Session 7：Museum Pests

The use of thermal control against insect pests of cultural property

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Abstract

Collections in cultural institutions are vulnerable to many deleterious events. Insects of concern are a blend of 'household pests', typified by clothes moth and dermestid species, 'timber pests' such as anobiid and lyctid species and 'food pests' of kitchen, pantry and granary as collections are quite varied in their composition across museum, archive, library, gallery, historic properties and cultural centers. There is a distribution of scale of museums and concomitant resources to apply against all modes of deterioration, as well as accomplishing operational goals using the collections as a core resource. There is a strong need for museum pest control methods inside an integrated pest management framework to be efficacious, have minimal effect on objects, and be economical in their costs. Through the 1980's and 90's museum staff became increasingly knowledgeable about industrial hygiene, harmful substances used in preparation methods, preservative solutions and residual insecticides. Some collections have been tested for residual arsenic, mercury, DDT, and other contaminants. Fumigants were curtailed for health and environmental impact so ethylene oxide (ETO), phosphine and methyl bromide (MeBr) followed the loss of grain fumigants which had been applied as liquids in museum storage cabinets. Thermal and controlled atmosphere methods offered a way forward for many museums which found they could not continue previous practices for controlling insects on and inside their objects. To gain widespread adoption, efficacy data had to be assembled to create confident schedules for treatment. Concerns about adverse effects arose as thermal treatments conflicted with the conservation profession's ideal of tight climate control for object preservation. Rudimentary knowledge on how humidity changes with temperature exacerbated concerns when cooling or heating an object. This paper shows the existing guidance for thermal efficacy against museum pest insects, how mitigation of adverse effects has been achieved in application of low and elevated temperature control, and topics for research.

Keywords: museum pests, thermal treatment, heat, harm mitigation

1. Introduction

Preventing collection's loss to insect pests is part of the responsibility undertaken by people running heritage institutions. Susceptibility to harm goes hand in hand with the continued existence of physical objects which we save to interpret the past and discuss the present and future. Pests, through their ability to breed in collections may start as insignificant nuisances, and end up consuming large portions of material record. Ask how long any artwork or book or garment will last when discarded onto a forest floor and insects will be a significant part of the resulting image of loss.

Collections in cultural institutions are vulnerable to many deleterious events, caused by what the Canadian Conservation Institute (CCI) has collated as 'agents of deterioration' and

organized as an overview of both the main sources of harm and their mitigation (Michalski, 1994a; Costain, 1994, CCI, 2014). In synopsis these agents are: Physical forces; Thieves and vandals; Dissociation; Fire; Water; Pests; Pollutants and contaminants; Light, ultraviolet and infrared; Incorrect temperature; Incorrect relative humidity. The common pests are then coarsely divided as Insects, Vermin or Microbes. The infrastructure to limit pest harm is split across three means: Buildings; Portable fittings; and Procedures. Individual decisions and activities to reduce the impact of agents within the means are described as five stages where: that which one cannot Avoid, one Blocks; and to that which is Detected, one Responds. Recovery from a pest event is the final stage by which to reset the cycle of prevention and reassess control measures for improving their effectiveness (Strang, 1998, 1999a; Kigawa et al., 2003a; Strang and Kigawa, 2009). Some of these deleterious agents can both derive from or contribute to pest exposure, or pests can be found independent of other direct contributions (Strang, 1998).

Incorporating more specific evidence on pest impact, the effectiveness of primary containment of cultural property significantly affects its preservation history and exposure to pests. These have been structured as an index to progressive 'levels' within IPM: Outdoors with unrestrained access by harmful agents; Roof or tarp only; Roof, walls and loose fitting doors; Basic habitation; Adapted commercial; Purpose built; Preservation. Along with these levels are overlaid scales of mitigation by many contributing features or procedures categorized by the five stages: Avoidance: environment, site, object condition, food waste, lighting, plantings, and sanitation; Blocking: physical barrier, physical resistance, object enclosure, object shelving; Detection methods, trapping, visual inspection; Response: maintenance, suppression; and Recovery activities (Strang and Kigawa, 2006, 2009).

To assist those institutions where there is a considerable volume to protect and have competing uses of space including the common division between public spaces versus collection stores, a 'risk zones' approach can be applied to identify particular vulnerabilities with require or proscribe specific activities (Doyle et al., 2007; Doyle et al., 2011; Ryder and Mendez this volume). Within this overarching integrated approach to managing pests of collections which has developed in recent decades in response to reduction of fumigants and elimination of pervasive pesticides in collection storage such as paradichlorobenzene (PDB), naphthalene and dichlorvos (DDVP), the thermal control methods have definitely found a place as part of the response cycle.

2. Scope of the problem: protecting cultural objects from insects

2.1. What is a pest of cultural property?

There is some latitude in picking the pests which attack cultural objects. Certainly the 'household pests' typified by clothes moth and dermestid species that damage textile and fur, and the timber pests such as anobiid and lyctid species that live out their lives in the relatively dry timber of our heritage buildings and furniture are easy to acknowledge. So are the structural pests like termites and carpenter ants which generally are dependent on the heritage site's environment for support. Often enough, the stored product pests from kitchen, pantry and granary find opportunity in our collections of food products, seed or nut based ornaments, plant materials, as well as the food services which are part of museum operations.

This wide definition of pest stems from the reason that collections are necessarily varied in their composition across museums, archives and libraries, art galleries, historic properties and cultural centers. Not only the raw constituent of an object's manufacture such as wool, paper, wood, and leather, which are functional descriptions for the dominant macromolecules, keratin, cellulose, and collagen, etc. but minor components such as glues, paints, starches,

dyes and especially soiling nutrients from human use contribute to altering the object's vulnerability. The physical conformation of the materials is also a contributor where small dimensioned, interwoven natural fibres are potentially more amenable to colonization by grazers than large expanses of smooth hard coated wood surfaces which may resist or merely hide the activity of borers. At risk too are the considerable investments in materials used to contain support or wrap objects. Here, even synthetics are susceptible to boring activity for pupation chambers and disfigurement from soiling.

Museum objects can be relics of industrial activity which supported significant pest activity in the past, moving these pests between national and continental borders well prior to the conception and implementation of quarantine. These insects spawned early work in economic entomology to find means to supress them. The advent of modern synthetics with lower to little pest vulnerability has meant some pests of museums were less studied in recent decades with view to solving current problems than in the past (Strang, 2012). Household pests were actively studied in the early to the mid1900's for their impact on non-comestible goods such as textiles and furniture. Then, the modernizing heating strategies for households were a concern should they amplify the risk (Griswold and Greenwald, 1941), while now, there is a replacement concern for impact of climate change on insect driven harms (Stengård Hansen et al., 2012). Both these concerns are tied to the fundamental study of insect response to the thermal environment.

Some species are actively researched as they are still destructive to foodstuffs as well as materials found in collections of heritage objects such as: insect and animal collections, basketry, plant based decorations or textile fibres, ceremonial food offerings etc. Heritage sites which retain historic structures as operational mills for food and woven goods are prone to the same stored product pests as they were historically, and which are still found infesting their modern counterparts. As many of these sites will make and offer products (e.g., flour, bread, cloth) from their operations as part of their interpretation program there is a need to control these pests.

Additionally, the species whose presence is noisome to the visiting public such as flies and wasps associated with food, garbage, compost, stables and manures, don't directly affect collections except by action of random defecation on a water sensitive paint finish or someone swatting one onto a heritage wallpaper. The numbers of bodies from sheltering cluster flies and similar insect detritus do pose a direct hazard by supporting populations of collection damaging dermestids so their control is necessary.

While termites, wood boring beetles and carpenter ants are complicit in harming structures they also invade contents like books and furniture. A scale of nuisance from plank boring by carpenter bees to grazing ultraviolet degraded surface wood fibre by paper wasps affects the exterior finishes of historic structures and over long time, accelerate their loss. Non-collection species can also greatly affect the quality of the environment around heritage and sacred sites, such as invasive and highly destructive beetles killing off tree species and damaging other flora.

There is still novelty to be found in the species affecting our objects. Some species are supplanting existing pest's local 'niche', and as they gain a foothold can be passed around (Pinniger, 2001). Others have quietly colonized structures until they are discovered many decades later with dramatic damages, such as *Priobium cylindricum* reported in Komine et al., (2009), Harada et al., (2010) and Kigawa et al. (2013) at Rinnoji in Nikkō, Japan, a UNESCO world heritage site. Determining these introduced and new pest's response to thermal control is very useful knowledge to contribute to of the treatment decision process.

To assist in education about and identification of heritage pests there are compilations of insects and other animals which have been associated with some severity of harm to cultural property (Beauchamp et al., 1988; Matei and Teodorescu, 2011; Pinniger, 2001; Skytte, 1993; Linnie, 1993; Yamano et al., 2001). Currently, three web based services that specialize in museum pests "MuseumPests.net", "WhatsEatingYourCollection.com", and INRA's "insectes-du-patrimoine" (see references for URL) provide aids to identification and publish advice on control. Amalgamating these lists and then leaving off the more nuisance species still approaches 200 insects of interest (Tables 1 and 2).

The published lists are individually selective by region of origin or intention of comprehensiveness, but they also include insects in common which confers greater world status as a collection pest. However, nuisance in one region may be far more damaging in another, as the frequency of attack, prevalence of species, and extent of observed harms and value of what was affected factor in this assessment as much as any raw potential for damage to a material.

To be certain, not all of these species are amenable to application of thermal control. There are disfiguring nuisance pests such as potter wasp's mud constructions or flies which leave specks for which the environment is an 'infinite' supplier. There are species to which the exterior environment is both source and sustenance while actively deteriorating heritage structures and collections, such as subterranean termites and the carpenter ants, bees and moths and the wood boring beetles. For these, an IPM plan offers coordinated control measures to avoid and block, as well as controlling their presence in any collection space where local thermal treatment might be warranted to mop up the problem. However, a number of species are able to go through their most damaging consumption phase solely within collections (i.e. stored product). Those which are not likely to survive locally outdoors can be imagined as essentially quarantined and thus amenable to full control by thermal eradication methods.

One can propose three regional classes of object pests: Fully exterior dependant (nuisance to damaging, commonly to exterior surfaces, non-viable when contained indoors); Colonizer (replenished viable population from exterior source, damaging to collections); Restricted to collections (only viable year round within the interior environment). These rough divisions influence the control strategy in both utility and frequency of application.

