Catastrophic Failures and a Robust Fix of the Atmospheric Emitted Radiance Interferometer (AERI) Detector Dewars

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Introduction

The Atmospheric Emitted Radiance Interferometer (AERI) is a ground-based infrared spectroradiometer that was developed at the University of Wisconsin Space Science and Engineering Center (SSEC) for the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program to measure the downwelling infrared emission from CO_2, H_2O, and clouds. Nine continuously operating AERIs are deployed throughout the world, including Lamont, Oklahoma; Barrow, Alaska; Madison, Wisconsin; and Nauru Island in the tropical western Pacific. The AERI instruments are used to improve our understanding of atmospheric radiation transfer and cloud properties for climate studies, and for boundary level temperature and water vapor retrieval and water vapor transport for weather applications (Knuteson, 2004a,b). Additionally, a marine version of the AERI called the MAERI has been developed for the University of Miami to measure sea surface temperature from on-board ships (Minnett, 2001).

Over the past several years five (AERI) detector dewars have experienced mysterious catastrophic mechanical failures in the field. The dewars house the infrared detectors in a vacuum environment and provide the thermal interface for the Stirling cycle cooler that keeps the detectors at cryogenic temperatures. This paper describes the failure investigation that was conducted at the University of Wisconsin Space Science and Engineering Center, and the search for a simple, easy to implement, and robust solution to the problem. We also describe the test program that was conducted to verify the most likely failure mechanism and to validate that the fix alleviates the problem without impacting cooler performance.

AERI Dewar Configuration

The AERI uses an infrared detector assembly manufactured by InfraRed Associates consisting of a 1 x 1 mm sandwich of Indium Antimonide (InSb) mounted in front of Mercury Cadmium Telluride. InfraRed Associates integrates the detector assembly into a vacuum dewar that also provides the thermal interface for a split-cycle Stirling cooler cold finger used to keep the detectors at 67 K (North Slope AERIs), or 77 K (all other AERIs). The AERI uses the 0.6 Watt Stirling cooler manufactured by Carleton Life Support Systems (formerly Litton). In a split cycle Stirling cooler the compressor and coldfinger/expander are separate and connected by a thin tube that carries the working thermodynamic helium gas. Figure 1 shows the Stirling cooler and detector dewar integrated into the AERI interferometer assembly. Figure 2 illustrates the detector assembly housed inside the vacuum dewar section and mounted to the front side to the Kovar disk at the bottom of the dewar well. The detector views outside the dewar through an infrared transmitting window. The Stirling cooler cold finger slides inside the tightly toleranced well of the dewar and is thermally coupled to the detector assembly through a compliant bellows and the Kovar disk. A gold wire "fuzz button" located inside the bellows also provides a parallel thermal

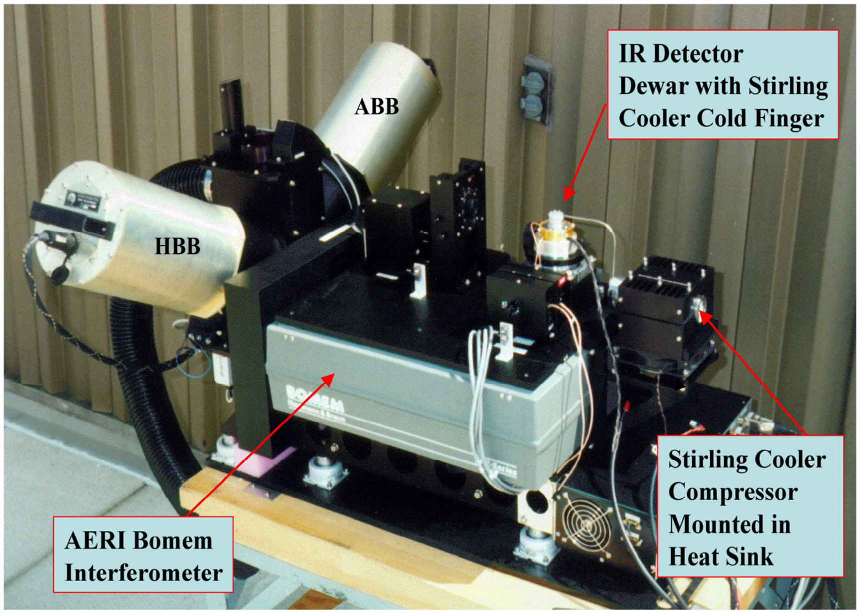

Figure 1. AERI Interferometer Assembly with cover removed, showing detector dewar and Stirling cooler assembly.

