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# Supplementary Information for

# SPEARED

# The Single Person Emergency Atmospheric Re-Entry Device

## Summary

This document provides more detailed technical data for “The Single-Person Emergency Atmospheric Re-Entry Device (SPEARED)”, an article submitted to *Analog Science Fiction and Fact*, expected to be published around their December 2014 issue. The article was written by Stephanie Osborn, Arlan Andrews, and Tom Ligon. Please read the *Analog* article. This supplement documents tests and data, but not the deeply personal motivations the authors had for pursuing SPEARED and for writing this material.

To summarize the Analog article, our concept is to make a rapidly-deployable heat shield, capable of surviving re-entry from Low Earth Orbit, which could be built into an ejection seat. One possible configuration is illustrated by Arlan Andrews here (http://www.tomligon.com/ATE/Whitepapers/SPEAREDSystemConfig.pdf). NASA is already working on inflatable heat shields, which allow the heat shields to be of much larger diameter than the launch vehicle, thus allowing lower temperatures and pressures on re-entry. Our contribution is to suggest that rather than inflate the heat shield with air or gas, that quick-setting foams are available which can survive re-entry, and to have the audacity to suggest this system for astronaut rescue.

**WARNING**

**Exposing polyisocyanurate foam, or any of its chemical cousins, to flames or high temperatures produces a noxious mix of gasses likely to cause all manner of bad effects including death, and worse, *slow painful* death. If you contemplate attempting any of these tests, please use adequate protection.**

## 2012 Small Propane Torch Tests

Included below is the text of an informal report provided by Tom to Stephanie and Arlan, used to prepare Stephanie's presentation to the Second Tennessee Valley Interstellar Workshop. The report is dated 7 November 2012, and the tests had been performed the previous day by Tom (with assistance from his wife Linda) in Manassas, VA.

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**Informal Test of Polyisocyanurate Foam Insulation for Possible Application for an Emergency Re-entry Heat Shield**

Tom Ligon

7 November 2012

## Test Material

This report documents torch-flame tests of Atlas foam insulation boards, of two inch nominal thickness, produced around the early 1990's. The boards are faced on both sides with a thin foil/paper/foil covering, and were marketed as building insulation. The investigator had previously noticed that this material charred but remained dimensionally stable when heated with a propane torch. The material has not been analyzed, but the pale yellow coloration, stiffness, and tendency to turn brown and decay when exposed to sunlight suggests polyisocyanurate, which is often called polyurethane foam (a broad term which is not strictly accurate for this material). Based on the age and the manufacturing history of this class of product, it is expected that this material used a Freon blowing agent. Markings on the facing include Atlas Energy and HF4191. The material is consistent with the Energy Shield product described in the link below:

http://www.thermalfoams.com/downloads/literature/Misc/atlas.pdf

Tabular data from the source above includes the following properties:

| Property | Test Method | Typical Results |
|---|---|---|
| DIMENSIONAL STABILITY | ASTM D 2126 | <2% linear change |
| WATER ABSORPTION | ASTM C 209 | <1% by volume |
| MOISTURE VAPOR TRANS. | ASTM E 96 | <One (l) Perm (57.5ng/(Pa•s•m2)) |
| PRODUCT DENSITY | ASTM D 1622 | Nominal 2.0 pcf |
| FLAME SPREAD** | ASTM E 84 | <75 |
| SMOKE DEVELOPMENT** | ASTM E 84 | <450 |
| SERVICE TEMPERATURE —— | | C14 to +250℉ Max. (-73° to 122℃) |

** Refers to a manufacturer disclaimer regarding the variability of actual fire conditions, and it should be admitted that the manufacturer certainly did not intend for humans to ride this material into the atmosphere at Mach 25!

The two inch nominal thickness of the boards used in this test indicate an expected R-value for undamaged foam (in American system units) of 12.8 $ft^2$-°F-hr/BTU, or about 2.25 $m^2$-°K/W in SI units. This yields a U value of about 0.444 W/($m^2$-°K).

The observation of relatively refractory behavior compared to other foam insulations used in building construction was communicated to James Victor Hugo Hill, the subject of a story ("Amateurs") and fact article ("Prospectus") pair which appeared in *Analog Science Fiction and Fact*, July 1996. Hill intended to use structural foam cores in his spacecraft designs.

Arlan Andrews, another contributor to this project, has prior experience with another member of the polyurethane foam family, toluene diisocyanate, which he reports had similar properties, and which he considered for re-entry applications.

More recently, the subject of emergency re-entry equipment for astronauts was raised, reviving the investigator's interest in this material, and prompting tests of remaining samples of the original foam.

**Apparatus**

Thermocouples:  Type K, Omega Engineering

GG-K-24 (24 AWG fiberglass insulated) used for flame face exposure
TT-K-30 (30 AWG Teflon insulated) used for lower temperatures
Assorted miniature Type K thermocouple connectors

Data Acquisition System

UEILogger 600 Data Acquisition Chassis
DNA-AI-207 16 Channel 18-bit A/D Card
DNA-STP-37 Terminal Block with ice-point circuit added.

FLIR i7 Thermal Imager

Bernzomatic JT539T Swirl Flame Brazing Torch.  A quick test was performed on this torch using a water manometer.  Using a length of ¼" OD copper tubing as a pitot tube, it was found that the torch caused a small movement of the water column, judged to be no more than about 2 mm (20 Pa or less), a very low dynamic pressure.  A standard propane torch, by comparison, supported a water column of approximately 6-7 mm, or about 64 Pa.

Pelouze PE10 Digital Scale, 5000 g full scale, 5 g resolution.

**Materials**

Fiberglass Cloth:  Bondo/3M 499

The tape used to affix the thermocouples is Nashua Tape Products 342A, 2.5 inches (64 mm) wide.  The following information on this product was found at http://tapes.berryplastics.com/Data/Transient/Docs/Products/Markets/Industrial/2011IndustrialTapeCatalog198_01-11s.pdf

Backing: 2.1 mil Printed Aluminum Foil

Adhesive: High Performance Acrylic

Outstanding performance in both cold and hot weather. Excellent conformability. Instant adhesion & superior quick stick. Mold-resistant. Low VOC.

Uses: Heavy-duty foil for indoor/outdoor and sealing in automotive and insulation applications. Seal duct work for heating, air conditioning and refrigeration systems. Excellent extreme temperature performance.

Thickness: 4.8 mils (121.92 mic)

Adhesion to Steel: 68 oz/in (7.44 N/cm)

Tensile: 23 lb/in (40.28 N/cm)

Operating Temperature: -20°- 325°F

Standard Sizes: 2.5”, 72mm x 55M

Worthington Propane Fuel, 16.4 oz (465 g) cylinder

**Sample Preparation**

The samples of foam board were cut to approximately 30 x 30 cm specimens. The unprinted aluminized paper facing was peeled off. The facing detached readily. The purpose for removing the unprinted facing was to minimize conduction of heat to the specimen perimeter in the Sandwich thermocouple interface.

Each sample was weighed with a resolution of 5 grams, and the weight marked on the specimen, along with the intended burn time.

The side with the printed facing was marked corner-to-corner with a permanent marker to locate the center. A strip of aluminum self-adhesive foil tape was applied across the specimen face to adhere the flame face (fiberglass-insulated) thermocouple.

**Setup**

This test setup is intended only to provide a rough preliminary assessment of the temperature performance of the foam samples, and is not a precision setup.

A height reference pointer was fabricated of 1/16” (1.54 mm) diameter stainless steel welding wire, and inserted into two blocks of scrap foam as shown on the left of Figure 1. The wire was bent to an L shape so that the tip extended close to the center of the test specimens and approximately 9.5 cm off of the surface. This served as a guide to hold the torch a fixed distance off of the specimens.

The apparatus shown in Figures 1 and 2 was laid flat on a metal mesh table for the first (8-minute) test, which was found to produce erratic torch performance. Following that test, the apparatus was propped up as shown in Figure 3 to improve torch performance.

The datalogging equipment was set up to record three type K thermocouples at a rate of 1 Hz. Channel 0 recorded ambient temperature from a TT-K-30 thermocouple epoxied to a stainless steel plate (the plate provides thermal mass to stabilize the temperature reading). The ambient thermocouple was set to the most sensitive range of the datalogger.

