] reported that with silk fibroin fiber treated with iodine/potassium iodide aqueous solution, the iodine component introduced intermolecular cross-linking to silk fibroin with heating above 270°C. Silk fibroin fiber can react with chemicals, such as iodine aqueous solution at very high temperature. But under the moderate temperature commonly applied to museum objects which was used for the tests with gaseous fumigants, no such drastic change occurred.

On the other hand, residual bromine or occasionally iodine was detected on glue sheets and silk textiles years after fumigation by methyl bromide or methyl iodide. Although the amount of the residual components may not be very high, it is a serious problem that the residues remain for so long a time on objects.

CONCLUSIONS

Fumigant effects on proteinaceous museum materials were examined in comparison with those by non-chemical treatment measures. Proteins appear to respond differently to fumigants based on their structure and amino acid composition. Though significant chemical alteration was observed with freeze-dried muscle, no significant change in characteristics was detected with animal glue and new and deteriorated silk textiles. However, residual bromine or occasionally iodine was detected in all kinds of samples fumigated by methyl bromide or methyl iodide years after a single fumigation.

Significant alterations/modifications by the fumigants methyl bromide, methyl iodide and sulfuryl fluoride were detected in the muscle protein molecules. This is the first concrete evidence of clear chemical alteration of a collection-based protein material such as a freeze-dried muscle specimen by the common treatment conditions for museum use, especially showing change by purer grade sulfuryl fluoride (Vikane®), whose definite mechanism of toxicity is still unknown. Methylation and denaturation by methyl bromide and methyl iodide, and denaturation and possible modification of the muscle specimen proteins by sulfuryl fluoride (Vikane®) were indicated.

Three thermal analytical techniques (DSC, TGA, T_{mic}) proved to be sensitive determinants of fumigation effects and support results of the direct investigation of molecular size distribution of soluble and insoluble protein fractions by electrophoresis and detection of changed chemical bonding by FTIR-ATR and amino acid analysis. Non-chemical treatments showed, as a whole, much smaller change and negligible effects on the muscle specimen, in comparison with the fumigants results.

Visual inspection of all samples did not show change in any of the proteins treated by any of the fumigants or treatments used in this study. However, at least original characteristics of the muscle protein specimens were changed by some fumigants, and residual components such as bromine or iodine were shown to reside for years in objects fumigated with methyl bromide or methyl iodide. For these, records of historical treatments are very important, as such treatments may affect the results of future analysis on the collection, and would be very helpful when it is necessary to consider a possibility of unknown toxicity of the residual components.

APPENDIX: EXPERIMENTAL DETAILS

Freeze-dried muscle electrophoresis

Two pieces weighing approximately 50 mg each were cut from treated samples and protein extraction was performed. The reason for using a duplicate was to look at the magnitude of experimental error for the same treatment sample. Pieces of protein were frozen by liquid nitrogen and ground. These samples were suspended into 1 mL of phosphate-buffered saline (PBS) [43]/1% sodium dodecyl sulfate (SDS) in plastic tubes and sonicated three times on ice for one minute each. The solutions were centrifuged (15000 rpm, 30 minutes, 4°C) and 10 μL of supernatant was subjected to protein electrophoresis as 'soluble protein fraction' with NuPAGE Bis-Tris 4-12% SDS-PAGE gel (Invitrogen). The remaining pellets were resuspended in 1 mL of 8 M urea solution, then centrifuged, and 10 μL of this supernatant was subjected to protein electrophoresis as 'insoluble protein fraction' in the same manner. All of the protein solutions were treated for 10 minutes at 70°C with 50 mM dithiothreitol (DTT) to reduce disulfide bonds prior to the electrophoresis. The SDS-PAGE gels were developed with Simply Blue stain using Coomassie brilliant blue [44].

Amino acid analysis

Approximately 5 mg of freeze-dried muscle sample was put into a glass test tube, then 200 μL of 6M HCl solution was added. The air was evacuated from the test tube and the sample was hydrolyzed at 110°C for 22 hours. The reacted solution was dried

under low vacuum. The pellet was dissolved in 200 μL of deionized water and passed through a 0.22 μm filter. The resulting solution was diluted one hundredfold with deionized water and 25 μL samples were used in a Hitachi L-8800 amino acid analyzer, in which amino acids are quantified colorimetrically by ninhydrin reaction after separation by chromatography. Identification of amino acid composition was based on retention time of each peak, in comparison with a standard amino acids mixture (a mixture of two kinds of standard amino acid mixture, AN-II and B, Wako Pure Chemical Industries, Ltd.) containing 38 amino acids: phosphoserine, taurine, phosphoethanolamine, urea, aspartic acid, hydroxyproline, threonine, serine, glutamic acid, sarcosine, alfa-amino-n-adipic acid, proline, glycine, alanine, citrulline, alfa-amino-n-butyric acid, valine, 1/2- cystine, methionine, cystathionine, isoleucine, leucine, tyrosine, phenylalanine, beta-alanine, beta- amino-i-butyric acid, gamma- amino-i-butyric acid, ethanolamine, hydroxylysine, ornithine, tryptophan, lysine, 1- methylhistidine, histidine, 3- methylhistidine, anserine, carnosine and arginine.

Fourier transform infrared spectroscopy (FTIR-ATR)

The samples were analyzed by the ATR method with a FTIR spectrophotometer (CFTS-55A, Bio-Rad Diglab). Spectra were acquired at a resolution of 2 cm^{-1} from 512 averaged scans.

