Results of All Polyimide, Etched Foil Heater Qualification and Failure Limit Testing

Gordon C. Cucullu III[1] and Michael Ochoa[2]
Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California, 91109

and

Joshua Ruby[3]
University of California San Diego (UCSD), 9500 Gilman Dr, La Jolla, California, 92093

Standard FEP polyimide (SFP) or Kapton film heaters—which have a long history of space flight—are output-power limited by the melting point of Teflon which is used as an adhesive and insulator between the encasing layers of Kapton. The limit is expressed as a power density or through maximum operating temperature limits. All-polyimide (AP) heaters (also known as adhesive-less heaters) do not contain FEP Teflon between the layers of Kapton so the heaters are unconstrained by the melting point of Teflon. Thus, AP heaters have a higher maximum power density and operating temperature. AP heaters have not been qualified or flown on JPL missions but could be useful in applications that require a higher power density (Watt density) than the SFP heaters can support. The purpose of this paper is to document the qualification and property testing of the AP heaters for flight purposes.

JPL tested several varieties of all-polyimide heaters to determine their functional equivalence to the standard heater which has substantial flight heritage and to determine their maximum limits. Tests included standard in-air burn-in tests, maximum power testing, lead pull strength, process qualification verification (PQV), long duration thermal cycling, and electro-magnetic compatibility shielding properties for copper cladded shielded heaters. The results show that the all-polyimide heater appears to be functionally equivalent to the standard heater and has a higher Watt density and maximum operating temperature limit. The tests, test articles, failure analysis of the test articles, and results are described herein. These test results indicate that the all-polyimide heater is ready for flight applications.

Nomenclature

AFT	=	Allowable Flight Temperature
AP	=	All Polyimide Heaters
ATLO	=	Assembly, Test, and Launch Operations
COO	=	Chief Operating Officer
Db	=	Decibels
DbuV	=	Decibels relative to one microVolt
DPA	=	Destructive Part Analysis
DS	=	Descent Stage

[1] Technical Group Supervisor, Thermal Fluid Systems and Mission Operations Group 353K, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, Ca, 91109-8099, Mail Stop 125-224.
[2] Technical Training Specialist, Training, Tools, Technology And Tracking Group 5126, Jet Propulsion Laboratory, 4800 Oak Grove Drive, M/S 125-224, Pasadena, Ca, 91109-8099.
[3] Undergraduate and 2015 JPL Summer Student, Thermal Fluid Systems and Mission Operations Group 353K, Jet Propulsion Laboratory, 4800 Oak Grove Drive, M/S 125-224, Pasadena, Ca, 91109-8099, Mail Stop 83-204.

EMI = Electro-Magnetic Interference
FEP = Fluorinated Ethylene Propylene
GHz = Gigahertz
HF = Hydrogen Fluoride
JPL = Jet Propulsion Laboratory
kHz = kilohertz
lb_f = Pounds force
LTST = Local True Solar Time
max = maximum
MER = Mars Exploration Rovers
Mil Std = Military Standard
min = minimum
mm = millimeter(s)
M2020 = Mars 2020 Rover
MSL = Mars Science Laboratory
OCIO = Office of the Chief Information Officer
PDM = Propellant Distribution Module
PFR = Problem Failure Report
PRT = Platinum Resistance Thermometer
PQV = Package Qualification and Verification
RBAA = Reflector Boom Assembly Actuator
S/C = Spacecraft
SFP = Standard FEP/Polyimide Heaters
S/N = Serial Number
TC = Thermocouple
XC = eXtra Carbon

I. Introduction

STANDARD Kapton film heaters consist of outer polyimide layers (Kapton) and an inner layer of fluorinated ethylene propylene (FEP). These standard FEP/polyimide (SFP) heaters have been a mainstay of thermal control for over four decades. Also known as etched foil or wire-wound Kapton film heaters, SFP heaters are lightweight, effectively spread heat over custom-defined surfaces, low out-gassing, vacuum compatible, and reliable. They are limited in power density and maximum operating temperature due to the FEP.

All-polyimide (AP) heaters[§] do not use the Teflon FEP inner layer for their construction and therefore can go to higher temperatures and have faster response times. These devices had not previously been qualified for flight applications at the Jet Propulsion Laboratory (JPL).[**] This paper details the testing done in 2015 by JPL to qualify these heaters for flight. Note that AP refers to the encapsulation of the heater circuit element. The element can be made from a helical wire (also known as wire-wound) or etched foil. The wire wound heaters can be made of Nichrome, Inconel 600, Alloy 715 for instance. The etched foil elements are made from either Inconel 600 and Alloy 715. The heater element in the test articles is the same type used in the SFP heaters.

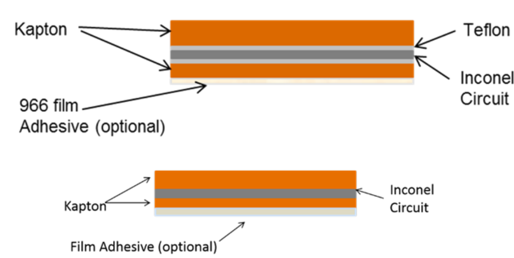

Figure 1 Illustration of the cross-section of an SFP heater (top) and an AP heater (bottom).