Tables 1 and 2 amalgamate cultural heritage pest listings from North America, Western Europe and Japan, Table 1 denotes those with thermal data shown in this review, and Table 2 shows those without. In summary only 60 of 183 species have some form of thermal limit data used in the plots in this paper, and of those only 51 species contributing 817 time/temperature pairs ranging from single individual super cooling point determinations, through small sample population exposures with or without buffers, to practical treatments reporting no survival. There is likely additional information on species to be found by further review, and some of the species for which there is no information would warrant study due to their potential impact on collections. Data taken from: Strang, 1992; Fields, 1992; Hou et al., 2001; Zhang, 2012; Denlinger and Yocum, 1998; Skytte, 1993; Gilberg and Brokerhof, 1991; Abdelghany et al., 2010; Yu et al., 2011; Brokerhof et al., 1992, 1993a,b; Linnie, 1999 were used to generate the point-clouds in figures below.

Table 1 Insects considered pests of cultural property, for which thermal data exists and is included in this review. Species data represented by less than 100% mortality or only population development limits marked with*.

Coleoptera Anobiidae	*Attagenus pellio* (Linnaeus)	**Dyctyoptera Blattelidae**
Anobium punctatum (De Geer)	*Attagenus smirnovi* (Zhantiev)	*Blattella germanica* (Linnaeus)
Gastrallus species	*Attagenus unicolor* (Brahm)	**Dyctyoptera Blattidae**
Lasioderma serricorne (Fabricius)	*Attagenus woodroffei* (Halstead, Green)	*Blatta orientalis* (Linnaeus)
Stegobium paniceum (Linnaeus)	*Dermestes coarctatus* Harold	*Periplaneta americana* (Linnaeus)
Xestobium rufovillosum (De Geer) *	*Dermestes haemorrhoidalis* Küster	**Hymenoptera Formicidae**
Coleptera Anobiidae, Ptininae	*Dermestes lardarius* Linnaeus	*Camponotus herculeanus* (Linnaeus)
Ptinus tectus (Boieldieu)	*Dermestes maculatus* De Geer	*Camponotus obscuripes* Mayr
Coleptera Bostrichidae	*Dermestes vorax* Motschulsky	*Camponotus pennsylvanicus* (De Geer)*
Rhyzopertha dominica (Fabricius)	*Reesa vespulae* (Milliron)	**Isoptera Kalotermitidae**
Coleoptera Cerambycidae	*Trogoderma granarium* (Everts)	*Cryptotermes brevis* (Walker)
Hylotrupes bajulus (Linnaeus)	*Trogoderma inclusum* Le Conte*	*Incisitermes minor* (Hagen)
Coleoptera Chrysomelidae	*Trogoderma variabile* (Ballion)	**Lepidoptera Gelchiidae**
Callosobruchus maculatus (Fabricius) *	**Coleoptera Lyctidae**	*Sitotroga cerealella* (Oliver)*
Coleoptera Cucujidae	*Lyctus africanus* Lesne	**Lepidoptera Pyralidae**
Cryptolestes ferrugineus (Stephens)	*Lyctus brunneus* (Stephens)	*Anagasta kuehniella* Zeller
Cryptolestes pusillus (Schoenherr) *	*Lyctus planicollis* LeConte	*Ephestia cautella* (Walker)
Coleoptera Curculonidae	**Coleoptera Sylvanidae**	*Ephestia elutella* (Huebner)
Sitophilus granarius (Linnaeus)	*Oryzaephilus mercator* (Fauvel)*	*Plodia interpunctella* (Huebner)
Sitophilus oryzae (Linnaeus)	*Oryzaephilus surinamensis* (Linnaeus)	*Tinea pellionella* (Linnaeus)
Coleoptera Dermestidae	**Coleoptera Tenebrionidae**	*Tineola bisselliella* (Hummel)
Anthrenus flavipes (LeConte)	*Tenebrio molitor* Linnaeus	*Tinea translucens* (Meyrick)
Anthrenus museorum (Linnaeus)	*Tenebrio obscurus* (Fabricius)	*Tinea dubiella* (Stainton)
Anthrenus sarnicus Mroczkowski*	*Tribolium castaneum* (Herbst)	**Zygentoma Lepismatidae**
Anthrenus scrophulariae (Linnaeus) *	*Tribolium confusum* Jaquelin du Val	*Lepisma saccharina* (Linnaeus)
Anthrenus verbasci (Linnaeus)	*Tribolium destructor* Uyttenboogart	*Thermobia domestica* (Packard)

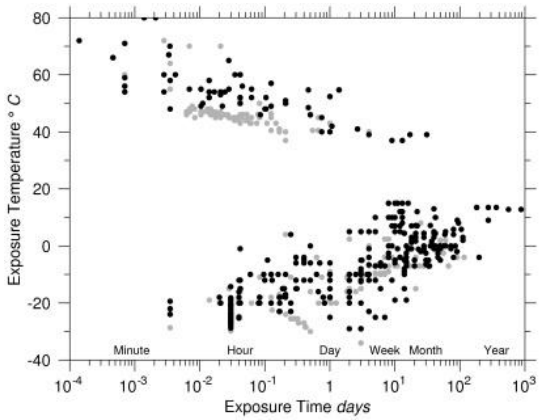
Table 2 Cultural pest insects for which thermal data does not exist, or was not found for review.

Coleoptera Anobiidae	*Anthrenus pimpinellae* Fabricius	**Diptera Muscidae**
Ernobius mollis (Linnaeus)	*Attagenus bifasciatus* Olivier	*Musca domestica* Linnaeus
Falsogastrallus sauteri Pic	*Attagenus cyphonoides* Reitter	**Dyctyoptera Blattelidae**
Gastrallus immarginatus (Mueller)	*Attagenus faciatus* (Thunberg)	*Supella longipalpa* (Fabricius)
Gibbium psylloides (Czempinski)	*Attagenus japonicus* Reitter	**Dyctyoptera Blattidae**
Hadrobregmus pertinax (Linnaeus)	*Dermestes ater* (De Geer)	*Periplaneta fuliginosa* (Serville)
Heterobostrychus aequalis	*Dermestes bicolor* Fabricius	*Periplaneta* japonica Karny
Mezium affine Boieldieu	*Dermestes carnivorus* Fabricius	**Hymenoptera Anthophoridae**
Mezium americanum Laporte de Castelnau	*Dermestes frischi* Kugelann	*Xylocopa appendiculata circumvolans* Smith
Nicobium castaneum Olivier	*Dermestes murinus* Linnaeus	**Hymenoptera Bethylidae**
Nicobium hirtum	*Dermestes peruvianus* Castelnau	*Cephalonomia gallicora* (Ashmead)
Niptus hololeucus (Faldermann)	*Dermestes undulatus* Brahm	*Sclerodermus nipponicus* Yuasa
*Oligomerus ptilino*ides Wollaston	*Megatoma undata* Linnaeus	**Hymenoptera Formicidae**
Priobium carpini (Herbst)	*Phradonoma villosulum* (Dufschmid)	*Camponotus acutirostris* Wheeler
Priobium cylindricum	*Sefrania bleusei* Pic	*Camponotus modoc* Wheeler
Coleoptera Anobiidae, Ptininae	*Thylodrias contractus* (Motschulsky)	*Camponotus tortuganus* (Emery)
Gibbium aequinoctiale Boidieu	*Trogoderma angustum* Solier	*Camponotus vicinus* (Mayr)
Ptinus japonicus Reitter	*Trogoderma glabrum* (Herbst)	*Camponous floridanus* (Buckley)
Pseudomesothes pulverulentus (Reitter)	*Trogoderma megatomoides* Reitter	**Hymenoptera Siricidae**
Ptilineurus marmotatus (Reitter)	**Coleoptera Lathridiidae**	*Urocerus japonicus* (Smith)
Ptilinus pectinicornis Linnaeus	*Adistemia watsoni* (Wollaston)	*Xeris spectrum* (Linnaeus)
Ptinus clavipes Panzer	*Cartodere constricta* (Gyllenhal)	**Hymenoptera Vespidae**
Ptinus fur (Linnaeus)	*Corticaria elongata* (Gyllenhal)	*Vespa simillima zanthoptera* Cameron
Ptinus latro Fabricius	*Cryptophagus acutangulus* Gyllenhal	**Isoptera Kalotermitidae**
Ptinus sexpunctatus Panzer	*Dienerella argus* (Reitter)	*Cryptotermes domesticus*
Ptinus variegatus Rossi	*Enicmus fungicola* Thomson	*Kalotermes flavicollis* (Fabricius)
Sculptotheca hilleri (Schilsky)	*Lathridius minutus* (Linnaeus)	**Isoptera Rhinotermitidae**
Trigonogenius globulus	*Mycetophagus quadriguttatus* (Mueller)	*Coptotermes formosanus* Shiraki
Coleoptera Bostrichidae	*Typgaea stercorea* (Linnaeus)	*Reticulitermes flavipes* (Kollar)
Bostrychus capucinus Linnaeus	**Coleoptera Lyctidae**	*Reticulitermes lucifugus* (Rossi)
Dinoderus minutus (Fabricius)	*Lyctoxylon dentatum* (Pascoe)	*Reticulitermes santonensis* (Rossi)
Dinoderus japonicus Lesne	*Lyctus linearis* Goeze	*Reticulitermes speratus* (Kolbe)
Heterobostrychus hamatipennis (Lesne)	*Lyctus sinensis* Lesne	*Reticulitermes virginicus* Banks
Sinoxylon japonicum	*Minthea* species	**Lepidoptera Oecophoridae**
Coleoptera Bruchidae	*Trogoxylon impressum* (Comolli)	*Endrosis sarcitrella* (Linnaeus)

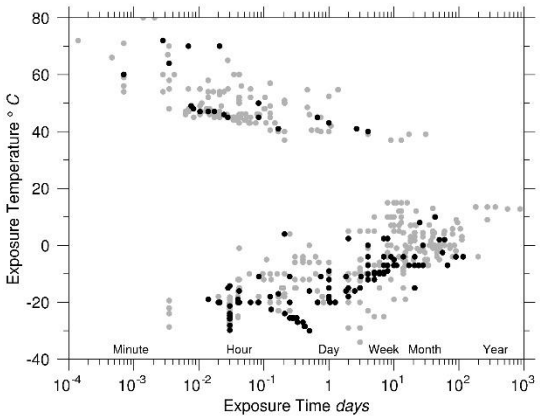
Table 2 (Con.)