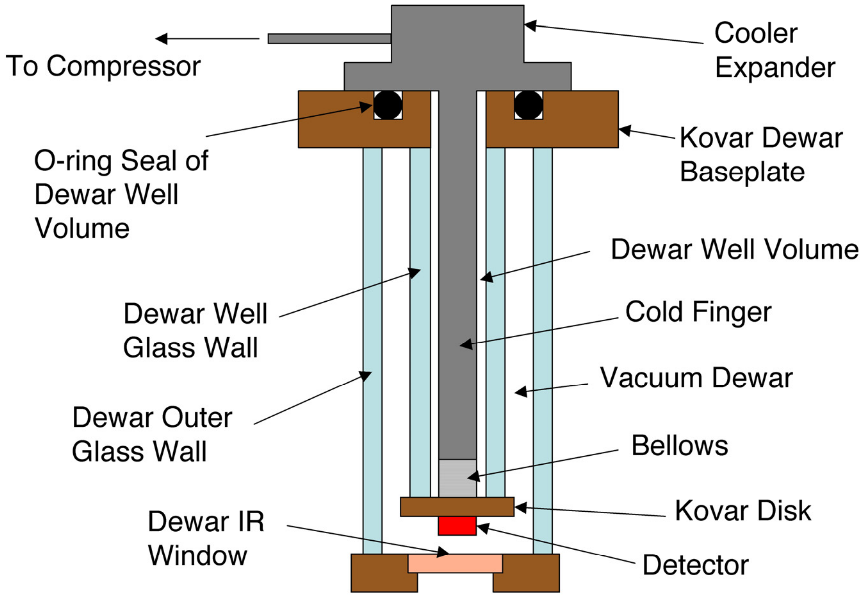

Figure 2. The AERI detector dewar with Stirling cooler cold finger installed. The aluminum case that surrounds the dewar assembly (except for at the dewar window) is not shown in this figure.

path between the cold finger and Kovar disk. A small quantity of thermally conductive grease (Wakefield Compound 120) is used to improve conduction between the cold finger and the bellows and between the bellows and the Kovar disk. With the cold finger installed, the dewar well volume is sealed where the cold finger flange compresses the O-ring at the top of the dewar body on the Kovar dewar baseplate. During normal operation the cold finger liquefies (cryopumps) the gas that is trapped in the sealed volume, creating a much-reduced pressure in the well, and thus eliminating heat loads due to gas conduction.

The split cycle Stirling cooler configuration is ideal for the AERI because it allows easy replacement of the fixed lifetime coolers without disturbing the optical alignment of the integrated detector and without compromising the system end-to-end characterization. When run under continuous operating conditions (24 hours a day, 7 days a week), AERI cooler lifetimes typically run from one to three years.

Observed Failures

An investigation at the University of Wisconsin (UW) indicated that the dewars failed after the units were powered off following several months of continuous operation. Figure 3 shows the results of a catastrophically failed dewar from an AERI that was deployed at Barrow. In this photo the interferometer protective metal cover has been removed in order to see the results of the failure - it is clear that significant energy was involved in this failure.

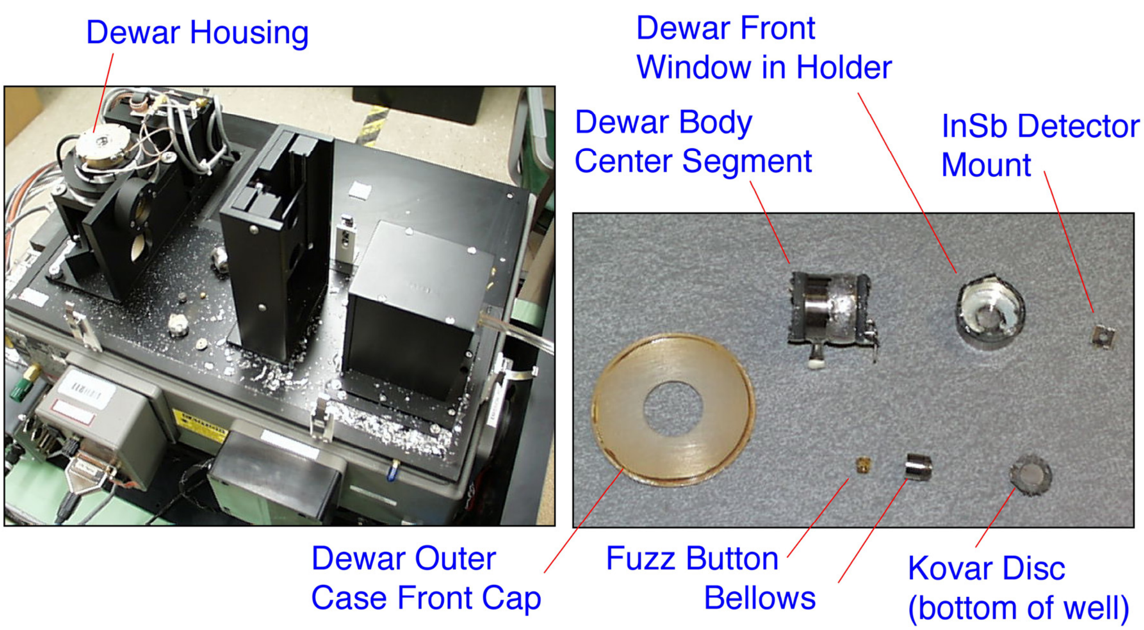

Figure 3. Pieces from a catastrophically failed dewar from a Barrow, Alaska deployment. The photo at left shows the top plate of the interferometer with the protective cover removed. Photo at right illustrates some of the failed pieces, along with the bellows and fuzz button that are used to couple the cold finger to the Kovar disk at the bottom of the well.