A lower square of the foam board being tested was stripped of its unprinted foil facing and placed with the stripped face up. A TT-K-30 thermocouple was taped over the center of the stripped face. This is channel 1 on the datalogger, identified as the “Sandwich” thermocouple. Figure 1 shows the lower foam board with the Sandwich thermocouple in place. This channel was set to record at the highest temperature range for K thermocouples.

The test specimens were placed over the lower foam board, with the stripped face down and the printed foil face up. A GG-K-24 thermocouple (heavier wire and fiberglass-insulated) was taped over the center of the upper face using foil tape, as seen in Figure 2. This is channel 3 of the datalogger, and is indicated as the “Face” thermocouple.  This channel was set to record at the highest temperature range for K thermocouples.

For the fiberglass cloth test, a piece of this material approximately 30 cm square was placed over the upper surface of the test specimen.

**Figure 1.  Test Setup with Test Specimen removed.**


**Figure 2.  Test Setup with Test Specimen in place.**

**Figure 3. After the initial 8-minute test, the test setup was angled as shown to improve air circulation to the torch.**

## Test Procedure

The tests were performed outdoors on a cool afternoon. The test was expected to produce toxic smoke, so precautions were taken to prevent exposure. The location was shaded from the afternoon sun.

The torch was operated at full throttle. It should be noted that small propane cylinders will reduce their operating pressure during prolonged operations, especially in cool conditions.

The datalogger was started approximately 60 seconds prior to the application of flame to the specimen. The flame was applied for 1, 2, 4, or 8 minutes as indicated. The specimen was typically removed from the lower foam board shortly after the flame was removed to inspect the stripped surface and to make a thermal image. The logger was typically still recording at this point. It is possible that some peak Sandwich thermocouple temperatures were missed due to removal of the specimen.

The torch was held approximately 9.5 cm off of the specimen surface as indicated in Figure 4. The first test (8 minute flame exposure) was conducted with the specimen and underlying foam board flat on the table. The following tests were performed propped up as shown in Figure 3. The torch was found to work more reliably if held at a slight angle to perpendicular to the specimen, to put the air intake orifices in cleaner air.

**Figure 4. Application of torch flame. A stainless steel wire pointer served as a torch height guide. The test shown is the initial 8-minute test in which the specimen face was horizontal.**

## Results

The time versus temperature charts are shown below. The face (flame-exposed) thermocouple is indicated on the left (1400 C) axis. The remaining thermocouples are indicated on the right (140 C) axis. The tests were performed in the following order.

8-minute
4-minute
2-minute
1-minute
4-minute with a covering of fiberglass cloth

The 8-minute test results show a clearly lower Face thermocouple temperature. This test was performed with the specimen flat, and as a result the smoke from the specimen was aspirated into the torch, causing inconsistent burn.

The thermal image shown was taken after the 8-minute test specimen was tilted up from the setup. It is not intended to show the maximum temperature achieved, but to give an idea of the temperature distribution.

Following the tests, each specimen was weighed again. The weight loss was indicated as 5-10 g. The 5 g resolution of the scale was insufficient to allow any precise quantitative conclusions to be drawn, other than the appearance that longer burn times caused more mass loss

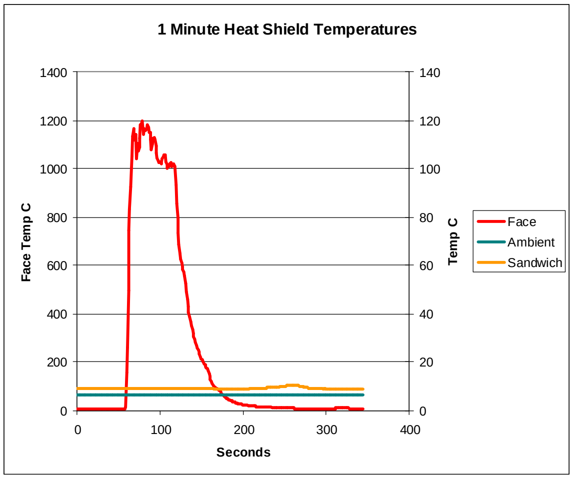
The 8-minute test showed a significant "dome" on the back of the specimen after the test. The 4-minute tests produced a similar but less-pronounced distortion.

The 4-minute test with fiberglass covering the face of the specimen showed that the fiberglass provides only a few seconds of protection. However, the specimen shows less damage than the unprotected 4-minute test.

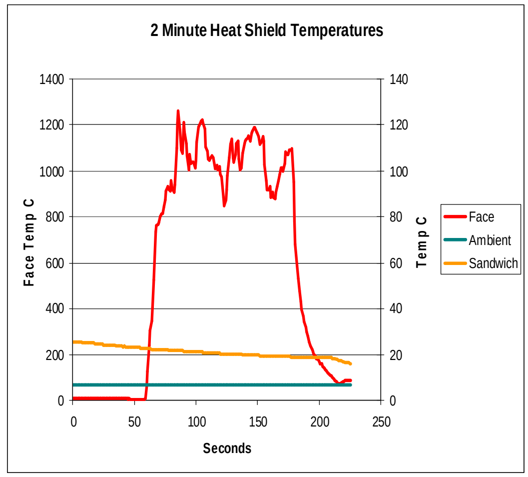
In all cases, the foil tape covering the thermocouples appeared to provide several seconds of protection, compared to the very thin foil-paper-foil covering provided on the foam.

Table 1. Mass loss and burn depth

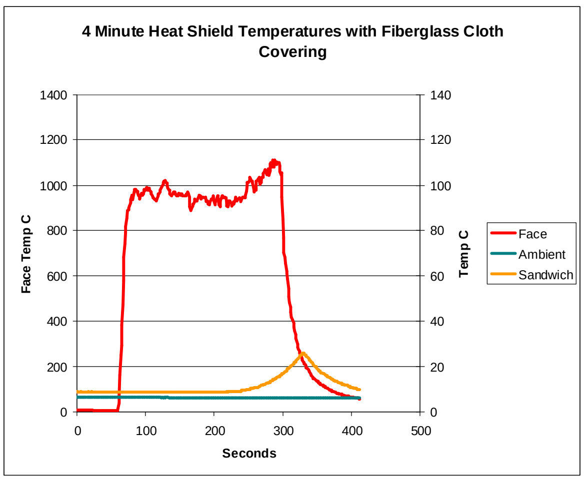
| Initial specimen thickness was 5.3 cm | | | | |
|---|---|---|---|---|
| Specimen Burn time | Mass Before, g | Mass After, g | Char Depth, cm | Browning Depth, cm |
| 8 min | 145 | 135 | 3.8 | 5.8 |
| 4 min | 145 | 140 | 3.7 | 5.2 |
| 2 min | 145 | 140 | 2.2 | 3.1 |
| 1 min | 145 | 140 | 1.8 | 2.1 |
| FG 4 min | 150 | 140 | 3.2 | 4.3 |
| The 8-minute specimen produced a significant dome on its back surface, allowing for a browning depth exceeding its thickness. | | | | |



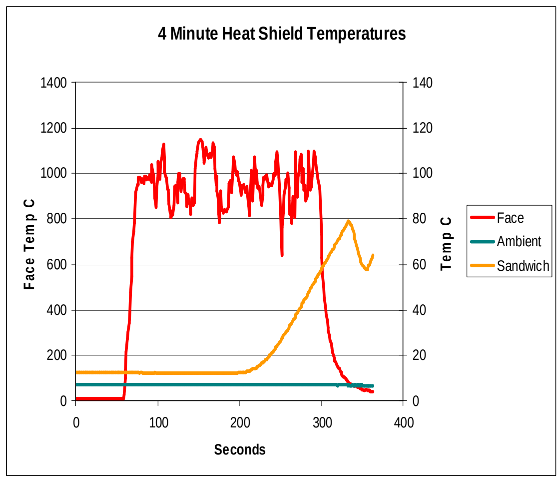
1 Minute Heat Shield Temperatures
Face Temp C
Temp C
Seconds
Face
Ambient
Sandwich

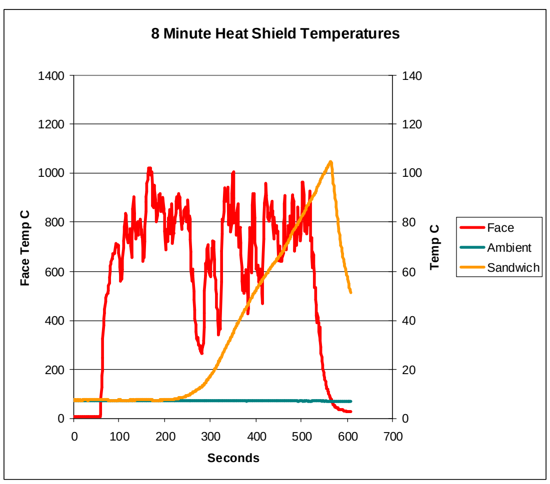
2 Minute Heat Shield Temperatures
Face Temp C
Temp C
Seconds
Face
Ambient
Sandwich