II. Background

Standard FEP/polyimide (SFP) heaters are formed by melting Teflon FEP (at 260 °C)[1] and an Inconel 600 and alloy 715 etched foil (or wire wound)[††] circuit as a heater element, sandwiched between layers of Kapton within a vacuum bag. At temperature

[§] AP heaters are also known as adhesive-less heaters (since there is no Teflon FEP binder used) or all-Kapton heaters.

[**] Fralock indicates that another aerospace company had used these in a flight application, but was not able to share the practice due to proprietary restrictions.

[††] Wire wound typical is Nichrome, Inconel 600, Alloy 715 (70% Copper, 30% Nickel).

and with pressure applied, the FEP Teflon flows between the circuit and binds the Kapton layers together (See Figure 1).

Teflon is both an electrical and thermal insulator (0.2 W/mK)[2]. This latter property promotes large temperature gradients between the heater element and the substrate. The FEP melting point limits the maximum heater service temperature to 200°C for the heater since the element is capable of reaching the melting point of Teflon and forming a 60°C gradient from the element to the substrate[3] (Sunada, 2001). If the Teflon melts at the internal heater element, the heater may bubble, delaminate, short, and fail. This restriction is referred to as a Watt density limitation in terms of heater power per unit area. The maximum Watt density for SFP heaters is between 0.54 W/cm^2 [3.5 - 5.0 W/in^2] but is also a function of operation temperature and substrate (see **Figure 2**).

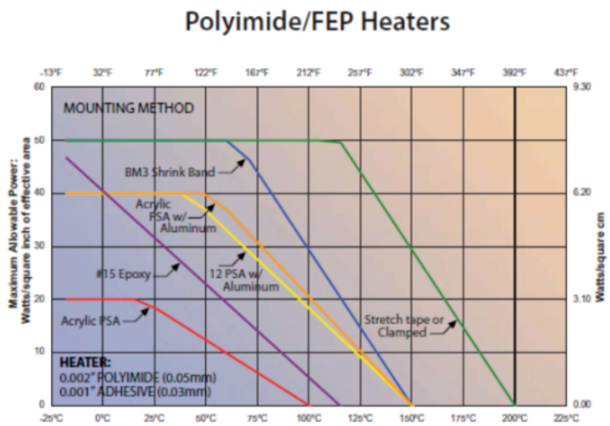

Figure 2 Maximum Watt Density Based on Mounting Method per Minco Film Heater Design Handbook. [3]

The AP heater has at least four advantages to the SFP heater: (1) the Watt density is significantly higher; (2) a faster response time; (3) improved flexibility without the restoration force of the Teflon—no hot forming is necessary for curved surfaces[‡‡]; and (4) the ability to bond directly to an outer foil layer for shielding or heat spreading without another layer of Teflon[§§].

However, heretofore there have been no significant publications on the use of this heater type for space applications, heritage applications, or qualification results.[***] This paper captures qualification testing performed to demonstrate qualification equivalence to the heritage film heater and demonstrate in what ways it exceeds the capabilities of the heritage film heater.

III. Methodology

The approach in our testing was to first show AP heater designs could pass the same qualification tests that are used to qualify SFP heaters for flight. The second objective was to determine the maximum capabilities of the AP heaters (test to failure and endurance testing). Finally, electro-magnetic compatibility (EMC) for a fully copper cladded AP heater with embedded shield to ground was tested.

IV. Test Articles Description

Three SFP heaters used on the Mars Science Laboratory (MSL) mission were used as a baseline for comparison. AP heaters were designed and made from the size, shape and resistance as the three SFP heaters. In destructive tests, the SFP heaters were tested in the same test configuration and conditions. The heaters employed and the part reference numbers are included below:

- 1410-1 MSL Mobility Actuator Heater

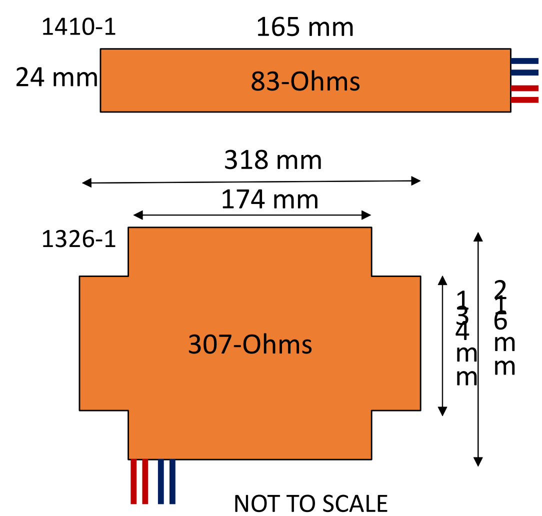

Figure 3 Dimensions and Resistances of the Test Articles

‡‡ Hot forming is used to take the flat heater surface and form it to fit around a cylinder. The Teflon tends to want to restore the shape over time. For helical hot formed heaters, this process makes installation of a film adhesive difficult.

§§ Metalized surfaces are used for either shielding or heat spreading. SFP heater can have layers added using and additional layer of FEP Teflon.

*** Concurrently, Goddard Space Flight Center GSFC has released the following specification for qualification of AP heaters, S-311-P-841.

- 1326-2 MSL Descent Stage (DS) Thermal Battery Heater

Figure 3 shows the sizes of each of the heater designs for the test articles. The heaters were chosen for the following reasons. The Mobility heater (1410-1) was hot-formed into a cylinder form, and the FEP had a tendency to want to restore to a flat form. A dual layer version of the 1410-1 heater was also produced to test the capability to make multi-layer heaters. The DS Thermal Battery heater was a larger size and saw temperatures above the FEP melting point during landing.