Most other dewar failures have been less severe, making it easier to identify the mode of failure. Physical inspections of these dewars showed that the Kovar disk at the bottom of the well fractured at its junction with the inner glass wall (see Figure 4 and 5). The disk (with detectors mounted on the front side) was pushed violently forward cracking the dewar infrared window. The observed failures can be explained if there were a build-up of varying amounts of internal pressure in the O-ring sealed dewar well.

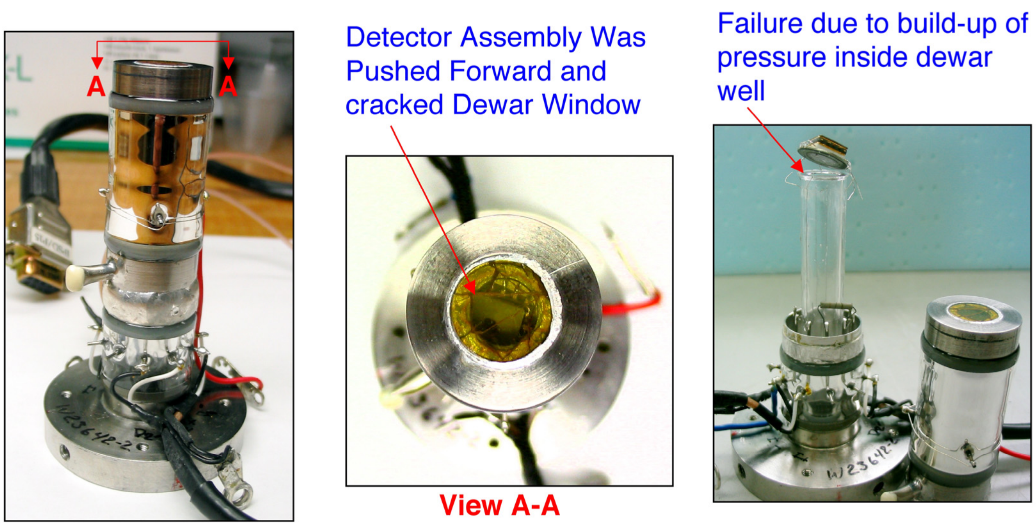

Figure 4. Failure of the AERI Morris dewar. Less violent dewar failures like this one help to pinpoint the mode of failure. The photo at right has the outer glass dewar forward segment removed to reveal the inner dewar wall. It can be seen that the Kovar disk at the bottom of the well fractured at its junction with the inner glass wall. The disk (with detectors mounted on the front side) was pushed violently forward cracking the dewar infrared window (center photo).

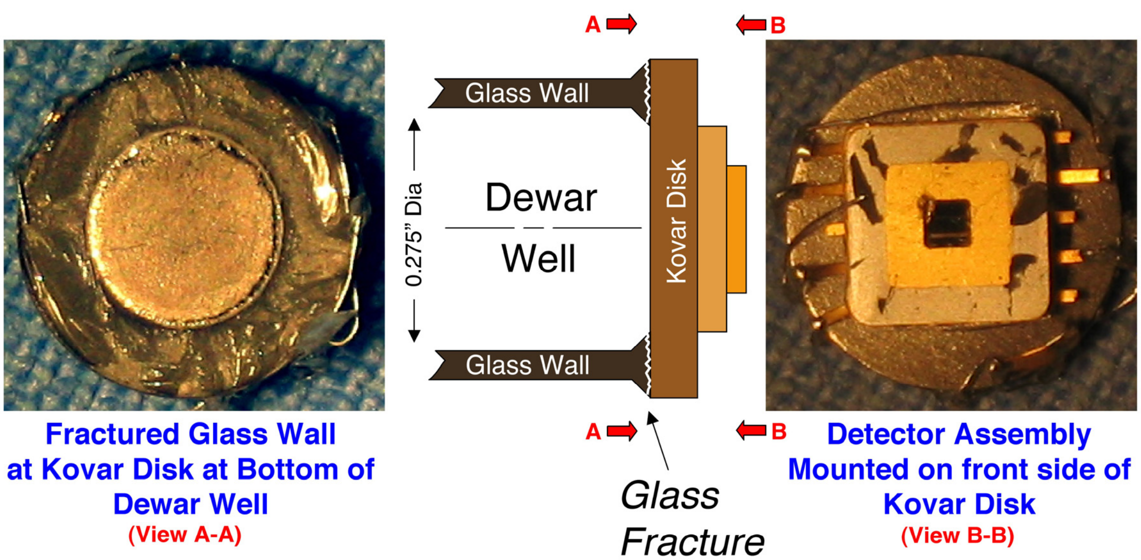

Figure 5. A fractured dewar well glass wall at the Kovar disk (left), and detector assembly mounted to front side of the disk (right).

