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Abstract

NASA Glenn Research Center has been supporting the development of Stirling energy conversion for use in space. Lockheed Martin has been contracted by the Department of Energy to design and fabricate flight-unit Advanced Stirling Radioisotope Generators, which utilize Sunpower, Inc., free-piston Advanced Stirling Convertors. The engineering unit generator has demonstrated conversion efficiency in excess of 20 percent, offering a significant improvement over existing radioisotope-fueled power systems. NASA Glenn has been supporting the development of this generator by developing the convertors through a technology development contract with Sunpower, and conducting research and experiments in a multitude of areas, such as high-temperature material properties, organics testing, and convertor-level extended operation. Since the generator must undergo launch, several launch simulation tests have also been performed at the convertor level. The standard test sequence for launch vibration exposure has consisted of workmanship and flight acceptance levels. Together, these exposures simulate what a flight convertor will experience. Recently, two supplementary tests were added to the launch vibration simulation activity. First was a vibration durability test of the convertor, intended to quantify the effect of vibration levels up to qualification level in both the lateral and axial directions. Second was qualification-level vibration of several heater heads with small oxide inclusions in the material. The goal of this test was to ascertain the effect of the inclusions on launch survivability to determine if the heater heads were suitable for flight.

Background

NASA Glenn Research Center has been researching Stirling energy conversion technologies for several decades (Schreiber (2006)). Its potential for long life and high conversion efficiency has made it an attractive technology for space applications. The free-piston configuration enables long life with high reliability due to its elimination of wear mechanisms. This configuration is also useful because it permits direct conversion of thermal to electrical power within one assembly. Several configurations were studied, fabricated, and tested. However, dynamic energy conversion has yet to be used in a space power application. In 1999, NASA and the Department of Energy initiated development of a 100-W_e-class radioisotope-fueled generator that would use free-piston Stirling conversion. The goal was to develop a new power system for space science missions that would require less plutonium fuel than the status quo thermoelectric power systems. Lockheed Martin (LM) was later selected as the system integrator. In 2006, the generator was given the title “Advanced Stirling Radioisotope Generator (ASRG),” when the project was redirected to use Sunpower’s Advanced Stirling Convertor (ASC) technology (Wong (2012)). The ASRG consists of two ASCs arranged in the dual-opposed configuration for dynamic balance. Each convertor is supplied one general purpose heat source (GPHS) module, located on the outer ends of the generator. A conductive flange connects the heat rejection zone of the convertor to the generator housing, which acts as a thermal radiator. The two convertors are mechanically coupled in the center via an interconnecting tube.

As with any current radioisotope power system (RPS) design, the thermal energy from the fuel cannot be turned off. This means the convertors must be operating once the generator is fueled and throughout launch. The flight convertors will actually experience more than just a single exposure to launch vibration. There are four instances that a convertor will be exposed to random vibration: convertor workmanship, generator workmanship, generator flight acceptance, and launch. The workmanship vibration profile used for these tests is defined by NASA Standard (STD) 7001A "Payload Vibroacoustic Test Criteria." The flight acceptance profile is defined by Jet Propulsion Laboratory's (JPL's) RPS flight acceptance profile. The workmanship profile amounts to 6.8 g_{rms} while the flight acceptance profile amounts to 8.7 g_{rms}, and represents the same level expected during launch. During convertor workmanship vibration, the NASA–STD–7001A workmanship profile will be applied in three orthogonal axes to the convertor alone. This test is intended to demonstrate that a hermetically sealed convertor in its final form has been assembled properly. Workmanship vibration will also be performed in three orthogonal axes on the generator once the convertors have been installed. Later, the generator will undergo a flight acceptance test, which will be at the same level expected for flight. Finally, the generator will undergo actual launch. Since the first mission to use ASRG has yet to be identified, the launch vehicle and spacecraft are unknown. However, the JPL RPS flight acceptance profile is based on historical launch vehicles and spacecraft that used RPS, and is intended to encompass all possibilities.

