

Touch Temperature Coating for Off-the-Shelf Electrical Equipment Used on Spacecraft

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Submitted for the 40th International Conference on Environmental Systems (ICES)

July 11 - 15, 2010

Barcelona, Spain

Abstract

Off-the-shelf electrical equipment is frequently used in space-based applications to control costs. However, the reduced heat transfer in the spacecraft microgravity environment causes the equipment to operate at significantly higher temperatures than it would in terrestrial applications. This creates touch temperature issues where items – particularly metallic ones – become too hot for the crew to handle safely. A touch temperature coating layup has been developed that can be added to space-based electrically powered hardware. The coating allows the crew to safely handle the hardware, but only slightly impedes the heat transfer from the component during normal operation.

In the present work, the coating generic requirements are developed and a layup is described that meets these specifications. Analytical and experimental results are presented that demonstrate the ability of the coating layup to increase the allowable limits of touch temperature while only marginally degrading heat transfer to the environment. This allows the spacecraft crew to handle objects that, if not coated, would be hot enough to cause pain or skin damage.

Introduction

To reduce costs, off-the-shelf equipment is being used more and more in the US human space program. Commercial items such as laptop computers and portable lights have become commonplace aboard the Space Shuttle and the International Space Station (ISS). Similar items will be used on the future Orion Spacecraft. Some commercially available items, such as laptop computers, have cooling fans to accommodate the bulk of their cooling – but others do not so their cooling is gravity sensitive.

For example, a commercial portable LED light is currently used on ISS to illuminate remote areas and to provide the required lighting level for high definition television. The light's brick-sized housing is fabricated from aluminum and the LEDs and their associated electronics consume 10 W of electrical power.

The LED light can be battery powered, so it must be handled to change out the batteries. The unit relies on natural convection for terrestrial cooling, but in microgravity the lack of buoyancy driven convection causes its steady-state temperature to exceed the 120°F aluminum touch temperature limit [1]. Therefore, either its time of operation or its power level must be restricted to maintain the housing

temperature below the 120°F limit. These types of restrictions are often necessary when using commercial electrically powered hardware in space applications.

If limiting the unit power level or duration of use is not desirable, another option is available to deal with the touch temperature issue. The object can be encased or coated to reduce the fingertip skin temperature at contact, thus increasing the range of use. Hook Velcro has been used to wrap hot objects flown on the Space Shuttle, but this is not an optimal solution. While the reduced conductivity and low thermal capacitance of the hook Velcro allows hot objects to be safely handled, the addition of the Velcro impedes the heat transfer to the cabin, causing the unit to run hotter than it would otherwise. This can decrease life or even cause component temperature limits to be exceeded. In addition, the flammable Velcro adds an undesirable fire load to the cabin.

To circumvent these issues, we have developed a coating layup that can be attached to electrically powered equipment (such as the LED light) to significantly increase the allowable touch temperature limit while only marginally degrading the heat transfer to the environment. The coating design is a balance of maintaining acceptable heat transfer to the cabin, while limiting the skin contact temperature once the object is grasped. The coating layup design parameters, its design details, and its performance are detailed in the present work.

Background

On Earth, natural convection can be relied upon as a mode of heat transfer. Many electrically powered terrestrial devices include vents that allow non-powered air circulation. In the cabin of a human spacecraft, the heat transfer is a combination of convection to the free-stream air and radiation to the cabin walls. The free-stream air is moved by the cabin airflow that is required by the crew and the intermittent acceleration of the vehicle by attitude control jets [2]. In the case of ISS, the attitude is controlled by control moment gyroscopes, so only ventilation airflow is present. ISS heat transfer is the limiting case and is used to define the design space in the present work.

Because of the lack of buoyancy-driven natural convection and the low cabin airflow (a nominal rate of 25 ft/min [3] is common to all US crew environments), the convective heat transfer coefficients on spacecraft are much lower than are normally found in terrestrial applications. For example, the Space Shuttle payload interface specification [4] gives a design convective heat transfer coefficient of 0.25 BTU/hr ft² °F for a 14.7 psia cabin. This is significantly lower than the free convection present in a terrestrial environment. For example, a 1 ft vertical wall in still air with a temperature difference of 54°F has a natural convective coefficient of 2.5 BTU/hr ft² °F [5], an order of magnitude higher than the on-orbit design value.

