SAFELY CONTAINING FRANGIBLE MATERIALS USED IN SPACE FLIGHT EQUIPMENT

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1.1 Introduction

Glass fragments in a habitable zero-g environment can be very hazardous to the crew, with a potential for causing eye injuries or inhalation mishaps. With the advent of the Space Shuttle Program, NASA had to manage many shatterable items in the habitable compartment, brought to the spacecraft by payload developers, NASA experiments, crew equipment and the vehicle's own avionics and other instrumentation. This effort has continued in the International Space Station Program, and will be a part of every future manned space effort.

1.2 Shatterable Materials in a Habitable Compartment

When the Orbiter vehicles were built, all but a few of the cockpit instruments were made with plastic covers over gages to protect the glass from the crew and the crew from the glass. The safety philosophy that drove this decision in the cockpit was flowed down to other hardware and equipment developers to provide a safe environment for the crew in the rest of the habitable module. Codifying this in the basic JSC design standard, JSC-8080 included the requirement G-9 which read: "*Material that can shatter shall not be used in the habitable compartment unless positive protection is provided to prevent fragments from entering the cabin environment*."

1.3 Program Implementation

1.3.1 Implementation in the Space Shuttle Program

Positive protection for the Space Shuttle Orbiter project was described in the contractor's implementation document, SD73-SH-0297:

> "Positive protection shall consist of one or more of the following:
>
> 1. Substitution of nonshatterable material wherever possible....
> 2. Use of guards to prevent damage to shatterable materials....
> 3. Use of containment devices....
> 4. Procedural controls to minimize activity around exposed glass until such glass is removed from the vehicle or protected...."

All hardware installed in the Orbiter Crew Module met this requirement, with the exceptions of the event indicators, heads-up display units, the elapsed time indicators, and the structural glass in the windows. NASA permitted the first three pieces of equipment to be exceptions from G-9 and wrote the end-item specification for the Orbiter vehicle with those items listed as acceptable without covers. The windows, since they are structural elements of the vehicle, are controlled by other requirements in JSC documents as well as in the Orbiter specification, and no internal safety covers were required or provided.

1.3.2 Implementation in the International Space Station

The ISS Program deals with the exact same issues as the Space Shuttle Program. There are many sources of shatterable materials in every module and in the equipment used on board. Each item designed for the ISS was procured to specifications written from requirements documents like the glass structural design requirements in SSP 30560, the general structural design requirements in SSP 30559, and the manned systems integration requirements in SSP 50005.

Containment of one source of shatterable materials is addressed directly in SSP 50005, paragraph 8.13.3.4 (D), which requires light fixtures to be designed so that lens or lamp failures will not release fragments. This requirement is also repeated in SSP 50021, the ISS Safety Requirements document. Other pieces of equipment derived a containment requirement from the hazard control process, which is intended to address all hazards to the vehicle's crew.

A significant effort focused on the various and numerous display screens used on ISS computer and video monitors. A walk through the ISS mock-up at JSC in the early 90s showed how many display screens were in or near the translation path. All of these would be exposed to the large pieces of equipment the crew would be moving through the modules, like racks and experiment boxes. Following this hazard review, all screens were procured with films covering the glass panels.

Figure 1.1 is a photograph downlinked from ISS showing damage to a monitor screen. There is no specific event known to have caused these scuff marks and the tear in the protective film, but the damage happened during orbital activities. The engineering of this particular monitor included successful impact tests to demonstrate the damage tolerance of the film and glass assembly.

[figure 1.1]

1.3.3 Implementation in the Payload Community

Payloads are one of the primary sources of glass components in the habitable volume. To address the payload community, the *Payload Verification Requirements*, NSTS-14046, includes a section dedicated to verification issues for glass and ceramic structures. The first two sentences of this section read

> "Uncontained ceramic and glass parts are always safety critical when located in a habitable area because of the inherent hazard to the crew. Therefore, glass in a habitable area must be shown safe from breakage or proven contained."

Proving a glass component "safe from breakage" is discussed in another chapter. Proving an item is contained is the subject of the next sections of this chapter.

1.3.3.1 Payload Safety Reviews

When the safety community is reviewing a proposed experiment or piece of equipment for manifest, the hardware provider must show that the hazards from potential glass fragments are contained in all phases of flight. The hardware provider must document the containment method and concept in the safety data packages provided to NASA.