4 Minute Heat Shield Temperatures with Fiberglass Cloth Covering
Face Temp C
Temp C
Seconds
Face
Ambient
Sandwich

4 Minute Heat Shield Temperatures
Face Temp C
Temp C
Seconds
Face
Ambient
Sandwich

8 Minute Heat Shield Temperatures
Face Temp C
Temp C
Seconds
Face
Ambient
Sandwich

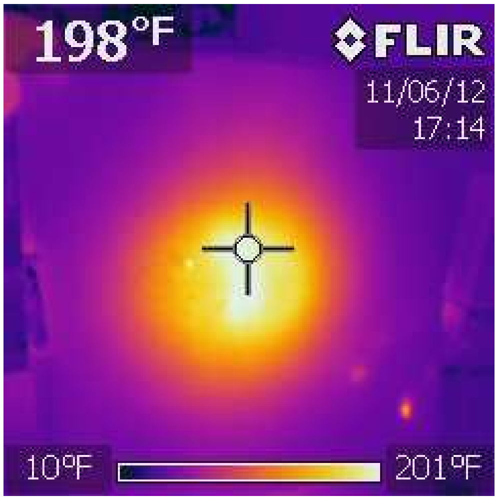



**Figure 5. Thermal image of the rear of the 8-minute test specimen following the test.**

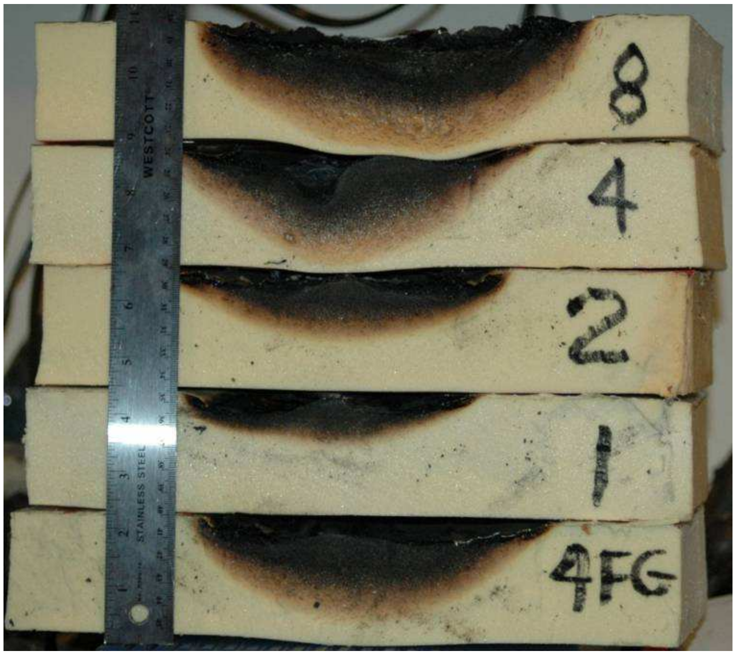



**Figure 6. Specimen sections to show depth of char. Number marked is the minutes of burn time. The lowest specimen had the fiberglass cloth overlay.**

## Conclusions

This test project, while certainly not a substitute for rigorous testing of spaceflight materials, suggests that polyisocyanurate foams may be capable of withstanding LEO re-entry conditions.

The key properties are excellent thermal insulation, rigidity, dimensional stability under extreme heat, and a tendency to char and decompose rather than melt.

It should be noted that this test did not achieve full re-entry temperature conditions, nor high dynamic pressure. If repeated, the test specimens should be left in contact with the lower foam board for several minutes to allow peak sandwich thermocouple temperature to be realized. It may be advisable to orient the specimens vertically and to supply clean air to the torch for consistent temperature operation.

The results, while limited, suggest that polyisocyanurate may be sufficiently robust that 10-15 cm of thickness may be sufficient to protect against LEO re-entry conditions.

The results are considered encouraging, and warrant a closer look at polyisocyanurate and related foams such as toluene diisocyanate as heat-shielding materials. The behavior of the charred foam under hypersonic conditions is yet unknown, and may require some fiber component to prevent the protective char from stripping away. Additional properties needed for a heat shield include the ability to form and set quickly, a demonstration of the ability to withstand dynamic pressures consistent with a survivable re-entry trajectory, the means of storing and deploying the foam, the form needed for the heat shield and a practical means of forming it, the safety of the materials aboard crewed spacecraft, and the mass required.

A possible form for such a re-entry heat shield is suggested by NASA's HIAD/IRVE project:

http://www.nasa.gov/offices/oct/stp/game_changing_development/HIAD/index.html

If sufficient interest is generated by this informal report to justify further testing, improvements in methodology are anticipated. Improvements should include the use of higher-temperature thermocouples, a larger and higher-temperature torch with a forced clean air supply, or use of an electro-gasdynamics chamber to simulate high altitude and high hypersonic velocity.

## Some additional photos of the small torch tests:

Automotive grade fiberglass cloth: The fiberglass melted in a couple of seconds, and offered virtually no additional protection. This inspired the use of a more refractory fabric in the later compressed air torch tests. NASA uses 3M Nextel fabrics on IRVE, specifically mentioning Nextel 312.

http://www.3m.com/market/Industrial/ceramics/materials/fabric_312.html

Figure 7.  Overlaid with fiberglass cloth.

Figure 8.  Fiberglass offered little protection.

## Second Tennessee Valley Interstellar Workshop

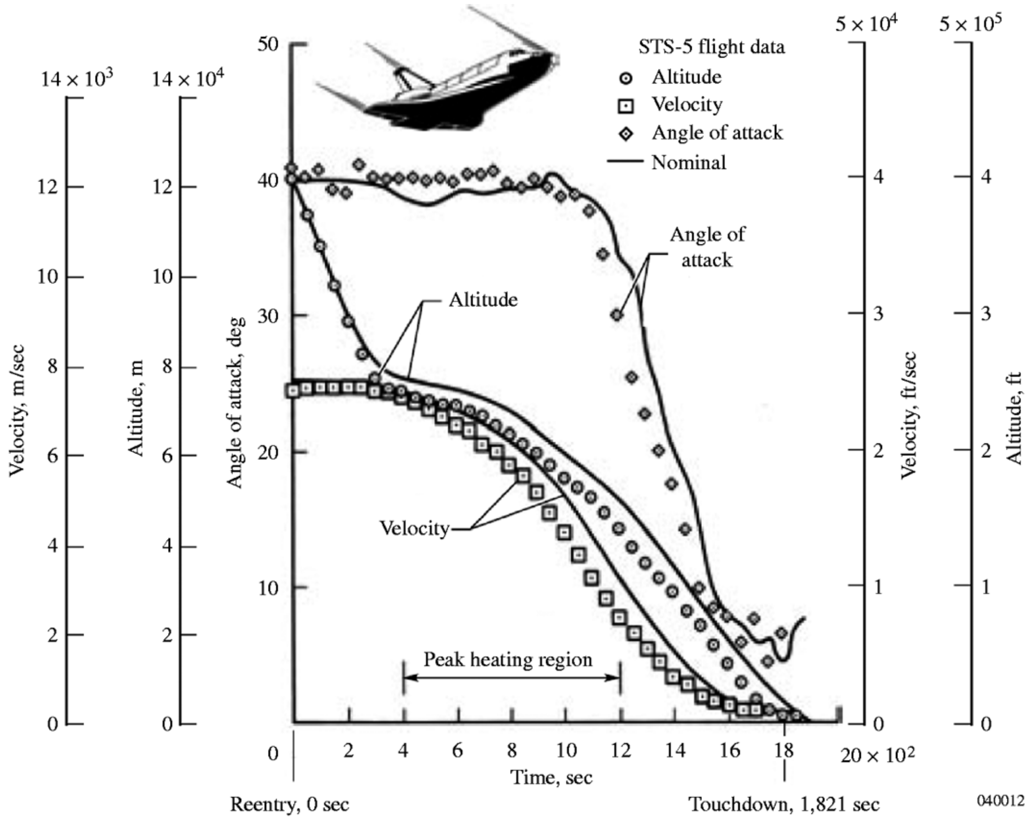
Stephanie Osborn prepared a presentation (http://www.tomligon.com/ATE/Whitepapers/SPEAREDPresentation2.pdf) for the Second Tennessee Valley Interstellar Workshop.  Reception to this presentation was excellent, and resulted in an invitation to submit a paper to the *Journal of the British Interplanetary Society*. This is a proper peer-reviewed journal, and we understood as soon as we were invited that this little project was apt to run into problems in peer review.  Indeed, it did.  One prominent criticism was that there was no mention at all in our paper of “heat flux”.