The poor on-orbit heat transfer environment causes electrically powered units to run significantly hotter than on the ground. This results in increased emphasis on touch temperature limits, but also constrains the designer from adding significantly to the heat transfer resistance so as not to cause the device to overheat.

Design

A successful touch temperature coating must limit skin temperature levels below the pain threshold while causing minimal degradation to normal on-orbit heat transfer. At first glance, these objectives are at cross purposes. An insulating coating could meet the touch temperature limit but would degrade the normal heat transfer. However because the local effective heat transfer coefficient during normal operation is low compared to the conduction dominated heat transfer that occurs during contact, a low thermal mass coating with tuned heat transfer characteristics can successfully meet both objectives.

A layered coating was developed that meets these performance goals. A low thermal mass outer layer keeps the initial contact temperature low and a tuned overall conductance limits the heat transfer into the skin. The layup shown in Figure 1.

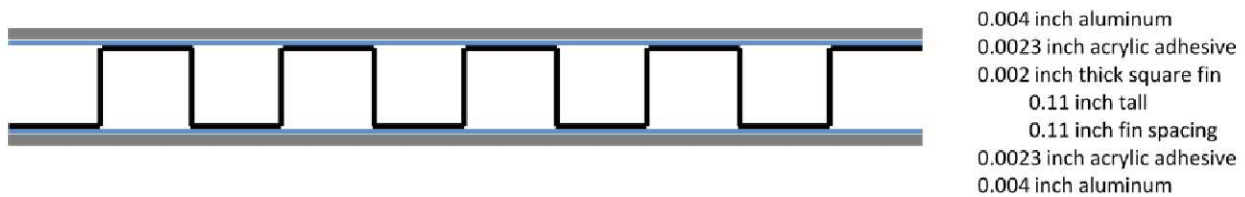


Figure 1 – Coating Layup

The layers are – from top to bottom:

- A 0.004 inch thick aluminum outer layer.
- A 0.0023 inch thick high temperature acrylic transfer adhesive.
- A 0.002 inch thick square stainless steel fin with longitudinal waves that add crush strength.
- A second layer of transfer adhesive.
- A second aluminum facesheet.

The two aluminum facesheets act as the outer heat transfer layer and the layer that is bonded to the equipment. The facesheets are identical for convenience, but are sized by the requirements for the outer heat transfer layer. The outer facesheet must be thick enough to be effectively isothermal during normal operation, but must be thermally thin so that it does not cause pain when grasped. The acrylic adhesive bonds the dissimilar metals and is thin enough that it does not pose any appreciable resistance to heat transfer in normal operation. The 0.002 inch thick stainless steel fin is 0.11 inches tall and has a void fraction of 98.18%. It is the main impediment to heat flow. A high emissivity coating is applied to the outer facesheet to improve the overall nominal heat transfer.

The LED light on ISS was used to assess the performance of the touch temperature-limiting surface coating layup. For a unit the size of the LED light (approximately 5.5 x 3.5 x 6.75 inches), a convective coefficient of 0.56 BTU/hr ft² °F would be expected for the nominal airflow velocity of 25 ft/min (based on the methodology outlined in [6]). For the measured light surface emissivity of 0.85, at 120°F in a 70°F cabin, the unit has an overall conductance of 1.55 BTU/hr ft² °F to the cabin. The heat transfer is split 1/3 convection and 2/3 radiation.

The layup shown in Figure 1 has an overall calculated conductance of 13.85 BTU/hr ft² °F, so if it was added to the worklight while maintaining the same surface optics, the resulting overall conductance would change to 1.39 BTU/hr ft² °F, a reduction of 10%. If the coating outer layer is treated to obtain an emissivity of 0.90, the overall heat transfer coefficient is reduced by only 7%. Decreasing the conductance by these small amounts results in minor increases in the normal operating temperature of the equipment, but yields a greatly increased range of safe handling temperatures.

