The Design and Operation of a Passive Humidity-Controlled Cold Storage Vault Using Conventional Freezer Technology and Moisture-Sealed Cabinets

Mark McCormick-Goodhart and Henry Wilhelm
Wilhelm Imaging Research, Inc.
Grinnell, Iowa/USA

Abstract

This paper presents results from a research project sponsored by the Smithsonian Institution to construct and operate a low-cost subzero temperature storage vault for photographic and manuscript collections. It uses conventional walk-in freezer technology and passive moisture control methods to achieve large savings in both construction and ongoing operational costs.

Introduction

The ultimate design for a low temperature storage facility to preserve a photograph and manuscript collection would incorporate the following features:

1) Redundant compressors and dehumidification equipment combined with electrical generator back-up to provide an uninterrupted steady-state environment at approximately –20˚C (–4˚F) and 25% RH.

2) An inert fire suppression system backed up by a dry pipe sprinkler system.

3) Special cabinets to isolate the collection materials from direct contact with water in the event of sprinkler system action or other situations where water might enter the vault. At the same time the cabinets would allow ventilation with perhaps four to five air exchanges daily. Volatile gases emanating from the collection materials (e.g., residual solvents from inkjet prints, acetic acid from dye transfer prints or degraded films, etc.) would thus be prevented from building up and potentially interacting with other items inside each cabinet.

4) Filtered make-up air entering the vault to completely exchange at least four times daily. The incoming air would be filtered to remove dust and air pollutants such as ozone, nitrous oxides and sulfur dioxides, etc.

5) Thermally insulated and heated windows to allow especially fragile objects to remain inside the vault while permitting viewing by patrons situated in an adjoining room maintained at human comfort levels.

6) Placement or removal of materials from the vault accomplished not by a single intermediate temperature staging room, but by a chamber or room that allows temperature to be ramped up and down according to a very gradual pre programmed cycle. Such a controlled temperature gradient is not needed to prevent thermal shock. Thermal shock is not an issue with cold stored photographic materials. Rather, the staging room guarantees that moisture gradients do not form within archival boxes or oversized framed items that do not have uniform thermal conductivity.

7) A security system and item tracking capability as required.

The vault described above is technologically possible, but it would be very expensive to build and operate. High air exchange rates require constant cooling and conditioning of the make-up air, and operating costs would escalate dramatically. Few museums and archives will undertake this idealized specification. Large financial resources are usually allocated to high-profile exhibits that generate immediate public good will, not to the unglamorous but vital task of upgrading storage environments for important collections. Fear of unknown or untested storage recommendations within the conservation community has also slowed the adoption of cold storage on a large scale even though the museum world can now examine an over thirty year record of low temperature storage results. The implementation of low temperature storage for photographic collections has its roots in a key paper published by Adelstein, Graham, and West in 1970.[1]

Museums and archives must take a more pragmatic approach in order to increase the percentage of 19th and 20th century materials that will be optimally preserved

Carol Brower Wilhelm 2004

Figure 1. Henry Wilhelm (left) and Mark McCormick-Goodhart stand inside the WIR cold storage vault. On the left wall (front to back) are cabinets VK2, SF1, and VK1. At center is SF2, and on the right (back to front) are cabinets DD1, DD2, and DD3. Refer to Table 1 for humidity measurements taken inside the respective cabinets. Note, also, the vinyl magnetic material covers on the recessed handles of some cabinets, the latex painted plywood for floor protection underneath the cabinets, and the acclimatization boxes made from ordinary picnic coolers.

by means of low temperature storage. Many conservators are now admirably undertaking special packaging methods to store small but important collections of photographic films and prints in reach-in refrigerators or freezers.[2-5] The methods are relatively low cost and practical for small collections, particularly ones of a very modular nature such as motion picture film cans or still film collections of negatives and/or transparencies. They become far less practical for large volumes of material or for prints of varying sizes, especially ones with very large formats. For bigger collections, a walk-in vault is more appropriate, but the cost and complexity of the project increases significantly. To date, walk-in cold storage vaults for photographic collections have employed high volume desiccant dryer technology in order to actively control the relative humidity level inside the vault. Combining refrigeration equipment with high volume desiccant dryers in a way that operates efficiently and also shuts down safely upon component failure requires the hiring of contractors with specialized knowledge of this application. Construction and ongoing maintenance is significantly higher than typical walk-in refrigerators and freezers built and serviced so widely in the food industry.