In addition to the **AP** test articles, the following variations to the AP heaters were included in as test articles the testing:

AP-XC is a heater with extra carbon (XC) making it semi-conductive (static dissipative) to reduce its capacity to build up electrostatic charge;

AP-HS is an all polyimide heater with a single side of aluminum or copper backing for heat spreading and extra carbon in the polyimide to create a semi-conductive, static dissipative film;

AP-CS: is a copper shielded heater; an AP heater with extra carbon, with an exterior completely clad in copper. It includes dedicated ground trace around the outer planar edge surrounding the heater for grounding.

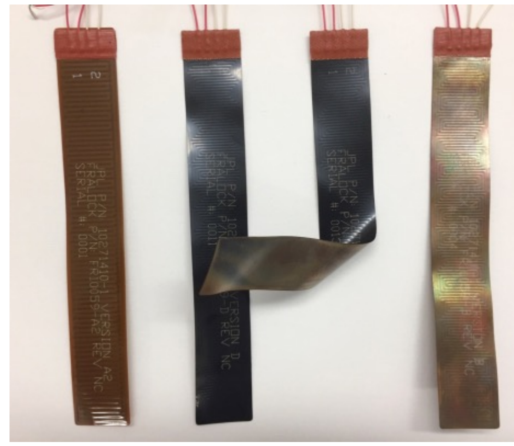

Figure 4 Variations of AP Heaters. (A) AP heater; (B) AP-XC heater; (C) AP-HS heater; (D) AP-CS heater.

Finally, three types of adhesives bonding methods were tested with all the test articles and put through a series of thermal cycling tests to validate their performance in a flight like condition. The film adhesives used were Nusil's A-3012 and 3M's 966 film adhesives. These were delivered installed. Additional a Stycast 2850 24/LV wet adhesive was used as well (more detailst to follow). Figure 4 shows each variation of AP heater. Table 1 summarizes the variations of heater test articles, quantities and tests performed.

Table 1 Table of Test Article and Test Summary

	AP, All Polyimide (Kapton)			**AP-HS Cu Heat Spreading XC**		**AP-HS Al Heat Spreading XC**		**AP-CS Copper Shielded**		**Adhesive Test Articles**	
	1410-1	1326-**2**	1410-1 A2	1410-1	1326-**2**	1410-1	1326-2	1410-1	1326-**2**	1410-1	1410-1
	Single Layer	Single Layer	Dual Layer	Single Layer	Large Area	Single Layer	Single Layer	Single Layer	Single Layer	966	A-3012
Qualification + spares	11	3	5	9	1	9	1	10	3	5	5
PQV testing temp cycling	2	1	1	2	1	2	1	2	1	5	5
EMI/EMC	--	--	--	--	--	--	--	1	1	--	--
In-air power to failure	2	1	2	1	--	1	--	1	--	--	--
Lead pull to failure	2	--	--	--	--	--	--	--	--	--	--
Long Duration Test	1							2		--	--
Cold Start Test	1	--	--	1	--	1	--	1	--	--	--

Unlike the SFP heaters in which the heater patch to welded wires are encased in the FEP and covered by the Kapton, AP heaters have to weld the wires after the heater patch has been made. To connect the leads to the heater, a 50-micron Nickel transition tab is gap welded to the egress wire so that half of the tab is welded to the egress wire. The remaining half of the tab is gap welded to the exposed pad on the film heater 180-degrees from the egress direction. Finally the wire and attached tab are folded over and again welded to the pad (so that the wire is sandwiched between the tab and the wire is in the correct egress direction), for a total of three welds. The pad and welded wire are then captured in 0.64 [25 mil] layer of Arlon (silicone). See Figure 9 the in the wire testing section.

V. Qualification Testing

Qualification tests were performed to verify that the AP heaters at a minimum could pass the same qualification tests required for SFP heaters. Qualification tests were defined per JPL's Acceptance Test Procedure for Kapton Film Heaters and included an in-air burn-in test and a lead pull test.

A. Burn-in Test Description and Results

All of the AP heaters first go through a 24-hour burn-in per JPL D-37197 for workmanship. The test apparatus consisted of hanging heaters by their lead wires, clothesline style, in room temperature air and run at maximum rated voltage for the heater via a 40 Volt, 38 Amp, 1520 Watt Agilent power supply(see the schematic and test set-up in **Figure 5**). A resistance measurement was taken before and after the burn-in, Heaters with a resistance change of greater than ±1% are typically rejected for flight. Note that both circuits on the film heater are energized during this test, and therefore qualified.