Performance

The touch temperature coating layup on was developed and assessed analytically and was verified experimentally.

A transient one-dimensional implicit finite-difference Fortran thermal model was developed using the following information:

1. The skin's pain receptors are located in the dermis, so the critical location in the fingertip is at the epidermal/dermal interface 0.010 inch below the skin surface [7].
2. The pain threshold of 111.2°F [8] is assessed at the epidermal/dermal interface.
3. The typical contact conductance between the fingertip and the object is 176 BTU/hr ft² °F [8].
4. The skin thermal conductivity is 0.31 BTU/hr ft °F and the thermal diffusivity is 1.4×10^{-6} ft²/s [8].

The skin and object were both modeled as one-dimensional semi-infinite solids. The skin was set to an initial uniform temperature of 90.5°F [7] and the object (plus coating layup, if applicable) was set to a uniform initial temperature. The model calculates the transient temperature profiles for the two solids after contact. It returns the time that is required to raise the epidermal/dermal interface temperature to the pain threshold of 111.2°F. The model was run for a bare aluminum object over a range of initial temperatures to calculate a baseline response curve. The model was then modified to include the coating layup and was rerun. The time to reach the pain threshold for both cases is shown in Figure 2.

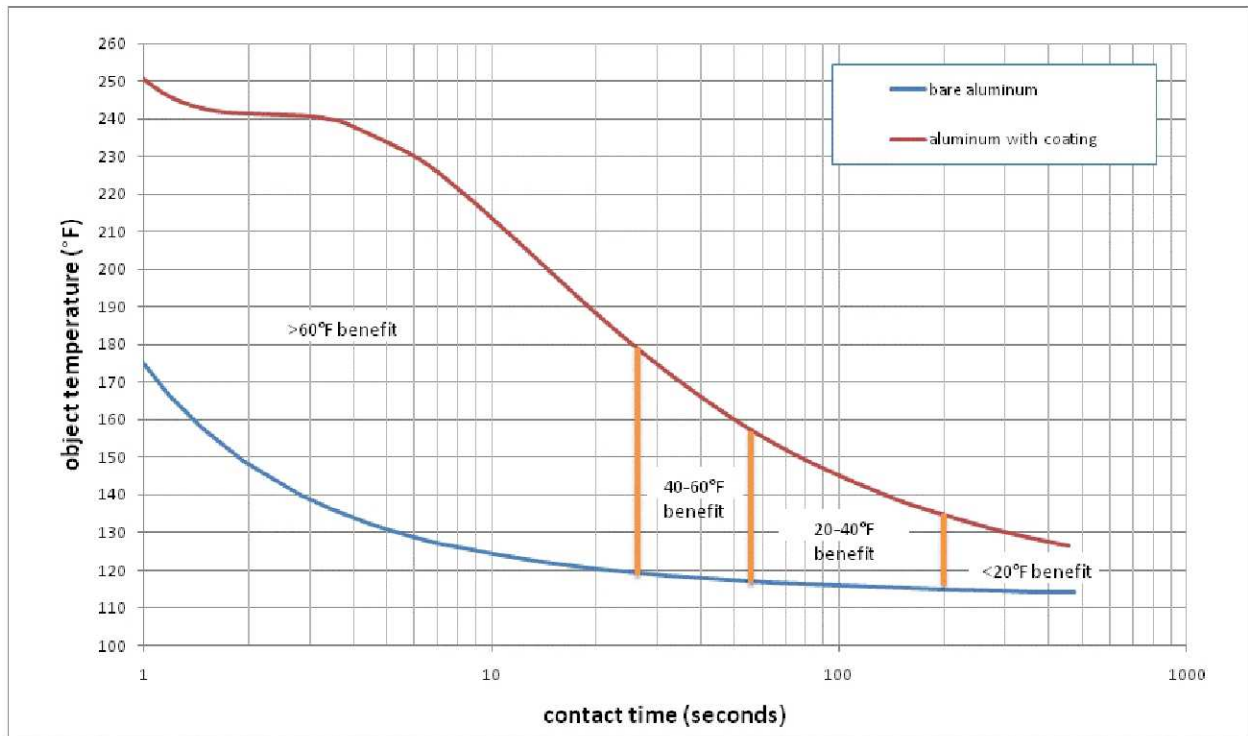


Figure 2 –Pain Threshold Limits from Analytical Model

The analytical results show that the coating layup dramatically improves the allowable object temperature for a given contact time – a 20°F increase for long times and as much as a 100°F increase for short times. The coating also increases the allowable time of contact for a given temperature. A bare 140°F aluminum item can be held for 2.5 seconds without pain, but with the coating layup, it can be held for more than two minutes before pain occurs.

The coating layup was also tested using a stagnant water column as a skin analog. Water's thermal properties make it an excellent analog for skin. The value of the quantity kpc for skin¹ is 19.39 BTU²/ft⁴ hr °F² based on the values referenced above. The same quantity is 22.55 BTU²/ft⁴ hr °F² for water.