Differential scanning calorimetry (DSC)

Excised 10 mg muscle samples were placed in Mettler 120 μL viton sealed medium-pressure crucibles with 40 μL of distilled deionized water. An isothermal step of 5 minutes at 15°C was followed by a 5°C per minute temperature ramp from 25°C to 110°C in a Mettler DSC30. Five replicates for each treatment were run against 40 μL water reference crucibles. The run data were normalized to 10 mg sample size, and means and sample standard deviations of the repeats calculated.

Thermal gravimetric analysis (TGA)

Portions of the treated muscle samples were excised and the fibers separated using microforceps into a uniform powder, then mixed, from which four replicates of 3 mg size were placed in open platinum pans and run on a TA Instruments TGA 5000 from 20°C to 500°C in modulated, high-resolution mode. Weight loss was recorded and derivative weight % per °C calculated. Means and sample standard deviations of the repeats were calculated and area % running integrals of thermal decomposition weight loss were calculated upward from 200°C.

Thermal microscopy (T_{mic})

Segments of individual muscle fibers were excised from treated samples and placed three per slide in distilled water between cover slips. A temperature profile of 5°C per minute was run on a Linkam hot stage, with image capture at half-minute intervals. Image processing by ImagePro, version 5.1 (Media Cybernetics, Bethseda, MD) and ImageJ version 1.43 (http://rsbweb.nih.gov/ij/) software was used to flatten the image background, edge detect the fibers, threshold select fiber area, perform edge closure, island removal, edge smoothing and determine shrinkage as major and minor axis of an ellipse fitted to the fibers recorded as pixels per degree centigrade. The pixel count data was subjected to B-spline curve fitting with TableCurve2D version 5.01 (Systat, San Jose, CA) and a size rate of change of 0.01% °C in the first derivative of the area-normalized curve was adopted as the measure of the threshold for the onset of shrinkage in lateral and axial dimensions for each fiber [45].

X-ray fluorescence spectroscopy (XRF)

XRF measurement of chemically fumigated samples was carried out to detect residual elements originated in fumigant compounds by an SEA5230E X-ray fluorescence analyzer (Seiko Instruments). Under proper conditions, XRF can detect sulfur originating in SF, bromine in MB and iodine in MI. For high S/N ratio detection, two different sets of tube voltage and current were selected: one, 15 kV and 800 μA for sulfur; and another, 45 kV and 28 μA for bromine and iodine. The diameter of the probe X-ray beam and the measurement time were fixed at about 2.0 mm and 60 s for all measurements.

Glue electrophoresis

Excised approximately 0.3 g pieces of treated glue sheets were dipped into 10 mL of sterile water and kept overnight in plastic tubes. The solutions were incubated at 60°C for 2 hours to dissolve the glue, then filtered through Whatman No. 1 paper. The extracted protein solution (10 μL each) was subjected to electrophoresis in the same manner as the protein solutions of freeze-dried muscle.

Silk (total protein) electrophoresis

The method of extracting total silk proteins is essentially according to Tse and Dupont [33], Takasu et al. [46, 47] and Teramoto [48]. 2 mL of saturated lithium thiocyanate (LiSCN) solution was added to a piece of degummed silk textile (approximately 1 cm^2, 50 mg) and incubated with agitation at 30°C for 16 hours. After centrifugation, the supernatant was made up to 2.5 mL with 40 mM tris-sulfate buffer (pH 8.0) containing 8 M urea. To eliminate salts, the solution was applied to Sephadex G-25 (PD10, Amersham Pharmacia Biotech), then eluted with 3.5 mL of 40 mM tris-sulfate buffer (pH 8.0) containing 8 M urea. The sample solution (0.02 μL each) was incubated at 60°C for 15 minutes with SDS-PAGE sample buffer (Invitrogen) and put on a 2–15% gradient gel (Daiichi Pure Chemicals). The gel was stained with SilverQuest silver staining kit (Invitrogen).

Silk (sericin) electrophoresis

Sericin was extracted according to Takasu et al. [46, 47]. 3 mL of 8 M urea containing 5% 2-mercaptoethanol (preheated at 80°C) was added to a 100 mg piece of raw silk textile (Eginu) and incubated with agitation at 80°C for 7 minutes. The residual pellet was immersed in deionized water, then dried to measure the weight. After centrifugation of the solution (6900 × g, 10 minutes), supernatant was recovered as sericin solution. The sample solution (0.05 μL each) was subjected to electrophoresis on a 2–15% gradient gel (Daiichi Pure Chemicals). The gel was stained with a SilverQuest silver staining kit (Invitrogen).

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SUPPLIERS

Chicken muscle: Akafudado, Nezu, Tokyo, Japan.

Glue: Daio, Sun-Orient Chemical, Japan.

Degummed silk: silk textile number 2-1 for JIS L 0803 tests, Japanese Standard Association, Japan.

Raw silk (Eginu): a raw silk textile roll (Nicho-hi), Kinkaido, Yanaka, Tokyo, Japan.

Artificially deteriorated raw silk for restoration: The Association Conservation of National Treasures, Kyoto, Japan.