Acanthocelides obtectus (Say)	**Coleoptera Mycetophagidae**	*Hofmannophila pseudospretella* (Stainton)
Coleoptera Buprestidae	*Litargus balteatus* LeConte	**Lepidoptera Pyralidae**
Buprestis haemorrhoidalis Herbst	*Thyphea stercorea* (Linnaeus)	*Ephestia calidella* (Guenée)
Chalcophora japonica japonica (Gory)	**Coleoptera Nitidulidae**	*Ephestia figulilella* (Gregson)
Coleoptera Cerambycidae	*Carpophilus dimidiatus* (Fabricius)	**Lepidoptera Tineidae**
Callidiellum rufipenne (Motschulsky)	*Carpophilus hemipterus* (Linnaeus)	*Monopis obviella* (Denis & Schiffermueller)
Chlorophorus annularis (Fabricius)	*Carpophilus ligneus* Murray	*Niditinea fuscella* (Linnaeus)
Hesperophanes cinereus (Villers)	*Carpophilus obsoletus* Erichson	*Trichophaga tapetzella* (Linnaeus)
Konoa granulata (Bates)	**Coleoptera Odemeridae**	**Orthoptera Gryllidae**
Stromatium longicorne (Newman)	*Nacerdes melanura* Linnaeus	*Acheta domesticus* (Linnaeus)
Coleoptera Cleridae	**Coleoptera Rhynchophoridae**	**Orthoptera Rhaphidophoridae**
Necrobia ruficollis (Fabricius)	*Sipalinus gigas* (Fabricius)	*Diestrammena naganoensis* Mori
Necrobia rufipes (DeGeer)	**Coleoptera Scolytidae**	**Psocoptera Liposcelidae**
Coleoptera Cryptophagidae	*Xyleborus saxeseni* (Ratzeburg)	*Liposcelis bostrychophilus* Badonnel
Cryptophagus cellaris (Scopoli)	**Coleptera Silvanidae**	*Liposcelis entomophius* (Enderlein)
Coleoptera Curculionidae	*Ahasverus advena* (Waltl)	*Liposcelis corrodens* (Heymons)
Hexarthrum exiguum (Boheman)	*Oryzaephilis surinamens*is (Linnaeus)	*Liposcelis decolor* (Pearman)
Sitophilus zeamais (Motschulsky)	*Psammoecus personatus* Grouvelle	*Liposcelis* species
Euophryum confine (Broun)	*Silvanus bidentatus* (Linnaeus)	**Psocoptera Psyllipscidae**
Hexarthrum brevicorne Wollaston	**Coleopotera Tenebrionidae**	*Dorypterix domestica* (Smithers)
Pentarthrum huttoni Wollaston	*Alphitobius diaperinus* (Panzer)	**Psocoptera Trogiidae**
Stenoscelodes hayashii Konishi	*Alphitobius laevigatus* (Linnaeus)	*Trogium pulsatorium* (Linnaeus)
Coleoptera Dermestidae	*Palorus depressus* Fabricius	**Zygentoma Lepismatidae**
Anthrenocerus australis Hope	**Diptera Fanniidae**	*Ctenolepisma villosa* (Fabricius)
Anthrenus fuscus Olivier	*Fannia canicularis* (Linnaeus)	*Lepismodes inquilinus* Newman

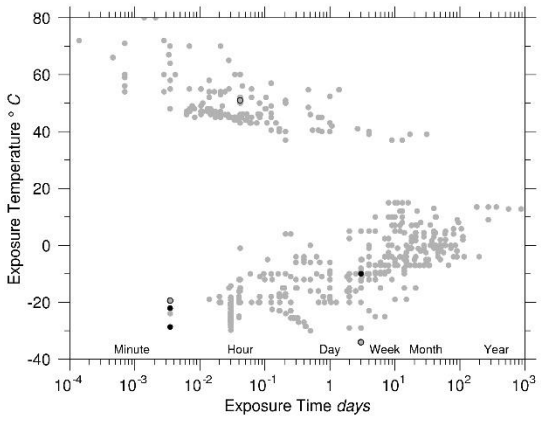
Thermal mortality data is presented as a point-cloud (Fig. 1) which shows distribution of species grouped by orders for which 100% mortality data exists in the literature.



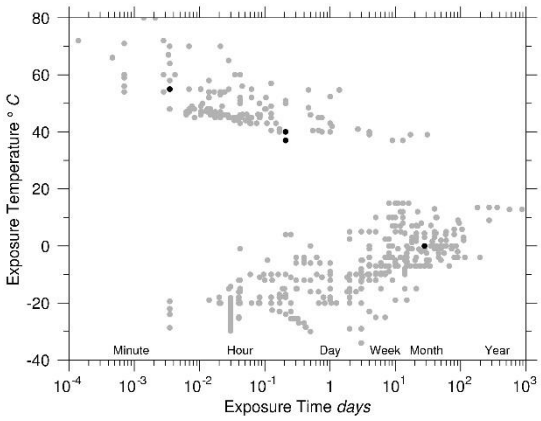
Coleoptera



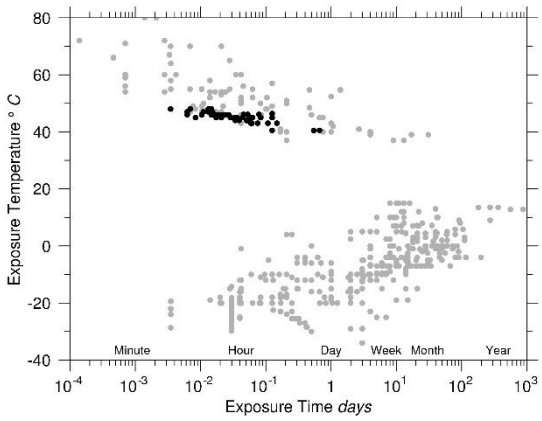
Lepidoptera



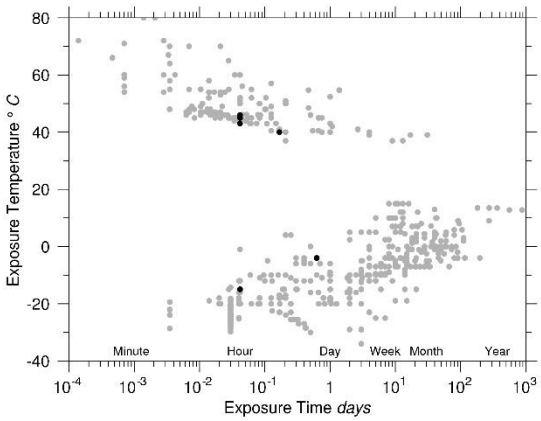
Hymenoptera ●, Isoptera ○



Zygentoma



Diptera



Dictyoptera

Figure 1#A. The distribution of thermal control values for species in Table 1, sorted by phylogenetic order. Diptera values from Denlinger and Yocum (1998) are not collections pests, but were cited along with Strang (1992) in Biosecurity Australia's (2006) discussion on application of ISPM 15 heat treatment of imported wood against insects for which there is no known thermal mortality data.

Some important orders are not well represented across the point-cloud even though the individual experiments may be reasonably definitive for the few species examined (number of individuals, selection of key species, stages represented).

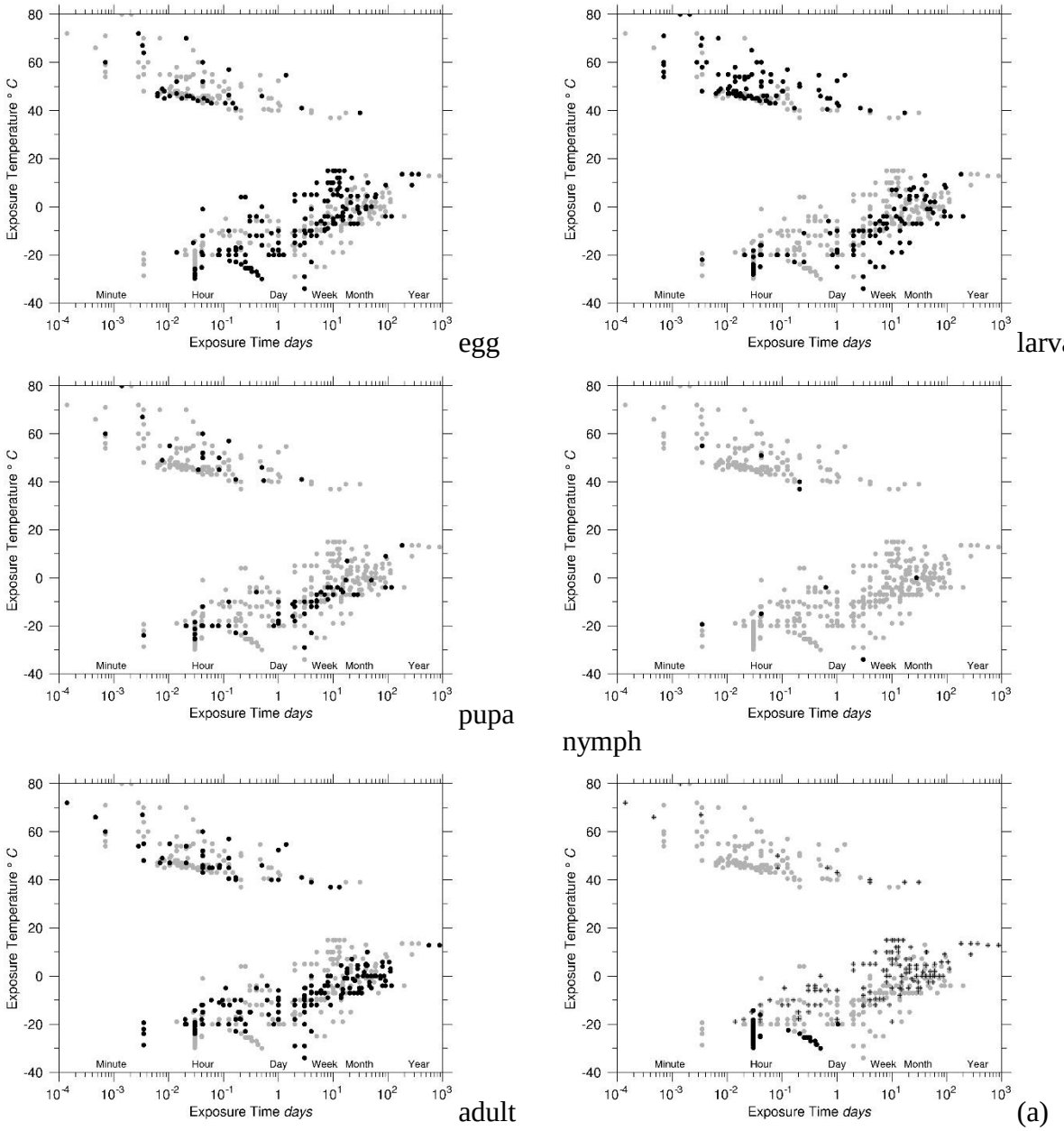


Figure 2#B. Thermal data selected by insect stage as titled. Graph (a): marginal museum pests and supercooling points: + grain pests, predominantly from Fields (1992) and largely overlapping data (grey) from Strang (1992, 2012). ●Supercooling data for museum pests from Skytte (1993), Brokerhof (1993b) and Strang (DSC data this paper).

