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NASA Flexible Screen Propellant Management Device (PMD) Demonstration With Cryogenic Liquid

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Abstract/Executive Summary

NASA GRC awarded IES a contract extension (contract number 4200236839) to demonstrate and evaluate a new, flexible screen propellant management device (PMD) concept with liquid nitrogen. The concept was developed while working on a lunar ascent and descent vehicle PMD study for GRC, which is documented in IES Report # 09-RPT-1004-ENG, “Cryogenic Propellant Management Device – Conceptual Design Study,” 30 April 2009. While evaluating various options for liquid methane and liquid oxygen propellant management for these lunar missions, IES conceived the flexible screen device as a potential simple alternative, and performed some proof-of-concept tests using water with internal funding.

Under the contract extension (Option A), an LN2 test apparatus was designed and fabricated, and improved screen forming tooling was built. Initial attempts to test with the first LN2 test apparatus were unsuccessful due to leakage problems with the test apparatus. IES provided additional funding to redesign and build an improved test apparatus, and the second test apparatus worked successfully.

Problems were encountered with the first screen specimens because the spring settings were too stiff to allow the screen to deflect as intended. These problems were solved by reducing the deflection spring force settings, improving the load application configuration, and selecting a finer mesh screen (325x2300 vs 200x1400).

Once these modifications were made, the device functioned very well, and as intended. The finer mesh screen was actually easier to form than the coarser mesh screen, and very low spring forces were more than adequate to return the screen to its fully expanded position. Hence the device can be made to operate with considerable margin between the screen bubble point pressure and the required deflection pressure. No significant degradation in the screen bubble point was observed either due to the screen stretching process or due to cyclic fatigue during testing.

Our initial goal of 100+ cycles at cryogenic temperatures could not be met due to budgetary and test apparatus limitations. However, an estimated 30 to 50 deflection cycles, and approximately 3 to 5 thermal cycles, were performed on the final screen specimen, prior to and between formally recorded testing. These cycles included some “abusive” pressure cycling, where gas or liquid was driven through the screen at

rates that produced differential pressures across the screen of several times the bubble point pressure. No obvious performance degradation or other changes were observed over the duration of testing.

In summary, it is felt by the author that these simple tests validated the feasibility of the flexible screen PMD concept for use with cryogenic propellants.

Recommendations for further work would be to 1) design and fabricate a full scale, flight-representative, flexible screen PMD, 2) install it in a flight-representative propellant tank for ground testing, and then 3) seek flight demonstration opportunities to prove out the concept in a low-gravity or zero-gravity environment.

1 Introduction and Overview

This report documents work performed for NASA Glenn Research Center (GRC) under an Option A extension to a prior contract. The original contract involved a study of various propellant management devices for lunar descent and ascent vehicle concepts using cryogenic propellants. The contract extension was exercised to evaluate a Flexible Screen Propellant Management Device (PMD) using liquid nitrogen. Significant background regarding the flexible screen concept is contained in the original report (Innovative Engineering Solutions report # 09-RPT-1004-ENG, “Cryogenic Propellant Management Device – Conceptual Design Study,” 30 April 2009), and the reader should review that report for background information.

Figure 1 below provides a very brief review of the concept as it would be installed in a spherical tank. Basically, the device functions by using a screen that has been pre-stretched into a spherical shape, and is then preloaded with a spring mechanism to “inflate” with liquid when the screen is in contact with liquid contained in the tank. If liquid is extracted from the device (or lost through evaporation) when the screen is not in contact with liquid in the tank, then the screen will deflect to accommodate this propellant loss without breaking down and admitting vapor. The device is therefore classified as a partial communication PMD. Preliminary work indicated that the device as envisioned should be capable of retaining between 4 and 5 % of the volume of a spherical tank between the fully expanded and fully contracted positions, as shown in Figure 1.