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Résumé — *Les effets des fumigants sur les matériaux à base de protéine ont été examinés et comparés a d'autres mesures non-chimiques pour éradiquer les nuisibles. Les réponses de six fumigants – bromure de méthyle, iodure de méthyle, oxyde d'éthylène, mélange de bromure de méthyle et d'oxyde d'éthylène, oxyde de propylène et fluorure de sulfuryle – ont été étudiées sous deux atmosphères contrôlées et suivant une série de traitements thermiques par électrophorèse des protéines, spectroscopie infrarouge à Transformée de Fourier (FTIR), calorimétrie différentielle à balayage (DSC), microscopie thermique (Tmic), analyse thermogravimétrique (TGA), analyse des acides aminés et spectrométrie de fluorescence X (XRF). Un modèle de protéine de tissus mou, un muscle de poulet lyophilisé, a montré être sensible à certains fumigants, en particulier le bromure de méthyle, l'iodure de méthyle et le fluorure de sulfuryle (Vikane®). Il s'agit de la première preuve détaillée des altérations chimiques subies par une matière protéique de la part de fumigants dans des conditions de traitement commun à l'usage dans les musées, en particulier montrant une possibilité de modification de la protéine par l'emploi de fluorure de sulfuryle de qualité plus pure dont le mécanisme précis de toxicité est encore inconnu. Le brome et l'iode résiduels sont détectés distinctement par XRF dans le muscle qui a été fumigé avec soit du bromure de méthyle soit de l'iodure de méthyle respectivement, même après une simple fumigation quelques années plus tôt. D'autre part, aucun changement significatif des caractéristiques de la colle animale et des textiles en soie neufs et détériorés n'a été détecté. Cependant, le brome et parfois l'iode résiduels ont été aussi détectés dans des échantillons de colle et soie fumigés à l'aide de bromure de méthyle ou d'iodure de méthyle plusieurs années auparavant.*

Zusammenfassung — *Die Effekte von Begasungsmitteln auf proteinhaltige Materialien wurden untersucht und mit Schädlingsbekämpfungsmethoden verglichen, die nicht auf Chemikalien beruhen. Sechs Begasungsmittel – Methylbromid, Methyliodid, Ethylenoxid, Mischungen von Methylbromid und Ethylenoxid, Propylenoxid sowie Sulfurylfluorid – wurden in zwei kontrollierten Atmosphären sowie zusammen mit verschiedenen Wärmebehandlungen eingesetzt und mit Hilfe von Proteinelektrophorese, Fouriertransforminfrarotspektroskopie (FTIR), Dynamischer Differenzkalorimetrie (DSC), Thermomikroskopie (Tmic), Thermogravimetrische Analyse (TGA), Aminosäureanalyse und Röntgenfluoreszenzspektrometrie (XRF) eingesetzt. Das Modell des Proteins eines weichen Gewebes, ein gefriergetrockneter Hühnermuskel, wurde durch einige Begasungsmittel angegriffen, vor allem Methylbromid, Methyliodid und Sulfurylfluorid (Vikane®). Dies ist der erste detaillierte Beleg für eine chemische Veränderung eines proteinhaltigen Materials durch Begasungsmittel unter gewöhnlichen Nutzungsbedingungen im Museum. Dabei konnte insbesondere eine Proteinmodifikation durch reines Sulfurylfluorid belegt werden, bei dem der Mechanismus der Toxizität bisher nicht bekannt ist. Rückstände von Brom und Iod konnten durch XRF im Muskelgewebe klar nachgewiesen werden, das entweder mit Methylbromid oder Methyliodid behandelt worden waren, sogar nach einer einzigen Behandlung, einige Jahre vorher. Auf der anderen Seite konnten keine signifikanten Veränderungen der Charakteristiken von tierischem Leim und gealterter Seide festgestellt werden. Gleichwohl konnten Rückstände von Brom und Iod in Leim- und Seidenproben nachgewiesen werden, die einige Jahre vorher mit Methylbromid oder Methyliodid behandelt worden waren.*

Resumen — *En este artículo se estudian los efectos producidos por el empleo de insecticidas en materiales proteicos y se comparan con los efectos derivados del uso de otros métodos no químicos para la erradicación de plagas. Para ello se estudió la respuesta a seis insecticidas -bromuro de metilo, yoduro de metilo, óxido de etileno, una mezcla de bromuro de metilo y óxido de etileno, óxido de propileno y fluoruro de sulfurilo- en dos ambientes controlados y mediante una serie de tratamientos térmicos, utilizando electroforesis de proteínas, espectroscopía por transformada de Fourier (FTIR), calorimetría diferencial de barrido (DSC), microscopía térmica (Tmic), análisis termogravimétrico (TGA), análisis de aminoácidos y espectrometría de fluorescencia de rayos X (XRF). El estudio evidenció cómo una muestra elaborada con un suave tejido proteico -un músculo de pollo liofilizado-, parecía verse afectado por algunos insecticidas, especialmente el bromuro de metilo, el yoduro de metilo y el fluoruro de sulfurilo (Vikane®). Ésta es la primera evidencia concreta de la alteración química experimentada por un material proteico debido al empleo de un insecticida en las condiciones propias de un museo, y en especial, demuestra la posibilidad de que la proteína se vea modificada en el caso del empleo del fluoruro de sulfurilo de mayor pureza, cuyo mecanismo de toxicidad es aún desconocido. Los residuos de bromo y yodo se detectaron claramente por fluorescencia de rayos X en la muestra de músculo que había sido desinsectada bien con bromuro de metilo, bien con yoduro de metilo respectivamente, incluso después de una fumigación realizada algunos años antes. Por otra parte, aunque no se detectó ningún cambio significativo en las características de la cola animal ni tampoco en tejidos de seda nueva ni deteriorada, sí se detectaron restos de bromo y ocasionalmente también de yodo en las muestras de cola y de seda desinsectadas con bromuro de metilo o con yoduro de metilo años atrás.*