In 1998, Wilhelm Imaging Research, Inc. began a cold storage research project to design, build, and operate a subzero temperature vault that passively controls moisture content of the collection materials using cabinets with sealed gaskets in lieu of active dehumidification equipment. The project was funded by a grant from the Smithsonian Institution in Washington, DC. The objective was to create an alternative method, one that combines the simplicity and cost effectiveness of conventional freezer technology with the collection management benefits of easier access to collection materials unencumbered by special packaging and repackaging requirements. Using this new approach, a conventional walk-in freezer of the type routinely installed by local refrigeration contractors was constructed. Moisture control is accomplished by sealed cabinetry as shown in Figure 1. It is important to note that the required moisture control takes advantage of the natural moisture buffering properties of the collection materials as well as the degrees of freedom afforded by more recent research into the allowable temperature and RH limits for the safe use and storage of photographic materials.[6] The vault was installed in January, 1999 and has operated continuously, efficiently, and safely with a unique photographic collection entrusted to its care since September, 1999. The WIR vault holds the personal collection of Henry and Carol Wilhelm with many historically important color and black and white negatives, prints, and slides, as well as a corporate collection of image permanence test samples of modern inkjet media. Additionally, the vault houses a growing newspaper collection, inspired in part by Nicholson Baker's book and also by recent historical events such as the presidential election of 2000, and the tragedy of September 11, 2001.[7]

Freezer Construction

Site preparation work was minimal since Wilhelm Imaging Research, Inc. (WIR) had free space with a level concrete floor in the interior of the building to locate the walk-in vault. By keeping the vault located a few feet away from the foundation exterior of the heated building, it was determined that an additional concrete pad with heated wires to prevent frost heaving of the building floor would not be necessary. The electrical hook-up cost approximately $2,000 dollars and made use of the building's three phase wiring capability. Powering the vault with three phase electrical wiring adds approximately 30% operating efficiency over single phase wiring. Our chosen local contractor, Industrial Refrigeration Services, Inc., was given a design specification for a 12.5 ft.(W) x 15 ft(L) X 9.5 ft.(H) conventional walk-in freezer to operate at –20˚C (–4˚F). A 42 inch wide heated door with heated window was also specified. Dimensions are critical in the design of a vault. The door had to be wide enough to bring the chosen cabinets into the vault, and the ceiling height had to allow clearance as the tall cabinets are brought horizontally though the door and then erected to stand in their final vertical position. The cost of the freezer was quoted at $17,450 bringing the total installation cost estimate to approximately $20,000 including the electrical hook-up. The vault took only 4 days to build and become operational. The cabinets are placed on outer walls with 4-6 inch clearance behind them to ensure good circulation and a uniform temperature envelope. One concern was that the cabinets are very heavy, and especially so when fully loaded. The Viking cabinets, in particular, use very small diameter leveling castors which might exceed the punch-through load rating of the floor panels. Quarter inch stainless steel floor liners are widely available in the industry for walk-in coolers that must carry heavy loads (e.g., where forklift trucks are used). However, we did not order this additional protection. Rather, we placed one inch thick latex-primed and painted plywood underneath the cabinets as can be seen in Figure 1.

During the initial days of operation a few problems were identified and corrected. The door heaters had been inadequately equipped for the subzero temperature operation, and frost began to build at the base of the door. The contractor opened the panel and installed additional heat tape which corrected this problem. Additionally, we asked the contractor to modify the wiring to the evaporator coil fans. In normal food applications, the fans are wired to run even when the compressors are off. This has the effect of evaporating water frozen on the coils and returning it to the room. For food applications, this extra humidity is desirable. For photographs, the natural dehumidification provided by the frozen evaporator coils is desired, so the wiring was changed to turn the fans off when the compressors are not running. This modification was trivial for the contractor to accomplish, and the modified operational behavior lowered the average humidity in the walk-in freezer from over 75% to about 58% RH. Lastly, we upgraded the freezer to a digital temperature controller (readily available in the industry) and added a power meter to give us precise data on the actual operating cost of the vault over time. The modifications and additions to the project brought the final construction cost to $22,275. Compare this figure to an actively dehumidified cold vault of similar size which would have cost $55–80K.