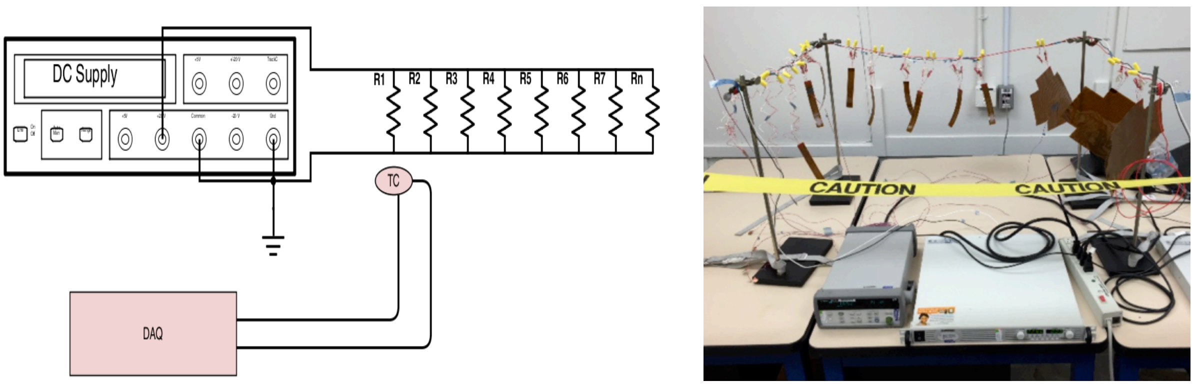

Figure 5 (A) Test set-up schematic for heater burn-in. (B) Image of the actual burn-in test set-up.

Results. The AP heaters had a pass rate of 98.1% for the burn-in. Only one of the 52 test articles failed to remain within ± 1% maximum resistance change allowed from the pre-test DC resistance values, and this by a very small amount. The rejected heater was out of specification on the final measurement by 1.04%. The initial resistance was 89.9 Ohms, and the final resistance was 89.0 Ohms. [†††]

B. Lead-pull Test Description and Results

To test the lead wire strength, a crimp pull tester, Alphatron MPT-250B was configured to test the welded wire strength of the test articles and MIL-STD-202, Method 211, test condition-A that prescribes a 3-pound [1.3 Kg] load for 10 seconds.[‡‡‡] **Figure 6** shows the lead-pull test set-up.

Results. The AP heaters passed both of the lead pull strength tests. A single wire on two different 1410-1 heaters was successfully pulled to 3.1 lb_f. Destructive part analysis (DPA) was performed following the lead maximum strength pull tests. That test and results are described in section VI, paragraph B.

Figure 6 AP Heater Lead Pull Strength Test using an Alphatron MPT-250B

[†††] The authors do not have statistics on the pass rate of SFP heaters.

[‡‡‡] Also per the internal heater qualification specification, JPL D-37197.

VI. Maximum Capability Testing

Following the qualification tests on 100% of the test articles, the maximum capabilities of the test articles were tested to understand where the AP heater might surpass the SFP heater. The tests performed were:

A. maximum in-air power test
B. maximum lead strength test
C. long duration powered-on in-air test
D. cold start
E. thermal cycling (PQV) tests
F. shielding capability—performed only for the AP-CS (shielded) heater

The purpose, set-up, and the subsequent results are discussed in each of the following paragraphs.

A. Maximum In-air Power Test Set-up and Results

The maximum power test used a similar set-up and apparatus as the screening burn-in setup employing a 600 V, 1.3 A, 780 W Agilent power supply. It was necessary however to do this test in a fume hood as a precaution against the release of HF gas as the Teflon reached its melting temperature. When possible, the max power tests were conducted side-by-side using SFP and AP heaters of like resistance, circuit design, and aspect ratio. In order to achieve the predicted power densities required to fail the test articles, and due to limitations of the power supplies available, it was not always possible to run both heaters simultaneously. Also, only one circuit in the heater was energized, as is visible in Figure 8.

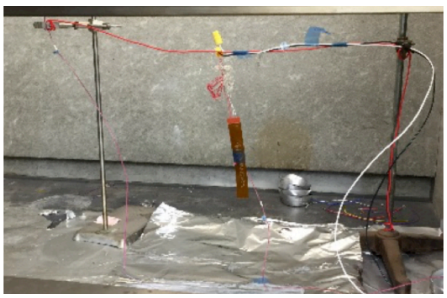

Figure 7 AP Heater Prior to Max Power Test in Fume Hood.

The Watt density was increased in 0.16 W/cm^2 [1 Watt/in^2] increments until complete failure. Complete failure was deemed to have occurred once the device burned, disintegrated, fully carbonized, and/or electrically opened.

Temperature data was again collected using type-E thermocouples held in place with Flashbreaker or Kapton tape and an Agilent 34972A data acquisition system. Since the temperature exceeded the thermocouple attachment max temperature, an off-the-shelf IR camera was employed. Consumer, off-the-shelf, Seek mobile iPhone and Android infrared cameras were employed for temperature measurements and to visualize the heat distribution over the surfaces of the heater test articles. Additionally, a non-contact IR "gun" thermometer was also used throughout the tests to provide backup temperature data above 330°C, since that is the maximum temperature capability of the Seek IR cameras. These were the primary temperature data collection vehicles as the thermocouples held in place by Kapton tape began carbonizing at ~400°C, lose contact with the test article, and completely disconnect and therefore were less reliable at high temperatures.[1]

Results. The all-polyimide heaters performed three to four times the power density of SFP heaters in all of the tests. One AP heaters achieved a maximum Watt density of 3.9 W/cm^2 [25 Watt/in^2] in a single case before it failed. All of the AP heaters exceeded 2.95 W/cm^2 [19 Watt/in^2] before failing. The side-by-side maximum power tests between the 1410-1 AP and SFP heaters demonstrated both a watt density improvement for the AP heaters as well achieved higher peak temperatures over the SFP heaters (see Figure 10).