Appendix — Low cost applications

> A monk said to Tōzan, "Cold and heat descend upon us. How can we avoid them?" Tōzan said, "Why don't you go to where there is no cold or heat?" The monk said, "Where is the place where there is no cold or heat?" Tōzan said, "When cold, let it be so cold that it kills you; when hot, let it be so hot that it kills you."
>
> The Blue Cliff Record,
> Trans. K. Sekida [236]

The following illustrations [8] were developed to convey thermal pest control by the simplest of means. The intention is to show how to build and use thermal pest control methods based on the principles that make them work: achieving efficacious temperature throughout, while protecting the object from harms.

The necessary details to prevent failure are clearly depicted, such as thermal breaks between objects and with freezer walls, or the simple manner of mixing hot and room air to obtain the correct supply temperature in an insulated crate and prevent over-heating.

The systems were designed and tested for use in museums which find themselves without resources, or desired to avoid gas fumigation or pesticides. They have also been used in field situations.

The plenum frame was originally developed for large flat textiles which can be folded over a dowel or otherwise hung in the treatment bag. It has also been tested with wool pile carpeting. The frame can be improvised with any fine support (plastic snow fence, fish net, wound string). It can even be made without access to black plastic film if a thin black fabric or paper layer is used to gain heat under a clear plastic cover as long as the black layer protects the object from direct sunlight and will not mar the object.

The solar 'pillow' which can pack flat was designed to strip to the bare minimum what is needed to heat the object yet retain the object's moisture content. It was tested with thick winter parkas.

The modified crate shows a quick insulation with a 'wind skin' or it can be dressed out with conventional foam plank insulation or equivalent material. It was based on converting a large standard painting shipping crate lined with soft "Ten-Test" wood fibre insulating panels.

An analysis of utility was presented in paper two figure 6, for Ottawa in the month of August 1994. Insect mortality data was overlaid against thermal records to illustrate the potential.

To further examine year round utility in the same location (Ottawa is a cool temperate location) the longest running annual record for weather located in the Central Experimental Farm weather station was obtained[8] and processed into figure 7.1. Temperatures for black surfaces laid horizontally, at 45°, and vertically from Yamasaki and Blaga [237] are plotted to show potential heating effects. The further enhancement of heating is shown with data from April and May experiments[9] with plenum frames and solar bags to determine maximum noon and mid morning and mid afternoon temperatures. Outdoor temperatures, top black surface, object midpoint temperature and object backside temperatures are shown. The range is consistent with an approximate 20 °*C* rise over the expected 45° surface temperatures. The April to October season is certainly available for using

[8]Climate normals 1899, 1971–2000. `http://climate.weatheroffice.gc.ca/climate_normals/index_e.html`

[9]Undertaken 0.8 kilometres from the C.E.F. weather station in 2003.

solar thermal methods requiring outdoors. Low temperature exposure (palleted goods illustration) has been used in cold snap conditions in several Canadian locations.

For heat treating objects, controlling peak temperature is done by monitoring the treatment bag top surface temperature and rotating the frame or pillow off axis to the sun. It is efficient to flip the treatment bag or pillow once the midpoint temperature rose sufficient to kill pests and finish the treatment by heating the former shade side.

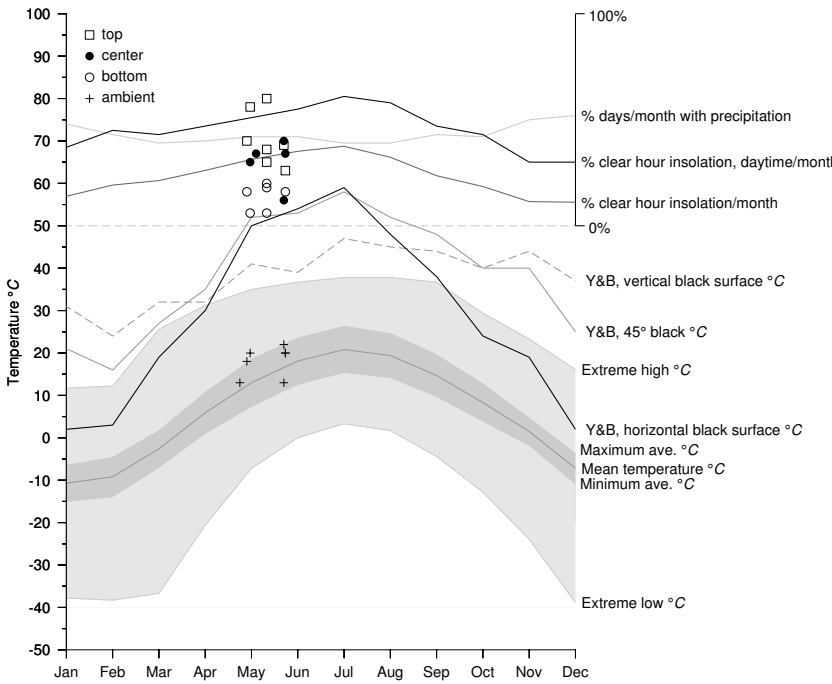
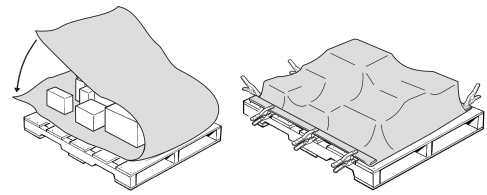