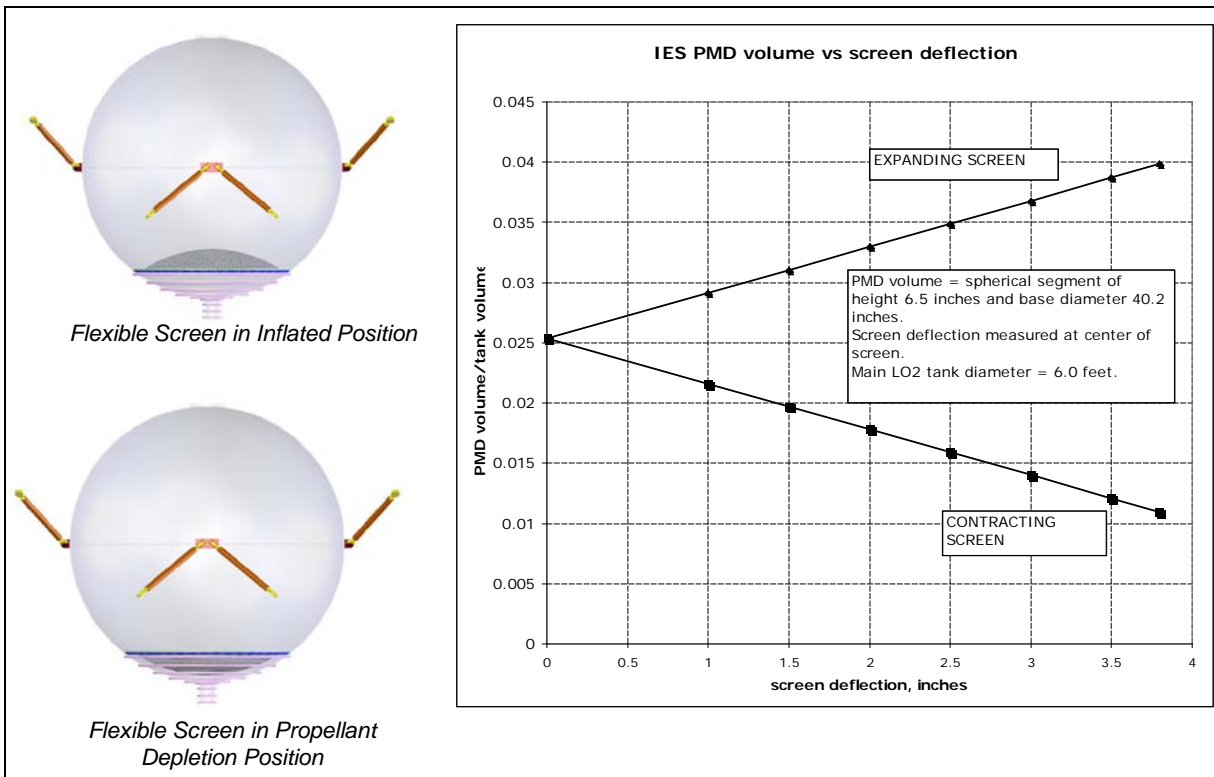


Figure 1. Flexible Screen PMD Concept in Spherical Propellant Tank

2 Screen Forming Process

The PMD Screen forming process consisted of inflating screen mesh using shop air in a custom-built screen forming device (See Figures 2 and 3, below). The screen was first cut and placed inside a plastic bag to stop any air leakage through the mesh during inflating and was then clamped with the device’s circular clamp. The clamp held the screen mesh in place while one enclosed side of the mesh was pressurized using shop air. The mesh was allowed to inflate and deform until a near spherical shape was observed. A few initial screen articles were allowed to burst to determine the strength characteristics of the screen mesh. The final undamaged mesh was then removed from the device and installed in the PMD for testing.



Figure 2. Screen Forming Tool (Close-up)



Figure 3. Screen Forming Tool (In-use)

3 Cryogenic Test Apparatus

3.1 Initial Design Concept

3.1.1 Overview

The initial design concept for the test apparatus used fully polycarbonate construction to allow for clear viewing of the screen article. See Figures 4, 5, and 6, and Table 1 for details of the design and plumbing. The device was designed to have a low static pressure (< 10 PSIG) while allowing a ΔP to build across the screen. The polycarbonate PMD was designed with a three layer construction consisting of an

outer gas cavity, a LN₂ cold wall, and the inner chamber. The outer wall consisted of multiple layers of Mylar sheeting to cut down convection from ambient air to the inner LN₂ cold wall chamber. This would reduce the frosting on the outer window to allow for visual inspection to the inner chamber containing the screen article. The cold wall of the device was filled with LN₂ during testing to intercept heat from the surrounding to allow for undisturbed LN₂ flow in the inner chamber. The inner chamber, which houses the screen article, can be pressurized on one side with He (g) to impose a ΔP across the screen. The other side can be filled with LN₂ or drained at will to simulate fuel use.

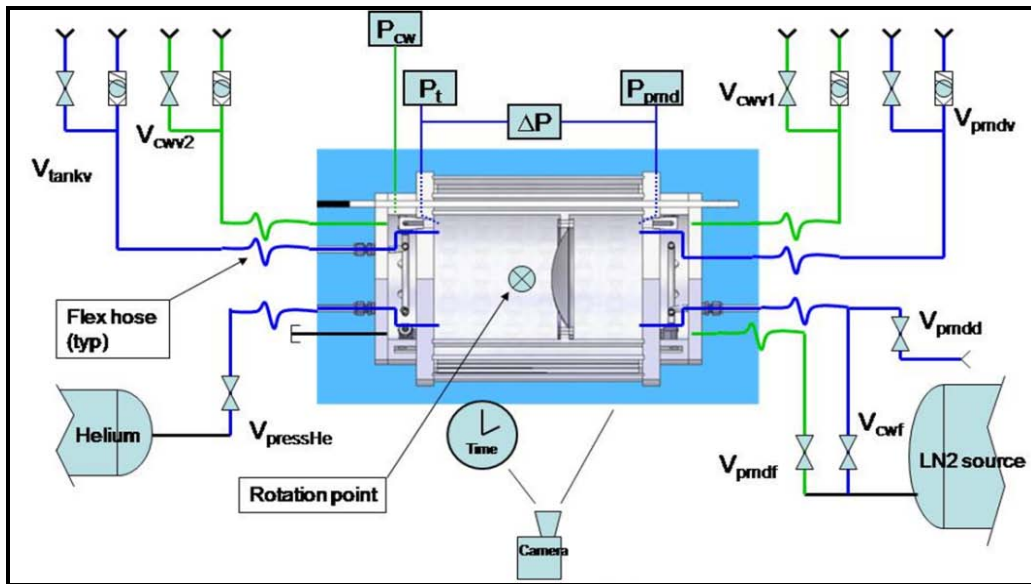


Figure 4. Test Apparatus Plumbing Diagram

Table 1. PMD Piping Diagram Symbols

Identifier:	Function:	Description:
Vcww1	Valve	Cold wall vent 1
Vcww2	Valve	Cold wall vent 2
Vpmdf	Valve	PMD fill
Vpmdv	Valve	PMD drain
Vpmd	Valve	PMD vent
Vtankd	Valve	Tank drain
Vtankv	Valve	Tank vent
VpressHe	Valve	Tank helium pressurization
Pcw	Pressure transducer	Cold wall cavity
Pt	Pressure transducer	Tank pressure
Ppmd	Pressure transducer	PMD internal pressure
DP	Pressure transducer	Differential across screen