The payload provider has a choice of describing the shatterable materials on the Standardized Hazard Control report form, JSC-1230, or of writing a unique hazard report on the shatterable materials in the payload. Usually the complexity of the equipment drives this decision. If the glass components are non-structural, it is likely that the controls can be described on the 1230. Experiments with many non-structural glass components requiring detailed descriptions of the hazard controls will probably need a unique hazard report. Structural glass will usually require a unique hazard report and also strength and fracture analysis (discussed elsewhere) unless it is completely contained by a simple design and failure of the structural glass is of no consequence to the crew or vehicle.

1.3.3.2 Standardized Hazard Control Options

On form JSC-1230, hazards from shatterable materials are listed in block 5. The hardware provider can select among three options for describing the hazard controls:

1. All materials are contained.
2. Optical glass (i.e. lenses, filters, etc.) components of crew cabin experiment hardware that are non-stressed (no delta pressure) and have passed both a vibration test at flight levels and a post-test visual inspection.
3. Payload bay hardware shatterable material components that weigh less than 0.25 lb and are non-stressed (no delta pressure) or non-structural.

The background and basis for these options are described in the sections 1.4 and 1.5.

1.4 Containment Concepts for Internal Equipment

The approach to controlling hazards from shatterable materials in the habitable environment starts with the four criteria listed in section 1.3.1, in the Orbiter contractor's implementation report. Containment of glass components has typically been achieved by plastic films and bags, or by transparent polycarbonate or acrylic covers or laminations.

From launch to orbit, many experiments are stowed in Orbiter middeck lockers or bags, or similar stowage compartments in International Space Station (ISS) or SpaceHab racks. These stowage compartments are not containment devices, since the crew will open them once it is time to unstow the hardware. If the equipment contains glass components, the hardware provider is well advised to put the equipment into a sealed plastic bag before it is stowed in the locker or rack before launch. Once on orbit, when the crew unstows the equipment they can perform a simple inspection of the bag to see if any glass fragments are present. If they were to find fragments, they can safely restow the equipment without risking a release of the fragments into the habitable environment.

During the time when the equipment is being used, the hardware should ideally contain all the glass components. However, there are many instances where this is not feasible. Cameras, for example, usually cannot have plastic covers over their lenses when photographs are being taken. Experiments with intricate internal optics cannot always be completely contained for a variety of reasons ranging from operational needs to cooling requirements. For these cases, special approaches have developed.

1.4.1 Cameras

Still-photo and moving-image cameras are pieces of optical equipment that virtually every adult has handled in his everyday life. We are all familiar with the techniques necessary to manage a camera and take a picture. Astronauts are trained further in how to make good photographs using the specific cameras provided for flight. Because of the crew's high level of familiarity with cameras, the hazards from potential glass fragments are managed in a special way.

Cameras and lenses, with lens covers attached, are wrapped in plastic bags with zippered closures. They are then packed in foam and stowed in middeck lockers or similar locations. Prior to use, the bags are taken out of the lockers and the contents are inspected to ensure no glass fragments are present. When the photography task is complete, the cameras are put back into plastic bags and restowed in the locker. At no time should cameras be left loose in the habitable compartment.

[figure 1.2]

Most cameras are subject to ground vibration tests to establish that they will function as required after exposure to the launch and ascent environment.

Given these procedures and tests, the safety community and technical experts agree that the hazards from shatterable materials release from digital and film cameras are appropriately managed as described above in numbers (2), (3) & (4) of section 1.3.1..

1.4.2 Experiment Boxes with Internal Optics

A common payload experiment configuration is a box built to fit into a Space Station rack or to replace an Orbiter middeck locker. An experiment box might have internal mirrors or lenses made from shatterable materials. Occasionally an experiment box might contain a glass window and camera. The basic safety requirement for these boxes is that all of the shatterable material must be contained.

The payload provider should plan to make the contents of the box completely contained. Openings can be closed with transparent polycarbonate covers that permit excellent viewing and also provide containment.

Some payload developers wish to approach hazard control for optics internal to boxes using the same philosophy as for handheld cameras described above. This presents difficulties, since the basis for accepting fewer positive controls with handheld cameras is due largely to the idea that the crew is familiar with this hardware and will handle it appropriately. Cameras and optics internal to boxes are not a direct part of the crew's handling of the experiment, and the crew might not even be aware that there are glass components inside an experiment.