The structure of the generator housing creates a particular vibration transfer function between the vibration source and the convertor. Thus, if a workmanship or flight acceptance profile is applied to the generator, the convertor will experience something different. To quantify this, LM performed vibration testing on the ASRG engineering unit (ASC–E) (Meer (2009) and Chan (2008)). Accelerometers were placed at various locations during these tests, including most importantly on the alternator housing of the convertors. The response of this accelerometer was recorded when the generator was exposed to workmanship and flight acceptance profiles in all three axes. These tests provided profiles that could later be used to expose a convertor by itself to the same vibration environment it would experience when installed in the generator. The generator utilized two ASC–Es, but the similarity to the flight design is sufficient that these data were applicable for generating the proper vibration profiles. This was necessary since there is only one generator engineering unit, and it is preoccupied with extended operation. No additional flight generator housing was available for vibration testing. However, there have been several stand-alone convertors, which were fabricated for developmental purposes, available for vibration testing. A fixture was designed to couple a stand-alone convertor to a vibration table. An example of a convertor installed in the fixture is shown in Figure 1. This fixture was designed to have high stiffness to yield high modal frequencies. This was done so that the transfer function between the table motion and the convertor would be as close to unity as possible. With this setup, the measured alternator housing response from the engineering unit testing can be used as the table control spectrum, and the convertor will experience the same vibration as if it were installed in the generator. The convertors can also be exposed to qualification-level vibration, which is defined as 3 dB above flight acceptance level. Increasing by 3 dB has the effect of increasing the average g_{rms} of a particular profile by a factor of 1.414 (square root of 2). More details about the vibration testing methods employed at Glenn can be found in Meer (2009).

Launch Vibration Durability

In 2009, a series of "durability" tests were conceived for the ASC-E2 engineering units that were being developed by Sunpower for Glenn. At this point in time, no non-hermetic ASC had been exposed to the vibration levels mentioned earlier. Thus, an in-depth internal inspection could not be completed to quantify the effect of vibration exposure. Also, a previous launch simulation vibration test on ASC–E #1 indicated the possibility of a limited number of contact events, due to piston motion excursions. To address this, one of the durability tests conceived consisted of launch vibration on a convertor with a removable alternator housing that would permit inspection. The goal of this durability test was to quantify the effect of launch on the convertor's internal components, such as the solid-lubricated surfaces, or the

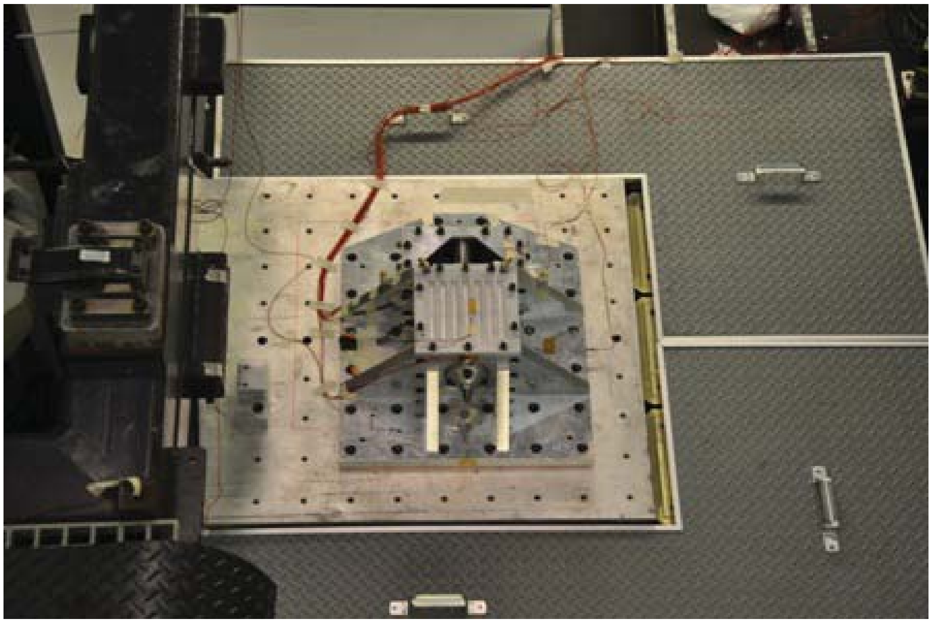

Figure 1.—Advanced Stirling Convertor installed in vibration test fixture on slip table.