Theory of Failure and Analysis

The failure investigation looked into various mechanisms that could provide the amount of energy necessary to cause the observed failures. Figure 6 illustrates the mechanism proposed and eventually verified as the most likely cause. In this scenario there is a leak of air past the O-ring into the "sealed" volume that is continually cryopumped to low pressure by the coldfinger. Over long periods of time, even very small leaks can allow significant volumes of air to be drawn inside the small sealed volume. This air is continuously liquefied by the cold finger during cooler operation. When the cooler is powered off, the accumulated liquid air boils and rapidly builds pressure because there is only a miniscule exit path (through the small leak aperture). If enough air has leaked into the small volume over time, there is a dewar failure when the cold finger warms up. It is interesting that the most frequent and violent failures were observed in the Barrow units that run at a colder detector temperature. With colder detector set points, cryogenic temperatures occur further up from the tip of the cold finger, allowing a greater volume of air to be liquefied out, causing higher pressures within the well of the dewar after the unit is powered off.

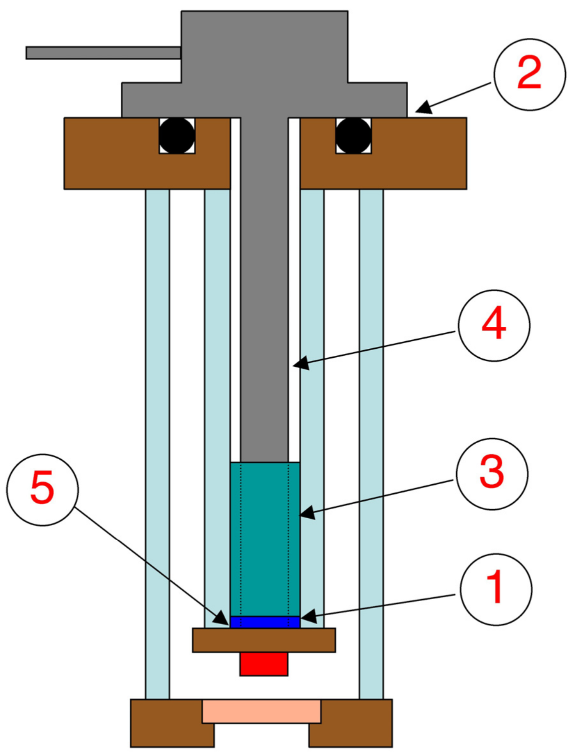

Figure 6. Mechanism that explains dewar failure: (1) during normal operation the gas in the O-ring sealed dewar well volume is liquefied at the bottom of the well by the cold finger that operates colder than the liquefaction temperature of both nitrogen and oxygen; (2) any small leak at the O-ring allows gas to be drawn into the cryopumped volume in the dewar cold finger well; (3) leaked gas is liquefied by the cold finger; (4) when the Stirling cooler is turned off, the liquefied gas boils and rapidly builds pressure because there is only a miniscule exit path (through the leak aperture); (5) the dewar well fails during liquid boil-off if enough gas has entered through the leak. The highest stress in the glass is near its junction with the Kovar Disk.

Figure 7 shows a close up photo of the point of failure. Remnants of glass are still adhered to the Kovar disk, indicating a good connection was made during the glass/Kovar fusion process at the time of dewar manufacture. This fusion takes place while both the glass tube and Kovar disk are spinning in a lathe. The disk is then evenly heated and pressed into the glass, creating a small radius (0.02 to 0.03 inches) of melted glass on each side of the glass wall [personal communication with O'Rourke, 2003].

Figure 7 also presents the results of the finite element analysis performed on the inner dewar to determine the magnitude of the internal pressure that would cause the observed failure of the glass wall at the Kovar disk. Prediction of failure is difficult in this case due to the sensitivity of glass failure strength to imperfections, the uncertainty in the actual fillet contour, and the likelihood of residual stresses from the glass/Kovar fusion process. Neglecting these effects, an internal pressure of 38 atmospheres would bring the glass to its published ultimate strength of 10,000 psi. When the other effects are considered, one would expect failure at significantly lower pressures. Only 14 cm^3 of air at Standard Temperature and Pressure (STP) is needed to leak into the small volume to generate the calculated failure pressure. The model predicts a higher stress in the Kovar disk, but failure will occur in the most highly stressed point in the glass because it is has a lower failure stress. The location of maximum stress in the glass (close to the Kovar) is consistent with the observed glass failure (Figure 7). This helps substantiate the overpressure as the cause of failure, as the glass would be unlikely to fail at this thicker section under other loading conditions.