Part of the reason was that we lacked data on the heat output of the small torch.  I did have an Omega® HFS-3 heat flux sensor on hand, but it was not intended for the high temperatures this test would produce, and would not have survived the first test.  I declined to waste a $270 sensor.  However, both Arlan and I have written fact articles for *Analog Science Fiction and Fact (http://www.analogsf.com/)*, and realized that this venue would reach a wider audience of space enthusiasts, including a lot of people in the industry, and would be more tolerant of our informal approach.

## NASA Data

Several sources of public NASA data have been useful benchmarks for the SPEARED tests.

The Figure 9 partly illustrates the re-entry severity of typical high-ballistic-coefficient spacecraft (i.e., craft such as the Shuttle Orbiter).  The time scale duration is 1800 seconds (check that $10^2$ at the right end of the axis).  Peak heating lasts 800 seconds, from 400 to 1200 seconds.




**Source:** William *et al.* (2004)

**Figure 9. NASA data on an early Shuttle re-entry (STS-5).**

NASA's IRVE (Inflatable Re-Entry Vehicle Experiment) is a specific part of their HIAD (Hypersonic Inflatable Aerodynamic Decelerator) program. Normal re-entry heat shields can be no larger in diameter that the launch vehicle. This limits the area available for aerodynamic braking. The re-entry payload thus puts its weight on a small braking area, resulting in a high ballistic coefficient that does not slow down much until it hits dense air … assuming there *is* dense air. But inflatable heat shields can be much larger than the launch vehicle diameter. They can be made to brake in thinner air, and spread the heat over more area , which, with proper trajectory choice, should result a cooler re-entry. Given a little air, beach balls slow down better than bowling balls.

This could be particularly handy for cases such as Mars, where the air density at the surface is about like Earth's atmosphere 20 miles (32 km) up. If you look at the graph above, that would leave the Shuttle still in the max heating range and moving about 3 km/sec when it ran out of altitude. The charm of an inflatable heat shield for an outfit planning Mars missions is clear.

In a paper called "Inflatable Re-entry Vehicle Experiment (IRVE) Design Overview" by Stephen J. Hughes, *et. al.*, *NASA Langley Research Center, Hampton, VA,* the HIAD/IRVE concept was outlined. Figure 1 of that paper (Stagnation point convective heat rate vs. altitude for both a rigid and an inflatable MSL concept 6km/s entry with equivalent landed mass) is reproduced below. In layman's terms, given a beach ball and a bowling ball of the same mass, heat flux on the beach ball is a whole lot lower. In the Design Overview, anticipated peak dynamic pressure was 600 Pa.

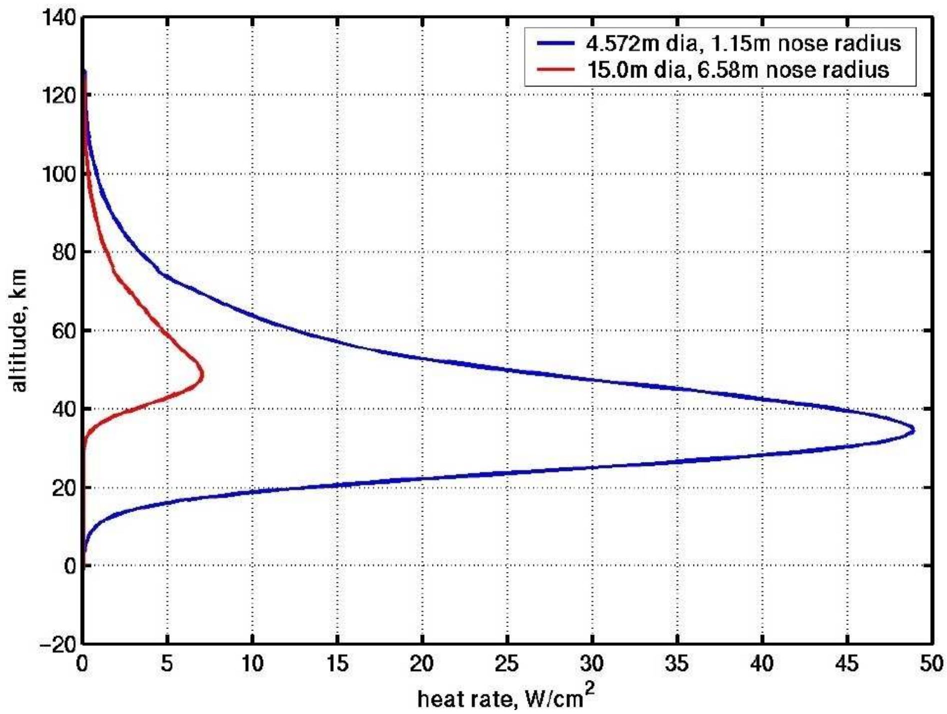



**Figure 10. Figure 1 from the IRVE Design Overview.**

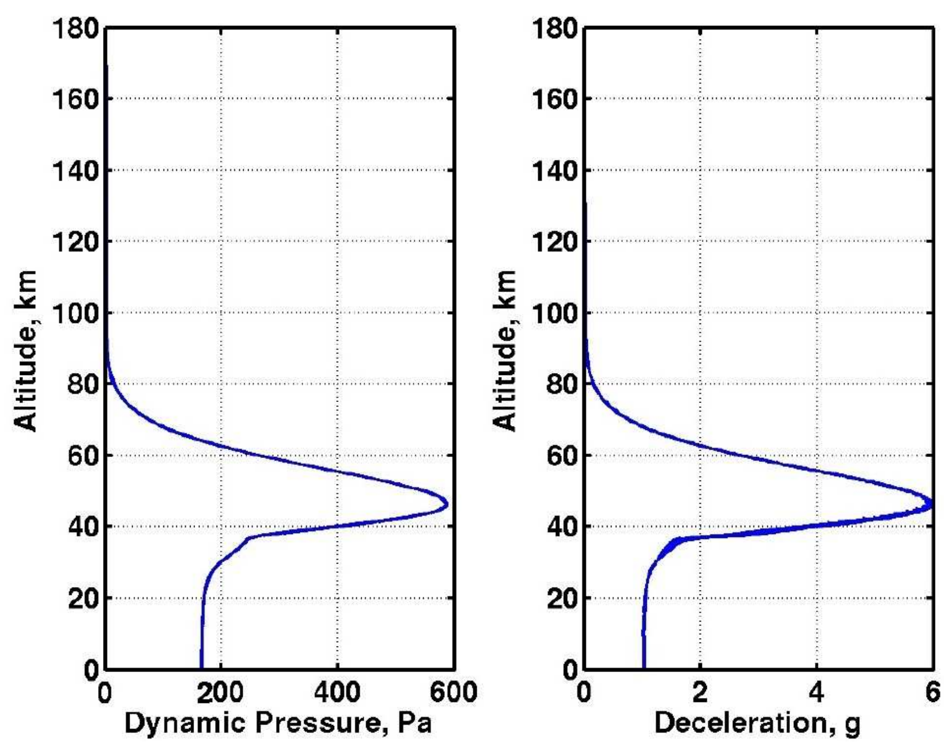



**Figure 11. Design Overview Figure 14 anticipated a peak IRVE dynamic pressure of 600 Pa, although IRVE-3 greatly exceeded that pressure.**

NASA's IRVE-3 test is the most severe of that program. While this test series is suborbital, the trajectory of IRVE-3 was deliberately designed to create the most severe heating and highest dynamic pressure possible, by using a nearly straight-in plunge from an altitude of about 470 km. The data below are taken from "IRVE-3 Post-Flight Reconstruction**",** by Aaron D. Olds, *et. al*., from *Analytical Mechanics Associates, Inc., NASA Langley Research Center,* and *Orbital Sciences Corporation.* Temperature data are conspicuously absent from that report, but a press release, "NASA - IRVE-3: Inflatable Heat Shield a Splashing Success", said peak temperatures "were as much as 1,000 degrees Fahrenheit (538 degrees Celsius)." The graphs below are figures 8 and 13 of that report.

