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# Comparing Mass Drying and Sterilization Protocols for Water-Damaged Books


## ABSTRACT

A 2004 research project investigated which of five drying and two sterilization techniques caused the least mechanical damage to eighteenth- to twentieth-century books. Mechanical testing revealed that air drying, vacuum freeze-drying, vacuum packing, and drying in a Vacme press with Zorbix had essentially no deleterious affect on handmade and machine-made book papers. Thermal drying, however, was shown to reduce paper's mechanical strength by fifteen percent. Sterilization with ethylene oxide caused no mechanical damage to moldy, water-damaged book paper, while gamma radiation weakened comparable book paper by twenty-five percent. Handmade papers dry with less distortion than machine-made papers treated by the same method. Books dried and pressed simultaneously produce flatter results than books dried without constraint. Of the nondamaging techniques tested, air drying and drying with a Vacme press proved the least expensive, while vacuum freeze-drying remains the most cost-effective approach to drying large numbers of books. Participating in the project were stakeholders (British Library, National Library of the Czech Republic, and University of Utah Marriott Library), research scientists (British Library, National Library of the Czech Republic, Huntsman Cancer Institute, and Applied Paper Technology, Inc.), and vendors of emergency drying services (Belfor USA, and Artifex Equipment, Inc.). Support for the research was generously provided by the National Center for Preservation Technology and Training.


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## OVERVIEW

Defining the most effective way to dry water-damaged books *en masse* is a problem endemic to all libraries, with the field of book conservation tracing its own origins directly back to the Florence flood. Yet, despite dozens of large-scale disasters and literally thousands of smaller events that have occurred in libraries worldwide since 1966, "best practices" remain unclear, especially for large-scale recovery efforts, because of the limited amount of research conducted on the long-term consequences of various drying and sterilization methods (National Library of the Czech Republic 2003; Carlsen 1999; Kaplan and Ludwig 2005).

Recovery specialists need to have a clear sense of the pros and cons of existing treatment options before they can respond effectively. This information is critical to making event-specific decisions so that collection permanence is optimized and distortion minimized within fiscal and operational constraints. Questions to be addressed in reaching those event-specific decisions include: What is the optimal approach to drying water-damaged books given the amount of material affected? What constraints are imposed by the availability and capacity of freezers, electricity, heating, ventilating and cooling (HVAC) systems, labor (trained and untrained), equipment (e.g., book presses, sorbents, fans), and vendors? What regional industrial resources can be called into service (e.g., freeze-driers, flash freezers, sub-zero warehouses)? What percentage of the damaged material is rare and which technical options are preferable for material with significant cultural or monetary value? How will a chosen treatment affect paper permanence or the physical cockling of damaged books? When is sterilization justified and what is a responsible treatment option? And if the collection is insured, what constitutes "restoration to usability"?

These judgments must be predicated upon an understanding of the comparative benefits, contraindications, and expenses of the proposed alternatives. The grim reality of flood situations where entire collections are submerged is that all choices are less-than-optimal, and a recovery can potentially be complicated by sewage-borne contaminants, pathogens, pollutants, and exponentially accelerated microbial growth.

Working with a sense of urgency to address these questions for the population of books most frequently affected by floods, a research project was forged in 2004 that included stakeholders (British Library, National Library of the Czech Republic, and University of Utah Marriott Library), research scientists (British Library, National Library of the Czech Republic, Huntsman Cancer Institute, and Applied Paper Technology, Inc.), and vendors of emergency drying services (Belfor USA and Artifex Equipment, Inc.). Support for the research was generously provided by the National Center for Preservation Technology and Training.

The goal of this research project was to define which of five drying and two sterilization techniques caused the least mechanical damage to eighteenth- to twentieth-century handmade and machine-made book papers. The inquiry hoped to determine reasons recovery specialists should choose one drying or sterilization technique over another given (1) the age and historical value of the collection, (2) predominant paper types comprising the damaged material, and (3) institutional or insurer-imposed fiscal constraints. Importantly, the performance of bindings and binding materials was not addressed in this study because books exposed to major flooding typically require rebinding.

## EXPERIMENTAL DESIGN

The sample set for this study was culled from books published between 1767 and 1979. Multi-volume sets were used in the expectation that the paper would be sufficiently similar among volumes within each set to provide a reasonable basis for comparison of the methods. While it was recognized at the outset that this choice eliminated the possibility of precisely replicating the study, the experimental design erred on the side of simulating real life situations so the results would correlate in a meaningful way with real library disasters.

A total of 171 volumes (thirty-nine three-, five-, and seven-volume sets) were used as samples. Of these, nine sets were published in the eighteenth or early nineteenth century and printed on handmade (cotton/linen) paper, while the remaining twenty-five sets were published in the nineteenth and twentieth centuries and printed on machine-made (wood fiber) paper. The ratio of handmade to machine-made paper roughly approximated the distribution that might be expected in a mid-sized research library collection, except that sets printed on clay-coated paper were unavailable for destructive testing.