Figure 7.1: Examining the yearly potential for solar disinfestation in the Ottawa area (45° 23'N 75° 43'W). Points mark sensor locations in solar frame and bag experiments conducted by the author. Bands plot climate normals, temperature extremes and precipitation risk (1899 to 2000) from C.E.F. weather station, Ottawa. Record of monthly clear-hour insolation and surface temperatures from Yamasaki and Blaga [237]

Low-temperature control in a chest freezer or outdoors

This method is quite simple, but a few guidelines noted in the captions on the drawing need to be observed to ensure that it will work. Similar guidelines to ensure pests are killed and damage to objects is avoided should be followed when exposing objects to the cold outdoors. Outdoor exposure also requires maximizing cooling while preventing solar heat gain (e.g. use a light-coloured tarpaulin).



Outdoors: cover bagged objects with white plastic or white tarp and place on a pallet when exposing them to cold, outdoor conditions. Place objects on the shady side of the building and secure against tampering or theft. This method is only useful if the weather forecast predicts several days at -30°C or a week at a daytime high of -20°C.

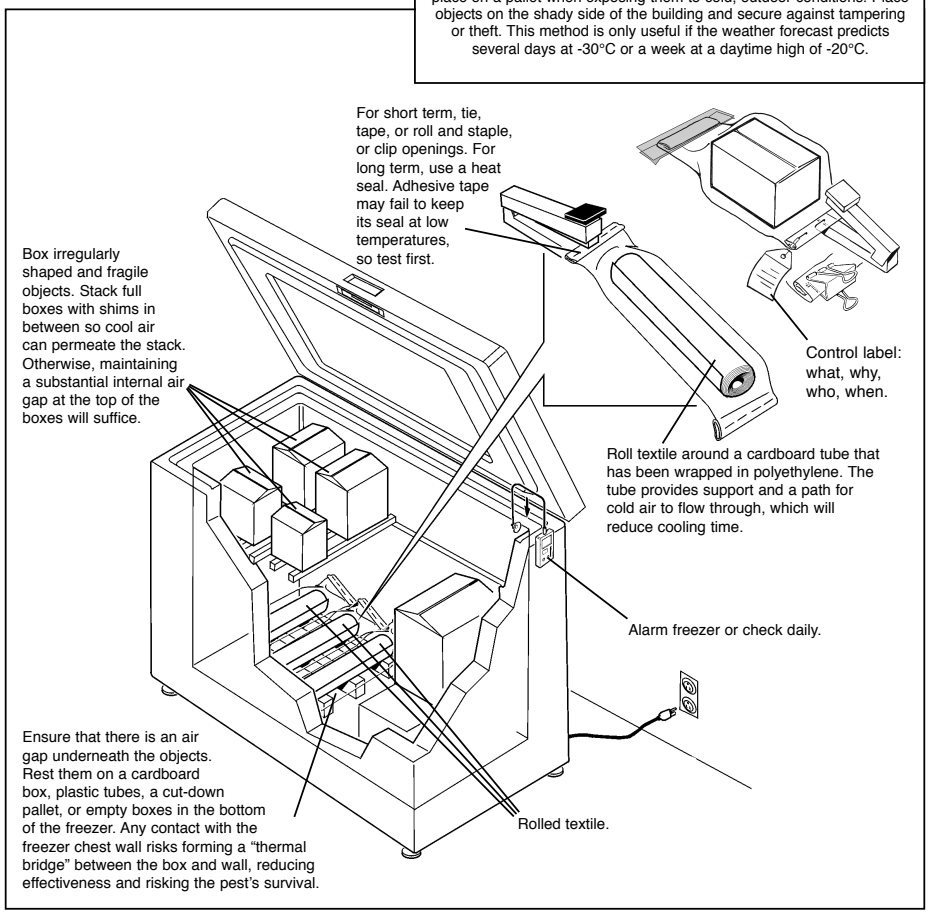


Figure 17. Low-temperature control in a chest freezer.

Heat disinfestation box

A wood shipping crate can be modified to make a heat disinfestation box, as shown in the diagram below. Heat is provided by one or two 1500-watt industrial, metal-bodied heat guns or an equivalent industrial hot air source. Do not use plastic hair dryers or household heaters because they are not designed for continuous operation at the necessary temperature. Safety is a primary issue. A Canadian Standards Association (CSA) approved heat source is placed outside the box, blowing heated air, mixed with room air, into the metal duct, which is insulated from the crate by an air gap. This technique must be supervised at all times. Pay attention to the thermometer readings especially if the box does not have automated temperature control.