The height of the water column was chosen to mimic the of 0.65 lbf median fingertip pressures used by Geng et al. [9] in their cold touch temperature experiments². Measurements of the index and middle fingertip contact areas using a copy machine gave contact areas of 0.5 in². These contact areas were found to be insensitive to pressure. The contact pressure calculated from the ratio of the force and measured area is 1.3 psi, which is equivalent to 35 inches of water.

The skin simulator was a 36 in length of 1 in PVC plastic pipe as shown in Figure 3. The pipe walls were rounded at the bottom end, which was sealed with a slightly slack piece of 0.0015 in Teflon film. A

¹ The quantity kpc , where k is the thermal conductivity, p is the density, and c is the specific heat is the sole independent variable in the exact touch temperature solution for two semi-infinite solids in intimate contact [10].

² No contact forces were reported by Stoll et al. [7] in their seminal hot touch temperature experiments.

0.003 inch bare wire copper/constantan butt welded thermocouple wire was attached to the inside of the Teflon film using a strip of 0.0012³ in Kapton tape. The junction was centered in the opening of the pipe. The pipe was filled with a water and Cabosil⁴ fumed silica mixture to a height of 35 inches.

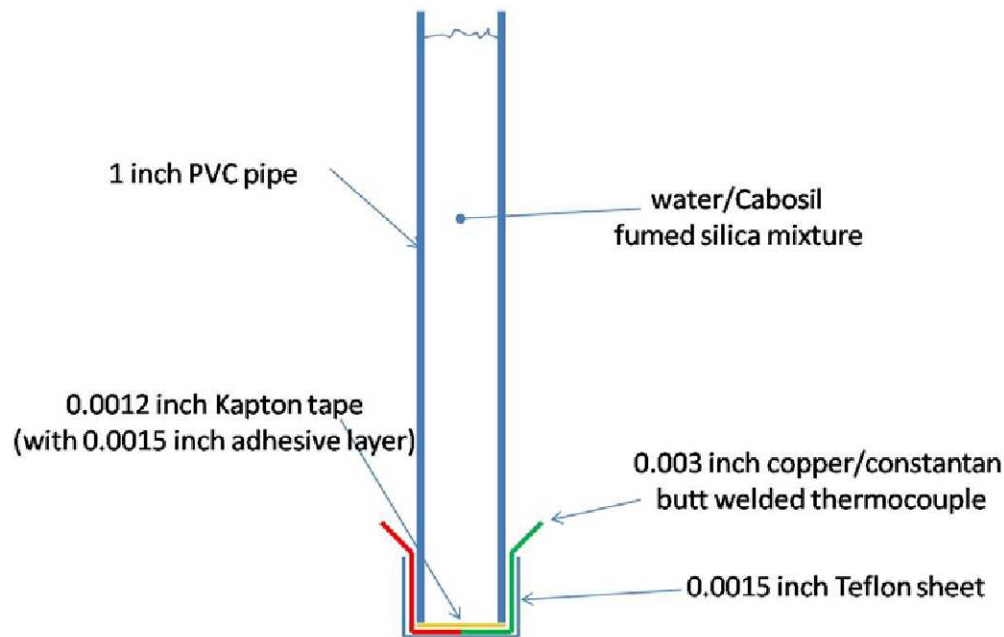


Figure 3 – Skin Simulator

A sample of the coating layup was attached to one side of a 1 inch thick electrically heated aluminum block. A 30 gage copper-constantan thermocouple was embedded between the coating layup and the block to sense the block temperature. To perform an experiment, the block was covered and heated. Once the desired temperature was reached, the block was removed from the heater, placed on an insulating surface, and re-covered to allow its temperature to stabilize. The insulating cover was then removed and the skin simulator was placed on the block, touching either the coated side of the uncoated side as desired.