One volume from each test group was retained undamaged as a control, while twenty-two volumes were wetted and subsequently dried by one of five contemporary drying techniques (air drying, vacuum freeze-drying, thermal drying, vacuum packing, and Vacme press drying with Zorbix), or were sterilized after freeze-drying with one of two commercially available options (ethylene oxide or gamma irradiation). The experimental design produced 528 data points for each of the seven protocols tested.

### Wetting Protocol

Each book was submerged completely for twenty-four hours in distilled water in a flat-bottomed sink (fig. 1). While not realistic, distilled water was used because of the difficulty of providing uniformly contaminated flood water at five sites in Europe and the United States. When buoyancy posed a problem the text was weighted slightly to maximize its submersion and the text's subsequent wetting. The wet books were then drained under a polyethylene sheet to maintain high relative humidity (approximately 95%) at ambient room temperature for twenty-four hours (22°C/72°F), simulating a flooded library prior to pack-out. Books to be vacuum freeze-dried were frozen (-18°C/0°F) using a commercial freezer facility, while each of the other techniques proceeded directly to drying.

Books prepared for sterilization followed the same wetting procedure but after draining for twenty-four hours were individually bagged in polyethylene freezer bags and left to mold at ambient room temperature for seven days (168 hours).

### Drying Protocols

Following wetting, five drying protocols were tested in five different locations.[1]

#### *Air Drying with Intermittent Pressing*

In a low relative humidity environment (30% RH) at the University of Utah (Salt Lake City, Utah, USA), wet

Fig. 1. Sample books submerged for twenty-four hours


Fig. 2. Air drying, University of Utah

books were stood on end on counter-high tables and fanned open to stimulate evaporation (fig. 2). None of the books were printed on coated-stock paper so interleaving with silicon release paper (or wax paper) was unnecessary. Supports to prevent books from falling over included plastic VeloBind combs inserted at the head of the text to act as a cross brace,[2] as well as five-pound weights placed as necessary at the base of the boards. Six large, electric fans were positioned around the table and turned on the maximum setting to circulate air thoroughly throughout the drying process, accelerating evaporation and discouraging microbial growth. As the still-wet books approached dryness (after approximately three days) they were pressed for approximately twelve hours overnight between boards in a bookbinder's standing press, and returned to the tables each morning for further fanning and air drying until all were thoroughly dry—five to seven days (fig. 3). Dried books were pressed between boards for an additional seven days following drying.