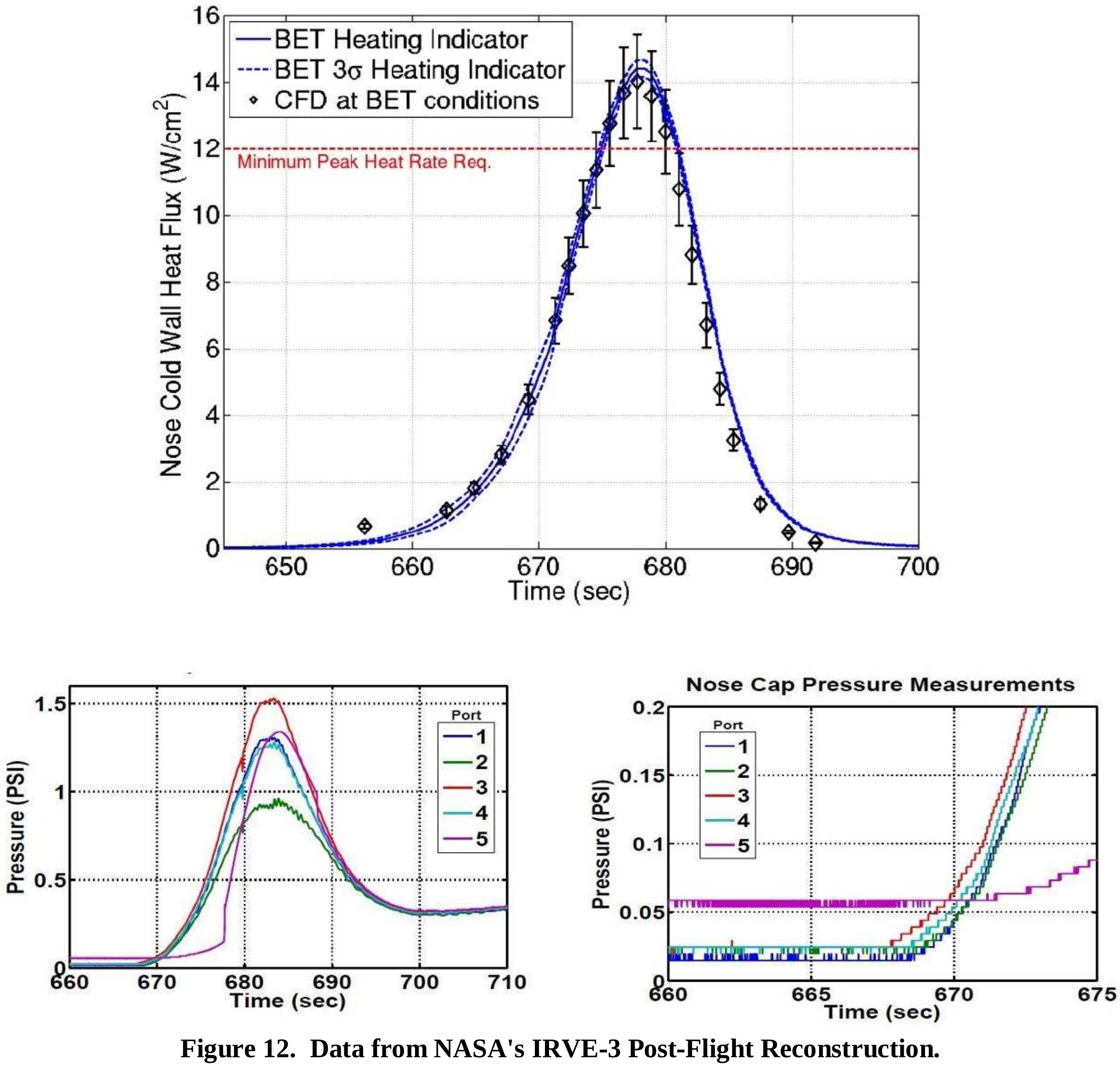



**Figure 12. Data from NASA's IRVE-3 Post-Flight Reconstruction.**

From the data above, it can be seen that the most severe portion of the deceleration of IRVE-3, and the only significant heating, was a period of about 30 seconds.

NASA's focus on heat flux made temperature data hard to find in IRVE materials, but "Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators", Joseph A. Del Corso, *et. al*. , *NASA Langley Research Center* and *NASA Glenn Research Center*, does indicate test conditions used in two test facilities. IRVE tests to date may not be achieving especially high temperatures, but lab tests are taking these materials to the 1200-1400 C ranges, with maximum gas temperatures (at 8 torr) exceeding 1500 C.

**Layups**

NASA used a variety of fabric "layups" during the design and experimentation phases of IRVE. The key material is a high-temperature fabric manufactured by 3M called Nextel 312, or several similar fabrics such as Nextel BF-20. Nextel is aluminoborosilicate fibers, with variants capable of handling up to 1370 C. Some configurations used several layers of Nextel, backed by relatively thin layers of Pyrogel 3350 (an aerogel capable of handling 1100 C) as thermal insulation. Since neither Nextel nor Pyrogel is airtight, there was typically a bladder (Kapton Kevlar Laminate was mentioned) inside to hold the inflation gas (usually nitrogen). Some insulation was needed to protect the bladder, as clearly a loss of inflation during re-entry is a *Bad Thing*. Layups also typically included a "structural bag."

A couple of comments were found on Pyrogel in the referenced documents which are worth mentioning. "Pyrogel® is a high-temperature flexible insulation blanket formed of silica aerogel and reinforced with a non-woven, carbon- and glass-fiber batting. The maximum one time use temperature is 1100$^{o}$C." "Pyrogel 3350, initially believed to be a much lower temperature insulating material, was discovered to be capable of sustaining significantly higher temperatures than expected, when during a run the outer fabric and outer insulator layers of the layup sheared away, exposing the Pyrogel 3350 backing insulator directly to Mach 7 flow for duration of nearly 70 seconds."

I quote the Pyrogel comments because my impression of polyisocyanurate has parallels. For one-time short exposures, polyisocyanurate foams seem able to withstand temperatures far in excess of their normal ratings. Even the charred material retains a foam structure. It does shrink, but maintains roughly its original shape. And, unlike most aerogels, it can be dispensed and set rapidly.

## Rapid Dispensing of Foam

An amusing test was performed in the summer of 2013 on two cans of Great Stuff® foam, a single-component product with some chemical similarity to the polyisocyanurate foams investigated for SPEARED. One formulation of Great Stuff is intended for use as a fireblock. While these do not set up as quickly, they dispense *very* quickly. I made a short video of one can as I punctured it with a pellet rifle to see just how fast one might possibly dispense foam. http://youtu.be/zssTcR-SGSg

## 2013 CG-200 200,000 BTU/Hr Compressed Air/Propane Tests

The shortcomings of the original tests with the small propane torch were apparent. Its main advantage was that it was cheap and available, on a zero budget backyard science test. It was also apparent that the test configuration was flawed. Combustion products from the flames were aspirated back into the torch. A new test configuration with the torch *below* the test article was preferable. And to get more dynamic pressure while assuring clean air for combustion, it was decided to try a compressed air/propane torch.

The HIAD and IRVE papers use heat flux almost exclusively to describe the thermal stress encountered by a heat shield, but the real analysis goes deeper. The full set of calculations would require knowing the balance of heat in versus heat out. The heat shield will radiate heat away (the rate of radiation is a function of temperature), conduct it away by gas, carry it away by ablation, or carry it by conduction to the inside of the spacecraft. The net result is that the heat shield gets hot. Since our heating mechanism would need to get our heat shield hot in an environment very different from an actual re-entry, likely all those heat loss mechanisms would be way off from actual flight conditions. But an actual temperature was something we could measure.

I reasoned that direct measurement of heat flux was a fairly meaningless in this case. The material we were testing is an excellent thermal insulation, so little of the applied heat would actually flow through the sensor into the material if we just placed the sensor on the flame-exposed face. I felt that temperature and dynamic pressure were the more important parameters. We had a vague 1260 C target temperature from the IRVE program, and much lower actual temperatures from IRVE-3. The small torch could just reach 1260 C under perfect conditions, and we hoped to find a torch which exceeded that temperature and had a more realistic dynamic pressure.