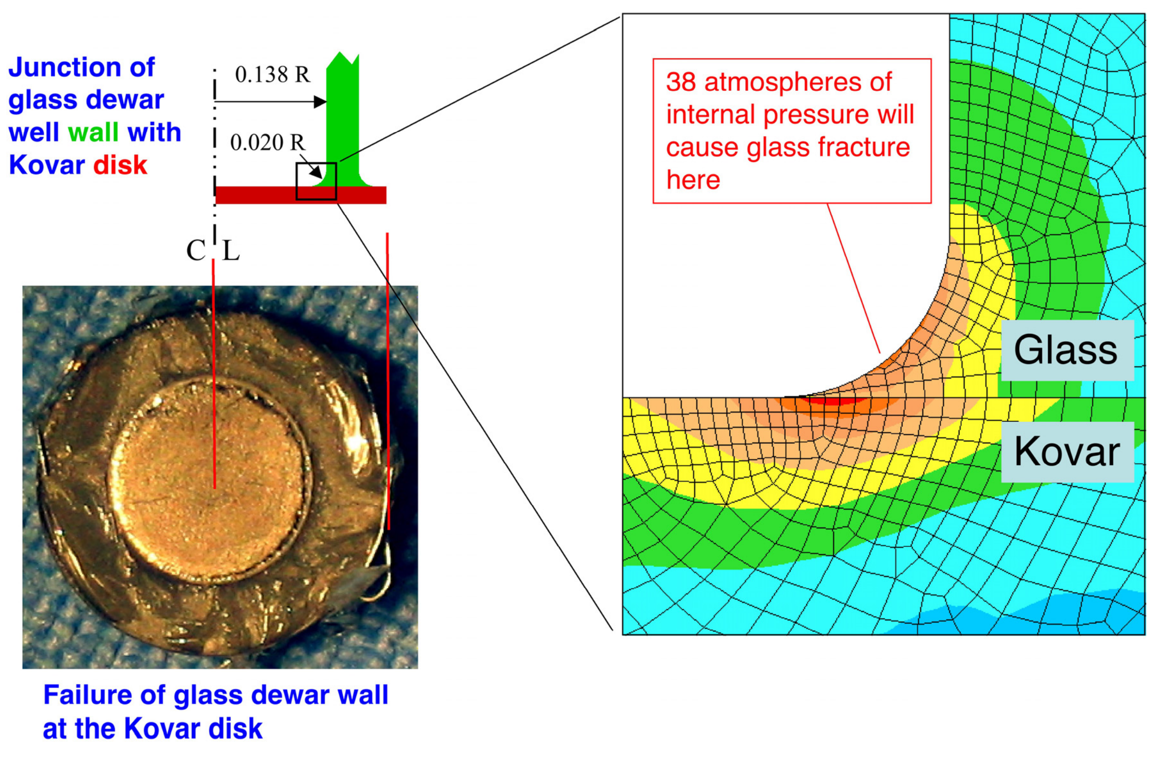

Figure 7. Failure of the dewar well glass wall, at its junction with the Kovar disk, is predicted to occur with 38 atmospheres of internal pressure.

Following the analysis, a test was set up to measure the maximum amount of boil-off gas that could be liquefied in the well of the dewar during cooler operation. Figure 8 shows the AERI test dewar mounted in the AERI Stirling cooler test stand and configured to measure boil-off gas. In this test configuration, there is a boil-off port connected to the dewar well volume. The port is open to ambient air (Tygon line disconnected) except for when the cold finger is warming up and it is desired to measure boil-off gas volume (by displacing a column of water). This simulates an exaggerated leak into the dewar well when the cooler is operating and liquefying incoming air.

A gas boil-off volume of 90 cm^3 was measured with a detector set point temperature of 67 K and with an exaggerated leak. Figure 8 shows this STP gas volume, when liquefied, will rise up to a level of 13 mm above the bottom of the dewar well. For perspective, the plot in the figure also shows the gas boil-off volume of 14 cm^3, that when constrained in the dewar volume, will generate the failure pressure of 38 atmospheres. In the plot of Figure 9, "Vgas" was calculated by taking the ratio of the STP gas volume to liquid volume (700), times the open volume available for liquid to form from the bottom of the well. Because more than 6 times more boil-off gas was measured (with and exaggerated leak) than is needed to account for failure, the tests confirmed that the proposed failure mechanism seems viable, if there is enough of a leak present at the dewar O-ring.