2.2. What is a museum, how many are there, and do they need thermal control methods?

The scope for application of pest control methods to protect world heritage is large and dispersed. The International Council on Museums (ICOM) "is not aware of the accurate

number of museums in the world. However, in its 21st edition (2014), the most comprehensive directory *Museums of the World* published by De Gruyter covers more than 55,000 museums in 202 countries" (ICOM, 2014a).

Even the definition of museum is flexible. ICOM has more recently defined: "A museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment" (ICOM, 2014b).

Estimates place the number of museums *per se* in Canada around 2400 (Canadian Heritage Information Network (CHIN, 2011)) or at 4,000 museums, archives and allied heritage institutions (Canadian Museums Association, 1997). For distribution of museum types see Figure 3-Left.

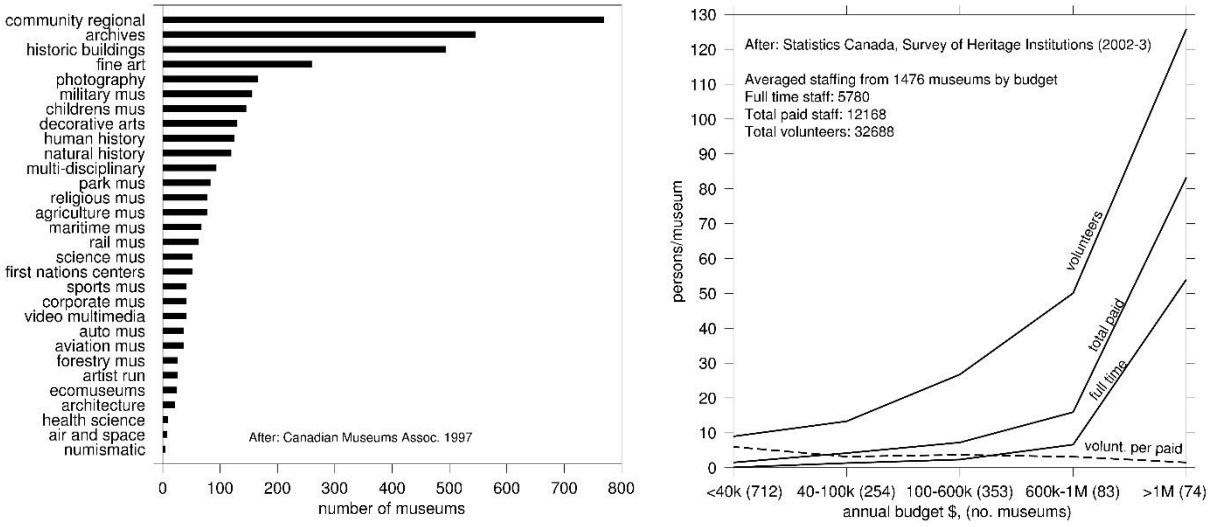


Figure 3 Left: distribution of Canadian cultural institutions (excluding libraries) by main function (after data from CMA, 1997). Right: distribution of staffing for collection care and other key functions in Canadian museums showing predominant volunteer base at all levels of funding, and volunteer/paid ratio. Data from Statistics Canada 'Survey of Heritage Institutions' (2002), plots after Strang and Kigawa (2011).

Reading into the institutions' labels (Figure 3#C Left) one might assume where there is more severity of the threat by insects. However, while one expects less insect problems in video multimedia than in a community regional museum, none are really impervious. There is often vulnerable material to be found in any collection or heavily infested materials to remedy during acquisition.

2.3. Who takes care of the objects, what are their abilities to control pests?

When it comes to determining who takes care of the objects, there is as wide variety as there is in people's background experience. This is because the staffing of museums has a predominantly volunteer component (Figure 3-Right). While larger institutions are more likely run by paid staff with academic qualifications in some direct aspect of museology such as curatorial, collection management, registrar, and less commonly conservation, the largest numbers of museums have greater proportion of volunteers carrying out the work (Statistics Canada, 2002).This survey was received by 2604 heritage institutions of which 2478 responded in part, and 1476 provided staffing numbers. Heritage institutions are those "whose

purpose is to acquire, preserve, study, interpret, and make accessible to the public (for its instruction and enjoyment) objects, specimens, documents, buildings, and land areas of educational and cultural value including artistic, scientific, historical, technological and nature-related material." (Statistics Canada, 2002).

Also from this survey, 303 institutions were inactive or no longer functioning, an indication of the potential for collections to suffer lack of care. Infrequent access to museum collections risks insect destruction (Merril, 1948; Strang, 1999a). Even with functioning institutions, having no staff on site is a common issue to contend with, as seasonal closure is a common method of running smaller museums. In 2010 a survey of Canadian natural history collections (ANHMC, 2011) found 39% of 510 collections reviewed were "weak/inactive" which leads to orphaning collections, an un-curated state which has allowed rampant insect attack as well as other harms to proceed. Rescue of these collections is a concern for both natural and human history. These rescue opportunities also bring serious concern of insect infestation into otherwise well managed circumstances. The scale of influx can be pallet-load to truckloads in volume.

As an example of collections to staff ratio from the large end of the scale, the Smithsonian Institution, National Museum of Natural History posts holdings at 125 million specimens and is visited by 8 million people each year (SI-NMNH, 2014). With 433 full time staff available for estimated 844,000 hours per year this gives a rough ratio of 150 objects per person-care-hour per year. Of course not all staff are directly caring for objects, nor are all objects in immediate need of care. However these numbers attest to the limited time per object available for all collection care activities at the object level. In a survey across 6879 museums in the USA with 1210 responding insitutions, only 54% stated they practiced IPM with only 39% having a formal IPM plan (Merritt, 2005). State associations identified 15,848 museums in the USA (Merritt, 2005).

There are estimated 500 museum associations in 132 countries (ICOM, 2014a) whose responsibilities will often include training of museums staff in professional topics as well as funding projects on collection care. One finds other professional groups, such as those running the building physical plant, providing security and sanitation services in larger institutions, who can have some impact on finding and controlling pest events if they are invited into the IPM program. There are also public legislations on food safety and sanitation which contribute to fostering some basic care – although commonly around restaurant operations not the collection. Pest insect control advice and access to technology and methods to perform the control is a significant issue given the worldwide scales of distribution of collections, physical vulnerabilities of museum holdings, budget constraints on care, and training in objects care. Thermal control methods are a great equalizer, as most people have some access to sources of heat or cold. The principles behind treatment are simple, efficacy is high, and the health consequences are minimal.

2.4. Estimation of susceptible holdings worldwide

The notable Dodo specimen from the Oxford University Museumof Natural History has acuratorial history that exemplifies the threat of loss of unique information to pests (Pinniger, 2010) with only a small portion of the original specimen remaining for DNA extraction (Shapiro et al., 2002). But less publicly noted are the millions of type specimens and unique historical items which abound. Museums elevate status of the most mundane vulnerable items simply by protection from loss. Linnie's (1993) report reveals more than 6 million specimens are held in two thirds of 72 natural history museums he surveyed, with the remaining third exceeded a million specimens each. However, the worldwide number of natural history specimens is between 1.5 billion gathered over 250 years (GBIF, 2014) to as high as 3.5

billion combining known and estimated unknown size of collections (Howie, 1992). Much of these collections are susceptible to loss to pests, not in the least part because insect specimens tend to dominate the collections in sheer numbers. Estimates of world human history collection holdings are even harder to obtain but are certainly in the billions of items as well.

The ratio of objects to people who are charged with their care is part of the problem of object vulnerability to insect pest damage. The number of museum objects worldwide is certainly on a scale equal to the human population now extant. However, care is often apportioned as many hundreds to many thousands of objects to one responsible person.

2.5. Pressure to change control methods stemming from reduction in pesticide use

Strang (2012) reviews the main line of discussion around thermal control methods formative use on collection in the early 1800 and 1900's. The earliest well documented use of heat (Kuckahn, 1771) was in direct competition with secretive preservation formulas including the discovery of arsenic salts for animal taxidermy. Cold storage and subsequent cold treatment to kill pests (Howard 1896) came out of the newly developing bank and insurance sector for deciding the temperature for cold storage of wealthy Washington ladies' fur garments.

Collection's management and conservation disciplines became increasingly knowledgeable about industrial hygiene through the 1980's and 90's (see Rossol, in Hawks et al. 2011). The harmful substances used in preparation methods, preservatives and residual insecticides came under discussion, warning and scrutiny (Rossol and Jessup 1996, Hawks and Williams 1986; Hawks 2001; Hawks and Makos 2000; Goldberg 1996, Odegard and Sadongei 2005; Sirois and Sansoucy 2001; Johnson et al. 2005; Askew 1988; Dawson 1986; Lee 1984) including conference focus at the Society for the Preservation of Natural History Collections (SPNHC) 17th annual meeting in 2002 and Smithsonian's MCI Workshop (Charola and Koestler 2010).

Collection testing by conservation scientists and occupational health professionals examined the hazard of museum staff exposure to residual arsenic, mercury, DDT and other contaminants as part of the complete picture of work place hazards (Makos, 2000).The reassessment of fumigant hazards across industries, to both the environment and human health reduced availability through fumigant re-labelling (Strang 2012) so ethylene oxide, phosphine and methyl bromide use was curtailed and eliminated, similar to the grain fumigants which had been applied as liquids in storage cabinets up to the 1980's.

Operation costs were driven upward with newly imposed increased health monitoring obligations and ensuring the lower targets of allowable emissions fumigant into the environment. Previous to this in the 1960's to 80's, fumigation chambers had dumped the waste gas to the outside, in one case the author has seen, venting horizontally out through an exterior wall over a waste collection zone in a parking lot. The anathema of chemical adulteration of objects was reinforced when increased application of sensitive analytical techniques in museums more routinely supplemented knowledge about museum object's state of preservation and constituents. The profession of conservation codified an ethical default that superficially states "if we don't know the outcome, don't do the treatment". This stance is a deliberate back-stop against wholesale changes which unintentionally or deliberately falsify the 'reading' of an original object, or are known to unduly accelerate loss (IIC-CG and CAPC, 1989; Cato and Williams, 1993; Clavir, 1994; Sease, 1998). However this stance is also be open to discussion with curatorial input when it is challenged by needs for stabilization, interpretation, or the object is being subjected to ongoing harms. Pesticide or fumigant use, and decisions on alternate insect control measures fall within the scope of this discussion.