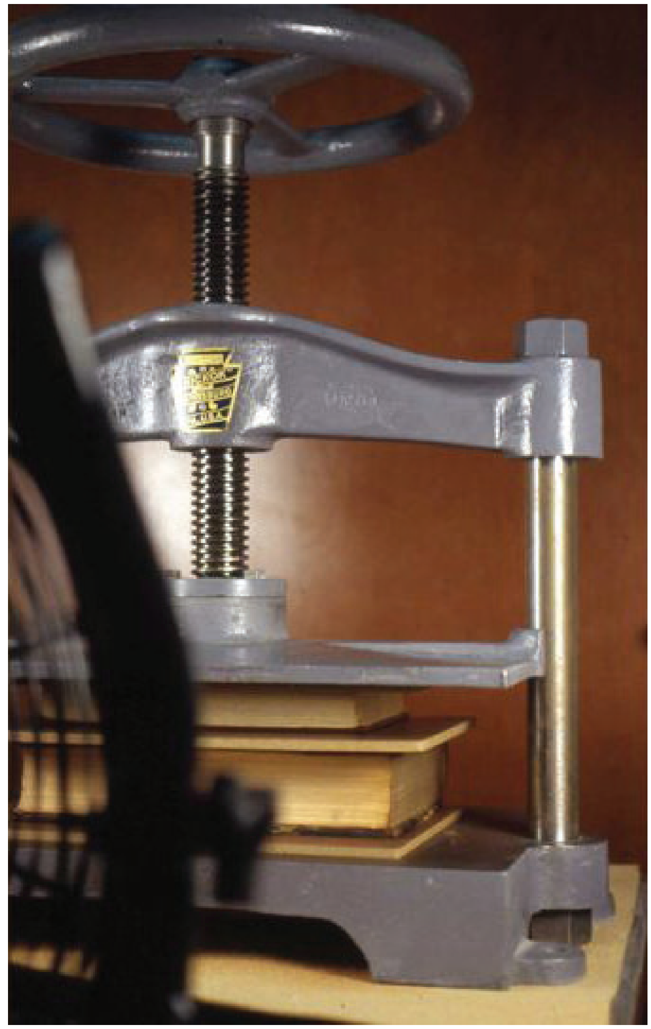

Fig. 3. Intermittent pressing during air drying, University of Utah

*Vacuum Freeze-Drying*

At Belfor USA (Fort Worth, Texas, USA) frozen books were placed on rolling wire racks inside a commercial vacuum freeze-drying chamber (fig. 4). The books were firmly packed together on the racks, spine down, to help maintain their shape during drying (fig. 5). Vapor pressure within the chamber was reduced below the triple point of water (4.57 torr/0.6092833 kilopascals). A slight amount of heat (40.5°C/105°F), was introduced intermittently to the chamber to stimulate sublimation (direct conversion from solid to vapor).[3] Ice from the frozen books sublimed and was captured as ice on the unit's evaporator coils outside the chamber. The chamber contents were checked daily after the fourth day, and thoroughly dry books were removed until all books were finished (approximately seven days). Although the vendor provides more expensive services in which books are freeze-dried while physically compressed to yield flatter text blocks, this

Fig. 4. Vacuum freeze drying chamber, Belfor USA

Fig. 5. Books on wire racks prepared for vacuum freeze drying, Belfor USA

option was not part of this study in order to reflect financial constraints typical of most post-disaster recoveries.

*Thermal Drying*

In a commercial wood-drying kiln outside Prague, Czech Republic, staff of the National Library of the Czech Republic placed wet books on elevated wire racks, and interleaved each book with sheets of absorbent paper (printed newsprint) every ten to fifteen pages (figs. 6–7). In addition to facilitating egress of water from the text block through wicking, these sheets were replaced daily to provide bulk removal of water. Books were then stacked vertically between pairs of unglazed ceramic tiles, and sheets of Hollytex (100% polyester, nonwoven polyolefin sheet) were placed between the unglazed tile surface and the book cover to promote diffusion of moisture while preventing wet bindings from sticking to the tiles due to adhesive migration or thermoplastic adhesion. Each stack of books was weighted on top (3.2 kg/7.0 lb) to produce constant pressure that reduced text block distortion during drying.

Fig. 6. Wood-drying kiln adapted for thermal drying, Czech Republic

Air was circulated within the closed kiln and the temperature raised to 60°C/140° F with the relative humidity set at 70%. After two days the relative humidity was reduced to 40 to 50% while the temperature remained constant. Complete drying time took between seven and twenty days depending on the size and physical characteristics of each text block and cover. Books with plasticized covers took much longer to dry as moisture was eliminated only through the edges of the text. Interleaving was replaced daily during routine inspection for dampness. When the drying cycle was completed, the kiln was slowly returned to ambient conditions to allow books to equilibrate while still under mechanical restraint.

*Vacuum Packing*

At the British Library (London, United Kingdom) wet books were interleaved with sheets of printed newsprint every ten to fifteen pages (fig. 8). If the wet binding felt slippery it was wrapped with Bondina to prevent the covering material from adhering to the polyester vacuum pouch.[4] Placing the book inside the pouch (manufactured by Archipress), the edge was sealed with an Archipress Vacuum Packing Machine and a vacuum pulled (fig. 9). After several days the pouch was opened and the interleaving exchanged for dry blotting paper to remove bulk water, and a new pouch used to reseal the book. Drying took up to twenty exchanges of bag and blotter over sixty days.

*Vacme Press with Zorbix*

At Artifex Equipment, Inc. (Penngrove, California, USA), wet books were interleaved with sheets of Zorbix every ten to fifteen pages.[5] The covers were wrapped with Hollytex to prevent binding materials from adhering to the inside of a proprietary, resealable vinyl bag integrated with

Fig. 7. Books stacked between unglazed ceramic tiles in kiln, Czech Republic

a vacuum hose fitting (made by Artifex). The vinyl bag's resealable opening was rendered airtight with a Teflon folder while it was evacuated with a vacuum pump (fig. 10). Saturated Zorbix interleaving was replaced at forty-eight-hour intervals. Drying required approximately six exchanges of Zorbix over fourteen days.

Sterilization

Following wetting, molding, and subsequent vacuum freeze-drying, books were sterilized by licensed practitioners using either ethylene oxide (EtO) or gamma radiation. It should be noted that both sterilization methods required books to be free of liquid water before treatment as any moisture not chemically bound to the cellulose would otherwise react with the sterilizing agent.

*Ethylene Oxide*

In the Czech National Archives in Prague (Czech Republic), vacuum freeze-dried moldy books were placed in a 6.4 m3 vacuum sterilization chamber (Matachana, type 3.100 LGE-2) (fig. 11). The chamber was preheated to 30°C/86° F, air was evacuated to 0.069 bar, and a calculated amount of water injected. The water was evaporated at 0.09 bar and the air evacuated a second time to reach 0.054 bar. At 1,125 torr (150 kilopascals) the temperature was held at 30°C/86° F and 80% relative humidity. Books were exposed to a 10% ethylene oxide:90% carbon dioxide mixture (trade name, Etoxen) for six hours at 1.5-2.5 bar.