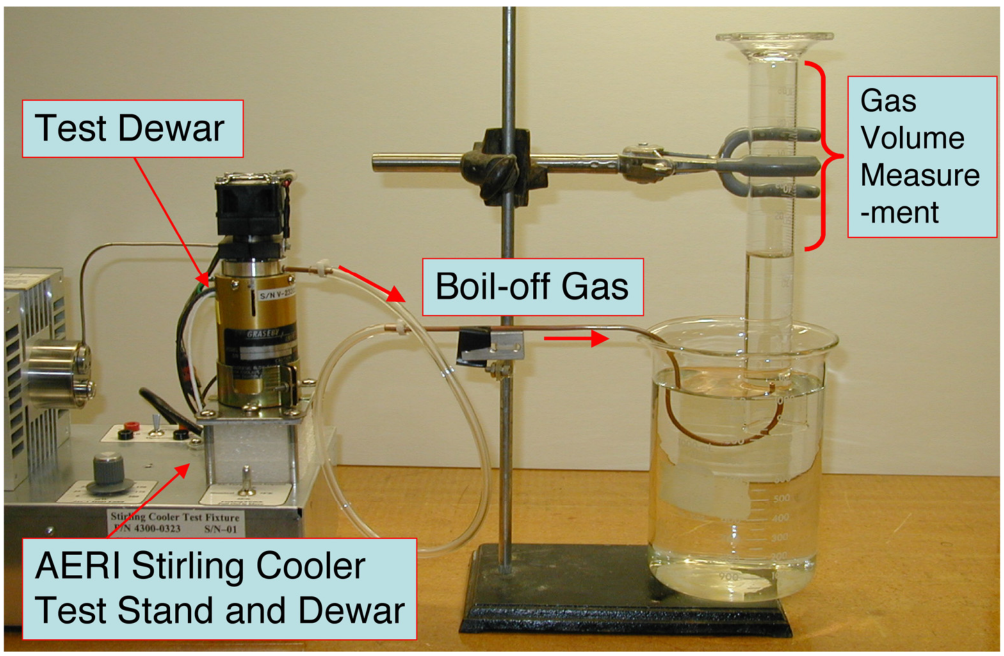

Figure 8. The AERI Test Dewar mounted in the Stirling Cooler Test Stand and configured to measure boil-off gas. The boil-off port at the dewar is opened to ambient air (Tygon line disconnected) except for when the cold finger is warming up and it is desired to measure boil-off volume by displacing column of water. This simulates an exaggerated leak into the dewar well when the cooler is on and liquefying any incoming air. This fixture was used to verify that there was no boil-off gas after the fix was implemented.

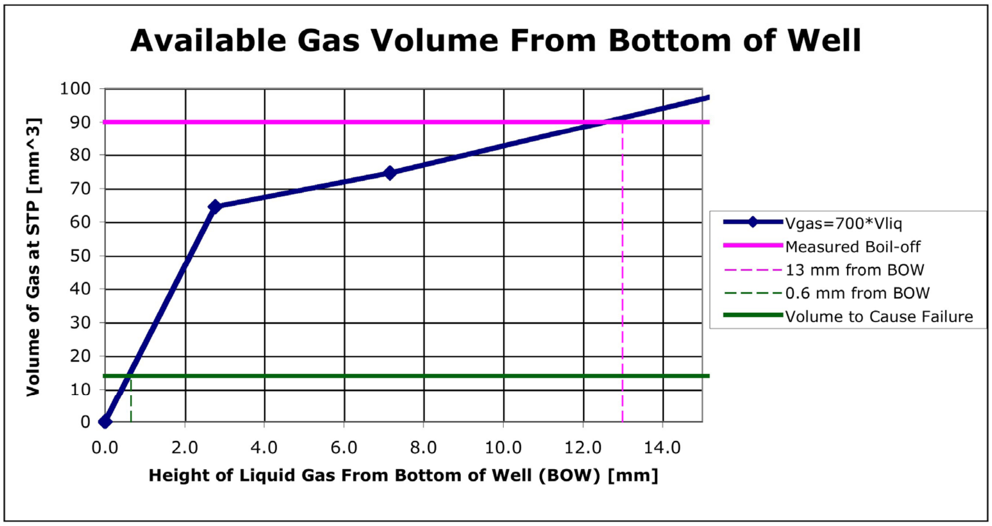

Figure 9. The volume of gas leakage into the dewar well that is needed to cause failure is only 15% of the volume of boil-off gas that was measured with an exaggerated leak. This indicates that there is definitely the capacity for failure if there is enough of a leak present.

The volume of boil-off gas measured is also consistent with the temperature distribution along the cold finger that was suggested by the Stirling cooler manufacturer (personal communication with Nelson, 2003). With a detector set point temperature of 67 K, there will be temperatures cold enough to liquefy the major constituents of air as high as 17 mm from the bottom of the well. This is roughly consistent with the measured gas boil-off that suggests a distance of 13 mm (see Figure 9). The discrepancy is most likely due to uncertainties in both the volume and temperature models, and the fact that a small quantity of grease and the small glass radius were not accounted for in the volume model.

Another part of the investigation looked at the O-ring seal. Inspections found slight scratches and gouges in some of the O-ring grooves that are machined into the Kovar dewar baseplate. However, there was no correlation between O-ring groove integrity and dewar failure. But even with a perfect seal, air can pass through the O-ring by diffusion. Calculations indicate that about 14 cm^3 of air (enough to cause dewar failure) will pass through the O-ring over the period of about 16 months. So with even a perfect O-ring implementation, there is the potential for dewar failure with long periods of continuous operation.

The dewar design employed for the AERI is used extensively by the military for night vision systems. InfraRed Associates has no records of catastrophic failures of these systems (personal communication with Rothe, 2003). An explanation for why the AERI dewars experience mechanical failure, whereas the military units do not, has to do with usage. The military units might be used every day, but they are powered off for a significant fraction of a day between times of operation. This gives time for any gas that might have built up inside the well of the dewar to leak back out. By comparison, the AERI units operate for many months continuously. When powered off, the total volume of gas that leaked in during the entire period of operation suddenly builds up far faster than it can escape – leading to failure.