During the test, all temperatures were measured by Omega HH84 stand-alone thermocouple readers. The test data was recorded in two ways, the first data set using a video camera with the block and thermocouple readouts in the camera field of view. The time for the measure skin simulator temperature to rise 20.7°F was assessed using the built-in video time. A second set of data was taken using a stopwatch to measure the time required for the simulator temperature to rise 20.7°F. A minimum of 5 minutes was always allowed between tests to permit relaxation of the skin simulator temperature.

The 20.7°F temperature rise was derived from the pain threshold using superposition principles. At the onset of pain, the skin temperature profile has changed from a uniform temperature of 90.5°F to a point

³ With 0.0015 inch adhesive layer – total thickness was 0.0027 inches.

⁴ The fumed silica prevented natural convection within the pipe - forcing a pure conduction heat transfer mode.

where the epidermal/dermal interface has reached 111.2°F - a local temperature rise of 20.7°F. Therefore, the tests were run until the measured skin simulator temperature increased by 20.7°F.

The results of the tests are listed in Table 1. The table lists the initial aluminum block and skin simulator temperatures plus the time for the skin simulator thermocouple temperature to rise 20.7°F⁵. The table also includes the initial block temperature scaled to a 90.5°F initial water column temperature⁶.

Table 1 –Test Results

Initial Fingertip Simulator Temp. (°F)	Block Initial Temp. (°F)	Coated with Layup or Uncoated	Time to Change 20.7°F (sec)	Equivalent ⁶ Block Initial Temp. (°F)
70.88	116.6	coated	108.0	136.2
82.04	130.64	coated	97.6	139.1
87.8	143.6	coated	81.0	146.3
76.46	137.3	coated	40.9	151.3
75.2	145.4	coated	22.5	160.7
87.26	158.9	coated	21.0	162.1
76.64	152.96	coated	20.7	166.8
72.86	149.72	coated	23.9	167.4
76.46	156.2	coated	18.7	170.2
75.2	157.82	coated	14.0	173.1
76.64	168.08	coated	10.7	181.9
74.3	167	coated	13.8	183.2
76.46	169.16	coated	<1	183.2
76.64	186.98	coated	<1	200.8
76.1	192.38	coated	<1	206.8
75.74	211.46	coated	<1	226.2
75.02	101.48	uncoated	44.8	117.0
72.68	101.48	uncoated	10.1	119.3
73.76	105.44	uncoated	9.9	122.2
74.3	110.48	uncoated	2.8	126.7
72.32	110.48	uncoated	7.4	128.7
75.2	113.54	uncoated	1.9	128.8
73.76	113.36	uncoated	5.5	130.1
75.2	125.6	uncoated	<1	140.9
76.1	136.4	uncoated	3.6	150.8

⁵ The times that are in whole seconds were taken from the video. The other times were taken using a stopwatch.

⁶ By adding the difference between 90.5°F and the initial water temperature to the initial block temperature.

The scaled data are plotted in Figure 4. A dashed line at the 111.2°F limit is shown for the uncoated case for times >100 seconds as this matches the physical limit. A discontinuity in the coated data occurs near an equivalent initial block temperature of ~183°F. At higher temperatures, the measured temperature spiked above the 20.7°F temperature rise limit very quickly (in less than 1 second). At these temperatures the initial heat soak from the facesheet spiked the measured temperature above the limit. For lower temperatures, the initial spike did not exceed the limit. The limit was reached after 10 seconds or more as the measured temperature increased. This discontinuity is an artifact of measuring the temperature so close to the heated surface (0.0015 in vs. 0.010 in). A deeper measurement would not have had as great of an initial transient.