Fig. 8. Interleaved book in pouch prepared for vacuum packing, British Library

Fig. 9. Vacuum packing machine, British Library

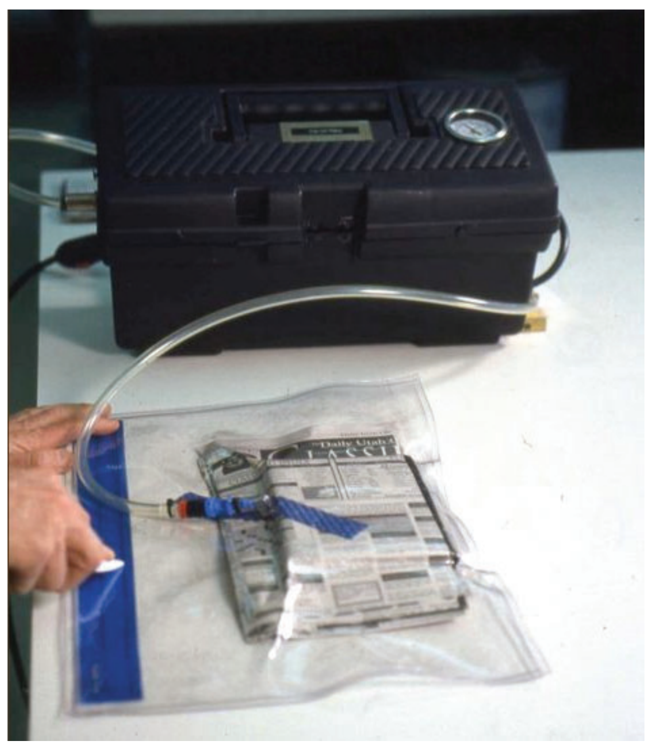

Fig. 10. Interleaved book in pouch with Vacme Press

Fig. 11. Books in ethylene oxide chamber, Czech National Archives

Fig. 12. Conveyor leading to gamma radiation facility, Corona, California

The chamber was then aerated, exhausted, and refilled thirty times with the EtO gas incinerated in a plasma flame. At the end of the process books were transferred to a ventilation tunnel where they offgassed for six days.

*Gamma Radiation*

At Sterigenics, a licensed commercial gamma irradiation facility in Fort Worth, Texas (USA), vacuum freeze-dried moldy books were passed through an irradiation chamber where they received a calculated dosage in the range 12.6–18.8 kilogray (kGy) (fig. 12). No pretreatment dehydration or post-treatment equilibration was required.

## ANALYTICAL TESTING

To evaluate treatment-associated loss of mechanical integrity, twenty-four leaves were removed at equal intervals from each dried or sterilized book and sent to one of two analytical labs. Each leaf was subjected to four internationally standardized mechanical tests: tensile strength, stretch-to-break, tearing resistance, and MIT fold endurance (figs. 13–14).[6]

## DISCUSSION

Four drying methods (air drying, vacuum freeze-drying, vacuum packing, and drying in a Vacme press with Zorbix), and one sterilization technique (ethylene oxide) retained essentially all of the pre-treatment mechanical integrity of the book papers tested and were deemed non-damaging (fig. 15). By contrast, samples from the thermally dried and gamma-irradiated books lost 19% and 24%, respectively, of their mechanical integrity and were determined to be inappropriate for treating water-damaged books of permanent retention value.

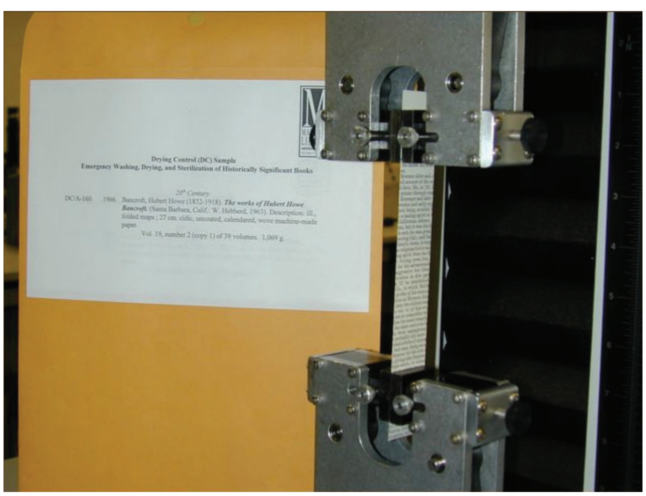


Fig. 13. Analytical testing: tensile test, Applied Paper Technology, Inc

Fig. 14. Examining physical characteristics after drying, British Library

Physical cockling in treated material was most successfully minimized when book paper was pressed as the moisture was removed (figs. 16–17). Vacuum packing and Vacme press drying best achieved this ideal but at different levels of fiscal investment. The initial cost of a vacuum packing machine may prove prohibitive for many collecting institutions in addition to which numerous, disposable polyester vacuum pouches were required for each book dried.[7] The Vacme press, conversely, is so inexpensive that even relatively poor libraries might consider acquiring one as a precautionary measure in the event that a limited numbers of rare books ever require drying. Used in conjunction with Zorbix the Vacme press can significantly reduce drying time, but in trials conducted outside of this study the Vacme press also proved effective when readily available newsprint (printed or unprinted) was used as interleaving.