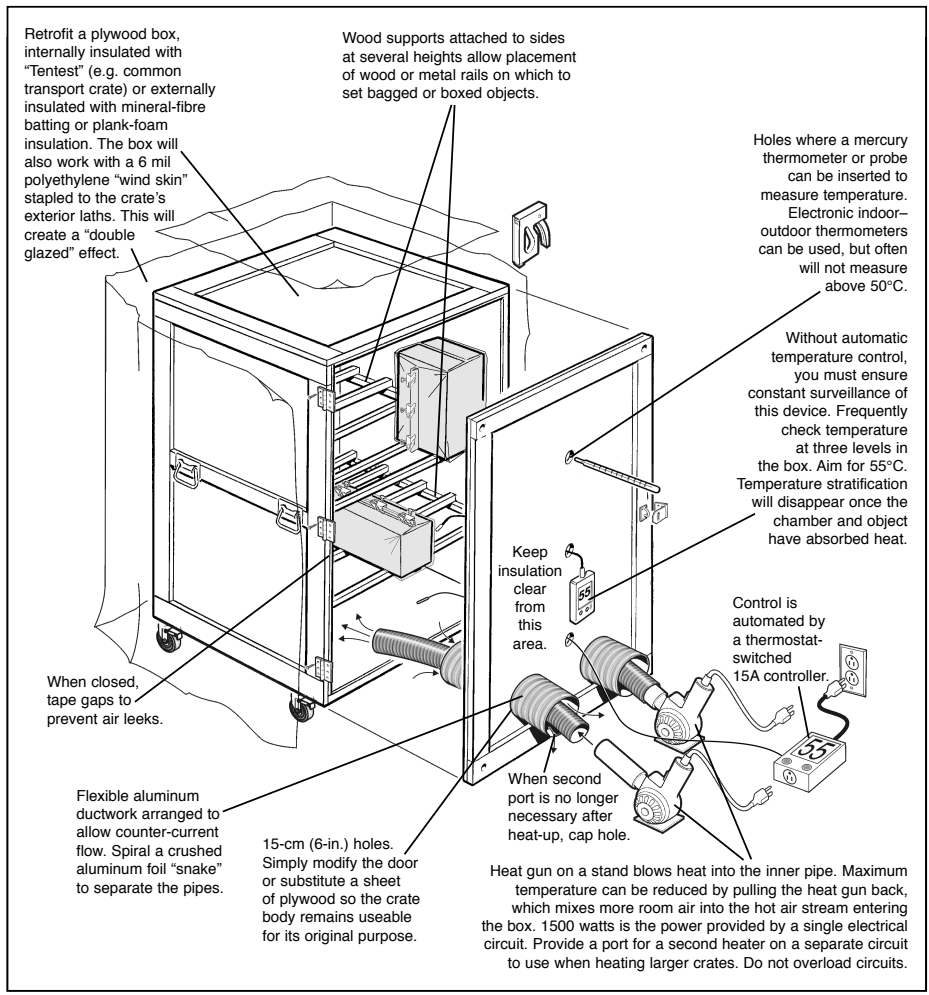


Figure 18. Heat disinfestation box.

Solar disinfestation plenum frame

This simple frame provides sufficient heat gain from spring to fall when used on a clear day in Canada to disinfest thick, folded textiles or other materials. The plenum design transfers heat to the shady side of the object bag, eliminating the risk of dampness forming on the shade side of the object. It also speeds up the disinfestation process. Use a thermometer to measure the temperature on the surface of the black bag containing the object, or a temperature probe or wireless thermometer inside the object bag. When the temperature appears to be rising too high (above 60°C), you can control it by turning the frame off-axis from the sun. The frame should be tied to a support to prevent the wind from toppling it.