Interestingly, when looking at the NASA IRVE tests, I noticed that IRVE-3 carried a heat flux sensor, but they didn't use it. They also recognized that a heat flux sensor on an insulated surface would tell them little, and had made a special spot in the nose of the decelerator that had nothing behind it, just for that purpose. In their reports, they did not use the readings from their heat flux sensor, but instead implied heat flux from other measurements.

And, in "Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators", Joseph A. Del Corso, *et. al*., *NASA Langley Research Center* and *NASA Glenn Research Center*, I discovered that they had tested the candidate lay-ups of fabrics using a fuel-air combustor. Admittedly, that combustor was part of a hypersonic wind tunnel, which would have been sweet, but we were on a budget that prohibited multimillion dollar equipment.

With that information in hand, we looked at available torches we thought we could afford. The Burners Inc.® CG-200 looked like a good bet. The output is rated at 200,000 BTU/Hr. That converts to roughly 60 kW (adding a digit of precision on a torch with a highly variable output would be unwarranted). Applied to a 12 inch square test article, (30.5 cm square) we clearly would have more heat flux aimed at the test article than the IRVE test data indicated was anticipated or produced in their test flights. In fact, we could come pretty close to normal re-entry conditions of higher ballistic coefficient shapes and masses such as a shuttle.

Implied heat flux to foam squares: 60 kW / (930 $cm^2$) = 65 $W/cm^2$

IRVE3 peak heat flux: 14 $W/cm^2$

Peak heat flux during the Columbia accident: 98 $W/cm^2$

The estimate above assumes uniform heat flux across the test article surface, but the most cursory examination will show that the flame front from the torch was anything but uniform. It was concentrated into a stream perhaps 10 cm in diameter, and the test specimens had a circular area in the center with more severe damage than the periphery. Treat the estimate above as conservative for the center of the specimen. Likely the heat flux in the center of our foam specimens meets or exceeds the heat flux in typical heat shields for crewed spacecraft returning from Low Earth Orbit.

I found that, properly adjusted, the CG-200 flame could reach 1370 C (the temperature of a type K thermocouple re-radiating orange hot in the flame), and routinely exceeded the temperature of the small torch used in the earlier tests.  That's only 200 C less than the combustor temperature of the hypersonic system mentioned above, but hot enough to equal the temperature limits for the fabrics under consideration.  The hypersonic system operated at 8 torr, but the estimated atmospheric pressure for the torch tests is around 713 torr, so the flame density is much higher with the torch.

The remaining question was, would the CG-200 produce interesting dynamic pressure?  Based on the IRVE Design Overview, the value of 600 Pa was used in early IRVE designs.  Later, more in-depth study suggested pressures about an order of magnitude higher were produced on IRVE-3.  Burners Inc. was nice enough to try a dynamic pressure reading on one of these torches in a test oven, and was unable to get 600 Pa, but did produce a lot higher than normally aspirated torches.  After finding out our proposed test configuration, the engineer thought we might be able to come pretty close.  Based on this, the purchase was made.  Also purchased were an adjustable propane regulator and a hose to connect the torch system, as the connections on these components are not hardware-store items.

In practice, we rarely saw above 400 Pa from the CG-200, but it was a vast improvement over the smaller torch.  We did attempt to increase dynamic pressure using a blower. The CG-200 uses compressed air but also aspirates ambient air, and Burners Inc. thought a blower would help.  In practice, we saw little if any improvement in dynamic pressure using the blower.

http://www.burnersinc.com/pages/cgtorches.html

3M® was suspicious of us and was not forthcoming with samples of Nextel 312®, so I identified a silica fabric intended for protecting surfaces from weld spatter, sold by McMaster-Carr.  They also provided alumina ceramic tubes to make a high-temperature pitot tube and insulators for the thermocouples directly exposed to the torch flames.

http://www.3m.com/market/Industrial/ceramics/materials/fabric_312.html

Keep in mind, also, that in the final form a SPEARED device would have a fabric envelope of Nextel 312 or a close relative, already being tested in HIAD/IRVE applications.  It is this material which will take the hypersonic dynamic pressure exposure.  The foam behind the fabric will not be exposed to hypersonic flow.  Building construction foams of this sort can withstand high distributed loading, however, including supporting concrete floors or entire buildings.  Adequately covered, there is little question that the pressure itself is easily handled.

A small manometer intended for measuring air duct pressures was obtained, but abandoned when the calibration appeared questionable.  A similar manometer was built using clear plastic tubing and a computer-generated scale adjusted for the fluid density used, using the original holder.  The working fluid was pink RV antifreeze, checked by a precision hydrometer for density.  This manometer appears in some of the videos and was also used to verify calibration of an electronic pressure sensor obtained for the tests.  The manometer gave a convenient visual indication of pressure during tests, and was visible on videos.  The scale markings are at 100 Pa intervals.

Pieces of the originally-tested foam insulation were used for the preliminary tests, but the real intent was to try rapidly-deployed polyisocyanurate foam insulation.  Because the test articles would be as small as the budget, the larger kits intended for bulk insulation were considered excessive. Generally, these are intended to be completely used within a few hours of initially dispensing foam, and the mixer wands supplied cannot be reused at all as the foam is very quick-setting. We looked into the small patch kit available from Foam-It Green:

http://www.sprayfoamkit.com/products/spray-foam-kits/foam-it-12-patch-a-repair-kit-detail

A consultation with their sales department suggests that the Foam-It 12 kit has a somewhat different foam formula than their larger kits, so the results below may not be representative of the larger kits. Our hope was that the small kit would produce sufficiently promising results to warrant larger-scale tests. We were also particularly interested in testing the foam quickly after dispensing was completed, since our application requires that the foam set quickly enough to protect astronauts in an emergency ejection-seat situation. In any case, it is unlikely that an off-the-shelf foam would be used as-is for spaceflight, and we assumed that additional development would be called for. Our goal was simply to see if this material is “close” to being adequate.

## Equipment and Materials

Foam:

Atlas Energy HF4191
Foam It Green “Foam It 12” patch kit.

Burners Inc. Torch:

Torch: CG-200 200,000 BTU/Hr Compressed Air/Propane
Regulator: 1200-3057 Regulator, 3-30 psig, 750,000 BTU/hr, vapor
Hose: custom assembly, 6 ft

Thermocouples: Type K, Omega Engineering

GG-K-24 (24 AWG fiberglass insulated) used for flame face exposure
TT-K-30 (30 AWG Teflon insulated) used for lower temperatures
Assorted miniature Type K thermocouple connectors

Data Acquisition System

UEILogger 600 Data Acquisition Chassis
DNA-AI-207 16 Channel 18-bit A/D Card
DNA-STP-37 Terminal Block with ice-point circuit added.

Pressure Sensor

Freescale Semiconductor® MPX2010DP 10 kPa full scale, ratiometric
Hand-built 10 V supply based on 7810 regulator (gives 10 kPa = 25 mV out)

McMaster-Carr Items

| | |
|---|---|
| 8851K33 | High Temperature Silica Fabric Sheeting, 0.090” thick |
| 87175K77 | Non-Porous High Alumina Ceramic Tube, 2-bore, 0.125” OD x 0.040” ID (Used for insulating 24 AWG thermocouples exposed to flame) |
| 8746K342 | Non-Porous High Alumina Ceramic Tube, 0.187 OD, 1/8” ID (Used for high temperature pitot tube) |
| 9245K15 | Machinable and Bendable Clear PETG Tube, 5/16 OD, 3/16 ID (Used for manometers) |

Manometer Fluid: Easy-Go -50 pink propylene glycol RV antifreeze solution, 1.0365 SG

Propane Supply: Blue Rhino® 20 lb cylinder, regulator set at 20 psig.

Air Compressor: 2.6 CFM, regulator set at 90-92 psig. Note: this air source is below the 3 CFM recommended by the torch manufacturer. Output air pressure was not monitored continuously, but early tests suggest it dropped to about 80 psi during the tests.

Backing boards for mounting foam: Generic 3/8” thick concrete siding, similar to HardiePanel®.

Misc. Supplies: Steel wire, steel pipe hangar straps, aluminum tape, steel machine screws.