The advent of 'non-chemical' alternatives, namely thermal controls and controlled atmosphere fumigation (CAF) are a response to residual pesticides becoming seen as museum

contaminants, not protectants. There has been some effort expended in finding means to reduce the pesticide concentrations (Ormsby et al., 2006; Glasstrup, 2001), especially where their presence has been a source of emotional harm and institutional embarrassment around repatriation of human remains or cultural items (Nason, 2001; Oddegard and Sadongei, 2005). Also, there is concern for the longer term work environment of museum staff and risk of exposure for the visiting public (Marcotte et al., 2014). Specific approaches for surveys of volatiles (Hawks et al., 2004), our understanding of pesticides as contaminants across many types of collections (Sirois et al., 2007; Blaser and Peckham, 2005) and improving means of detection and removal (Charola and Koestler, 2010) are still topical areas of museum conservation science. Pesticide residues have also been noted as problem for subsequent heat treatments by microwave due to risk of volatilization of mercury from mercuric chloride treated specimens which would add to the already present background level exposure risk (Briggs et al., 1983; Oyarzun et al., 2007).Success in reducing pesticide contamination will put more performance pressure on IPM in general, as well as the efficacy of CAF and thermal control methods.

3. Concerns going forward with thermal control: material harms and efficacy failure

3.1. Modes of deterioration, thermal control concerns and performance compared to other methods.

Beyond efficacy, there were also concerns about potential for adverse effects. Thermal control specifying cold below −20°C or heat over 50°C greatly conflicted with the conservation profession's near uniformly avowed ideal of tight climate control near human comfort levels. Based on wartime observation of paintings held in safe underground storage and later investigations on mechanical fracture, a lot of credence was invested in defining standards for artwork and objects held in air conditioned buildings. Rudimentary knowledge on how humidity changes with increased temperature (presumed to plummet) exacerbated concerns when proposing the cooling or heating of an object far from norms of human comfort and in confined enclosures.

In fact, the climate norms were, and remain, not wholly constructive when one considers ongoing chemical deterioration rates at room temperature. But as these norms were under discussion in the 1990's to set standards, and are being revisited in relation to questions of sustainability (Ashley-Smith, 2013), it was important to extend the discussion to include thermal control measures. Table 3 lists the concerns reviewed in greater detail in Strang, 1995, 1997, 1998, 1999b, 2001; Kigawa and Strang, 2011; Kigawa et al., 2011; Shchepanek 1996, 2001;Ackery et al., 2004, 2005;Kigawa et al., 2003b, Ball 2011.

Table 3 Concerns about harm, vulnerable objects, and harm mitigation in thermal treatment.

Concern: Material affected	**Mitigation**
Stiffening: Paint layers, acrylic, oil, glues, and varnishes.	Careful handling when object is cold.
Melting and softening: Glues, resin varnishes, waxes.	Heat below 60 °C generally fine excepting some low melting range waxes or admixtures with oils. Pre-testing with microscopic methods.
Blooming: Waxes, resins	Heat or cold can modify the physical structure

Table 3 (Con.)

Concern: Material affected	Mitigation
Chemical deterioration, and discoloration: Decreased by cooling, increased by heating.	Heat treatments are short duration compared to 'long burn' at room temperature
Permanent molecular distortion: Collagen, keratin, muscle, plastics.	Heat treatments are generally too low in temperature and moisture content to affect collagen our material. Plastic shrinkage temperatures are determinable or published.
Heat aging: Paper, and other organic polymers that undergo hydrolytic depolymerization.	Most materials not significantly aged by heat treatments, although it is a cumulative risk. Aside from frequent heat treatments, long term storage at room temperature is a greater risk. Cool storage `buys time'.
Water loss induced dimensional change: Wood, textile, herbarium specimens, an isotropic extent of motion (wood grain effect).	Control vapour passively in heat treatments with vapour barriers or active moisture control. Thermal contraction generally small for −30 °C cold or to 55 °C high. Any thermal motion is counteracted by opposing moisture exchange driven motion which moderates total change.
Difference in rate of temperature and moisture change: Organics that absorb and desorb water.	Moisture exchange will occur orders of magnitude slower than temperature change. Generally a good thing, further mitigated by surface coatings or vapour barriers.
Moisture pump and condensation: Organics that absorb and desorb combined with moisture sensitive layers.	Moisture collects on cold surfaces (moves to lowest vapour pressure regime). This is directed away from objects when cooling down during cold, and after heat treatments. Mitigated by dunnage to control moisture content, or actively controlled chamber humidity. Allow time for resorption before opening vapour containment.
Mould risk: Organics supporting saprophytic microbial life.	Initial conditions of low mould risk translate to low risk during and after treatment for both heat and cold.
Death: Seeds, live animals (wanted).	Mammal lethal limit is in mid 40's °C, avoid exposure. Dry seeds tolerate heat treatment and have high post treatment germination.
DNA loss: Specimens, natural history, anthropology	None noted except very high moisture content samples in heat treatment. None in low temperature treatment.
Protein change: Natural history specimens and natural materials retaining cell nuclear material.	None noted in heat treated silk or dry collagen, minor shift in thermostability in muscle compared to fumigant effects.
Physical harm: Non-robust objects.	Precautions in protection and handling during treatments.

When thermal methods were considered avant-garde to many in museums, despite heat and cold's long history in stored products or forgotten early use on collections, they fostered experimentation and assessment. Local materials and culturally specific assemblages need to be tested to provide estimations of safety for treating objects such a Japanese woods, basketry,

lacquer wood to −30°C (Ishizaki, 1999). The author has found blooming on a wax doll head treated with its infested garments. No physical damage and the bloom was readily wiped off in conservation cleaning treatment that followed. The choice of cold was taken to disinfest as disassembly for separate treatment of the body and garments was considered more likely to harm the object through wax breakage.

Examining heat disinfestation with the Thermo-Lignum® chamber for specific materials suspected of having some changes due to heat treatments. The Kultuhistorisk Museum in Norway had heat treated 25,000 objects, of which Ball et al. (2011) note an unreported number of distortions on shaped keratin (heat reformed horn) and some blooming of waxy and oily woods. They also selected resins with glass transition temperatures close to the treatment temperature to assess for changes. Thermo-Lignum® has communicated their ability to successfully heat treat complex objects through controlling both the vapour pressure to stabilize EMC, as well as restricting the surface to core temperature differential through the treatment cycle (K. Roux, pers. com.).

It is important to determine any assemblage of materials which will suffer harms in treatment. But it is equally important that their consequence be placed in the perspective of collection's care. Neither Ball et al. (2011) nor Kjerulff (2010) report statistics on percentage of the treated collection which any recorded harms represent, despite having access to the raw numbers. This reportage would be a valuable addition as it generates a better image of actual risk in mixed collections. The area of discerning harm to objects is still an area that needs extension, given the variety of objects museums hold, however large portions are well covered by the existing advice.

3.2. An example, fragile herbarium specimens and claims of harm and thermal control

Shchepanek (1996, 2001) whose insect of concern was the parthenogenic dermestid *Reesa vespulae* damaging herbarium collections addressed concerns on moisture change and thermal shrinkage in herbarium sheet preparations and refuted reports of damage to adhesive bonded herbarium preparations by cold treatment. By demonstrably re-creating the purported damage showed in Egenberg and Moe (1991) as just shrinkage from incompletely dried tissue he demonstrated safe use of cold treatment of herbarium specimens to −33 °C corroborated with the experience of other major herbaria.

Strang and Shchepanek also worked out a protocol for quickly heat disinfesting herbarium materials accompanying visiting scholars by modifying standard format herbarium drying cards to include a plenum and restricting specimen stack height (Strang, 2001). Strang (1999b) demonstrated the high likelihood of seed survival (no DNA or other macromolecule damage) of heat treatments and was corroborated by Kigawa (2003b) and Ackery et al. (2004) investigating DNA recovery after heat treatment from fungal, avian and insect sources. Obermeyer considered −20 °C safe for treating lichen collections which are prone to harm from a few dermestid and booklouse species. Lichen systematics relies on chemical tests, and low temperature exposure generally confers stability to dry macromolecules by resisting hydrolysis degradation over the long term.

3.3. Balancing thermal control concerns against previous and widely used fumigants

It is important to consider the impact previously used pest control methods had on specimens with the same modern instrumentation and methods of analysis which are used to look critically at effects from thermal treatments. In this way, we reduce demonizing biases. Past use of fumigants and pesticides did deliver positive results in preservation as do thermal controls now. Similarly, faults will inevitably be found with either strategy. When investigating fumigation by "methyl bromide, methyl bromide/ethylene oxide mixed gas,

ethylene oxide, propylene oxide and methyl iodide, all caused significant degradation of specimen DNA, even with a single fumigation" through decreased efficiency of PCR amplification, whereas thermal control methods did not (Kigawa et al., 2003b). With freeze dried muscle protein which was treated in multiple ways, similar distribution of macromolecular loss of structure and deterioration was observed in the methyl bromide and sulfuryl fluoride fumigated samples. Thermal analytical techniques which measure changes in macromolecular stability (TGA, DSC and thermal microscopy) recorded greater changes to protein by single use of fumigants (those with methyl bromide or sulfuryl fluoride) at normal treatment concentrations and times, than the changes seen from incremental heat exposure. These were correlated with other investigative molecular and spectroscopic techniques in Kigawa et al., 2011.

Dawson (1981, 1986) reviewed pesticide interactions with objects and Florian (1983, 1988) in particular reviewed ethylene oxide effects as cautionary warnings to the conservation community. Florian (1986) which included the earlier efficacy work of Ketcham-Troszak (1984) on *D. maculates* became the focal document shifting conservators towards using low temperature to control pests. Strang (1992) reviewed thermal control applications in cultural property to establish a comprehensive record of efficacy, and Strang (2012) reviewed the early history of low and elevated temperature control and how the various authors influenced each other with efficacy data and treatment protocols, as well as the early interplay with the early developments of pesticide and fumigant practices on cultural property.

Low and high temperature are not without some risk to objects. The investment in climate control for long term care is related to our understanding of object's mechanical properties and tolerances for change (Michalski, 2013). From CCI, Michalski (1996) published a caution on the mechanical fracture risk of exceeding −40°C for low temperature storage and hence exposure for insect control. This was incorporated into CCI advice on cold disinfestation in the early 1990's as some museums have access to −40°C or lower when they store biological materials for long term chemical stability (DNA, protein).

Kjerulff (2010) looked at low temperature problems discovered in the Danish museum context. By the late 1990's the National Museum of Denmark had frozen a half a million objects at −30°C (NMD staff to Strang, pers. Com, 1998). However, *Anobium punctatum* (DeGeer) has proven to be the most cold resistant insect in the Danish experience. Stengård Hansen (1992) had published mortality data on 6000 *A. punctatum* eggs on experimental wood biscuits treated at −14, −22, −27 and −30°C. Out of all these treatments, only two larvae developed 304 days later, subjected to −30°C for one and two days. Stengård Hansen's finding that over 99% control is achieved at even −14°C makes this survival a rare event, and concluded that the threat to objects with such rare survival is very low, as the likelihood of population die-off due to lack of reproductive success is very high. This is a key point for practitioners to grasp.