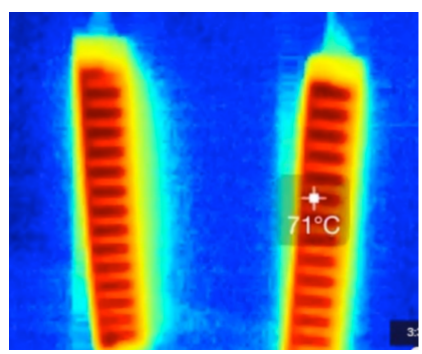

Figure 8 Seek Camera Image of the Side-by-side Max Power Test of a SFP and AP heaters.

Note that the maximum Watt density is dependent upon temperature, so that these tests show that the AP heater in the same conditions, exceeds the capability of the SFP heater. Minco and JPL design principles allow higher maximum watt densities for different configurations (up to 3 W/cm^2 [19 W/in^2] as a limitation for heritage film heaters.)[5] such as heaters (A) mounted in good thermal contact with a substrate, (B) mounting to a substrate with excellent thermal conductivity properties, and (C) operating at a very cold temperature (see again Figure 2).[1] It is reasonable to expect that the AP heaters would surpass the SFP heaters when tested in the same conditions whether in air or mounted.

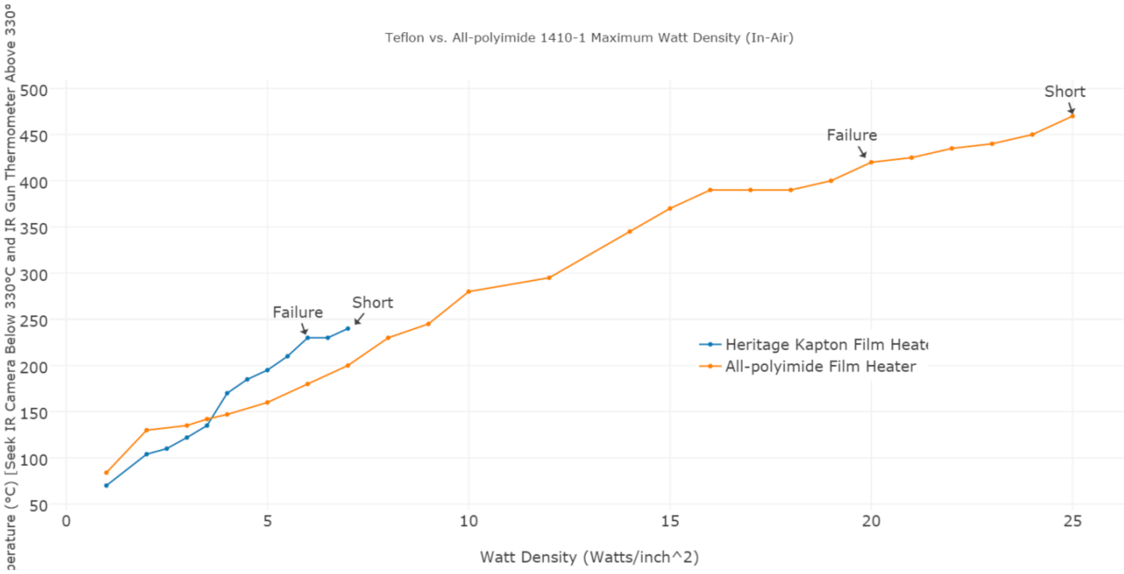

Figure 10 Temperature versus Watt density for in side-by-side testing for the SFP (blue line, first to fail) and the AP heater (orange line, higher temperature) before failure for the 1410-1 heater design.

B. Lead Pull max-strength Test Description and Results

The same wire pull test set-up described in the qualification testing was used to determine the maximum strength of the welded wire to heater element connection using the crimp pull tester, Alphatron MPT-250B.

Results. The AP heater leads survived up to 9.6-pounds, just over three times the JPL specification for lead-wire strength of 3-pounds. Two AP heaters were tested. One wire was pulled in each case. The failed heater article was inspected in the JPL Reliability and Failure Analysis Laboratory with an optical microscope, a Fein Focus X-ray, and a scanning electron microscope. Post failure analysis indicated that the lead wire and not the weld were the source of the failure. Preliminary photos revealed a ductile fracture. Since the wire type used for this application is the same as that used for SFP, this result indicates that the wire connection process is sufficiently strong for flight applications. See Figure 9 and Figure 11.

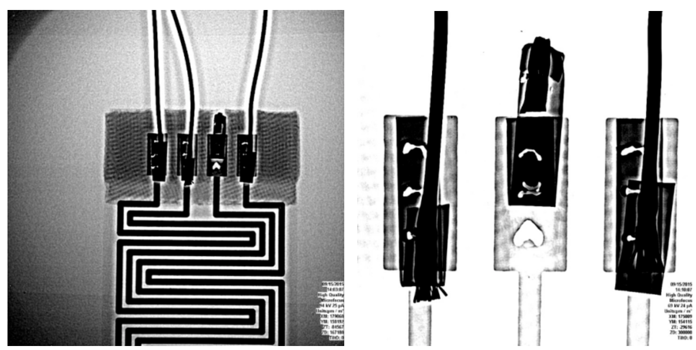

Figure 9 (a) X-Ray image of the lead wire pulled to failure, and (b) close up of the broken lead wire near the weld.