Test Altitude: 1840 ft MSL. For 760 torr at sea level, this gives 95 kPa (713 torr)

## Early Trials with Original Atlas Foam Test Specimens

Figures 13 and 14 show the earliest configuration of the basic test frame. The lower portions are 2x4 dimension lumber, and the upper portion is assembled from perforated steel angles, using common hardware. Two U bolts allowed a vertical pipe to be adjusted, moving the supports for the foam specimens. The support consisted of two squares of concrete siding panel, which in the actual test configurations were spaced slightly using nuts or washers to reduce heat conduction. The upper panel was attached using screws to a piece of 2x6 dimension lumber, which in turn attached to the pipe using a threaded mounting flange. The alumina pitot tube was routed thru a hole in the flange and holes drilled in the panels.

The pitot system was a chronic problem. The amount of heat reaching the pitot plumbing was not anticipated in the early configurations. Aquarium hose was initially used to carry pressure to the manometer (seen on the left staunchion of the frame) and pressure transducer. This melted through in spite of several attempts to cover it. Later, copper tubing was attached to the upper end of the pitot tube to avoid melt-through, but prolonged application of heat degraded the silicone sealant used to seal between the alumina and copper. Consequently, many of the tests lack reliable dynamic pressure readings.

After several early tests without foam, the wooden board above the concrete panels was badly charred, and was replaced by a section of concrete 1x6 trim board. At that point, the concrete panels had also been damaged and were replaced by fresh sections. Most of the damage was incurred during preliminary tests with no foam in place.

**Figure 13. Test frame under construction.**

**Figure 14. Closer view. Manometer on the left.**

**Figure 15. Back foam panel. Aluminum tape covers the sandwich thermocouple.**

**Figure 16. Lower foam panel installed.**

Several tests on just the concrete panel supports and on the Atlas foam were performed to work out the bugs. The procedure that evolved was to watch the sandwich thermocouple temperature, and terminate the test when it rose dramatically. This resulted in the consistent degree of burn-through seen in these tests. Typically the lower foam panel was charred to chunks by the end of the test, and the back panel was blackened about half way through its thickness.

**Figure 17. Flame ON!**

**Figure 18. Typical result: lower panel completely charred, back panel is charred about halfway through. (Panels are inverted from the test configuration.)**

The data acquisition system for these tests was configured as follows. Individual tests configurations varied. Usually the #1 thermocouple was not used. The flame thermocouples, 3 and 4, were GG-K-24, stripped back and with the wires inserted through the 2-hole alumina tubes. All of the thermocouples were made from the wire specified, spot welded by the experimenter.

The data acquisition system resolution was 18 bits. The data acquisition scan rate was 10 Hz.

The thermocouple sensitivities were set to full range, -260 to 1370 C, except as indicated for Ch 0. The pressure sensor sensitivity was +/- 0.0.025 V, with a scale of 136 + 400370 x.

The pressure sensor data showed very high noise levels when the flame was on. This was reduced in post-processing using a moving average. The pressure sensor was also subject to high bias drift, and the system tended to develop leaks.

| Ch. | Sensor |
|---|---|
| 0 | K Thermocouple, Ambient (-260-300 C range, TT-K-30) |
| 1 | K Thermocouple, Not used in first test, behind backing in later tests |
| 2 | K Thermocouple, GG-K-24, Sandwich (Between front and backing foam layers) |
| 3 | K Thermocouple, alumina sheath, in upper part of flame |
| 4 | K Thermocouple, alumina sheath, in lower part of flame |
| 8 | Pressure sensor (Pitot Pressure, Q), 25 mV = 10 kPa. |

The flame was on for a total of 175 seconds. Flame temperature was optimized at about 115 seconds, producing a large temperature increase, with peak flame temperature of the upper flame thermocouple reaching about 1370 C, the maximum recommended range for type K thermocouples. This exposure, a few seconds less than 3 minutes, charred the front test foam specimen totally, and charred the backing sheet about half way through its thickness. The previous test series with the small hand-held torch had never damaged the backing foam sheet, even with 8-minute exposures.

However, the heat flux in these experiments should greatly exceed anything tested in the IRVE series, including the particularly severe IRVE-3 test, and the duration of peak heating on IRVE3 was only about 30 seconds.

Video Link: http://youtu.be/K9V5lFZnDog

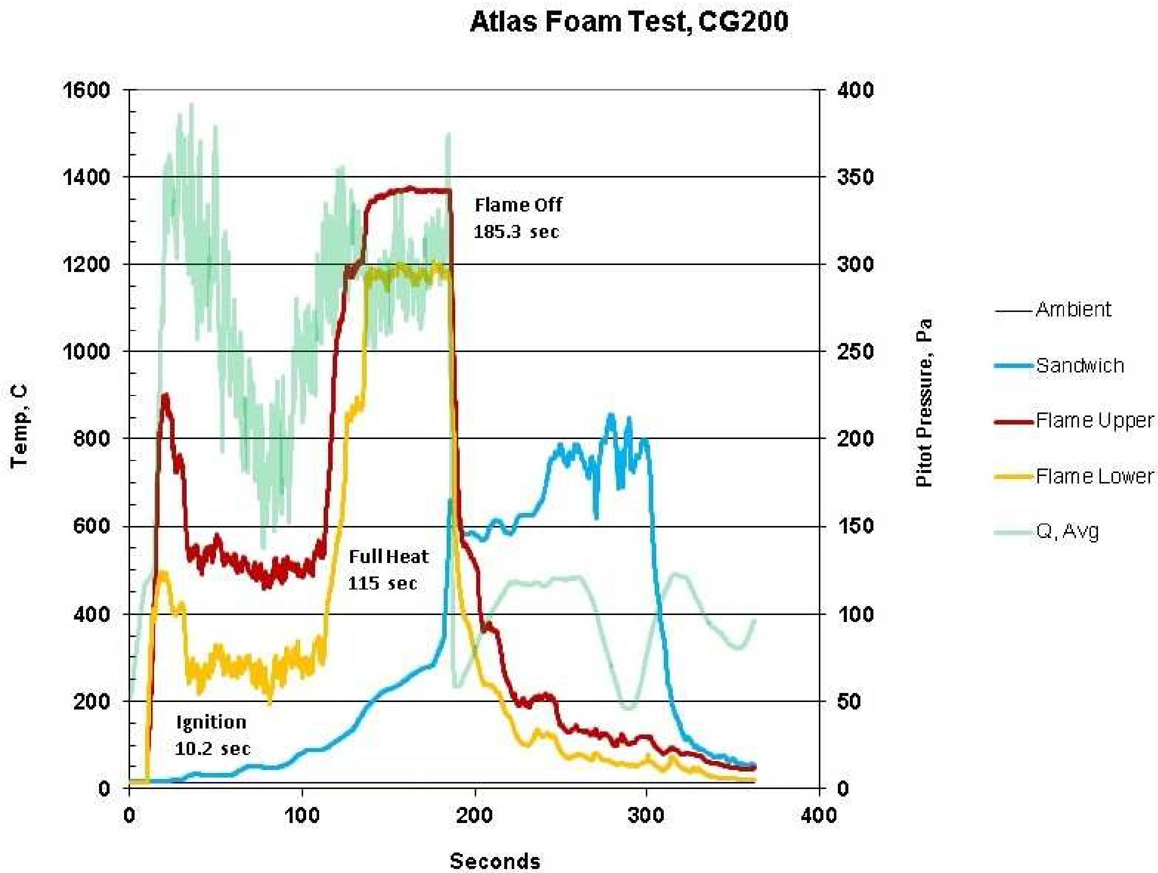



**Figure 19. Temperature and pressure record for the plain Atlas foam test.**

## Silica Fabric Overlay

The high-temperature welders blanket material from McMaster-Carr is described in there catalog as:

> High Temperature—The fabric's thickness (0.090 inches) makes it resistant to higher temperatures than flexible sheeting and strips. Maximum temperature is 2300°F. Color is off-white.