Danish climate gives prolonged periods of cool weather about 10°C above ambient and summer averages of 18°C. Ambient cool temperature may influence retention of this insect's super-cooling point at the times treatments are done. The efficacy concerns have tended to push down the operating temperature to ensure complete mortality rather than explore the time dimension. Kjerulff (2010) lists only a couple failures to control *A. punctatum*, one with an exposures of 3 days at -38°C, a low frequency akin to Stengård Hansen's findings.

To assay for object harm, the materials Kjerulff studied were the thin film paint materials, with test samples on glass. Such samples deliberately maximize the potential for thermal coefficients to contribute to fracture. Linseed oil varnish and lacquers did not show problems, but shellac and alkyd lacquer applied to glass surfaces did fracture with exposure at -38°C and

five cold/warm cycles. These scenarios are consistent with Michalski's predictions for harm to thin films. Construction of test cases to explore boundaries of potential material failure is common in engineering, but rare in the museum world. Triage of what goes into a freezer and what doesn't is still an area of concern and refinement. However, the argument will still be cast as "most good with least harm" versus "all good and no harm" as these are not binary comparisons of equal magnitude and need data at the core of discussion.

The conservator approach naturally falls on balancing the loss of something valuable in the particular to pests or treatment, where the effects are different harms to trade. The collection manager's approach naturally falls on balancing the loss of a large collection to pests or treatment, and is more readily accepting of low numbers of harms from treatment if they are less than losses to pests. Based on the direct experience of treating the half million objects, National Museum of Denmark staff who have every reason to be particular in their assessment, had informed this author that the number of harms to objects was very, very low, notably an old glass mirror where additional silvered film separation was suspected to be cold induced (staff pers. com. to Strang, 1998).These situations where significant numbers of objects are treated are a fertile area for applying the developing formal risk management practices in cultural property (Waller, 2003) and have been the driving force behind this author's collation of data sets to formulate the big-picture risk around measured properties in the context of thermal control so we can have an informed discussion about what goes right as much as what goes wrong.

3.4. Selecting datafor predicting mortality

What is the value of a data point towards predicting control of a pest? There are many factors which are tugging at the value of any data point, some key ones are shown in Figure 4.

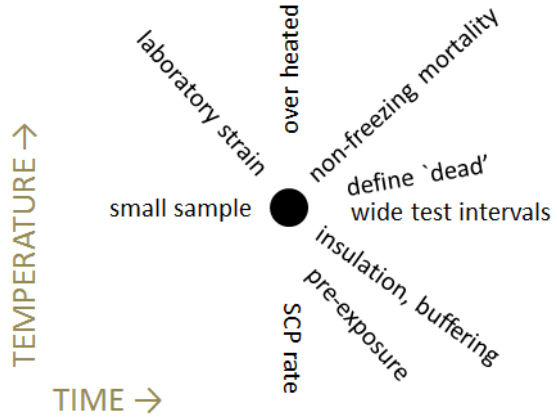


Figure 4 Any thermal mortality data point has influences beyond simple measurement error. As part of the point cloud its contribution to defining a comprehensive lethal boundary for collection damaging pests can be constructive, neutral, or degradative, in part depending on how many points represent the species, span of temperature and time.

Any one point's properly weighted contribution towards defining the end goal of a predictive lethal boundary for cultural pests may not be adequately known or even definable. They are prey to lack of definition of pre-test conditioning, potential for rapid or slow cold hardening (Denlinger and Lee, 1998),definition of 'dead' used in the experiment (immobile for a specified time, turns brown, doesn't develop or reproduce), lack of full representation of insect capability through selective filters (Danks, 1983), harm above the super cooling point

(Danks, 1996), not observing the relationship of the supercooling point (SCP) and lower lethal temperature (LLT) nor any assessment of the cryoprotectant routes available to the insects(Sinclair, 1999). These are embedded influences which exist despite the assumed best efforts of the experimenters to eliminate measurement error in both time and temperature, be accurate with species identification, and choose the level of detail on stage of development to report what was observed. Absence of data on parameters that refine the definition of a data point impairs multivariate approaches of inspecting the point cloud. Earlier works often used simple concepts matched by what information they collected.

Vernon and Vannier (2002) discuss the increased number of possible classifications of cold survival strategies: from susceptible versus tolerant (Salt, 1961) to those reflecting more subtle interpretation of insect freeze coping mechanisms (Bale, 1993; Sinclair, 1999; Nedved, 2000) into an informative visualization of the annually driven continuum of fluctuating cold survival capability for different species (Vernon and Vannier, 2002). Arguably, the need for increasing word-distinctions for a point cloud is reduced if the data presentation can simply and properly represent a residual risk for predicting outcome of a treatment. Currently, the value of the point cloud is reliant on estimating the severity of influence of any outliers, the indication of particularly tough pests that need be reckoned with and examining how definitively their limits were measured. If the significant museum pests'cold adaptation were determined and plotted as in Vernon and Vannier (2002) it would go a long way towards clearing up any confusions collection managers face when looking at the distilled advice on how to treat.

Time series and temperature series data for species and their stages have been the gold standard for determining efficacy. Time and temperature are the two `control knobs'conservators have at their disposal. Few key museum pest species have been examined with the detail and number Brokerhof et al. (1992, 1993a,b) on many hundreds of eggs of *Tineola bisselliella* (Hummel). Determining 0 to 2 day old eggs as the most tolerant stage to cold, they were able to fit an Arrhenius mortality function to predict mortality as well as create a diffusion model based cooling curve predictor for the wool food of *T. bisselliella*. If anything these studies show the hard work needed to get to an improved simple answer. However, for the museum practitioner, the mathematical nature of the proposed tool, and need for programming a calculator in 1993, was unfortunately not something that saw ready adoption across the museum community. In direct comparison, this author had done unpublished work (CCI, Jan. to Aug. 1990) to investigate the potential application of differential scanning calorimetry (Mettler DSC30) to the problem of *T. bisselliella* (clothes moth) eggs. The DSC was calibrated against indium, gallium and mercury standards, then with T-butanol drops as a test material.

The Canada Science and Technology museum near to CCI had anongoing problem in their carriage and automotive collection storage warehouse (ultimately controlled by CO_2 CAF, see Warren, 2001) and provided the breeding subjects. Eggs were gently collected off rearing colony jar walls with a hair loop, and transferred to Mettler Type 1 aluminium sealable DSC pans. An empty pan was used as reference. Eggs were not allowed to touch each other when multiples were tested so as to isolate their response. Preliminarily, an individual egg (0.02 mg) was and run against an empty pan at −1°C/minute from 20°C to −50°C. A peak was obtained at −24.2°C (0.2 mW peak height, 4.6 mJ area, onset −23.9°C with a slope of 0.54 mW/K), Figure 5. This result was a significantly lower temperature than the egg values of 3 hours at -18°C provided by Florian (1986) as personal communication from Billings, or even Back and Cotton (1927) who reported one day for complete egg mortality at −18°C to −15°C. There was considerable concern in the conservation field over eggs as they were hard to find and people suspected them to be the hardest stage to kill (as Brokerhof showed they were by

1992-3). In comparison, a single larvae filling a DSC pan scanned at −1°C/min froze at −18°C.

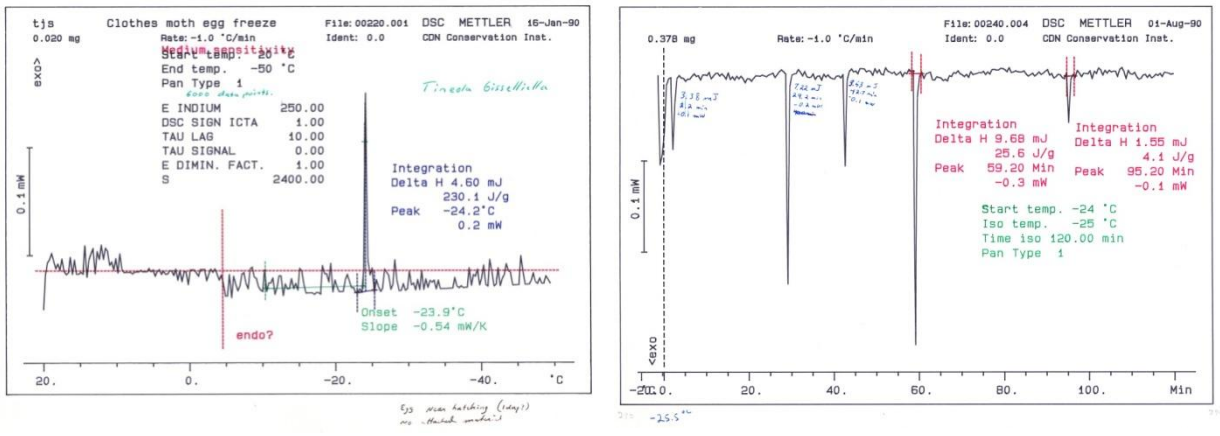


Figure 5 Left: DSC run of single *T. bisselliella* egg from 20 to −50C at −1.0 C/min. Right: DSC isotherm of five freezing *T. bisselliel*la eggs held at −25.5 °C for 120 minutes. Left side dashed line indicates position of ramp down from −24.0 generating a coincident 'peak' as an artifact associated with heat difference from using an empty reference pan. (Strang, CCI internal report, 1990).

To bracket this single egg result, fourteen eggs (0.378 mg) were cooled from 25°C to −21°C at −3°C/minute and held for 120 minutes, six subsequent isothermal stages were held for 120 minutes each after a −1°C/minute drop of −1.5°C per stage. Fourteen freezing events were recorded, see Figure 5-Right for the 25.5°C events. A trailing run from −30 to −50 at 1°C /min showed no discernable peaks from residual egg material.

Table 4 Distribution of *Tineola bisselliella* (Hummel) egg freezing by DSC. Time markedwith* occurred during 1.5°C/min temperature ramp to next isotherm, peak was readily deconvolved.

Temperature, °C	Time of peak in isotherm, minutes	Peak area, mJ	Peak height, mW
-21	No event		
-22.5	71.73	2.7	0.05
-24.0	68.2	11.3	0.1
-25.5	2.2, 29.2, 42.7, 59.2, 95.2	3.38, 7.22, 3.53, 25.6, 4.1	0.1, 0.2, 0.1, 0.3, 0.1
-27	0.0*, 1.7, 96.7	19.0, 22.0, 5.9	0.4, 0.3, 0.1
-28.5	0.4, 1.8, 21.7	17.6, 14.7, 5.2	0.5, 0.4, 0.1
-30	0.2	5.2	0.5
-30 to -50	No event		

Freezing peaks were sharp (Fig. 5) and could be integrated. The mode temperature for freezing was −25.5°C and events occurred from −22.5 to −30°C. The data indicated eggs which froze at lower temperatures may have larger peaks but peak integrations were simple horizontal baselines on unsmoothed data so subject a percentage of signal noise.