Solution and Implementation

Many solutions were investigated and two different relief valve implementations were prototyped and tested. The prototyped solutions relieve any boil-off pressure that might be generated as the cold finger warms after cooler power-off, but they require reworking of existing hardware and they did not prove to be robust under extensive testing. Eventually, we found a robust solution that eliminates the root cause of the problem. By packing thermally conductive grease in the bottom of the well of the dewar up to the point on the cold finger where the temperatures are above the liquefying temperature of both nitrogen and oxygen, air is prevented from liquefying out. This solution is called the “Packed Grease” configuration and is illustrated in Figure 10.

Extensive testing was performed on this solution. The boil-off test set-up (shown in Figure 8) was used to verify no boil-off gas was generated after cooler power off, under conditions of an exaggerated leak. Additionally, performance tests were conducted using the AERI Stirling cooler test stand to verify that there was no degradation in cooler performance with the added grease in the dewar well. Figure 11 shows the results of these tests. The plot shows the current drawn by the Stirling cooler with different detector bias powers at both 67 K and 77 K. Current draw is a measure of how hard the cooler is working to maintain the detector set point temperature. The detector bias power is a heat load that is applied directly at the detector, using the test stand. The results of the performance tests show that the new “Packed Grease” configuration actually improves cooler performance (lower cooler current draw for a given detector bias power) over the original or “Standard” configuration. The tests also show that even with an exaggerated leak, there is no significant change in cooler performance. This is not surprising since in the Packed Grease configuration none of the air that is trapped in the well of the dewar will liquefy out, because the grease occupies the volume where there are liquefying temperatures. This means that there will be nearly atmospheric pressure in the well of the dewar (for both the no leak and exaggerated leak cases) and no differential pressure to force air into the well. So the conditions inside the dewar well for the case of no leak compared to the case with an exaggerated leak should be similar, which is borne out by the performance tests. The improved performance between the two packed grease cases compared with the un-packed grease cases is most likely due to the improved thermal coupling that the grease provides between the cold finger and the bottom of the dewar well.

The trickiest part of the new implementation is the installation of the cold finger into the dewar well. Care must be used to properly pack the thermally conductive grease inside the bellows (and fuzz button) and into the bottom of the well of the dewar. Figure 12 shows some of the tools developed for the implementation of the new “Packed Grease” configuration. The left photo shows the tool for aligning the new cold finger centering ring that must now be installed on each dewar. This ring places the cold finger more precisely in the center of the well, ensuring that the thermally conductive grease will be displaced evenly around the circumference of the cold finger. The right photo shows the tool for dispensing the exact quantity of grease required at the bottom of the dewar well, while keeping the sides of the well grease free. Detailed procedures were developed along with these specialized tools to ensure proper Stirling cooler installation.

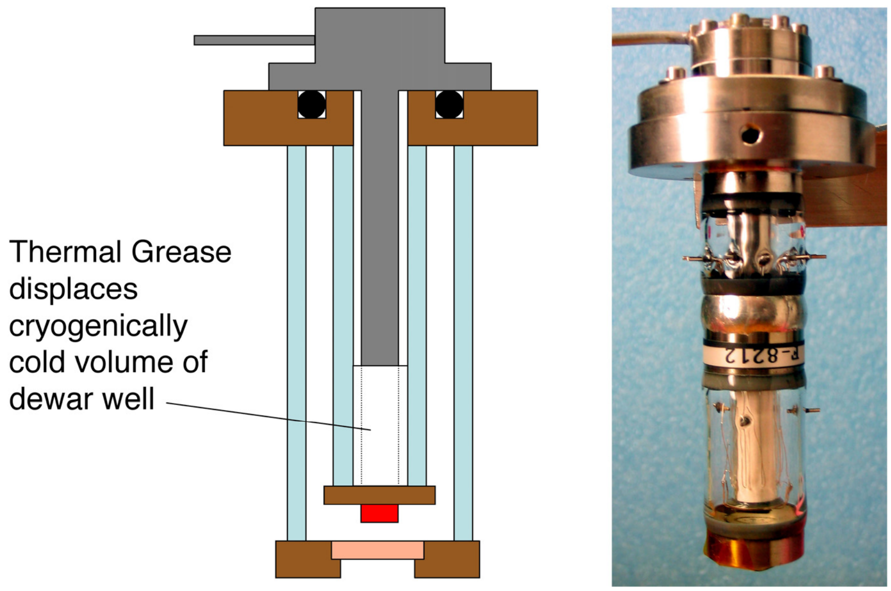

Figure 10. Detector dewar with cold finger installed in the "Packed Grease" configuration. Grease displaces any air in the region of the cold finger that gets cold enough to liquefy air, thus eliminating the potential for formation of damaging boil-off gasses during cold finger warm-up, after the cooler is powered-off.