Air drying, which remains the most commonly applied book drying technique due to its low setup cost, produced far better results in terms of physical flatness when semi-dried books were pressed overnight, followed by further air drying the next day. Mold did not form inside the books given the limited duration of this damp pressing, but intermittent exposure to freely circulating air is requisite and, of course, this unrestrained period promotes further page cockling.[8] A final long pressing as the book reaches its dry state helps reduce this recurring distortion.

Air drying, vacuum packing, and drying in a Vacme press with Zorbix are all labor intensive methods best monitored by trained technicians handling relatively small batches of books (e.g., less than 100 volumes at a time). Given sufficient freezer capacity to forestall microbial growth, these three techniques can be applied to several

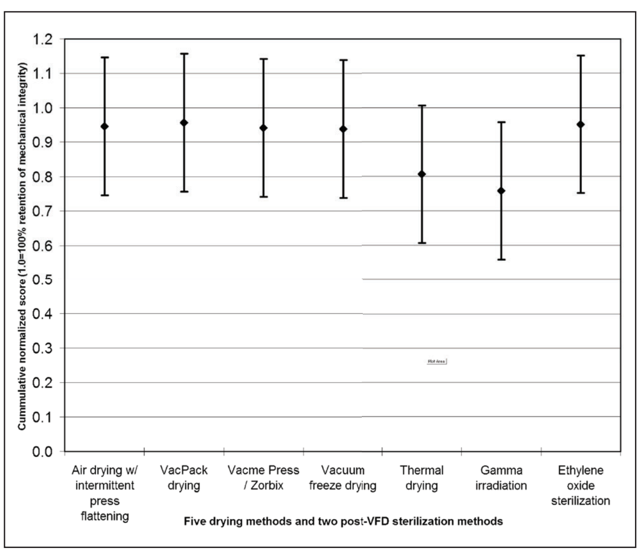


Fig. 15. Comparison of mechanical integrity in five drying and two sterilization techniques

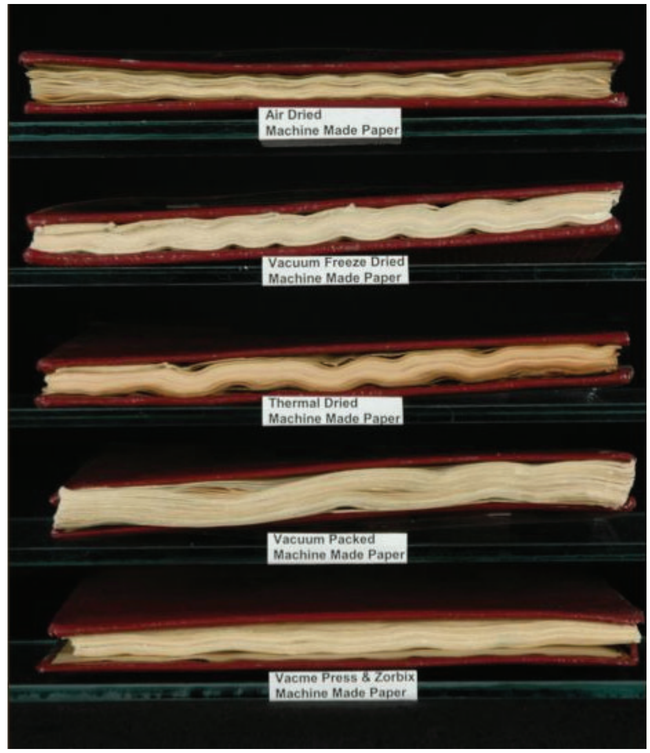


Fig. 16. Comparison of physical cockling in machine-made paper


Fig. 17. Comparison of physical cockling in handmade paper

hundred books by simply thawing manageable batches prior to treatment.