Passive Moisture Control At Low Temperature

Passive climate control is a well established concept in museums. Sealed display cases containing moisture buffering materials such as silica gel are routinely used to create stable relative humidity conditions that are maintained in the display case for weeks or months at a time. Generally, for large display cases containing collection objects that may or may not have much moisture buffering capacity in their own right, a significant amount of conditioned silica gel or other buffering agent is pre loaded into the display case to create the stable climate. Such heavy use of conditioning agent would be impractical for a large cold vault with many cabinets. However, calculations based on standard psychometric principles demonstrate that at subzero temperatures the absolute amount of available airborne moisture is two orders of magnitude lower than at room temperature. This is one reason why high volume desiccant dryers become inefficient and expensive to operate at low temperature. They are trying to scavenge much fewer numbers of water molecules from the air in order to maintain the low relative humidity in the cold air. Recall that moisture content in the collection materials is proportional to relative humidity not absolute humidity. On the other hand, the properties of low temperature air work to our advantage for passive moisture control because the volume of desiccant required to offset the moisture entering the cabinets can be greatly reduced. The need to periodically replace the desiccant is also proportionately reduced. Moreover, the moisture absorbing properties of paper and photographic materials also serves as a large moisture buffering reservoir, and this capacity is enormous when the cabinet is moderately to fully loaded with items.

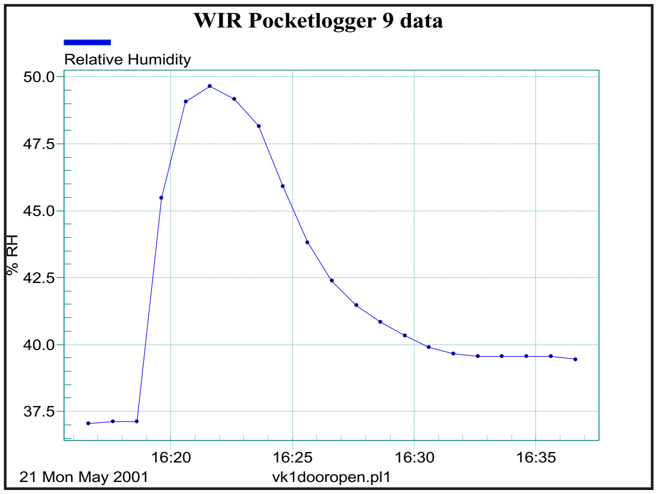

Figure 2. Cabinet recovery after a door opening. The door was left open for approximately three minutes. The cabinet climbs from 37% RH (ie., within operating specification) to nearly 50% RH. Approximately five minutes after closing the door the RH level has dropped to within the desired RH range (21–42% RH). After a few hours the cabinet will finally reach the beginning RH level.

When a cabinet door is opened to retrieve items and high relative humidity air from the vault mixes with the cabinet air, the total moisture that must then be absorbed by the materials in the cabinet after the door is closed is correspondingly low as a consequence of the low absolute humidity level in the cold air. Recovery of the cabinet occurs fairly quickly (See Figure 2). Also, we practice a "one layer" principle whereby collection objects are enclosed in document boxes or at the very least a paper or plastic enclosure inside the cabinets. In this way, the collection materials never experience momentary exposure to high humidity conditions. The impact on the collection materials of a door opening or when they are being transferred to and from cabinets is analogous to passing one's hand through a candle flame. If the dwell time is small, the adverse effects of more prolonged exposure do not occur.

Sealed Gasket Cabinet Issues

Sealed gasket cabinets are available as stock items to the museums and archives community. The Smithsonian Institution, for example, uses them extensively at the Museum Support Center located in Suitland, Maryland to house natural history specimens. The cabinets feature doors that close against a silicone or elastomeric gasket, preventing among other things, insect infestation. Locking doors and easy gliding shelving features add many convenient handling and security features. One objective in this research project was to determine if stock cabinets would provide satisfactory moisture control performance in a subzero temperature environment without requiring serious modifications. Three vendors kindly donated samples of their cabinets. One cabinet featured glass viewing doors and had stationary but adjustable shelves. Two were designed to hold large flat files on sliding shelves (e.g., matted photographic prints as large as 35 x 50 inches) and were countertop height. Two were small storage cabinets also of countertop height. Two cabinets were tall double-door units with convenient retractable shelving that glided on smooth bearings. The tall vertical cabinets required the 9.5 ft. high ceiling to erect once inside the vault. The total storage capacity of the donated cabinets is 367 cu. ft. With net capacity utilization factored at 50% the WIR cold vault presently has a net storage capacity of 183 cu. ft. Had we purchased cabinets for the vault, the net storage capacity could have been optimized in excess of 250 cu. ft. It would take approximately 24 domestic reach-in freezers to achieve this storage volume, and, of course, large photographic prints would be difficult if not impossible to fit into reach-in style freezers.