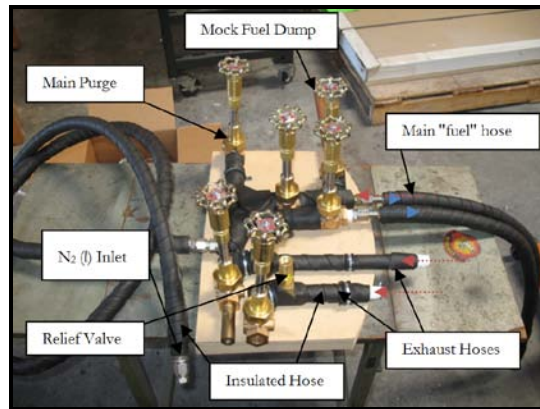


Figure 5. Test Apparatus Manual Control Valves

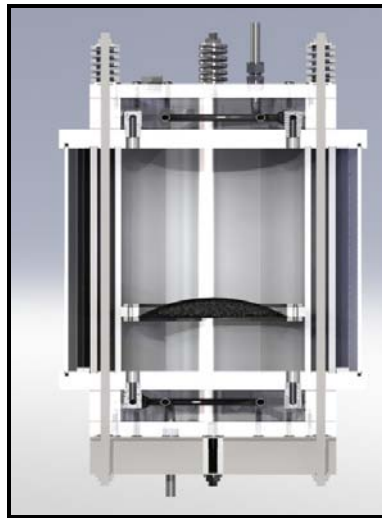


Figure 6. Polycarbonate PMD CAD Model

3.1.2 Fabrication

The polycarbonate PMD was built using extruded Polycarbonate cylinder shells as well as flat sheets of polycarbonate for endcaps. Below are some of the specific pieces constructed along with a short description of their function.

Figure 7 shows the stand, which allowed the test apparatus to be swiveled.

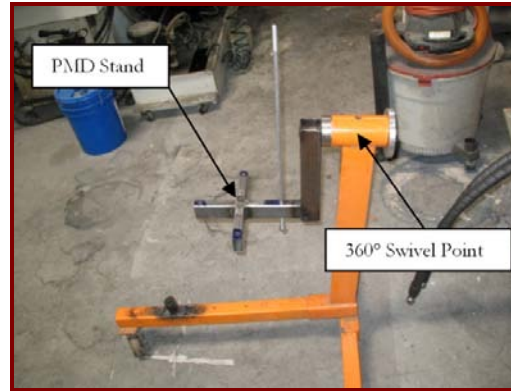


Figure 7. Test Apparatus Stand

Figure 8 shows the inner chamber support ring for the screen.



Figure 8. Inner Support Ring

Below (Figures 9 and 10) are two pieces of the end assembly. The main hub (right) holds the walls in place with concentric grooves cut in the piece. The vent holes can be seen which allow the filling and draining of LN₂ into and out of the cold wall chamber. There is also a pressure transducer hole on each side to measure the ΔP across the screen during testing.

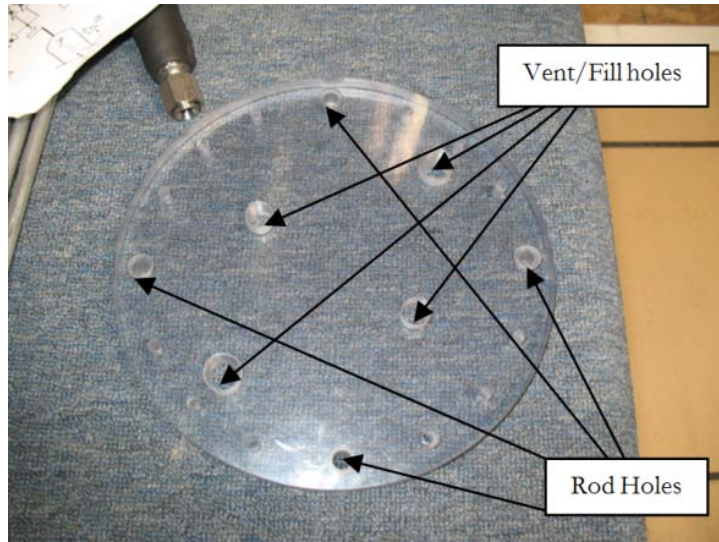


Figure 9. End Cap

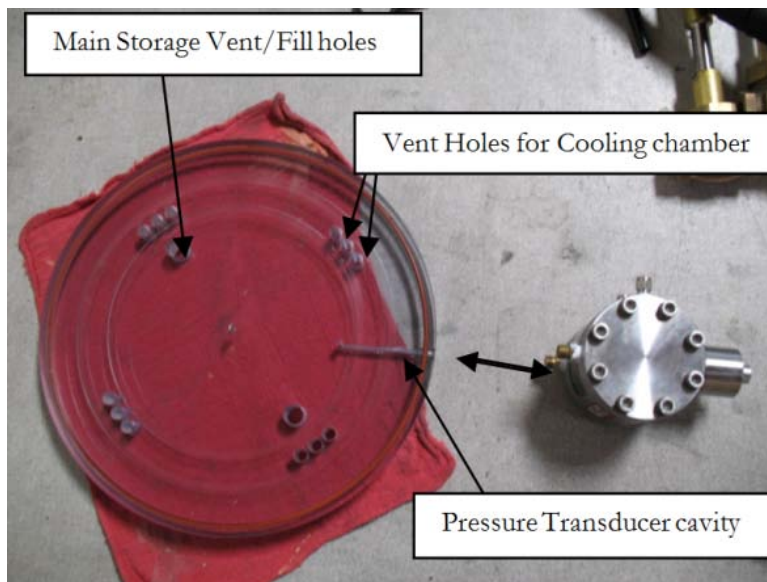


Figure 10. Opposite End Cap

Figure 11 shows a picture of the inner retaining ring for the diaphragm assembly and the mesh article (in plastic bag) after coming out of the forming device.



Figure 11. Inner retaining ring and PMD Screen

Figures 12, 13, and 14 below show the completely assembled PMD test apparatus. Figure 15 shows the spring mechanism that pushes against the screen to deflect the screen into the fully inflated position. In the spring mechanism, the 6 aluminum pieces are formed into a circular radius (to match the fully inflated screen) which maximizes the volume of the lower chamber when the screen is fully expanded. The springs are low enough below the sides of the mesh not to interfere with its flexure in the contracting direction (while expending fuel). The screen is capable of attaining a nearly spherical shape in either direction.



Figure 12. Test Apparatus Front View



Figure 13. Test Apparatus Side View



Figure 14. Test Apparatus End Cap View



Figure 15. Initial Spring Loading Mechanism Below Screen

3.1.3 Testing

Checkout testing using water showed the screen performing as expected. Difficulties encountered with this test apparatus when switching to LN2 are discussed below.