fasteners. The “vibration durability” test plan consists of three phases, the first of which has been completed. First, the convertor was exposed to the workmanship-level vibration tests in all three axes. This consisted of a total of six exposures for this phase, as in each axis there is a convertor-alone workmanship profile, and a profile for workmanship when installed in the generator. A disassembly and inspection of the convertor followed this phase. The second phase will consist of exposing the convertor to qualification-level vibration in the lateral directions only. For this case, there is only a generator-level vibration profile, as only the ASRG qualification unit (QU) will be subjected to qualification-level vibration. A disassembly and inspection of the convertor will follow this phase as well. Finally, the convertor will be subjected to qualification-level vibration in the axial direction. Again, this will be a profile to simulate what the convertor sees when installed in the generator. During this test the piston stroke will also be deliberately increased to induce a controlled number of contact events. The goal is to accumulate 30 contact events. This phase of the durability test is intended to address the possibility of a launch that was more violent than expected. The deliberate contact portion of this durability test will provide data that will allow assessment of the effect of such contacts. It should be noted that contact in this manner is with relatively low energy, as the reciprocating piston would be near a zero velocity at its end points of motion.

ASC-E2 #2 was identified and prepared for the vibration durability test. The first phase of this test was conducted in June 2012. Prior to this, the convertor had undergone standard performance testing at Glenn, EMI characterization, and a centrifugal acceleration test (Meer (2012)). The convertor was returned to Sunpower for inspection after the first phase of vibration testing and all results were positive based on phase inspection of the fasteners and solid-lubricant surface. Prior to the test, the fasteners were marked with torque stripes. No fasteners showed signs of motion. The break-loose torque values for all fasteners were within 10 percent or their installation torques. There was no discernable change to the solid-lubricant surfaces. These data suggest the convertor design has sufficient margin to withstand workmanship-level vibration exposure. This is concluded because there was no fastener motion, and any piston/cylinder or displacer/cylinder contact did not generate surface wear nor debris. Phase 2 of the vibration durability test is scheduled to be completed in the spring of 2013.

Heater Head Oxide Vibration Testing

A series of vibration tests of ASC heater heads was initiated in June 2012. During post-production nondestructive evaluation of several heater heads, oxide inclusions were discovered. The effect of these oxide inclusions on the pressure containment capability of the heater heads was unknown, but the initial evaluation suggested they would not compromise the pressure boundary. A series of tests were planned and conducted to characterize the behavior of these inclusions and their suitability for use in ASC flight units. The tests consisted of exposing several of these heater heads to workmanship and qualification-level vibration, followed by inspection. The inspection consisted of a helium leak rate measurement to ascertain hermeticity, and examination of the oxide inclusion to look for signs of crack propagation. After evaluating all the stress states throughout the life and mission of the heater heads, these two vibration exposures were deemed the most severe and thought to be the best opportunity to induce crack propagation. A total of five heater heads were tested: heater heads E08, G02, G03, G05, and F06. These heater heads each contained several inclusions of varying length, depth and position, and thus were a good sampling of nonconforming heads.

Since only a subcomponent of the convertor was going to be tested, mounting fixtures had to be designed to simulate the loads the heater heads would experience when configured as part of the convertor, and to allow the heater heads to be installed into the existing vibration test fixture (described previously). The most desired configuration was to use as many ASC production parts as possible to best represent the connection of the heater head to the source of vibration. Spare ASC parts were assembled to form an “ASC mockup.” This mockup included all of the ASC structural components and the internal alternator, but none of the moving internal parts. This configuration was used on testing two of the units (E08 and G05), and is shown in Figure 2 (left).