Moisture vapor transmission rate (MVTR) studies were conducted to determine the moisture buffering performance of the cabinets. One surprising result of this investigation was that two of the three cabinet manufacturers' products required a significantly re-engineered seal design. Both vendors use a silicone seal that did not adequately seal when the doors were closed no matter how carefully the cabinets were aligned and leveled. This fact could be seen by simple visual inspection of the cabinets, and it is therefore surprising that the problem went unnoticed by the manufacturers. We retrofitted the offending cabinets with a new gasket that was made using elastomeric automotive gasket material obtained at a local auto supply store. This task was time consuming, but we succeeded in bringing these cabinets up to the MVTR performance level we were looking for. The third vendor, Viking Metal Cabinet Company, uses an elastomeric seal design neatly trapped in a metal channel of the cabinet. The two cabinets donated by Viking Metal Cabinet Company required no modification to the seals, and were determined to function very successfully at subzero temperature after one minor correction was made. Our MVTR tests revealed that key hole in the door lock on most cabinets was a significant source of air leakage into the cabinets (one company's cabinet design uses a double panel door construction that isolates the lock mechanism from the cabinet interior which eliminates the problem). We simply taped the keyholes closed with an aluminum foil tape on the cabinets with standard door handles, and also covered the larger recessed style handles with easily removable vinyl magnetic signage material. The reason a small hole increases MVTR in the cabinets so dramatically relates to barometric pressure. As the air in the vault cycles in temperature by a few degrees while the interior temperature of the cabinets remains more stable due to thermal mass, a small but significant pressure differential between the vault air and the cabinet air occurs if the cabinets are truly sealed. This pressure differential serves to "push" air in and out of a key hole thus equalizing the pressure and in turn more rapidly exchanging

Figure 3. 4-ply mat board was inserted on the side and rear walls of the cabinets. It was also used to line shelves. Some shelves have a lip underneath that allows a carefully fitted piece of mat board to be suspended on the underside of the shelf. This location is preferable because the surface does not get covered as collection materials are added, although the addition of collection materials usually enhance rather than hinder the moisture buffering performance of the cabinet.

Figure 4. A transfer box for acclimitization made from an inexpensive picnic cooler. Two layers of Styrofoam (2 inch total thickness) were added to the bottom (picnic coolers typically do not have insulation on the bottom). The top layer is fitted with a wireless thermocouple (available at Radio Schack, Inc. for under $60.00). The acclimatization is complete when the thermocouple reads within a few degrees of the surrounding environment.

air than would occur if only simple Brownian motion of the air molecules was involved.

One final task was to pre load the cabinets with a moisture buffering reserve so that cabinets with few collection materials inside still control effectively for reasonable lengths of time without have to be attended. A concurrent goal is to maximize the surface area of the moisture absorbing charge so that the cabinets respond rapidly after the door is closed (again refer to Figure 2). These two objectives were achieved simultaneously by lining the shelves and side walls of the cabinets with museum quality 4-ply mat board (see Figure 3). Calculations showed that this procedure would establish proper moisture control for one year or more with an otherwise empty cabinet.

Acclimatization

The WIR vault was deliberately designed without a staging room. Our approach to bringing materials in and out of the vault was also to once again use cost-effective passive climate control methods. Dehumidified cold vaults have traditionally made use of an antechamber or "staging" room that operates at an intermediate temperature halfway between the cold zone and the ambient room temperature in the user environment. This staging room is also dehumidified to low RH levels. The use of a temporary vapor barrier such as a recloseable polyethylene bag has also been recommended as a practical method for item transfer, the theory being that condensation is kept to the outside surface of the bag. We had never questioned either methodology until we conducted some staging experiments that brought to light a potential problem with both approaches. The intermediate temperature/low RH approach may prevent condensation for cold vaults operating at above freezing temperatures, but may fall short of that mark when subzero vaults are employed. Furthermore, the low RH in the staging room only has relevance to the outside of the container or box that houses the collection material. Internally, the RH may be higher, especially when a document box, for example, has not had the often lengthy time needed to equilibrate to a dehumidified cold vault climate. When a steep temperature gradient forms across a container that has hygroscopic walls (e.g., a document box made of mat board) the walls will warm faster than the contents of the box, and moisture can then be released from the box walls, increase the RH inside the free space in the box, and in a worse case scenario condense on the colder contents inside the box. Neither a staging room with low RH nor a vapor barrier surrounding the box can prevent this from happening. The key to eliminating the problem is to reduce the temperature gradient. This can be passively accomplished by creating a thermal barrier as well as a vapor barrier around the collection materials. Figure 4 shows a simple transfer box made from a "picnic cooler" with Styrofoam insulation that acts as both thermal barrier and humidity barrier. Collection materials housed in standard museum boxes are placed inside the transfer box when they are brought into and out of the vault. The transfer box itself is first acclimatized before adding the collection materials. An inexpensive thermocouple can be installed in the transfer box to notify the user when the materials have acclimated to vault temperature or room temperature prior to opening the box. For larger objects, the "picnic cooler" concept can be scaled to make a larger transfer box using materials such as Styrofoam and wood to provide thermal mass and insulation. Again, slowing the cooling or warming time is not necessary to avoid what many conservators fear to be "thermal shock".