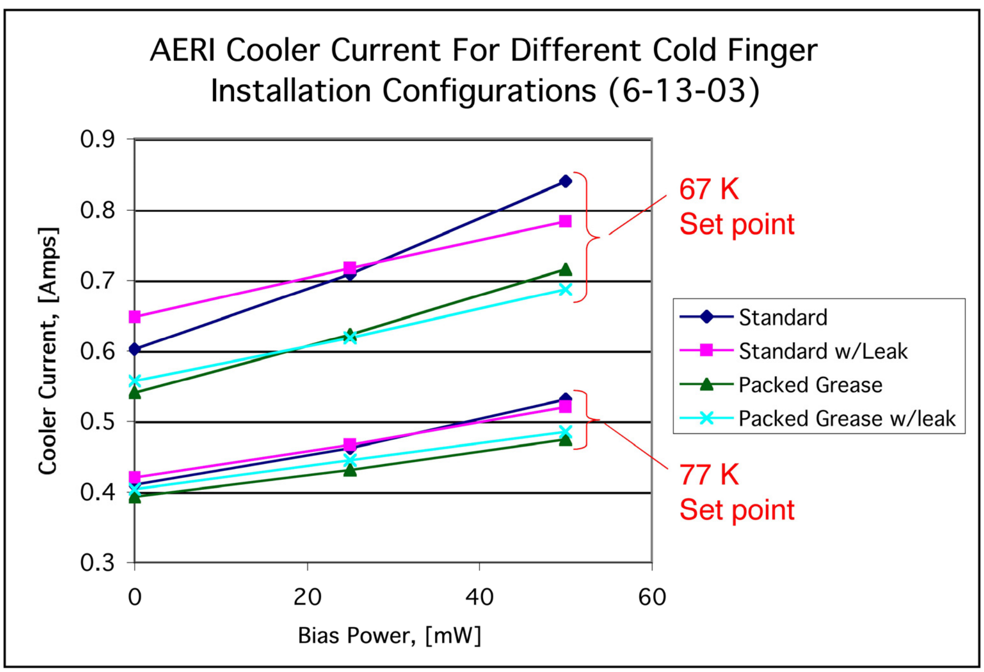

Figure 11. Stirling cooler current draw with different detector bias powers (heat loads), at both 67 K and 77 K set point temperatures. The new "Packed Grease" configuration improves cooler performance (cooler current for a given bias power) over the original or "Standard" configuration. A leak past the dewar O-ring will not significantly change cooler performance.

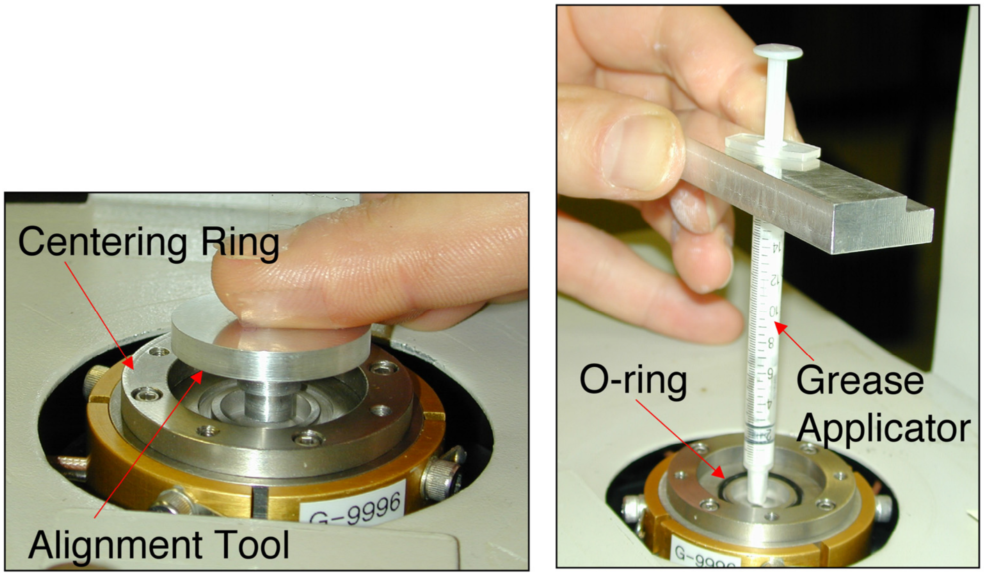

Figure 12. Some of the tools developed for the implementation of the new "Packed Grease" configuration.

Conclusions

A theory that explains the most likely mechanism for the catastrophic AERI dewar failures has been identified and verified by analysis and test. A robust solution that eliminates the root cause of the problem has been identified and all details of the implementation have been developed and tested. No modifications of existing hardware are necessary (a centering ring for the cold finger flange needs to be added and aligned to each dewar, but this ring uses existing threaded holes in the dewar flange). The new cold finger installation procedure can be implemented in the field, using verified procedures. It is expected that the new configuration will completely eliminate future AERI dewar failures.

Acknowledgements

Several people have helped in our quest to define the dewar failure mechanism and identify a robust solution that will prevent future problems. In particular, we wish to thank the following for their time and thoughts: Fred Rothe of InfraRed Associates, the detector manufacturer and integrator (into the dewar); Randy Nelson of Carleton Life Support Systems (formerly Litton), the split cycle Stirling cooler manufacturer; and Bill O'Rourke of O'Rourke Enterprises, the dewar manufacturer.

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