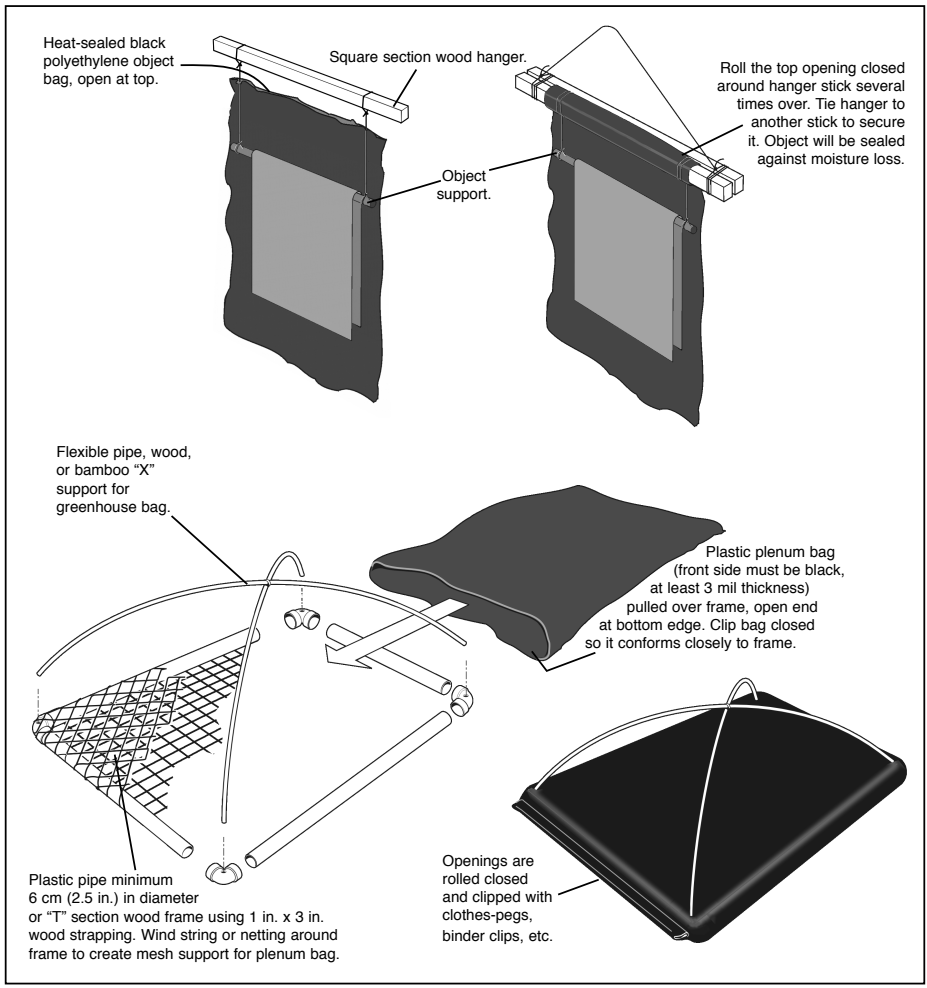


Figure 19. Solar disinfestation plenum frame.

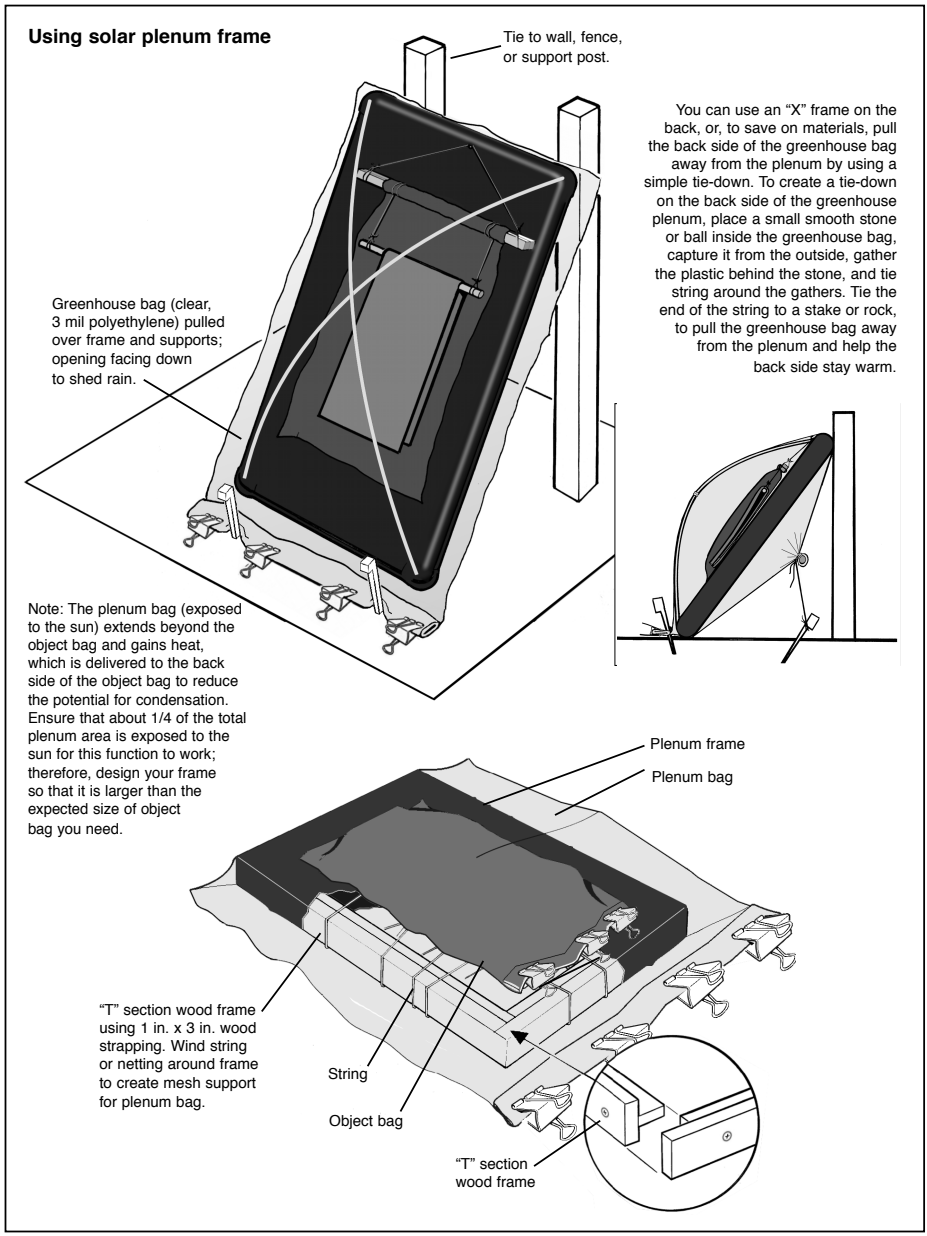


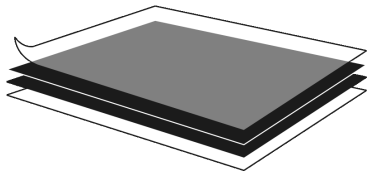
Figure 19. Solar disinfestation plenum frame (cont.).