Thermal shock to materials generally requires extremely rapid temperature changes within the bulk of an object, an unsustainable event in this application. Rather, the need to lower the temperature gradient is specifically to address the problem of high humidity or condensation layers forming at collection material surfaces. This stratification is due to the thermal gradient spread across a group of materials such as those housed in a document box where continuity of thermal mass is disrupted by pockets of free space surrounding the materials. To summarize:

1) For thin, single items of contiguous mass, a polyethylene vapor barrier is more than adequate to safely remove items from the cold vault. Such items generally have low thermal mass, and will warm safely in minutes to room temperature (or cool to vault temperature). This is an efficient way to bring single matted prints, negative, slides, etc., in and out of the vault.

2) Larger items housed in non-hygroscopic containers (e.g., motion picture film in plastic or metal containers) may also be safely removed or returned to a vault by tape sealing the container or enclosing it in a polyethylene bag.

3) Items grouped in document boxes, Solander boxes, or other larger containers made of materials that are in themselves hygroscopic, must be brought to and from a vault in a transfer box or package that has sufficient thermal mass and insulation to slow the rate of temperature change and reduce the temperature gradient across the collection materials to a satisfactorily low level. These types of transfer boxes can be easily designed, constructed, and verified for proper performance. An alternative approach is to design a temperature programmable chamber that can be ramped slowly between vault temperature and room temperature.

WIR has made very successful and routine use of thermally insulated boxes (as per Figure 4). However, on two separate occasions we moved very large quantities of materials into the cabinets, and a simple and effective approach was simply to use the walk-in freezer itself as the staging room. By shutting off the power, the thermal mass of the vault contents and the insulating properties of the walls allowed the vault to rise gradually to room temperature whereupon the collection materials were immediately stocked in the cabinets and the vault then turned back on. We don't recommend this method as a normal course of action, but it can be useful on planned occasions when very large quantities of materials must be added or removed from the vault.

Overall Performance Results

After the modifications to the cabinets with poor seals, The MVTR of the cabinets was held to less than 150 grams per year calculated at a constant interior RH level of 30% with exterior RH level at 60%. When a door is opened, a large empty cabinet will have an additional uptake of up to 2 grams of water. Factoring one weekly entry per cabinet, one needs to compensate for a total yearly increase in moisture content of about 250 grams in the largest cabinets. This can be accomplished with little difficulty by exchanging about two pounds of silica gel per cabinet per year. However, in our practical use of the vault over the past four years we have not exchanged any desiccant, and all cabinets have remained easily within the desired RH limits. The relative humidity in the cabinets is continuously monitored by data loggers made by Pace-Scientific, Inc., and we also have a very effective low cost monitor in the form of a cobaltous chloride humidity plug installed on the door of each cabinet. There are three basic reasons why we have not had to do any cabinet maintenance whatsoever. First, the cabinets are moderately to fully loaded with collection materials at this point in time which gives enormous moisture buffering capacity. Second, we do routinely open cabinet doors to add or retrieve items, but not on a repetitious daily or weekly schedule. Third, as materials are removed and later returned to the vault their moisture content gets "reset" to equilibrium with the normal display environment which is maintained within safe allowable limits. Thus, during the routine use of the vault the collection materials dominate the moisture buffering function, and we have had no cause to add or replenish any additional desiccants. Table I lists the average internal RH of all seven cabinets during the most recent year of operation, 2003. The cabinets have remained at similar levels during the entire 3.5 years that the vault has housed the WIR collection, some increasing slightly and others decreasing slightly in response to various collection materials added or removed from each cabinet. At this rate, the cabinets will likely stay in control for decades without ever needing further maintenance.