In these cases the payload safety engineers have required that the experiment hardware go through an acceptance vibration test that envelopes the launch and ascent environment. Following the test, the hardware is inspected as thoroughly as possible. Functionality is also tested to ensure that the optics are all working as expected. The shatterable components are not accessible by the crew, cannot be damaged by handling, and they are demonstrably resilient to the environment.

Many payload providers have been able to provide containment up until the time the experiment is begun. The crew can inspect the equipment and even look through the optics before the containment device or material is removed, thus establishing that no shatterable material release is imminent.

1.4.3 Acceptable Released Fragment Size

If the experiment requires cooling, the box will include a ventilator fan and air vents. These air vents are open paths for fragments of broken glass to escape, so complete containment is not usually possible for these configurations. If an internal glass component were to fracture, fragments would be released into the habitable compartment through the ventilation system.

When considering this issue for the first time, NASA flight surgeons were asked to determine what size fragment would be acceptable. The result of their work was an upper limit of 50 microns for fragment characteristic length. Where appropriate, experiment boxes that cannot completely contain glass fragments must have a 50 micron screen on any open path so that hazardous fragments are not released into the habitable environment. If this can be achieved, safety engineers consider the hazard controlled.

1.5 Exterior Equipment

If payload or flight hardware will never be a part of the habitable environment, the hardware provider is not relieved of all hazard control responsibility. For example, an item that launches in the Shuttle payload bay must not release fragments that could become loose object hazards to the vehicle. The hardware provider must establish that no piece weighing more than 0.25 lb can be released by the equipment. Fragments smaller than 0.25 lb can also present hazards to mechanisms and may need to be evaluated by the Mechanical Systems Working Group at NASA/JSC. Containment is recommended, but this requirement can be met by test and analysis as well. Exterior equipment can also present hazards to the crew, through a contamination event that brings shards into the habitable compartment.

1.5.1 EVA Hazards

If a piece of equipment is in or near an EVA translation zone or worksite, any shatterable material exposed to the EVA crewman is at risk for damage by errant tools. If a tool strikes a piece of glass during an EVA, and shards are released, there are potential sharp edge hazards to the EVA crew, and also contamination hazards for the IVA crew once the EVA is complete and the contaminated suits are stowed in the airlock. To address this risk, NASA has defined the tool impact environment in the EVA Design Requirements and Considerations, JSC-28918, table 4-7, and hardware providers are required to show that fragments larger than 50 microns are not released by a tool impact event. This requirement can also be found in the Space Station Manned Systems Integration Requirements document, SSP 50005, paragraph 14.1.3.N.

Table 1 - Tool Impact Requirement for Shatterable Materials on the Spacecraft Exterior

Tool impact	60 lbm	Concentrated mass travelling at 1 fps on a 0.08” dia. circular area	Any direction	Windows and exposed glass surfaces or other shatterable materials	Applicable to all shatterable materials within translation paths or worksites

Although this is not strictly a “containment” issue, the ultimate hazard is the same – contamination of the habitable environment by fragments of shatterable materials. Controls available to the hardware provider include designing the equipment so that the shatterable materials are protected from tool impact (grids or screens), designating a mass limit on the tools and equipment brought near the hardware during the EVA, or specifying a keep-out zone for their hardware. Verification of the tool impact capability of a piece of shatterable material is usually achieved by an impact test. Figure 1.2 shows several photos from a test of a solar panel for an external device on ISS. Figure 1.3 shows an external light with a grille designed to keep tools away from the shatterable materials.

[figure 1.3]

[figure 1.4]

1.6 General Comments about Working with Shatterable Materials

1.6.1 Good Design Practices for Shatterable Components

The following suggestions should help any hardware designer successfully complete the design and verification cycle and also receive approval from NASA safety engineers.

- Design “glass friendly” mounting systems
    - do not use rigid mounting systems
    - simply support the glass, protect the glass edges from damage

   - use soft seal mounts (i.e. silicone)

- Prevent glass to metal contact (use non-metallic “bumpers” to prevent contact)
- Do not use tight tolerances between the mount and the glass
- Consider thermal effects of the mount on the glass
- Minimize the loads that are transmitted into the glass

1.6.2 Crew Handling of Shatterable Components

One of the greatest risks to a shatterable component is due to crew handling. Handling loads are very difficult to predict, and it is best to design hardware that doesn’t require crew handling. If crew handling is required, the worst-case handling loads must be considered in the design and verification of the shatterable components. Detailed crew procedures must be developed to control the loads as much as possible. Tests with crew men and women may be necessary to envelope all the conditions the hardware may experience.