Vacuum freeze-drying remains the most efficient method for drying large quantities of books (e.g., more than 500 volumes), especially for books printed on coated stock paper (Carlsen 1999). Unrestrained vacuum freeze-drying, however, produced the greatest amount of cockling in the book papers tested. While not tested as part of this study, examples of vacuum freeze-dried books pressed during sublimation were examined at the British Library and were shown to produce excellent results. The British Library's small vacuum freeze-drying chamber has been modified with a mechanical jack inside the chamber that is used to manually squeeze books between thin steel plates. The chamber must be opened every two days and the jack's pressure increased to compensate for decreasing book thickness caused by sublimating ice crystals. While approximately doubling the drying time and significantly increasing labor costs, this approach to vacuum freeze-drying produces far better results than books dried without constraint. Consequently, it is recommended that consumers insist that commercial vendors flatten permanent collections during the sublimation process and be prepared to compensate vendors for the added time and effort involved.

During the past three decades sterilization of cultural property has largely been downplayed as a technical option. Instead, conservators have learned to rely on environmental stabilization to return mold to a dormant state before removing the desiccated spores with a small vacuum aspirator or vacuum cleaner equipped with a high efficiency particulate air (HEPA) filter (Haines and Kohler 1986; Northeast Document Conservation Center). The literature does a poor job, however, of identifying appropriate technical options when sterilization must seriously be considered. As noted by Fausta Gallo in 1978, sterilization should be reserved for "cases in which arresting infection and infestations is an unarguable necessity." This can occur, for example, when significant delays in a recovery cause wet collections to mold excessively, or when floodwaters contain contamination such as sewage or other biological hazards. Ignoring sterilization in such circumstances, even when dealing with irreplaceable collections, can pose potential health risks to future users and result in long-term liability issues for recovery specialists and collecting institutions.

Gamma irradiation continues to suggest a promising alternative to ethylene oxide sterilization, but, as reported by Butterfield in 1987 and confirmed in the present study, this approach damages book paper to an unacceptable degree. The mechanism by which ionizing gamma radiation kills microbes and renders spores nonviable simultaneously cleaves the cellulosic (and other polysaccharidic) chains from which paper derives its mechanical integrity. Lower levels of damage have been reported in experimental settings where paper was treated with low levels of gamma radiation,[9] but it remains to be demonstrated that significant cellulose degradation can be avoided at doses that yield effective sterilization, or that this approach is commercially viable. Consequently the authors cannot recommend gamma irradiation over ethylene oxide for sterilizing books of enduring cultural significance under any circumstances we can envision.

The use of ethylene oxide remains controversial in the United States. Its detractors concede, however, that loss of lignocellulosic mechanical integrity as a result of ethylene oxide fumigation is not the issue. Objections focus instead on potential latent effects to book components other than paper such as plastics, adhesives, skin-derived materials, and media, as well as possible health risks associated with ethylene oxide off-gassing. The first concern has limited relevance in the context of a flooding incident of scope and severity so extreme that sterilization would need to be considered. Bindings in the recovery phase of such an event are quite often discarded, and the authors are unaware of any well-grounded studies reporting replicable findings of significant ethylene oxide-induced alteration of media likely to be encountered in books that would be considered for mass sterilization.[10] The present study corroborates the research of Flieder and Capderou (1999) and Gallo (1978) that found that book paper thoroughly sterilized by a commercial dosage of ethylene oxide remains mechanically undamaged.

An influential study performed at the Library of Congress by Hengemihle, Weberg, and Shahani (1995) determined that following sterilization, "off-gassing of ethylene oxide by library materials is a reality." This finding is often misconstrued to suggest that ethylene oxide is inappropriate for use in conservation, but, in fact, the study simply concludes that "fumigated materials should be added to the collections only after the ethylene oxide concentration is decisively under 1 ppm."[11] This conclusion mirrors U.S. workplace safety standards implemented nearly a decade before (in 1986) that mandate a twenty-four-hour off-gassing period following sterilization to permit ethylene oxide concentrations to fall below 1 ppm (Hengemihle, Weberg, and Shahani 1995). This legal standard is adhered to by licensed U.S. contractors and is readily achieved because ethylene oxide is a volatile and reactive gas that dissipates quickly, reacting with atmospheric water molecules to yield more benign species.

Both gamma-irradiated and ethylene oxide-sterilized books contained a residual and, by consensus, objectionable odor. It is speculated that this smell related to decomposing mold spores within the books. Whether this could be mitigated by surface vacuuming, subsequent aeration, or exposure to absorbent media (e.g., activated carbon, potassium permanganate, or baking soda) in a con-