Of particular importance to any cold vault design is whether the vault fails safely when equipment failures occur. To test the behavior of the WIR vault, we simulated a power failure that would cause complete loss of the cooling compressors and total warming of the vault to room temperature. This failure path is very obvious compared to the multiple ways in which a vault with both compressors and dehumidifiers may fail. One surprising result of the test was that water droplets formed and fell from the vault's ceiling beginning several hours after the power was lost. Typical panels for walk-in freezers are joined by tongue-and-groove construction and a vinyl gasket to form the seal between the panels. The large temperature gradient between the freezer's interior and exterior surface allows some moisture to penetrate and reside within the panel joints. When the power failed, this water accumulated and leaked into the vault. Small puddles were noted on cabinet tops and on the floor. However, the cabinets did their required job. They controlled the RH within the allowable limits as the cabinets warmed to room temperature, and they kept the water droplets away from the collection materials. Foil taping the outside seams of the vault would likely have reduced the water droplet problem within the vault, and we would recommend this simple procedure for any new vault construction because this panel behavior is not unique to our vault design. Actively dehumidified vaults operating at low temperatures may experience a similar situation. Thus, open shelving presents a risk to collections stored in cold vaults unless steps are taken to add a "roof" to the shelves. However, such a modification may not be enough to prevent damage to the collection in the event of burst pipes or sprinkler discharge. The cabinets clearly provide better protection against water and smoke damage.

In the last couple of years we have had two actual incidents of sustained power failure, the longer of the two caused by a winter storm. Again, the cabinets maintained excellent humidity control throughout the cycle including when the power was restored and the vault immediately commenced cooling.

Conclusion

The WIR cold vault has performed flawlessly for nearly four years and we continue to monitor its performance by collecting humidity and temperature data in all cabinets and the vault itself on a 2 measurement/hour basis with the data loggers. No effort to date has been made to readjust the humidity levels in the cabinets as they remain comfortably within specification of 21–42% RH at –20˚C operating temperature as can be seen in Table I. The vault uses 23.5 kilowatt-hours per day in energy consumption, and WIR pays $0.63/kwh. Thus, the daily cost of energy to keep the WIR collection stored in an optimal subzero temperature environment with passive moisture control is $1.46 per day or $531.38 per year. A comparably sized dehumidified cold vault is estimated to cost in excess of $3,000 per year at $0.63/kwh energy cost. In terms of costs per net cu. ft. of stored material, the WIR cold vault cost is $2.90 per cu. ft. per year of storage. Had capacity in the vault been optimized with deliberately purchased cabinet sizes, the cost would drop to approximately $2.12 per net cu. ft. per year of storage. The reduced construction and operating costs are demonstrable, and this goal, along with simplicity of maintenance and use, was the underlying motivation for the project. Had the cabinets not been donated, the purchase cost of cabinets compared to simple open shelving would have added an extra $12–15K to the capital cost of the project. With the remarkable energy savings provided by the sealed cabinet approach, the cabinets pay for themselves in less than seven years of operation. Since the cold storage of photographs and manuscripts is a long term commitment, significant long term savings accrue with the sealed cabinet method.

Table I - Cabinet RH Control

Cabinet	Dimensions (inches)	Ave. Daily RH Year 2003
VK1	51.5L x 22.5W x 78H	29 ± 1 %RH
VK2	56.75L x 38.5W x 39.5H	31 ± 1 %RH
DD1	58L x 32W x 76H	26 ± 1 %RH
DD2	58L x 32W x 39H	28 ± 1 %RH
DD3	58L x 32W x 76H	31 ± 1 %RH
SF1	58L x 32W x 37H	33 ± 1 %RH
SF2	29L x 32W x 37H	28 ± 1 %RH

Note: Ave. daily vault RH = 58% RH, RH range = 55–78% RH

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Paper by Mark McCormick-Goodhart and Henry Wilhelm (Wilhelm Imaging Research, Inc.) entitled: “The Design and Operation of a Passive Humidity-Controlled Cold Storage Vault Using Conventional Freezer Technology and Moisture-Sealed Cabinets” appeared on pages 176–182 in:

Final Program and Proceedings: IS&T Archiving Conference

ISBN: 0-89208-251-8

April 20–23, 2004
The Hyatt Regency San Antonio Hotel
San Antonio, Texas U.S.A.

Published by:

IS&T: The Society for Imaging Science and Technology
7003 Kilworth Lane
Springfield, Virginia 22151 U.S.A.
Phone: 703-642-9090; Fax: 703-642-9094
www.imaging.org