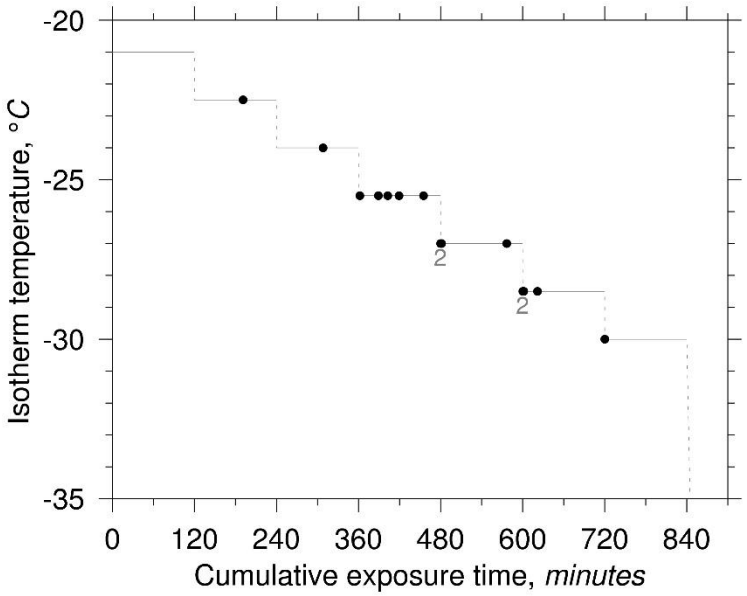


Figure 6 Freezing peak distribution at cumulative time during isothermal DSC at 1.5°C steps, freezing events of 14 *Tineola bisselliella* eggs. Doubled up points noted with "2".Dashed lines indicate −1.5 °C change at −1°C/minute.

As a final experiment, sixteen *T. bisselliella* eggs were transferred by hair loop and placed apart in a pan, temperature was dropped from 25°C to −20°Cat −3°C/minute and held for 32 hours at −20°C until the liquid nitrogen coolant ran out without a freeze event being recorded. Aluminum DSC pans can be reopened easily, no eggs hatched.

Generating data by this method had given several lessons: 1) Complete mortality for this insect stage was reported in the literature as warmer temperatures for both shorter and longer exposures than this study, and there should be an explanation for that. 2) Below −25°C six freeze events of the fourteen were more associated with the temperature change ramp than the isothermal plateau, supporting the idea that thermal gradient`stirring' triggers freeze events. 3) Conversely, the clean isothermal DSC pan with bare eggs is not representative of the messy situation on objects in chest freezers, although mimicking the insulation effect could be easily programmed into cooling rates. 4) This approach was limited to less than 20 eggs per pan so it could take an inordinate amount of resources to determine a general purpose guide from scratch for people who were calling in weekly for advice on disinfestation of many different insects, from large and small museums all over North America. Taking pans of eggs through many different paths in temperature/time would have to be performed and charted to get a better picture of *T. bisselliella* egg mortality. Testing adults and larvae would be more constrained due to their larger size.

Well controlled discrete experiments of this kind were not immediately scalable to general advice but could certainly address lacunae in the data. The decision was made to instead do a comprehensive review of the published data on museum pests and present that as an interim guide (Strang 1992).This is not to say information other than time and temperature should be

ignored. Generation of the point-cloud of museum pests is already an extremely selective filter function applied to the greater insect world whose capabilities are illustrated in ecological studies like Turnok and Fields (2005) or Sinclair (1999).There is opportunity for further exploratory data analysis to allow the users of thermal control advice to educate themselves on risk of treatment success or failure. Failure can come from poor quality advice (insect capability not known, or exceeds known values) or from poor implementation (sub-optimal treatment in time or temperature, breach of post treatment quarantine from residual infestation).

Clear presentation of raw data should also be part of the fluency of a decision making discussion (Tufte 1990). The conservation community tends to fix itself on easy to remember values: you must have 'X' temperature for 'Y' long. Strang (1992) was an attempt to break this log-jam, and provide a lethal boundary model (survival versus non-survival) so treatments can be adapted to local situations over a range of temperature or time (Strang 2012).The table assembled by Abdelgahany et al. (2010) on most susceptible stages would be worth extending to pests of cultural property to improve collection manager's ability to triage an infestation. Infestations in holdings or loans are regularly discovered just before exhibit deadlines.

The collections specialist wants an assured kill. This is due to the considerable logistical effort needed once an infestation scales beyond a cabinet or two. Once the affected volume greatly exceeds the per-treatment volume, and treatment volume cannot be scaled up through rental or donation of freezer space, the ability to easily eliminate an infestation disappears. This choke-point is where people have decided to try environmentally driven freeze-outs of herbaria (Miller and Rajer 1994) or using the outdoors as the big freezer container (application notes in Strang and Kigawa 2009). Otherwise, they can subdivide quarantine in situ using low cost polythene as temporary enclosures while progressively treating the materials by CAF (Warren 2001) or thermal means.

3.5. Supercooling data and thermal control recommendations

In 1990 Florian wrote: "Supercooling may prevent freezing from being lethal. Some insects which are freeze-resistant or cold-hardy produce glycerol in their body fluids, which allows them to supercool to −15°C." and continues with:

"Wigglesworth (1972) reported that after repeated freeze and thaw cycles, the supercooling ability is eliminated and freezing occurs as soon as freezing temperatures are reached. Florian (1978, 1986) suggested that repeated freeze-thaw cycles should be used for insect control in artifact to ensure that lethal conditions for eradication are obtained. Thus, to make insects most vulnerable to freezing they should be acclimated at a high temperature (room temperature) before freezing. They should be cooled to approximately 5°C in at least four hr, so that they cannot move. Materials in a chest freezer with adequate air movement will reach this temperature in less than four hr."Finally stating: "Situations in which there was an apparent failure can be traced to lack of monitoring of the temperature to −20C and not holding the specimen at this temperature tor the required 48 hours….This review is not intended to give specific advice." Florian 1990.

This specific non-advice led to unnecessary confusion in the collection care decision making. It is predicated on Florian's expectation of significant supercooling ability in museum pests (on no data other than a −15°C limit garnered from citations on non-pests). However, on examination of the reported data Strang (1992) concluded most pests didn't have significant supercoooling ability and even so would be readily controllable by the −20 to −30°C range of standard freezer technology (Strang 1992, 2012) in a single cooling cycle.

If a pest insect is tested individually and unbuffered as in most supercooling determinations such as Skytte (1993) for Danish museum pests, this was assumed to be the best measure of the insect to survive low temperatures and tends to give `lowest possible values' to project mortality. However the prior exposure history certainly matters as demonstrated for *Attagenus unicolor* (Brahm) by Hou et al. (2001), and the range of possible SCP for all insects is large and extends well below levels generally applied to collection pests (Strang 2012). Whether the ability to reduce cold hardening through warm quarantine storage prior to treatment is found across most species of concern would be a valuable addition to our knowledge. Such warming steps are generally taken on acquisition due to holding for processing, and setting a deliberate time in quarantine to break acclimation has also been given as weeks to a month (Strang to CCI clients, pers com.).

Comparing the above DSC results to the definitive Brokerhof et al. studies on *T. bisselliella* eggs at −2°C/hour where complete control was found at −20°C by 25 hours, it was clear there are factors other than a freezing event which affects the mortality results. The discussion on non-freezing mortality and cold injury, and temperatures at which insects could repair cold damage (Turnok and Fields 2005) are extremely useful concepts for collections practitioners, as they likely 'explain away' some of the variability in the data sets. But these concepts are not easy predictive tools like a collection of supercooling points. Just comparing the spread of the heat and cold point clouds in the figures above shows how much insects have to offer in cold survival strategies.

That freeze susceptible insects have a range of low SCP's is a concern, however few museum pests could be found with any reported ability to adapt (Strang 1992), and the majority of collection pest species are still readily controlled by the modestly low temperatures of −20 to −30°C being used (Strang, 1992; Kjerulff, 2010). The work by Hou et al. (2001) on *Attagenus unicolor* (Brahm) shows the effect environmental preconditioning has in cold hardiness from prior cold exposure and how it can be broken down by a week of 15°C acclimation. However, the practice of holding suspect collections in warm room temperature conditions for weeks prior to a low temperature treatment is reinforced by this same work comparing −15°C and 15°C pre-exposures where greatly increased mortality with −25°C exposure despite SCP's that exceeded this temperature.

In the case of low temperature control, the point cloud would only be 'wrong' if there are not enough of the hardest to kill species represented or their full variance captured in the original experiments. The more species included, the more this problem diminishes. Danks' (1983) concerns about a missing 'extreme individual' component through conscious selection of results would also trim out the necessary data to create a more assured lethal boundary model than if they were present. Published averages do not represent the distribution of variance for the point cloud. Short of missing remaining citations of value, this author has tried to show all points that can be attributed to measured experiment. One can then drill down to look at specific sources, examine lower lethality results, etc. to get a picture of the insect and our knowledge of its thermal limits. Another factor that improves the predictive value of the point cloud is having points from experiments treating insects in products. The delay provided by thermal insulation prolongs survival. Adding compensation for object cooling to an already overlong treatment time improves the prediction of high mortality.

One can also add a calculated time to cool down or heat up. Strang (1995, 2001) figure 7 is a graph which extended calculations by Michalski (1994b) for wood object moisture exchange rates using equations from Crank (1960, 1979) for examining response of painted wood objects to museum environment change. By adding data for thermal treatment half times and predictions for moisture loss in textiles and objects wrapped in polythene bags for different

thermal scenarios this graph gave anyone contemplating a thermal treatment access to an estimation tool that covers a broad range of likely materials, and thickness. The use of `time to half response' allows ready characterization of the temperature (cooling or heating) and moisture change curves. The key factor to instruct users is how to predict the end-point. Applying a four to five time multiplier of the half-change value for any thickness and conformation on the plot gives a practical endpoint, 97% to 99% of the expected value.