3.1.4 Problems Encountered

The main problem encountered with the initial polycarbonate test apparatus was leaking from the flange joints. Although the device sealed completely at ambient temperatures, once cooled to cryogenic temperatures, leakage was excessive. This was most likely caused by a combination of the differential shrinkage and the lower than recommended compression stress on the joint sealant itself. Repeated attempts to make this test apparatus seal adequately were unsuccessful, and it was decided to undertake a major redesign.

3.2 Redesigned Test Apparatus

3.2.1 Overview

The new concept design for the test apparatus was functionally identical to the first design, but consists of a welded aluminum frame with small, flat polycarbonate windows which are easier to seal. Bolts with belleville washers were placed around the windows to allow for continued stress on the joint sealant down to cryogenic temperatures (factor of safety ≈ 1.2). The outer polycarbonate cavity windows were evacuated with a vacuum pump (< 1 PSIA) to reduce the heat transfer due to convection between the cold wall and the atmosphere. This combined with a small fan resulted in no frosting of the windows during testing for extended periods. The device consists of an inner chamber which houses the screen test article, and an outer cold wall space which is filled with LN₂. Figure 16 below shows a rendering of the completed model as well as the fabricated device.

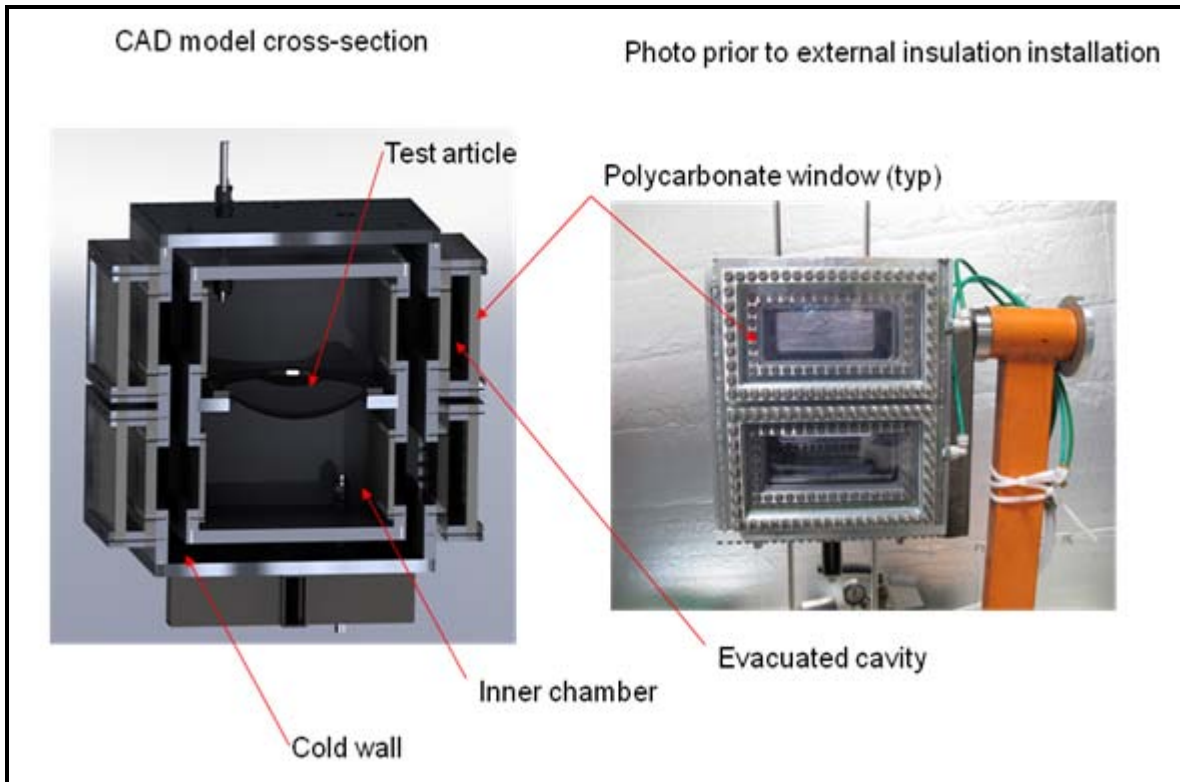


Figure 16. New PMD test device render and assembled unit.

3.2.2 Fabrication

The aluminum-body PMD was fabricated from 6061-T6 tooling plate. The pieces were then welded together to form the complete structures. The end caps of the boxes were bolted down with Gore Joint Sealant™ used to seal the joints. Figures 17, 18, and 19 show some of the specific pieces constructed along with a short description of their function.

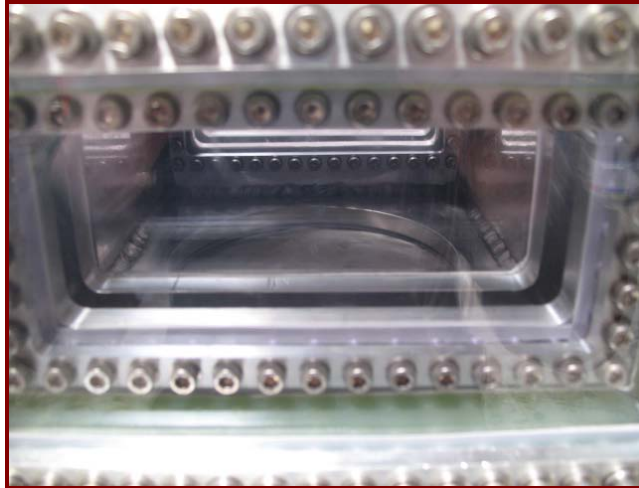


Figure 17. View of Window in Test Apparatus

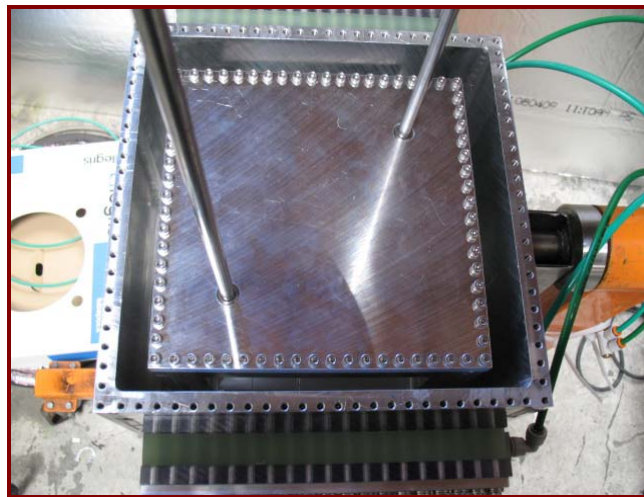


Figure 18. Top View of Apparatus prior to Close-out

Figures 19 and 20, below, (looking up from the bottom of screen) show the original and modified spring loading mechanism design. The final design (Figure 20) was more stable and easier to assemble than the first design. It also appeared to provide somewhat better load distribution, although there was no easy method to quantify this.