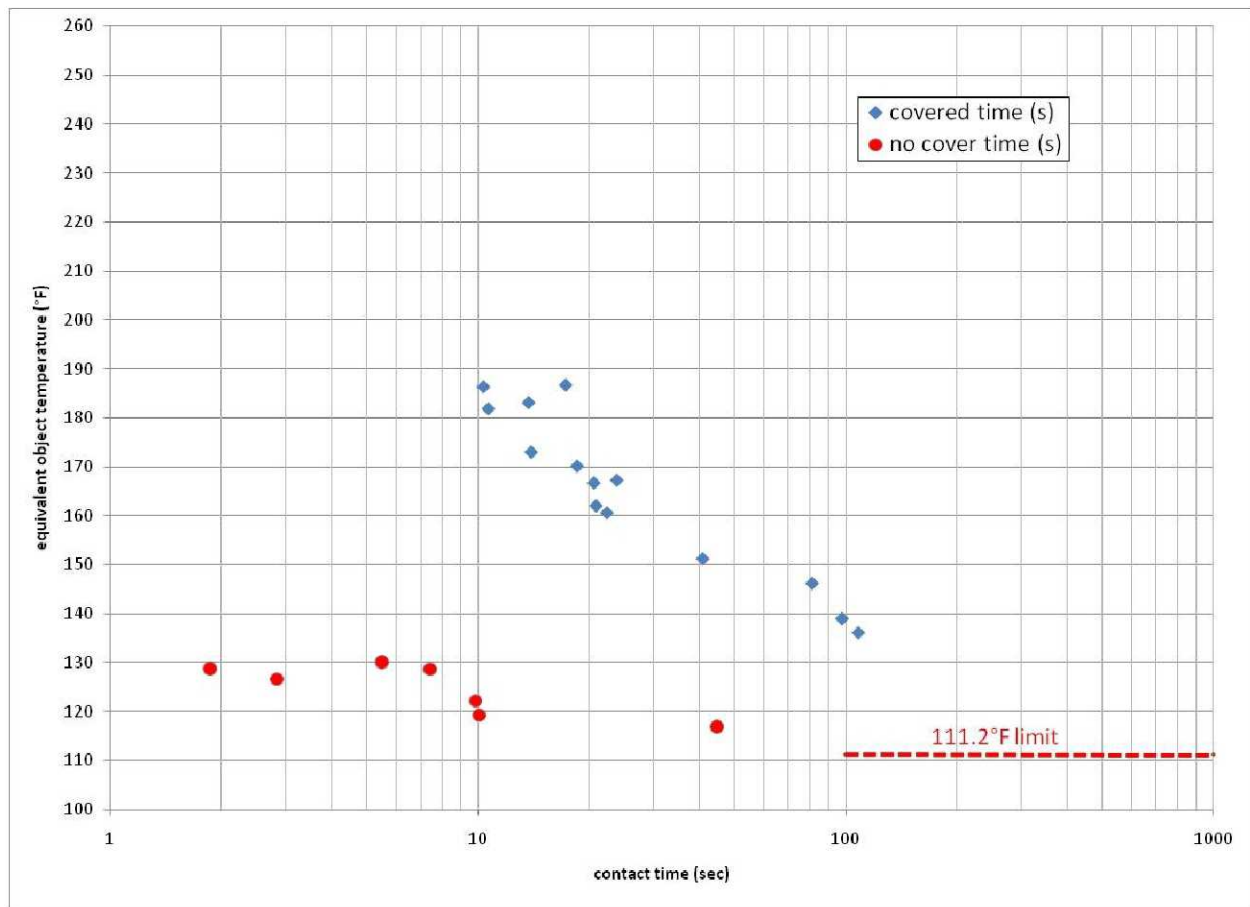


Figure 4 – Analogous Pain Threshold Limits from Test
Data Scaled to Equivalent of 111.2°F Pain Threshold

Figure 5 contains the scaled test data plotted with the analytical results from Figure 2. The analysis and the test data show excellent qualitative agreement. The agreement between the analysis and data is not exact because:

- The 111.2°F limit is assessed at the epidermal/dermal interface (0.010 inch deep) in Figure 2, and is measured at a depth of 0.0015 inches in the Teflon/Kapton layup in the test,
- The contact conductance is uniform and constant in the experiment, but it is not necessarily the same as the 176 BTU/hr ft² °F used in the analysis.