Table 1. Summary of techniques for drying and sterilization of books

| TECHNIQUE | TREATMENT CAPACITY (vols) | HISTORIC/ MONETARY VALUE | EQUIPMENT COST | ON-SITE LABOR REQUIRED | CONSIDERATIONS AND CONCERNS |
|---|---|---|---|---|---|
| Mass Drying | | | | | |
| Air drying | 1–200 comfortably; 200–500 with freezer | rare/ non-rare books | low | medium | Extremely labor intensive if pressed as described in this paper. Low-tech; can be attempted under difficult circumstances without power for fans. Produces relatively flat books with frequent pressing during final drying stages. Coated-stock paper requires page-by-page interleaving. |
| Vacuum packing | 1–200 comfortably; 200–500 with freezer | rare/ non-rare books | high | high | Labor intensive. Machine cost is rather high and up to 20 proprietary, non-reusable bags may be needed per book. Produces flat books. Incomplete vacuum may result in mold formation within bags. Needs power supply. Coated-stock paper requires page-by-page interleaving. |
| Vacme press and Zorbix | 1–200 comfortably; 200–500 with freezer | rare/ non-rare books | low | high | Labor intensive and low-tech. Produces flat books. Coated-stock paper requires page-by-page interleaving. Needs power supply. Press and a supply of reusable bags is sufficiently low cost that even tightly-budgeted institutions could afford one as a precautionary measure. |
| Vacuum freeze dry | 500–500,000 with freezer | non-rare books; rare with in-situ pressing | very high, but usually purchased as a service | low | A non-damaging, mass drying technique. Drying books under compression doubles drying time and labor cost but yields improved outcome for rare books. Most coated-stock papers successfully dry without blocking. Should not be confused with (1) thermal vacuum drying (TVD), which boils liquid-state water from books at elevated temperature (recommended only for books of low-intrinsic value); or with (2) thermal vacuum freeze drying (TVFD), a "premium" service that combines a proprietary heat-aided flattening with traditional vacuum freeze drying (consequences of heat-aided flattening for paper permanence are not yet established, but outcome discussed by Kaplan and Ludwig (2005)). |
| Thermal drying | 500–500,000 | non-rare books | very high, but usually rent space | low | Not recommended except under extenuating circumstances. Degrades paper's structural integrity (broadly defined) on the order of 15–25%. Needs access to wood-drying kilns. Availability is regional. Coated-stock paper requires page-by-page interleaving. |
| Sterilization | | | | | |
| Ethylene oxide | 500–500,000 | rare/ non-rare books | high, but usually purchased | low | EtO requires application by licensed contractor due to transient health risks: despite controversy, a non-damaging technique. Vacuuming dead mold spores may still be required. Short-term non-EtO odor may require exposure to odor-absorbent media in a non-circulating environment for some interval (weeks / months). |
| Gamma radiation | 500–500,000 | non-rare books | very high, but usually purchased as a service | low | Not recommended at irradiation dosages currently known to provide effective sterilization. Currently accepted dosage degrades paper's structural integrity (broadly defined) on the order of 20-30%. Vacuuming dead mold spores may still be required. Short-term non-gamma odor may require exposure to odor-absorbent media in a non-circulating environment for some interval (weeks / months). Research ongoing to determine if parameters exist to effectively sterilize paper without substantially damaging its permanence. |

fined space is outside the scope of the present study. Clearly, neither method is ideal. Further research into alternative mass sterilization techniques is desperately needed, including but not limited to an investigation into plasma fumigation.[12]

## CONCLUSION

Relying on surrogates to stand in for complex, real-world book collections, this study compared five drying and two sterilization techniques to determine the long-term effects of these recovery options on the permanence of handmade and machine-made book papers.

Mechanical testing revealed that air drying, vacuum freeze-drying, vacuum packing, and drying in a Vacme press with Zorbix had essentially no deleterious effect on handmade and machine-made book papers. Thermal drying, however, was shown to reduce paper's mechanical strength by fifteen percent. Similarly, sterilization with ethylene oxide caused no mechanical damage to moldy, water-damaged book paper while gamma radiation weakened comparable book paper by twenty-five percent. These findings indicate that thermal drying and gamma irradiation should be avoided when drying and sterilizing water-damaged books of permanent retention value.

Visual observation revealed that handmade papers dry with less distortion than machine-made papers treated by the same method. Books dried and pressed simultaneously (vacuum-packed, Vacme-press-dried with Zorbix, and thermal-dried under weight) produce flatter results than books dried without constraint. Thermal drying is therefore deceptive, producing visually flat books that are molecularly damaged. Air-dried books can be rendered reasonably flat if they are pressed overnight followed by further air drying the next day. Vacuum freeze-drying produced the least flat books in this study but the technique can be modified so that books are pressed during sublimation.

Cost factors for drying can vary considerably depending upon the availability and price of labor or the initial outlay required for equipment such as a vacuum packing machine. Of the nondamaging techniques tested, air drying and drying with a Vacme press proved the least expensive, while vacuum freeze-drying remains the most cost-effective approach to drying large numbers of books. Multiple approaches can also be applied to the same recovery, so it is reasonable to consider Vacme press drying, careful air drying, and vacuum packing books of enduring cultural significance, while less valuable parts of the collection could be vacuum freeze-dried. As mentioned above, vacuum freeze-drying can be modified to press books during sublimation when drying books of permanent retention value. Lastly, freezing wet books remains essential for delaying mold formation and thereby improving the quality of the recovery by allowing the books to be dried in manageable batches.