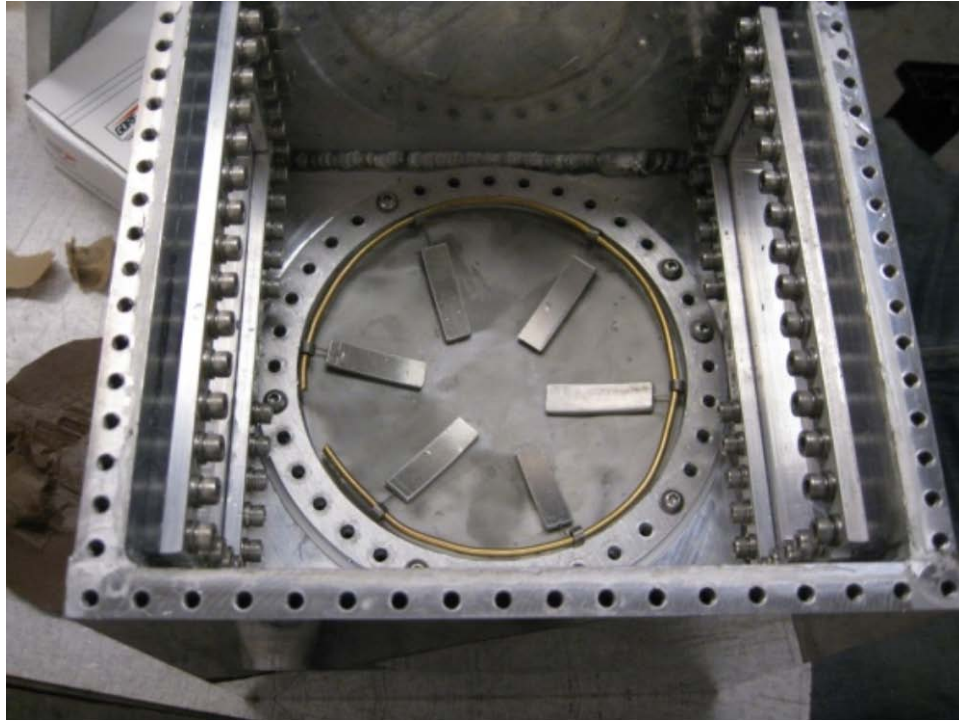


Figure 19. Original Spring Loading Mechanism

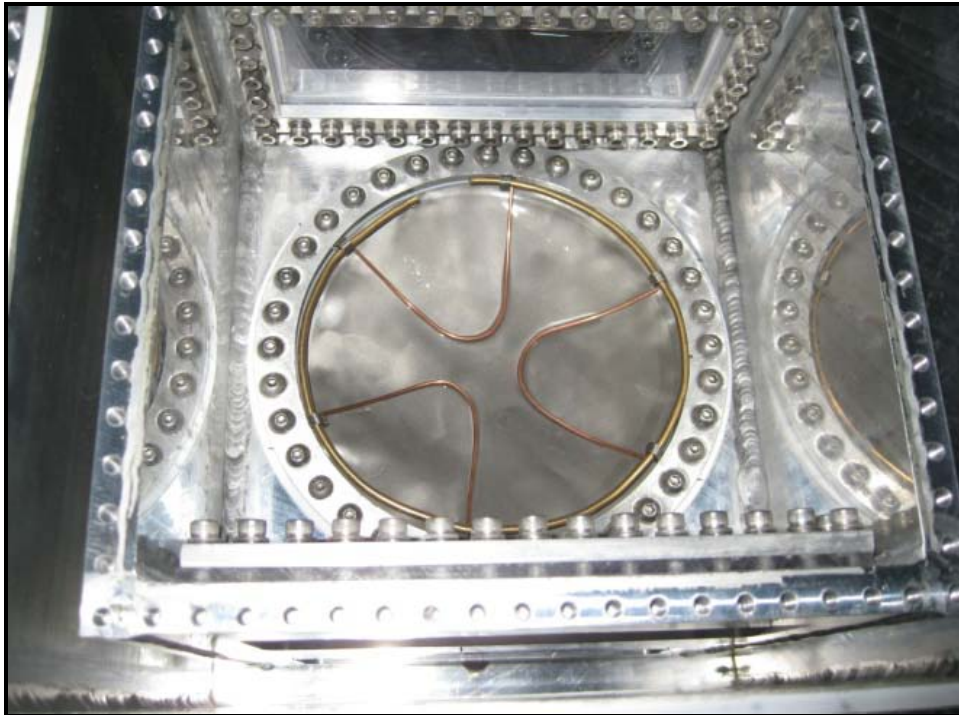


Figure 20. Redesigned Spring Loading Mechanism

Figure 21 shows a picture of the completely assembled, fully-insulated PMD testing device.