1.6.3 Failure Propagation and Shatterable Materials

Glass components inside an experiment box should be protected from other items in the experiment. Even if a failure inside an experiment box presents no direct hazards to the crew or mission, it is still important to consider whether this failure could propagate and damage the glass components. For example, internal fasteners might need to have redundant locking features to ensure that loose fasteners cannot rattle around an experiment box and cause impact damage to glass components.

1.6.4 Containment Materials and Devices

Lexan is a common polycarbonate material chosen for containment in the zero-g environment. It is a tough material with excellent optics, and provides a very good solution for the majority of experiments. Another brand-name polycarbonate that has been used successfully is Makrolon.

For small pieces of glass, Kapton tape has frequently been used. The tape is simply applied over the glass item and will contain any fragments should the component be damaged. This is the most common approach to containing the tiny glass covers of liquid crystal displays (LCDs) and light emitting diodes (LEDs). It should be noted, however, that many LCDs and LEDs are manufactured now without glass covers and won't require the Kapton tape.

Zippered plastic bags are a very effective means of enclosure for components of many different sizes. Cameras and experiment boxes have been stowed in plastic bags, as well as many other items with components made with shatterable materials.

For a detailed review of containment issues involving a series of glass failures during an orbital experiment, read 'Microgravity Furnaces And Sample Containment - A Reflective Perspective,' by Shaefer and Fiske, 2004.

1.7 Conclusion

Forty years of manned space flight have taught designers and safety engineers many things about the hazards of a zero-g habitable environment. Even with robust controls in place, some glass components have broken during spaceflight, but due to the redundant layers of controls no person has been injured. NASA intends to keep that safe record intact through good design specifications and vigorous safety reviews. The information in this chapter has outlined the important points for the reader and future hardware providers.

1.8 References

‘EVA Design Requirements and Considerations,’ JSC-29819, February 2005, NASA-JSC.

‘Implementation Report of the Manned Spacecraft Criteria And Standards JSCM 8080 for the Space Shuttle Orbiter,’ 1976, Boeing Corporation.

‘Payload Verification Requirements: Space Shuttle Program,’ NSTS 14046, Rev. E, March 2000, NASA-JSC.

Shaefer, David A., and Fiske, Michael R. 2004, ‘Microgravity Furnaces And Sample Containment - A Reflective Perspective,’ in Proceedings of the 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV.