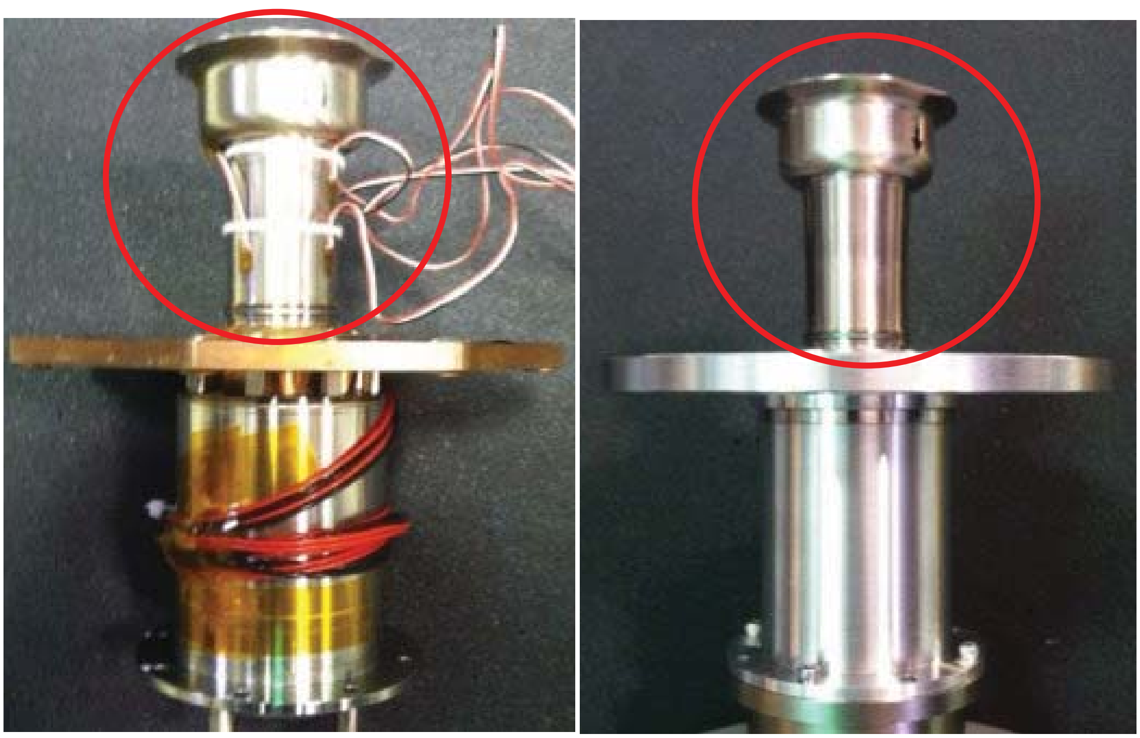

Figure 2.—Advanced Stirling Convertor (ASC) mockup with G05 (left) and ASC dynamic simulator with G02 (right). Heater heads are circled.

Due to the limited number of ASC spare parts, another fixture had to be designed and manufactured for the remaining heater heads. This fixture, deemed the “ASC dynamic simulator,” was designed to attach to the vibe test fixture and simulate the heater head mechanical interface and dynamic loading. This configuration is shown in Figure 2 (right). The ASC dynamic simulator was used for testing heater heads G02, G03, and F06. All of the heads were pressurized to the proper charge, installed in the standard ASC vibration test fixture, and separately tested to qualification-level random vibrations.

For this testing new instrumentation was installed that had not been included in previous Stirling convertor vibration tests. This included an accelerometer mounted on the collector of the heater head and strain gages mounted on the heater head. These were not included in previous testing because they would normally be in proximity to a hot component of the convertor. The heater head tests were conducted at room temperature as the area of highest stress is at the coldest part of the head, and analysis indicated the heater was not necessary. With the heater head at ambient temperature, these instruments could be added. This instrumentation was necessary to determine the amount of stress the inclusions were subjected to during testing, and how well the ASC dynamic simulator matched the ASC mockup. All of the tests included the heater head accelerometer, but due to the timeline for testing, strain gages were not included on the first three tests. Figure 3 shows the location of the heater head accelerometer and strain gages. Accelerometers were placed on the alternator housing and cold-side adapter flange (CSAF) for all of these tests, and these are shown in Figure 4.