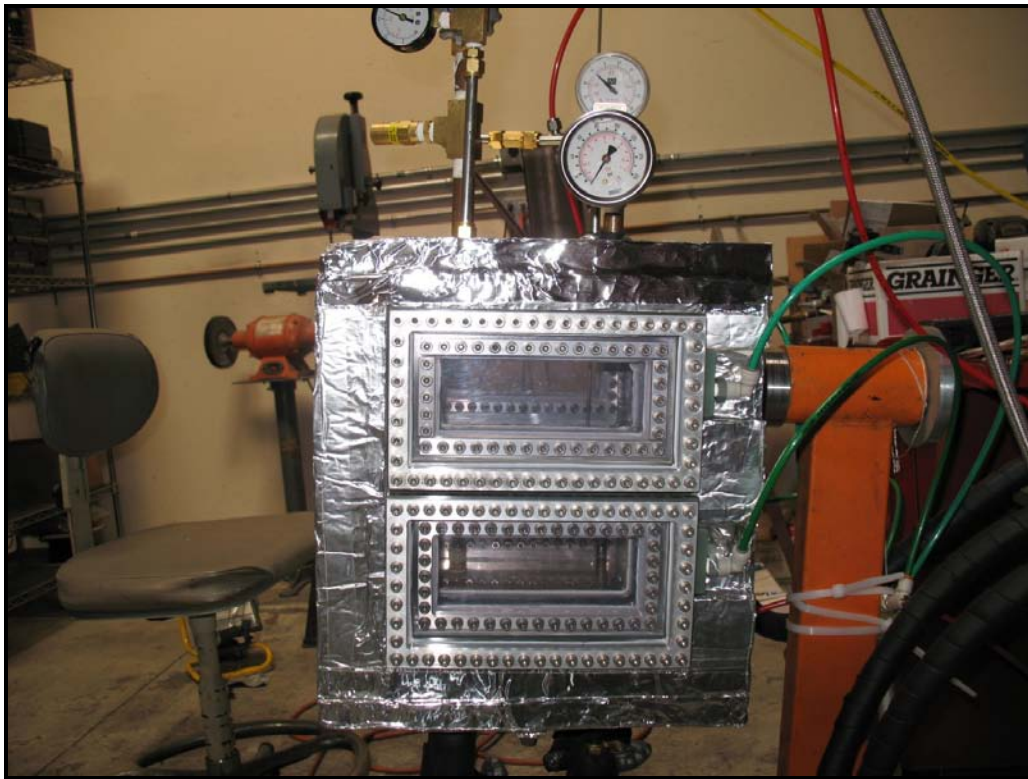


Figure 21. Fully Assembled Final Test Apparatus

3.2.3 Testing

The flexible screen was tested in the redesigned test apparatus with water, isopropyl alcohol, and LN₂. Initial water tests showed operation as expected. The screen deflected fully, as expected, before breakdown occurred. Initial testing of the 200 × 1400 screen mesh with LN₂ indicated a breakdown pressure close to what is expected for LN₂ ($\Delta P \approx 0.26$). However, no screen deflection was observed, apparently because the differential pressure required to deflect the screen was greater than the LN₂ bubble point pressure. This was resolved by forming test specimens of finer mesh (325x2300 versus 200x1400), adjusting the springs to achieve a lower spring force, and improving the design of the spring loading mechanism as previously discussed and shown in Figure 20. With these changes, the device functioned as intended, and a very large margin between screen bubble point and deflection

pressures was found to be possible, while still maintaining adequate spring deflection force to fully inflate the screen.

Significant test results are shown in Figure 22 through 25. All pressures are in English units of lbf/in², and time is in seconds, unless otherwise noted. Differential pressure is x100.

Figure 22 shows initial results with the coarser mesh (200x1400) screen and spring forces set too high to achieve significant screen deflection prior to screen breakdown. The tank is pressurized (at approximately 220 sec) to sub cool the liquid by approximately 16 psi, and liquid is then slowly extracted from beneath the screen. Measured differential pressure slowly rises due to the dropping hydrostatic liquid head as liquid is extracted. Once liquid is depleted from above the screen, differential pressure rapidly reaches the screen bubble point pressure and breakdown occurs (time approximately 320 sec).

Figure 23 shows similar test conditions as in Figure 22, after switching to the finer mesh screen and reducing the applied spring force. Here, the tank above the screen becomes completely drained at approximately 220 seconds, and the screen deflects as the differential pressure rises from approximately 0.03 to 0.06 psid. Full deflection is reached at approximately 250 seconds, at which point the screen differential pressure rapidly reaches the bubble point pressure. A breakdown and resealing cycle then develops as liquid continues to be drained. It is noteworthy that a substantial reduction in differential pressure across the screen must occur before the screen reseals. This is generally inconsequential to the operation of the device, since a functioning PMD of this type should never be driven to breakdown in normal operation. The characteristic does indicate, however, that substantial hysteresis may be present between breakdown and resealing, and/or there might be a significant time interval required for resealing to occur. These breakdown and resealing cycles are better shown in Figure 24.

Figure 23 also shows that the screen remains well sealed when outflow is stopped prior to breakdown with the screen deflected (see the time interval from approximately 300 to 480 seconds).

Finally, Figure 25 provides an example of repetitive cycling of the screen, including high positive and negative pressure differential as the screen is driven between fully

inflated and collapsed positions. Bubble point performance and other operational characteristics showed no changes as the result of any cyclic fatigue imposed by all of the testing (approximately 30 to 50 deflection cycles, and 3 to 5 thermal cycles).