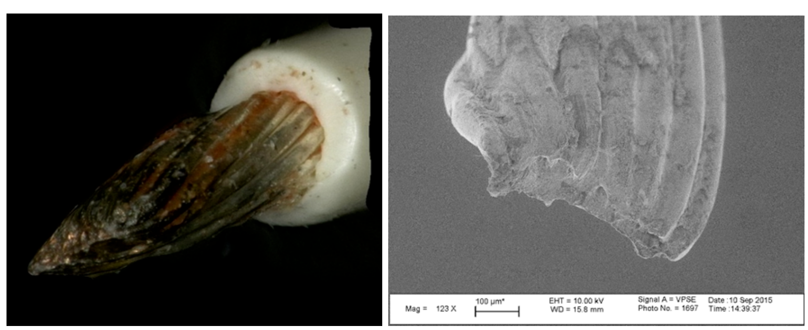

Figure 11 (a)Optical microscope (40x) image of the failed lead wire. (b) Scanning electron microscope image (123x) of the failed lead wire.

C. Long Duration Powered-On In-Air Tests and Results

The purpose of the long duration test was to observe effects on the heaters operating in-air at high watt density—at least twice the maximum in-air Watt density of the SFP heaters of 0.54 W/cm^2 (3.5 W/in^2). Whereas the max power tests determined the failure points for the heaters, these tests look for a Watt density below that failure point at which the heaters can be operated indefinitely. Due to limitations in funding and available test articles these tests used finite durations with the expectation that the most gross ill effects would manifest in the first 8-12 hours of operation. Thus test was conducted to a limited set of the available heaters. As with the other tests, the test articles had already passed the qualification tests.

The first test subjected an AP-CS test article to 1.16 W/cm^2 (7.5 W/in^2)for 24-hours. In the first test, the test article did not change in resistance and there was only a slight exterior discoloration of the copper surface.

The second test subjected another AP-CS test article to 1.4 W/cm^2 (9.0 W/in^2) for 24-hours. In the second test, the test article discolored at high temperature due to the copper oxidizing at elevated temperatures.

As in the qualification burn-in tests, both circuits of each test article were connected in series and energized (and unlike the maximum power tests). The resistance for the four circuits in each of the two heaters was measured before and after the test, and the change over time for the four circuits was much less than 1% (0.0%, 0.1%, 0.2% and 0.3%).

Using the copper cladded heater was perhaps a mistake for this test due to the copper oxidizing. However, this is a limit that would need to be observered for copper shielded heaters when turned on in ambient conditions for ground testing, so for that reason the authors were glad to have discovered this limitation.

D. Cold Start Test and Results

The purpose of the cold-start test was to verify the capability of the heaters to repeatedly start at low temperatures. The test articles were placed in a freezer at -80 °C ±5 °C and allowed 15-minutes to reach temperature, then powered on to achieve a Watt density of 0.54 W/cm^2 [3.5 W/in^2] for 15-minutes, then activated at 0.78 W/cm^2 [5.0 W/in^2] for 15-minutes. This process was repeated 10 times and was completed for each of the test articles. The AP, AP-XC, AP-CS heater types were included in the test.

For all heater test-articles, the resistance of both A and B circuits were measured then powered on individually at 0.54 W/cm^2 [3.5 W/in^2]. Thermocouples were affixed to the freezer wall, on the test-article and in the ambient air measuring room temperature. The power supply was set at 0.332 Amps and 61.9 Volts to ensure all aspects of the test would function. Once a heater reached the ambient steady-state temperature, it was then placed back into the freezer at -80°C in the powered-off state, and allowed to reach equilibrium. Each heater was then again activated to 0.54 W/cm2 [3.5 W/in2], then ramped up to .77 W/cm^2 [5 W/in^2] with 0.414 Amps and 71.4 Volts.

All heaters functioned as desired before and after the cold start test was performed. No heater test-article showed signs of external damage to the surface and the circuits indicated no change in resistance greater than ± 1%. This test demonstrated the capability of the heater to repeatedly function at cold temperatures.

E. Thermal Cycling Test (Package Qualification and Verification) and Results

The purpose of JPL's packaging qualification and verification (PQV) tests are to verify a packaged part's robustness to thermal cycling induced failures.[6] Unlike the cold start tests, the test articles in this test were not powered on or wired and measured during the test.

This test demonstrates the robustness of the heater construction and bonding implementation for flight missions, particularly for landed Mars missions. The test mimics the diurnal seasonal cycles for Martian summer and winter. One Martian year is represented by 200 winter thermal cycles and 470 summer thermal cycles for a total of 670 cycles. Winter cycles are represented by temperature extremes between -130°C to +15°C, and summer cycles -105°C to +40°C ,

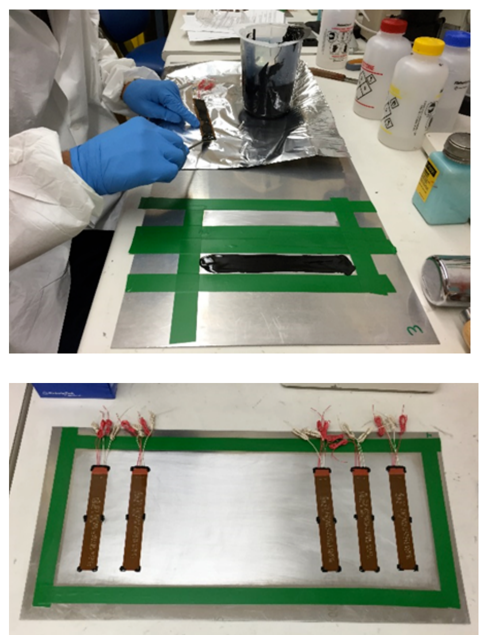

Figure 12 Bonding of the PQV Test Articles using (A) Stycast 2850 /24 LV with 3-5 mil glass beads and (B) 3M's 966 and Nusil's A-3012 (staked with Stycast 2850 /24 LV).

each with a total ΔT of 145°C.