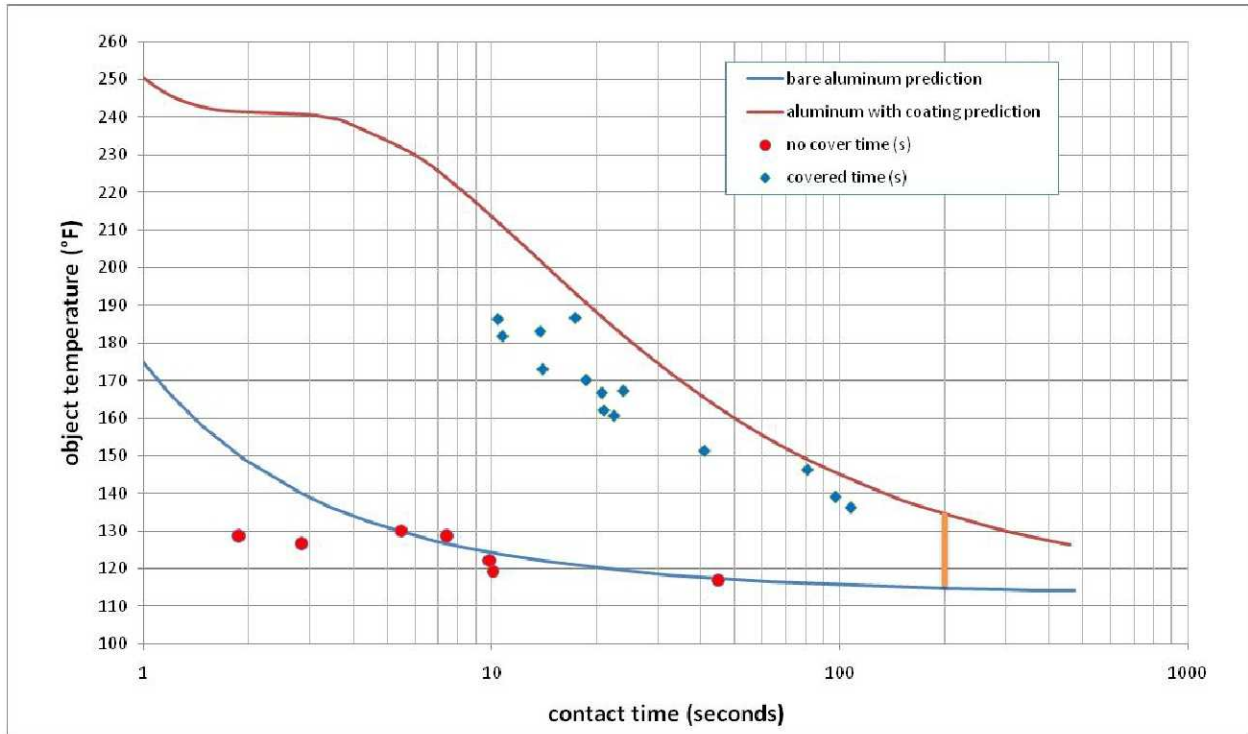


Figure 5 – Analysis and Data Comparison

The analysis and experiment demonstrate that the coating layup allows hotter objects to be safely handled for longer periods of time. For a given object temperature, the onset of pain is greatly delayed. Pain-free contact times are increased by an order of magnitude. For a given contact time, the object temperature limit for pain-free handling is significantly higher.

Summary

A multi-layer coating layup has been developed for use on off-the-shelf electrical equipment in space-based applications. The layup dramatically increases the touch temperature limits, allowing hot items to be handled without pain, but has only a minor adverse effect on normal heat transfer to the spacecraft environment.

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