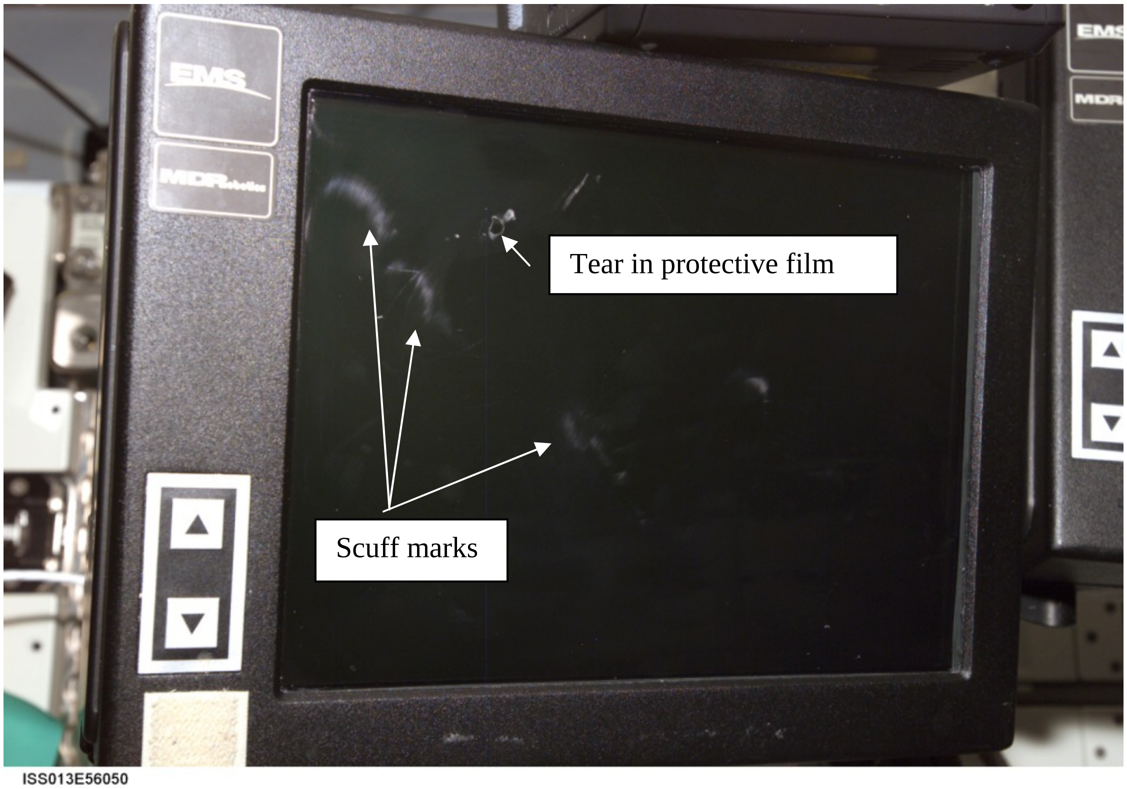

Figure 1.1 ISS monitor screen damaged by orbital activities

Figure 1.2 Camera packed for flight

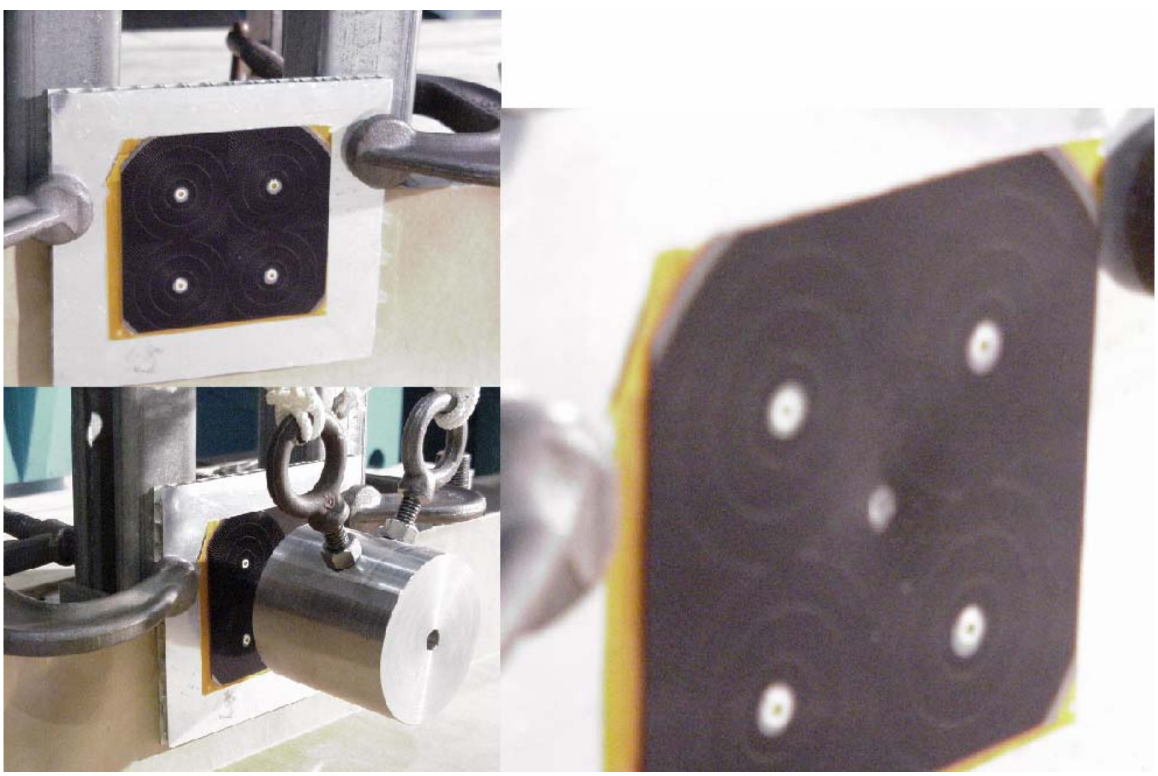

Figure 1.3 Impact test of solar panel for ISS external hardware

Figure 1.4 Luminaire lamp with grille