Note, because the AP test articles were riding piggy-back on a Mars 2020 mission test, the actual test was modified for the purposes of that particular subsystem. That subsystem had already performed many cycles to qualify it for MSL, nad was now performing an additional test from MSL. The test ended up completing 1033 cycles consisting of an additional 261 summer cycles and 102 winter cycles, for a total of 1033 cycles (470+261 =731 summer cycles and 200+102= 302 winter cycles).

Test Articles. Fourteen 1410-1 heaters (tweleve AP and two AP-XC) were bonded to aluminum substrates. Two test articles (one AP and one AP-XC) were bonded with Stycast 2850 24/LV. Two test articles (one AP and one AP-XC) were bonded using Hysol 9309.3. Then five heaters were bonded with A-3012, and five with 3M's 966 film adhesives. See Table 2.

Results. The completed test consisted of 1033 cycles, 731 cycles simulating Martian summer seasons (-105^{o}C to +40^{o}C) and 301 cycles simulating Martian winter (-130^{o}C to +15^{o}C).

Of the 28 heater circuits (14 test articles with two circuits each), 82% of the heater's resistances were within

Table 2 Thermal Cycling Test Resistance Measurement Results

Resitance Measurements: 1410-1 Test Articles				Initial 4/19/2016	400 Summer Cycles 6/2/2016		After 670 Cycles 6/30/2016		After 1033 Cycles 8/14/2016	
Bonding Ad-hesive	Heater Version	S/N	Circuit	Before (Ohms)	After (Ohms)	% Change	After (Ohms)	% Change	After (Ohms)	% Change
Stycast 2850	D	0006	Red	82.3	83	-0.9%	82.4	-0.1%	82.4	-0.12%
			White	83.1	83.8	-0.8%	83.2	-0.1%	83.2	-0.12%
Stycast 2850	A	0012	Red	87.3	88	-0.8%	87.4	-0.1%	87.5	-0.23%
			White	88.4	89.1	-0.8%	88.5	-0.1%	88.5	-0.11%
Hysol 9309.3	D	0005	Red	82.8	83.4	-0.7%	82.7	0.1%	82.8	0.00%
			White	83.4	84.3	-1.1%	83.4	0.0%	83.5	-0.12%
Hysol 9309.3	A	0013	Red	88.6	89.3	-0.8%	88.7	-0.1%	88.7	-0.11%
			White	89.6	90.2	-0.7%	89.6	0.0%	89.7	-0.11%
3M 966	A-966	0001	Red	89.9	89.7	0.2%	89.1	0.9%	89.1	0.89%
			White	90.2	90	0.2%	89.5	0.8%	89.5	0.78%
3M 966	A-966	0002	Red	91.0	91.2	-0.2%	90	1.1%	90	1.10%
			White	90.9	91.9	-1.1%	90.8	0.1%	90.8	0.11%
3M 966	A-966	0003	Red	90.5	91	-0.6%	86.9	4.0%	89.9	0.66%
			White	92.0	91.8	0.2%	90.8	1.3%	90.8	1.30%
3M 966	A-966	0004	Red	90.9	91.2	-0.3%	90.5	0.4%	90.5	0.44%
			White	91.5	92.3	-0.9%	91.3	0.2%	91.3	0.22%
3M 966	A-966	0005	Red	91.0	92.5	-1.6%	92.5	-1.6%	90.7	0.33%
			White	92.0	92.6	-0.7%	91.7	0.3%	91.7	0.33%
Nusil 3012	A-3012	0001	Red	85.9	85.3	0.7%	85.3	0.7%	84.7	1.40%
			White	87.3	86.1	1.4%	86.1	1.4%	85.5	2.06%
Nusil 3012	A-3012	0002	Red	85.8	86.3	-0.6%	86.3	-0.6%	85.7	0.12%
			White	86.4	86.9	-0.6%	86.9	-0.6%	86.4	0.00%
Nusil 3012	A-3012	0003	Red	85.6	86.1	-0.6%	86.1	-0.6%	85.5	0.12%
			White	87.2	86.8	0.5%	86.8	0.5%	86.3	1.03%
Nusil 3012	A-3012	0004	Red	86.1	87.2	-1.3%	87.2	-1.3%	85.8	0.35%
			White	86.6	86.4	0.2%	86.4	0.2%	86.7	-0.12%

1.0% of their initial resistance value (only 5 circuits fell outside of this range, with the worst being 2.1% out of range).[§§§] There was no visible change in the heater or the heater bonds.

F. Radiated Emissions Characterization Test Set-up and Results[7]

The purpose of the radiated emissions characterization was to test the effectiveness of the AP-CS heater over the 14 kHZ to 2 GHz frequency range. The tests were performaed in the JPL's EMC lab. The AP-CS heater was compared to an unshielded SFP heater (1326-1) of the same resistance, size and shape.