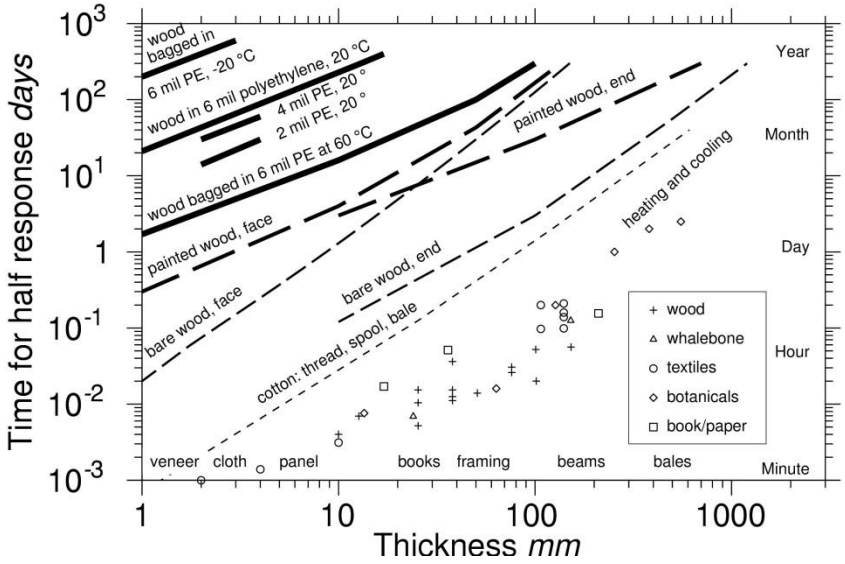


Figure 7 Calculating time to heat or cool to the core of materials for estimating thermal control treatments. Strang (1995, 2001). Pick a thickness, intercept heating points and multiply by four to five for exposure. Intercept moisture line of closest equivalent to object and multiply by four to five for determining risk of desiccation during heat treatment.

Several other papers have directly addressed the practical problem of time to complete cooling: Bergh et al. (2006) demonstrated the loss of efficacy through accidental thermal bridging of textile objects against the insulated wall of a small chest freezer but also ran mortality studies with several key species with insulation delays. Zhang (2012) sampled *Dermestes maculatus* over time at different depths of matting to examine efficacy in a model museum situation. Brokerhof et al. (1992) created a mathematical expression for cooling curves that integrates with their *T. bisselliella* mortality data.

3.6. Application of low and high temperature disinfestation

Standard practices for cold treatments include the following steps. Break any cold acclimation by holding in warm conditions at least a week to a month if previously cold. Protect from harm in treatment with a tray or support if too fragile to handle. Put the object in a water vapour resistant bag to protect against freezer breakdown and rewarming condensation. Use shelving or an empty box as a stand in the freezer to protect from thermal bridging. Treat with a sensor to warn of failure of the freezer. Remove by handling carefully. Allow to rewarm in the bag to eliminate condensation risk. Leave object in the bag for quality control quarantine, and to protect a now safe object from still infested conditions (for application notes see Strang, 1997; Strang and Kigawa, 2009).

Commonly, cold exposure guidelines fall between −20°C to −30°C for a week. The former is readily available in commodity household freezers and strongly indicated by species records

to be efficacious for pests common to collections with minimal to no acclimation to winter temperatures. The latter temperature is often chosen for walk-in freezer specifications as quarantine control for large natural history museums and prevalent wood borers.

Heat treatments for cultural property are undertaken by several means. There are a few commercial facilities which provide humidity controlled chambers to restrict moisture loss during heating and condensation during cooling back to room temperature (Thermo Lignum ®). Pest control companies offering bed-bug heat control have performed a few treatments on cultural property in private hands, where the objects have been bagged in polyethylene to protect from stress of moisture loss (Strang, CCI consultations). Museums have made simple insulated plywood chambers to treat large machines, or retrofitted crates heated with electrical heaters and blowers (for application notes see Strang and Kigawa, 2009). Solar disinfestation systems were also developed for museum use (Strang, 1995; Brokerhof, 1998, 2001, 2002).

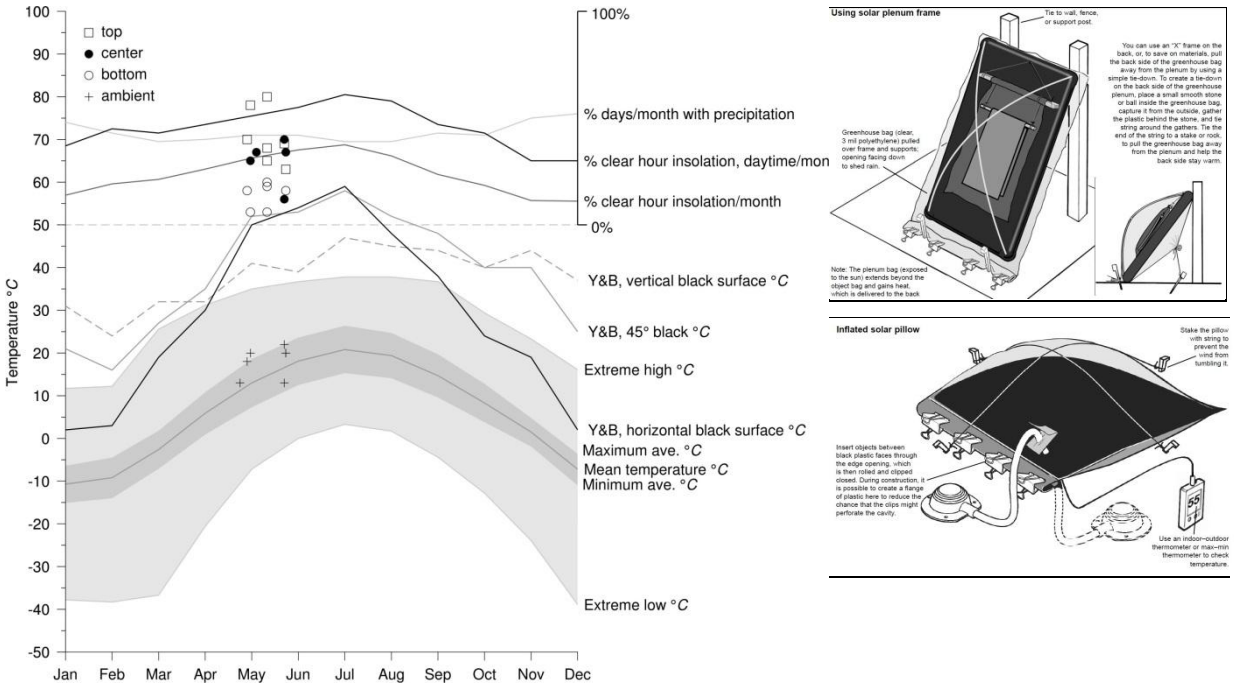


Figure 8 Left: Projection of efficacy for solar heat disinfestation treatments in the Ottawa regioncool spring season in 2003 (Strang, 2012). Treatments undertaken at ambient temperatures indicated by '+'.Right: solar plenum frame and pillow designs. (Strang and Kigawa, 2009)

Figure 8 shows the expected southern Canadian winter climate in Ottawa from monthly summaries of weather data from Environment Canada, Central Experimental Farm weather station records from 1899 to 2000. Monthly temperature of black PVC plastic panels exposed in three orientations in the Ottawa area are from Yamazaki and Blaga (1976). Data points are from experimental treatments with solar frames and bubbles done in 2003 (Strang, 2012).Tests showed the ability to elevate temperature in thick garments into lethal range in cool ambient conditions. Figure 8 also shows the added heating effect of the 'greenhouse' containment by reducing surface cooling, compared to the black panel data. Potential for over-heating the upper surface is present, but can be mitigated by treatment system designs (for application notes see Strang and Kigawa, 2009) and a simple temperature measurement guiding changes to the angle of incidence to sun. The effect of angular change is also

illustrated by crossovers in the three black panel orientation temperatures against month of exposure. Heat can also be passed through to the shade side, reducing treatment time and moisture migration risks. The designs also allow easy flipping over of the object containment to distribute treatment from the verso – cutting total exposure time.

The first object pest treatment by solar means in Canada was the early 1990's for a rural museum in Prince Edward Island which needed a means to kill pests found in quilting at the end of their program season. They didn't have freezer space available, so by describing a simple frame and bag system they could afford to do a treatment (Strang, CCI consultation). Heat treatment was further developed to meet the needs of museums primarily at the spring opening and fall closure. Figure 8 shows tests of solar frames and bags to confirm utility in these `shoulder seasons' under Canadian climate conditions. These designs were shared with conservators needing a solution when they felt they had no options with more traditional methods. Baskin (2001) describes the result of just such a successful collaboration for a museum in Laos.

As an instructive case study of integrating thermal control with their IPM approach, Morita et al. (2004), Sonoda and Hidaka (2011) describe treatment of a large wood boat from India within the gallery of the National Museum of Ethnology, Japan. Heat was chosen after reviewing other fumigation methods including nitrogen CAF. In-situ heat treatment allowed this highly visited museum to continue operation as the boat was not removable from its display location. The system used a polythene bag to control moisture in the boat anditsrigging as per Strang (2001) and a custom 18 meter long polystyrene foam insulated container with recirculation ducts and electric heaters which targeted 21 hours at 55°C to ensure heating through the largest timber and killing the wood borers. They also employ a −35°C freezer for textiles, carpets and furs, which can also be converted to use as a heating chamber. As they have active collections coming in from worldwide sources, they employ an ETO chamber with catalytic combustion of exhaust gas on all foreign sourced materials as quarantine to protect Japan from potential invasive pests then subsequently they use a chamber with CO_2 or nitrogen CAF.

4. Conclusions

The protection of cultural property from pests is best viewed as a layered strategy. Within this there is a need for methods to kill insects without bringing undue harm to the objects. At the most passive, storing objects in cool conditions or moderating warm conditions slows the depredations of insect pests as well as conserving chemical and mechanical properties of organic polymers. To have the best effect for museums, disinfestation methods have to be widely available, at low cost, and be readily practicable by paid or volunteer staff. Thermal control with low temperature is a commodity method. It simply requires a basic water vapour intercepting envelope and freezer capacity of −20°C or lower to be reasonably efficacious and productive. This has led to widespread adoption in leading museums as well as the many more which previously had no capacity for in-house pest control other than householder pesticides and sanitation. Thermal control with elevated temperature has been slower to be adopted. It is becoming a commodity method with the advent of response to bed bug infestation. It is finding its way into museum practice where speed with more assured efficacy than cold treatments are important or delivery is practical. Refining our efficacy data and extending to more pests is still an important area for contribution. Moreover, modernizing the visualization tools for collection managers and conservators to estimate treatment times and verify against efficacy data would go a long way to extending uptake of the method and improving results. Discovering restrictions to treating materials and assemblages are still an area of discussion; however they are commonly around objects which are already recognized

as difficult, fragile, peeling, or otherwise particularly valuable. This leaves a tremendous amount of material in collections that has low `worry cost' and is amenable to thermal treatment: textiles, furs, skins, paper archives, wood constructions etc. Since the late 1980's the number of objects worldwide which have undergone low temperature treatment to eliminate insect pests is certainly in the rising millions.

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