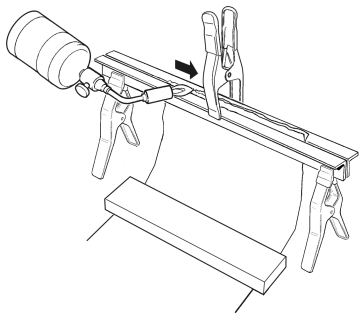
Solar disinfestation pillow

This arrangement does not require making a rigid frame. Therefore it involves a bit more careful heat sealing than does the plenum frame, but when deflated, the pillow can be stored in a much smaller space. As well, many of these pillows can be easily constructed. It is just as efficient as the plenum frame. However it is vulnerable to windy conditions; therefore, tying a pillow to stakes using a strong line is advised.

Cut four sheets of 3 mil polyethylene, two clear and two black, and stack them as follows: clear – black – black – clear, as illustrated.

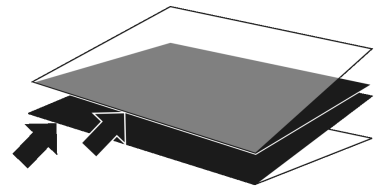
(A doubled layer makes an inflated cavity just below the greenhouse cavity that will smooth out spikes in temperature from solar gain over the object. This starts with a six-layer stack of plastic sheets: clear – black – clear – clear – black – clear. Create additional taped inflation seals inside the object cavity. Slide the object between the two inner clear sheets.)



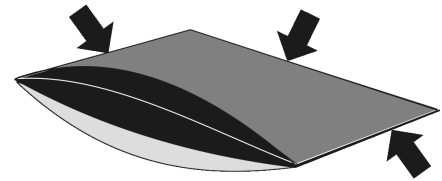


Heat sealing without a specific tool can be done by using two sharp-cornered bars of aluminum angle, a few strong spring clamps, and a small gas torch. Clamp plastic between angles and slice to within 2 mm of the angle bars with sharp scissors. Weigh down loose sheets with planks to prevent them from being lifted by the wind. Quickly pass flame along the protruding edge of plastic until it rolls together. Do this outdoors, away from combustibles, and protect yourself from any plastic fumes. Before removing clamps, ensure the seam is not burning. Properly done, this allows fast assembly of sheet films, and will form a strong bead seam that is airtight.

Heat seal a clear sheet to an adjacent black sheet along one edge for both top and bottom pairs of clear and black sheets.



Heat seal all four sheets together on remaining three edges.



As with the plenum frame, the pillow is oversized so the shady side can heat up (due to transferred radiation that has bypassed the object).

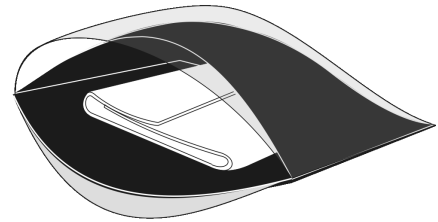
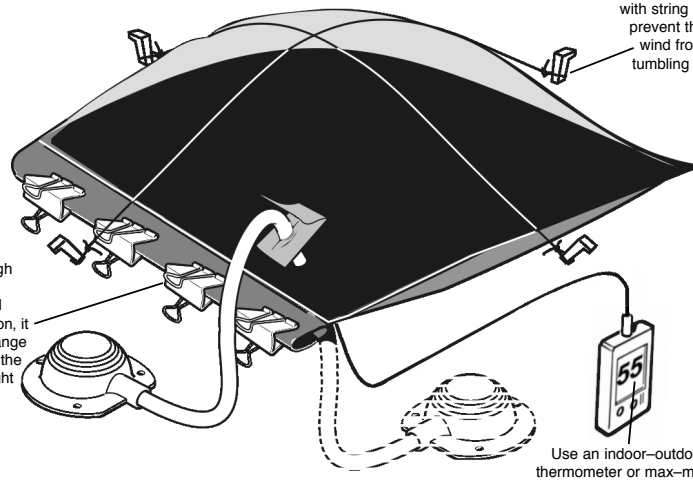
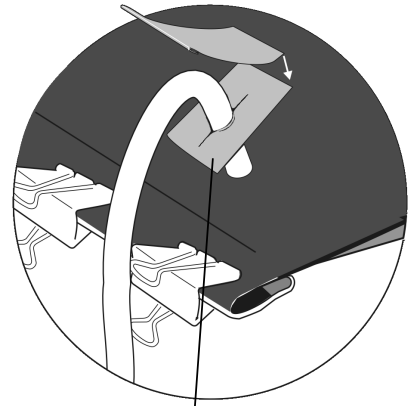


Figure 20. Solar disinfestation pillow.

Inflated solar pillow



If adhesive tape is unavailable, a valve can be made by inserting a plastic soda bottle neck with its cap into the bag, sealing it with gum, tire repair sealant, etc., and binding it by wrapping strong twine around the bottle neck.



Put a patch of strong tape (ideally vinyl) on each clear cover. Make a small slit through the tape into just the clear covers. Insert the hose from an air pump or bellows and inflate both cavities until the black plastic faces are pressing together. Tape the slit closed with another patch of the same vinyl tape. Make a tab to grip the sealing tape by folding its end back.

Figure 20. Solar disinfestation pillow (cont.).

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