The test articles were taped to a block wrapped in aluminum foil. The block was bonded to a copper table for grounding. See Figure 13. Aluminum foil wrapping was used to eliminate any possible emission leaks via cables and connectors. The test articles were contained within an EMC shield room and all cables passed through bulkheads that further isolated the test article from stray noise.

For each test, the signal generator was connected to the leads of the heater (AP or SFP), and step-wise, 32-discreet frequencies radiated via the test articles. An antenna 1-meter from the test article connected to a monitoring receiver was used to detect the vertical polarization.

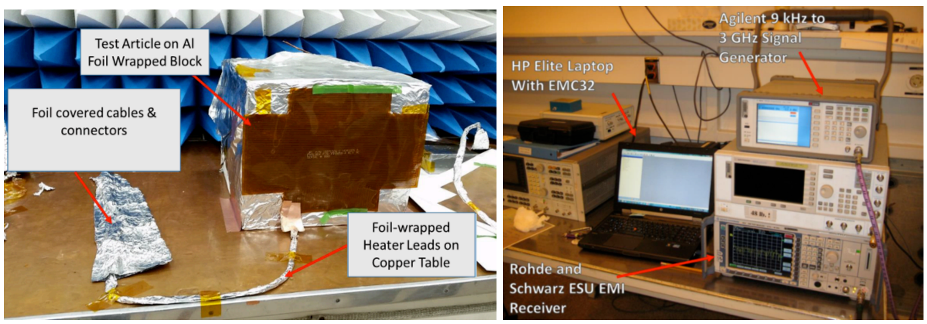

Figure 13 (a) Radiated Emissions Characterization Test Article Configuration . (b) Signal Generators.[7]

Results. The shielded polyimide heater produced less radiated emissions compared to the unshielded heater from 14 kHz to 500 MHz, however, at 1 GHz, the shielded polyimide heater performance degrades and radiates a higher signal. The heaters do not operate in the 1 GHz range, so the degradation is a low concern. The AP-CS heater does offer an effective method of shielding heaters.[7]

One alternate shielding method is to cover the heater in a shielding tape once the heater is installed. This generally occurs during subsystem integration or ATLO when access is more difficult and the project schedule is difficult to manage. There is a distinct advantage to having the AP-CS heater to remove this extra step in the process.[****]

[§§§] Note the ±1% resistance change is one used for qualification purposes and is not a standard for judging the outcome of a long duration thermal cycling test. This resistance change is an acceptable range, not indicating some potential failure in the device. The design tolerance of the heater circuits is ±5% for flight applications. At the end of mission to have that resistance range change by 2.1% is not an exceptional result.

[****] Other manufacturers of SFP heaters offer shielding within the Kapton matrix, such as a phosphorous bronze mesh, but JPL has not qualified this product.

Table 3 Radiated emissions testing results of an AP-CS heater compared to an unshielded test article.[7]

Test Frequency	Ambient (dBuV/m)	Unshielded Heater (dBuV/m)	AP-CS Shielded Heater (dBuV/m)	Delta (Unshielded-Shielded) (dB)
14 kHz	-9.8	49.624	0	49.624
20 kHz	-12.3	49.808	0	49.808
50 kHz	-14	51.235	12.46	38.775
100 kHz	-7.2	51.428	18.086	33.342
200 kHz	-11.6	51.707	22.893	28.814
500 kHz	-10.8	51.723	24.033	27.69
1 MHz	-7.8	52.306	24.911	27.395
2 MHz	-8.9	52.88	26.45	26.43
5 MHz	-11.3	63.806	39.42	24.386
10 MHz	-8.9	49.794	30.633	19.161
20 MHz	-8.2	59.713	38.343	21.37
50 MHz	-1	50.725	31.868	18.857
100 MHz	10	48.241	33.673	14.568
200.5 MHz	9.7	56.229	44.19	12.039
500 MHz	14.6	64.039	60.777	3.262
1 GHz	24	69.308	73.896	-4.588
2 GHz	28.5	83.741	52.511	31.23

I. Conclusion

The qualification tests demonstrate that the all-polyimide heater can pass the equivalent burn-in and lead pull tests required for the standard FEP polyimide heater that has been a mainstay in flight applications for decades. The maximum power tests demonstrate the overall robusteness of the all polyimide heaters, indicating that they can be trusted in flight applications. The AP heater has a maximum power density three times that of the SFP heater. The AP heater can repeatedly and safely start at cold temperatures. The AP heaters can safely maintain power densities of 1.4 W/cm2 [9 W/in^2]for 24-hours, with the exception, as noted for the copper cladded surfaces, in which an ambient air environment (O2 present) where copper surfaces can oxidize. These tests also have shown that the AP heaters can be repeatedly thermally cycled without damage and continue to peform without any notable degradation.

In addition to the higher power density, the AP heater has the advantages that it is more flexible. The Teflon in the SFP heater has a tendency to restore to a flat shape, even when hot formed. AP heaters can include metalized surfaces for heat spreading or for shielding from radiated emissions. AP heaters also can include a static dissipative construction (extra carbon in the Kapton). The manufacturer asserts the capability of the AP heaters to meet Mil-Std insulation and di-electric tests. These have not been completed as of the writing of this paper. Those tests notwithstanding, the successful testing captured herein demonstrates that the AP heaters are ready and qualified for flight applications. JPL's Europa project is interested in these heaters since Teflon is not a viable material to use in the high radiation environment around Jupiter, and likely will perform follow-on tests simulating that radiation environment with the AP heaters.

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