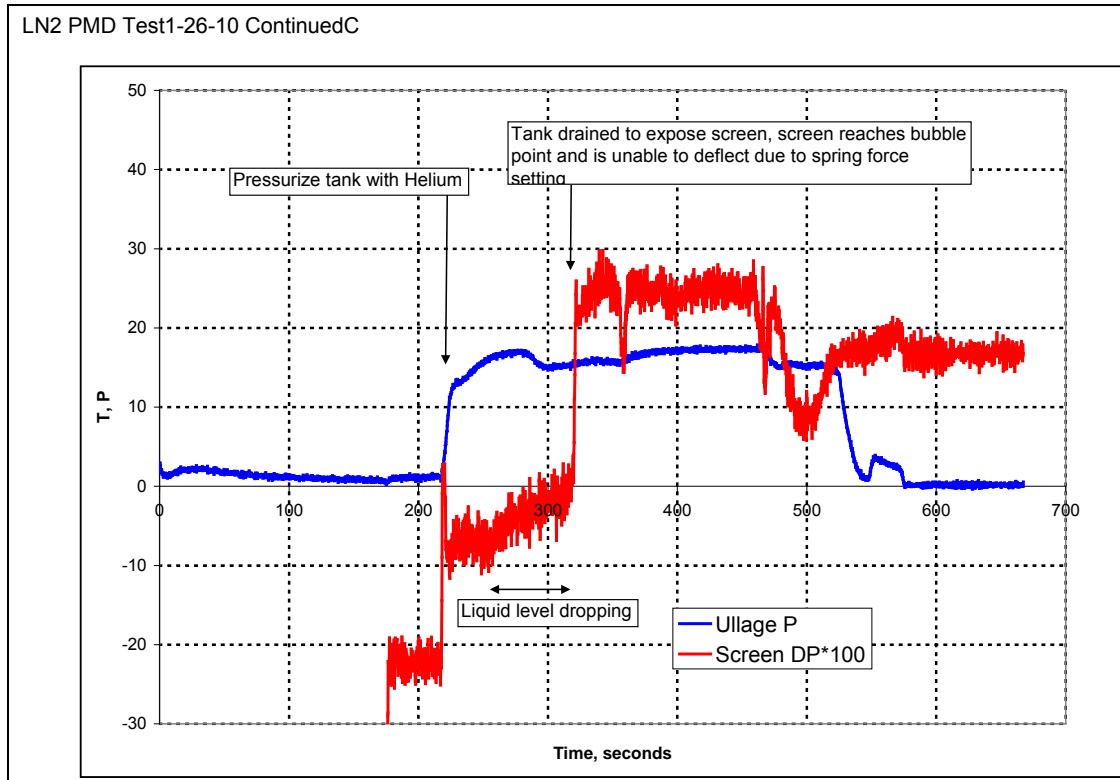


Figure 22. Test Results with 200x1400 Screen and Heavy Spring Force Setting

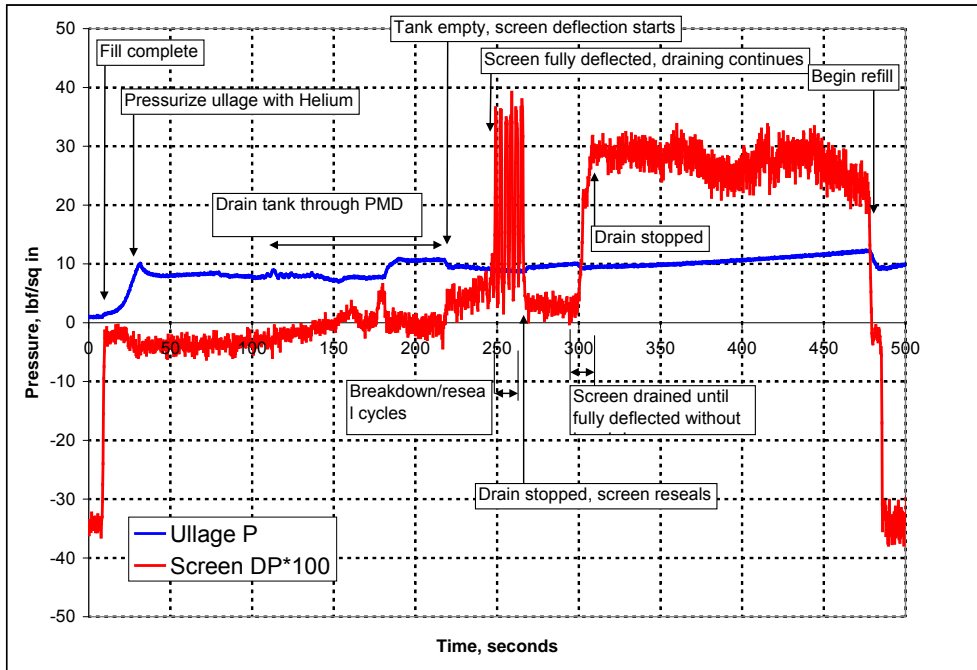


Figure 23. Test Results with 325x2300 Screen and Reduced Spring Force Setting

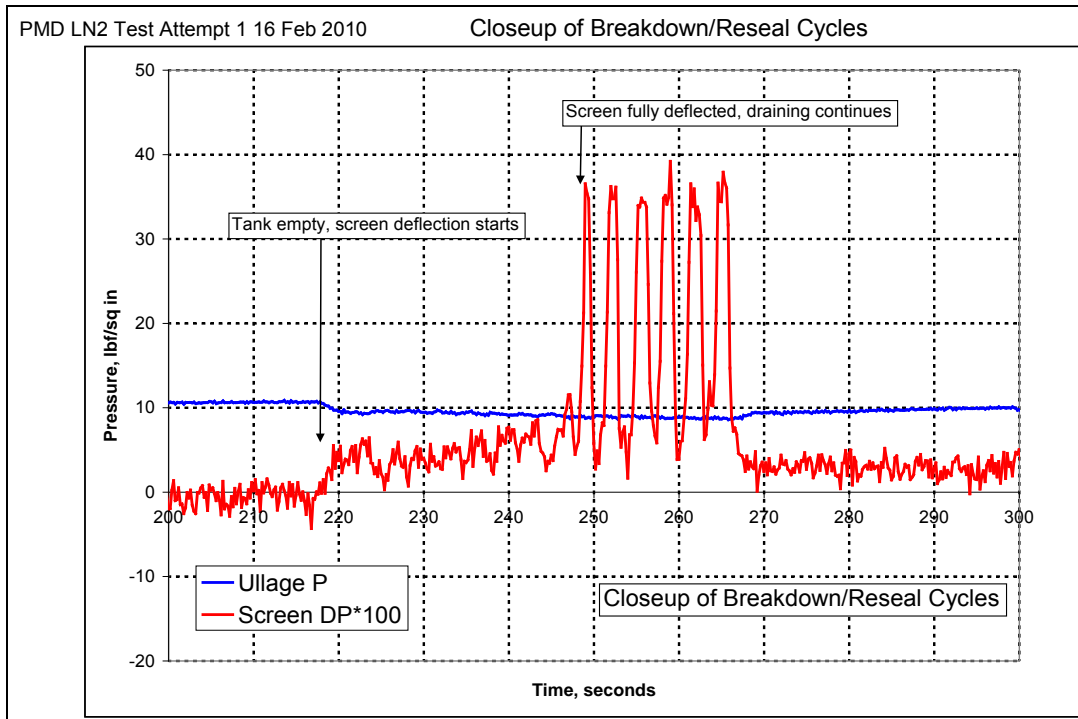


Figure 24. Test Results Showing Details of Forced Breakdown and Resealing

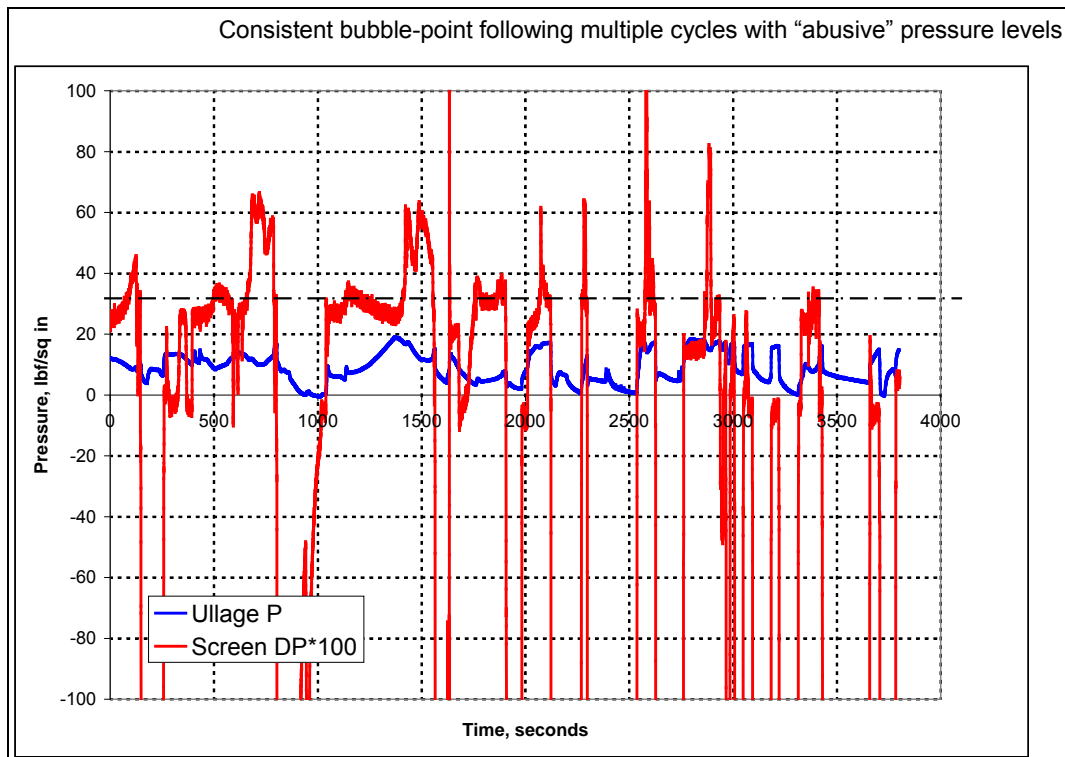


Figure 25. Example of Cyclic Testing Over 1 Hour Duration

4 Conclusions/Recommendations

Once test apparatus difficulties were resolved and adjustments to the spring loading mechanism were performed, the flexible screen PMD concept functioned as anticipated in all respects. It appears that substantial margin can be maintained between screen bubble point pressure and screen full deflection pressure, yet still have adequate spring force to fully re-inflate the deflected screen. Furthermore, although test duration was limited and cyclic testing not recorded rigorously for these tests, it appears that screen degradation due to mechanical or thermal cyclic fatigue will not be a serious problem.

Even the simple screen forming tooling used for this study easily yielded test specimens capable of nearly 1 inch vertical deflection per 3.5 inches radius, and did not appear to degrade screen bubble point measurably (indeed, post stretching bubble point was in most cases as high or higher than pre-stretching bubble point!). Further refinement of the forming tooling is recommended if even greater deflection range is desired. Furthermore, screen preparation such as annealing and then heat treating before and after the forming process might provide additional benefits.