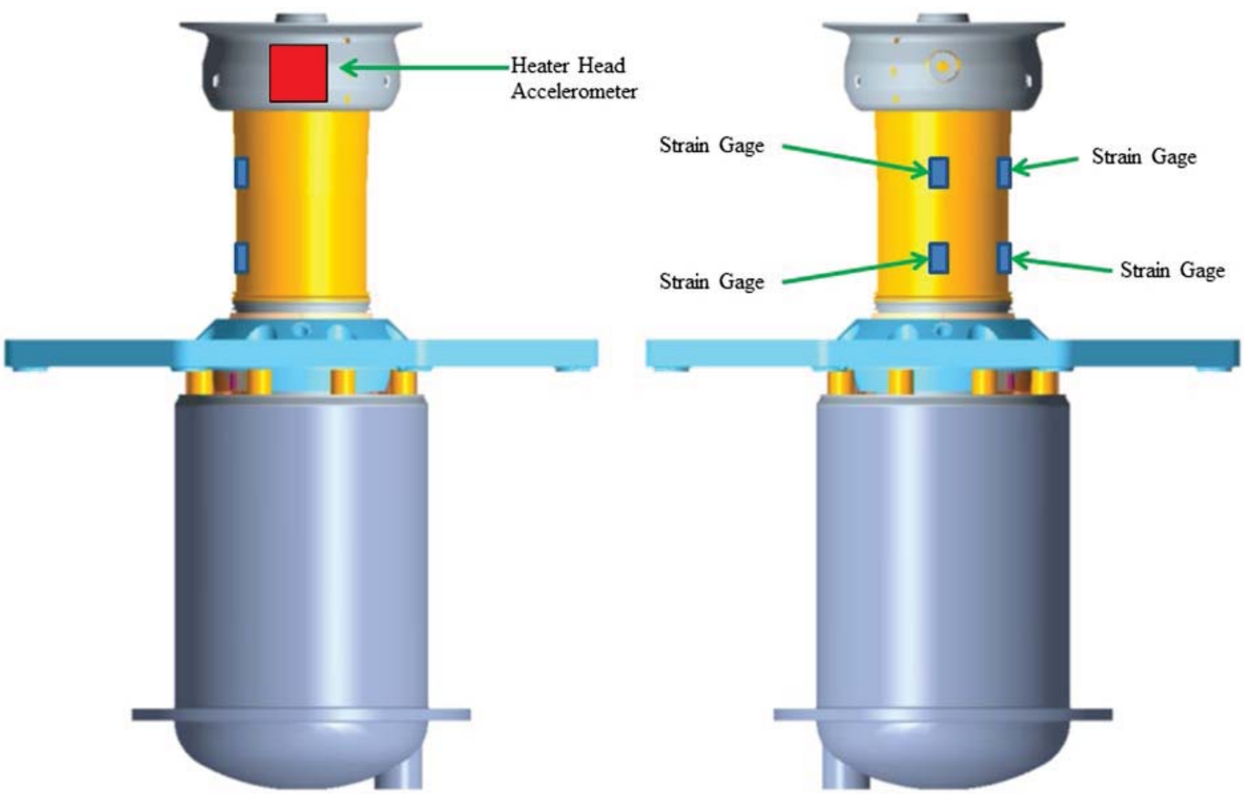

Figure 3.—Location of heater head accelerometer and strain gages. Heater head portion is circled.

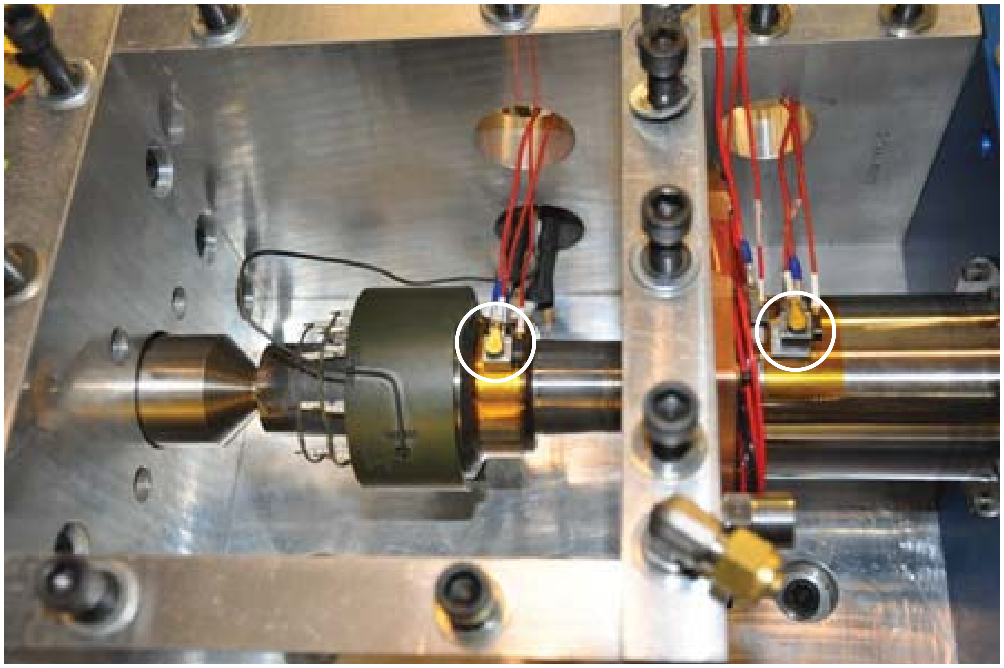

Figure 4.—Photograph of the Advanced Stirling Convertor (ASC) mockup installed in the vibration test fixture and locations of accelerometers.