It is hoped this study's findings help clarify for disaster responders the implications for permanence of specifying one drying or sterilization technique over another when treating water-damaged books.

## ACKNOWLEDGMENTS

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## MATERIALS/SUPPLIES

Vacme Press and Zorbix are available exclusively from:
Artifex Equipment, Inc.
9595 Main St., #1
P.O .Box 319
Penngrove, CA 94951
cel. (707) 331-0237
artifex@pipeline.com
www.artifexequipment.com.

Archipress Vacuum Packing Machine and Polyester Vacuum Pouches
Conservation By Design
www.conservation-by-design.co.uk/equipment/archipress4.html (accessed September 3, 2007).

Midwest Freeze Dry Ltd.
7326 N. Central Park
Skokie, IL. 60076
www.midwestfreezedry.com/pestinfestation.html

## NOTES

1. While vacuum freeze-drying and thermal drying were part of this study, these techniques must not be confused with similarly-named thermal vacuum drying (TVD), in which bulk liquid water is boiled away at the intermediately elevated temperatures permitted by a vacuum chamber, or thermal vacuum freeze-drying (TVFD), in which a proprietary method of thermally-aided flattening is applied to vacuum freeze-dried materials. TVD and TVFD were not considered for testing due to significant limitations but have been summarized in the work by Kaplan and Ludwig.

2. VeloBind combs, developed by the General Binding Corporation (now merged with ACCO), are inserted into perforated leaf edges in a proprietary quick-binding method. The combs—variously called "spines" or "hot knife strips"—are available from office supply companies specializing in quick-binding equipment.

3. Temperature in vacuum freeze-drying is critical. Heat is required to provide the energy for sublimation, but increasing the drying temperature causes cellulose damage. Some vendors refer to their product as "vacuum freeze-drying," but introduce an excess of heat (TVD), e.g., 54°C (130° F), to accelerate the sublimation. While faster turnaround of treatment batches potentially increases profit for the service provider, it results in permanent damage to paper.

4. Bondina is a proprietary nonwoven polyester material with a smooth surface that facilitates release.

5. Designed by Artifex Equipment, Inc., and the United States Department of Agriculture's National Agricultural Library, Zorbix is a super-absorbent polymer embedded in a sheet of blotting paper able to absorb fifty times its weight in water.

6. Paper samples were tested by or under the supervision of two of the authors (Miranda Bliss and Barry Knight) at their respective institutions. Tests included: tensile strength and stretch-to-break (ISO 1924-2; machine direction and cross-machine direction: maximum load, strain percent, and tensile energy absorption); tearing resistance (ISO 1974; machine direction and cross-machine direction, mN/ply); and MIT folding endurance (ISO 5626; machine direction and cross-machine direction; note that number of double-folds (#DF) is deprecated in favor of log10#DF).

7. Conservation By Design Limited is the sole manufacturer of Archipress Vacuum Packing Machine and Polyester Vacuum Pouches. Three models available sell for £2652.00 ($5,331.83); £4604.00 ($9,256.32); and £6528.00 ($13,124.51). See Materials/Supplies for more information.) Dissatisfaction has been reported by some who used a vacuum packing machine following the 2004 floods in the Czech Republic because of damage caused to fragile books by the significant pressure applied by the pouch and by mold that formed inside of incompletely sealed pouches.

8. Pressing can only be applied to semi-dry books printed on uncoated paper. Books wholly or partially printed on coated stock must have every coated leaf separated with silicon release or waxed paper interleaving and allowed to dry thoroughly prior to pressing. Cockling is therefore maximized by air drying books of this type and alternative drying methods are suggested.

9. For further information see da Silvaa et al. 2006; Magaudda 2004; Adamo et al. 2001; Adamo et al. 1998; and Havermans et al. 2007.

10. Reports dealing with ethylene oxide-induced damage include: Florian 1988; Florian 1987; and Green and Daniels 1987.

11. The U.S. Department of Labor, Occupational Safety and Health Administration (OSHA), regulations/standards on ethylene oxide state: "8-hour time-weighted average (TWA): The employer shall ensure that no employee is exposed to an airborne concentration of EtO in excess of one (1) part EtO per million parts of air (1 ppm) as an (8)-hour time-weighted average (8-hour TWA)."

12. Plasma fumigation relies on radio waves. Wet, moldy books are placed inside a vacuum chamber, a vacuum is pulled, and the chamber is backfilled with an inert gas. Radio waves directed within the chamber convert the inert gas to argon, nitrogen, and helium and draw hydrogen molecules from all water within the vacuum. Creating plasma energy in this way damages the DNA of mold, destroying its viability. More on the application of plasma fumigation to sterilization of library material may be found from Midwest Freeze Dry Ltd.

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