Recommendations for future work (other than the screen forming refinements mentioned above) would be to design and fabricate a larger scale device, representative of flight-like hardware, and install this in a flight-representative cryogenic propellant tank, followed by ground testing, and eventually flight testing in a low or zero-g environment. Further refinements and alternatives for applying the inflation load on the screen should also be considered for the next device (although the simple spring loading mechanism currently employed seemed to work very well).

5 References

IES Report # 09-RPT-1004-ENG, “Cryogenic Propellant Management Device – Conceptual Design Study,” Mark Wollen, Fred Merino, John Schuster, Christopher Newton, 30 April 2009

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14. ABSTRACT While evaluating various options for liquid methane and liquid oxygen propellant management for lunar missions, Innovative Engineering Solutions (IES) conceived the flexible screen device as a potential simple alternative to conventional propellant management devices (PMD). An apparatus was designed and fabricated to test flexible screen devices in liquid nitrogen. After resolution of a number of issues (discussed in detail in the paper), a fine mesh screen (325 by 2300 wires per inch) spring return assembly was successfully tested. No significant degradation in the screen bubble point was observed either due to the screen stretching process or due to cyclic fatigue during testing. An estimated 30 to 50 deflection cycles, and approximately 3 to 5 thermal cycles, were performed on the final screen specimen, prior to and between formally recorded testing. These cycles included some "abusive" pressure cycling, where gas or liquid was driven through the screen at rates that produced differential pressures across the screen of several times the bubble point pressure. No obvious performance degradation or other changes were observed over the duration of testing. In summary, it is felt by the author that these simple tests validated the feasibility of the flexible screen PMD concept for use with cryogenic propellants.					
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