TABLE I.—SUMMARY OF OXIDE INCLUSION HEATER HEAD TESTING AT QUALIFICATION-LEVEL VIBRATION

	E08	G05			G02	G03	F06	
Test date	6/19	8/22	9/13	9/28	8/23	9/05	9/06	9/25
Axes	All	All	Z-axis (lateral)	Z-axis (lateral)	All	All	All	Z-axis (lateral)
Post-test leak check	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Success was defined by surviving the vibration exposure without crack propagation nor helium leakage. This was tested by performing a pre- and post-vibration exposure hermeticity test with the same equipment and methods used to test flight hermetic convertors. All of the tested heater heads passed the hermeticity check. After the initial round of testing, head G05 was subjected to two more qualification-level vibration exposures, and heater head F06 was subjected to one more exposure. A summary of testing is shown in Table I.

All of the test articles passed the vibration exposures, as none developed leaks, and no crack propagation was induced. No cracks were initiated even in the case of the G05 article, which was exposed to qualification-level vibration three times. It was also concluded from this testing and evaluation that the oxide flaws do not behave as cracks, and thus do not have the potential to propagate like separated base material would. The data from the accelerometers and strain gages were used to improve the finite element models that were previously constructed to predict oxide flaw behavior. These results were then used to guide selection criteria for the remaining flight heater head builds. The flaw size acceptance criteria were revised, thus making several previously suspect heater heads eligible. With this, the project will have an ample supply of heater heads to support the flight unit builds.

There were several lessons learned via examination of data from the new instrumentation used for these tests. The vibration test fixture has features to apply a preload to the heater head, which is intended to replicate the use of a radioisotope heat source. The mechanism uses Belleville washers to effect an adjustable spring load. Upon installation, during which strain gages were present, the strain gage readings were higher than expected. This suggested that the applied force was actually higher than anticipated. The spring stack stiffness was measured using onsite laboratory equipment and found to be 30 percent higher than the manufacturer's published data. This meant that the first four tests to be conducted were with a higher preload value than originally thought. Because of this, future use of these types of spring washers will require measured stiffness data to set the preload, rather than only manufacturer's data.

Another lesson learned was in the area of preload geometric alignment. It is desired to have a uniform axial load applied to the heater head by the preload mechanism. During installation of the preload on the heater heads with strain gages, it was found to be a difficult process to apply preload coaxial with the convertor's axis. The standard installation procedure did not result in uniform loading. A sequence of tightening and loosening the preload bolts while monitoring at the strain gage readings was required to achieve a uniform, coaxial load. If needed for future testing, the loading mechanism of the vibration test fixture should be reexamined. Pre- and post-test sine sweeps showed a shift of the heater head resonant frequency in some cases. This indicated that something was changing within the fixture during vibration. Initially, this was thought to be caused by a broken ceramic washer used in the preload path. This washer was replaced by a metal washer, which reduced the magnitude of the natural frequency shift, but did not eliminate it. A more in-depth investigation needs to be conducted to understand the cause of this shift during testing.

Conclusions

Two unique structural dynamics tests have been conducted at NASA Glenn Research Center in support of the Advanced Stirling Radioisotope Generator (ASRG) towards flight. The first test consisted of exposing a convertor to workmanship-level vibration. The effect of this vibration on the internal components was quantified via inspection, which had not been possible with previous convertors. The results of the inspection demonstrated sufficient margin in the Advanced Stirling Convertor (ASC) design to withstand workmanship-level vibration. During follow-on test phases, this convertor will also undergo qualification-level vibration in the lateral directions and qualification-level vibration with induced piston contacts. These phases of the test will further determine design margin for qualification-level vibration exposure, as well as quantify the effect of a limited number of moving component contacts. ASC heater heads with oxide inclusions were during relevant vibration conditions. The results of these tests suggest that even the largest inclusions did not fail or propagate cracks when exposed to qualification-level vibration. These data suggest that heater heads with this type of flaw can still be used for flight.

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