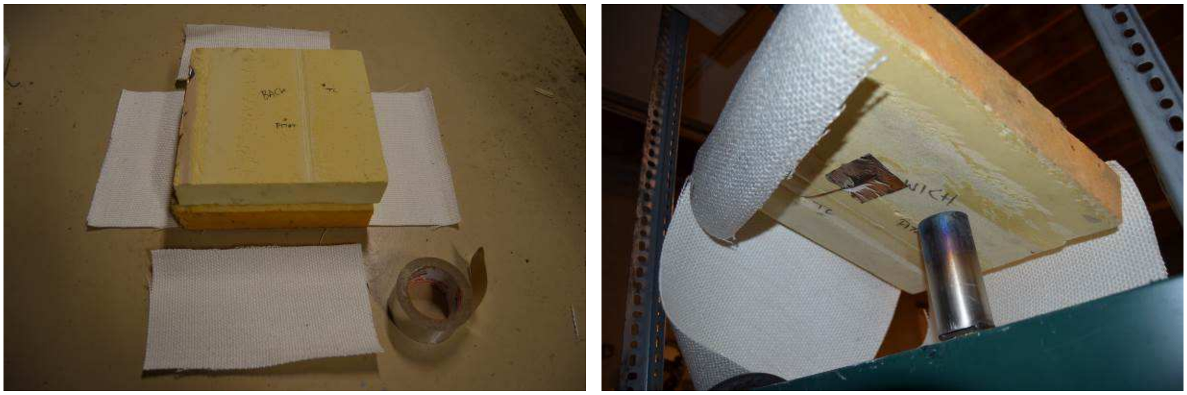


**Figure 20. The wrapping layout of the foam sections for the silica fabric overlay tests. Three pieces were used to achieve a 5-sided wrap.**

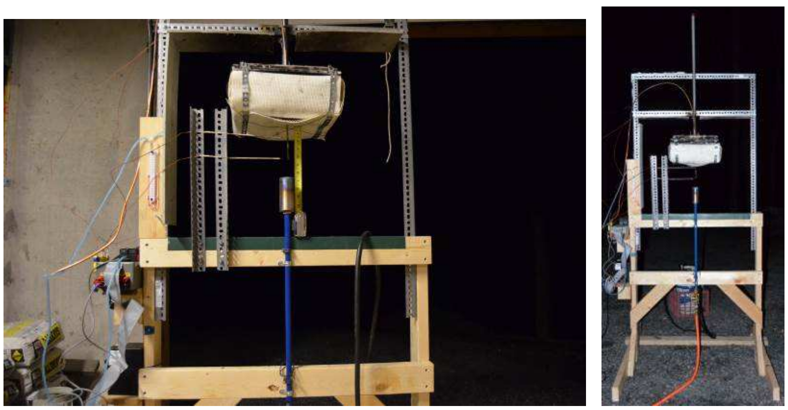


**Figure 21. The wrapped Atlas foam blocks were secured by two steel pipe hanger straps.**

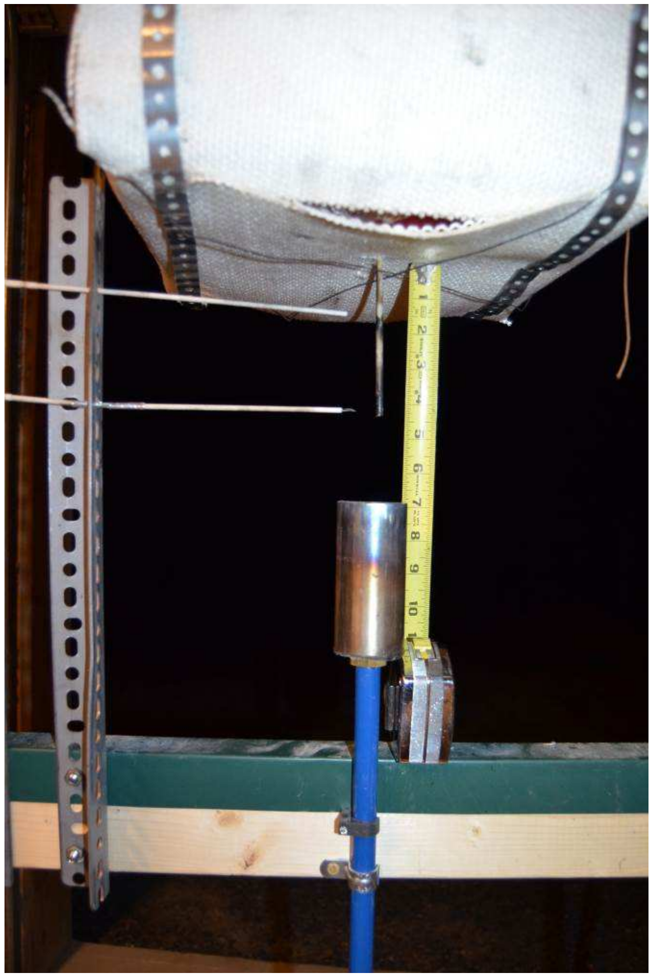


**Figure 22. The fabric was not installed tightly. Two edges were open and the face exposed to the flame did have a significant gap between the fabric and the foam.**

The fabric did appear to add significant protection. While the foam experienced about the same amount of damage as seen in prior tests (due to using sandwich thermocouple temperature as the end-of-test indicator), the duration of the burn was significantly longer, 354 seconds versus 175 seconds. Following the test, the silica fabric was still as pliable as before the test, although quite sooty.

http://youtu.be/0WjGwsqhRkY

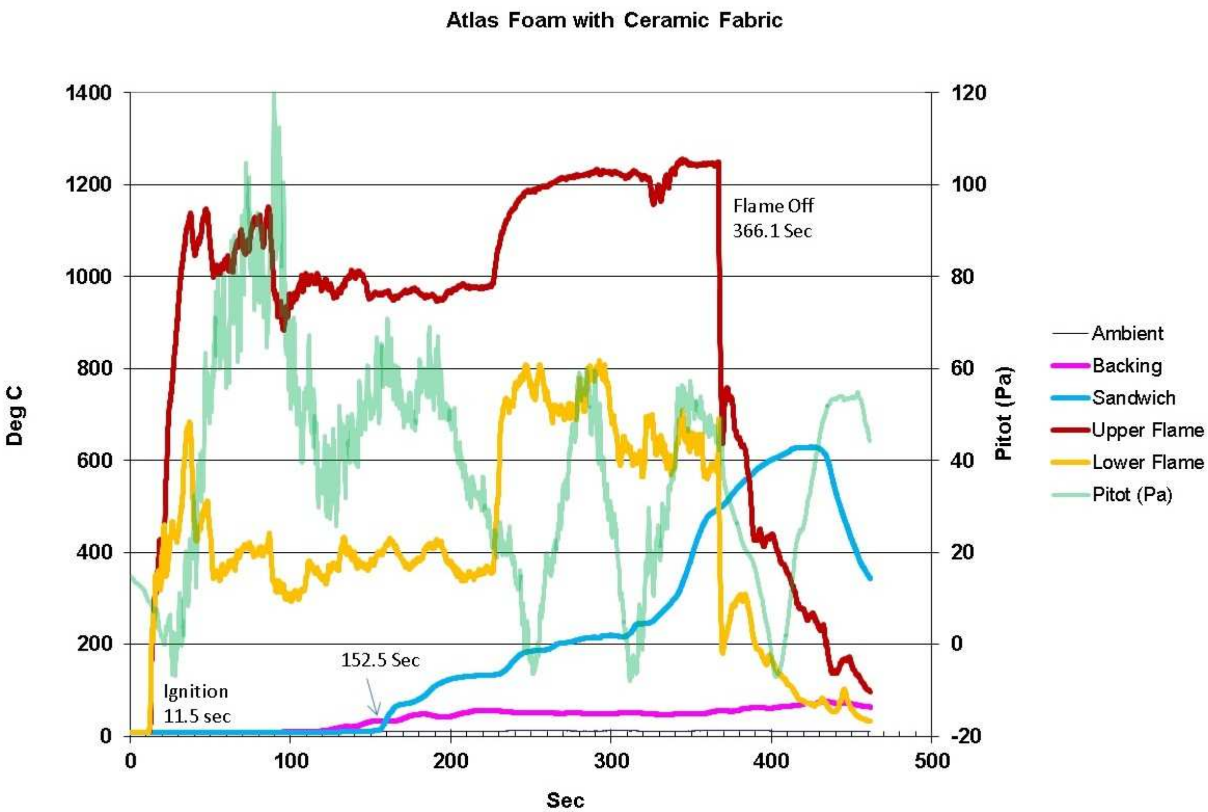



**Figure 23. Temperature and pressure record of the Atlas foam test covered with ceramic fabric. Note the greatly increased duration compared to uncovered Atlas foam. The backing thermocouple was used in this test and did not exceed 100 C. Pitot pressure may have been limited by poor placement of the pitot tube (see side video view).**

## Dispensed Foam Cone Test

The left figure below is an illustration, courtesy of NASA, of the IRVE test heat shield. The 120º cone shape qualifies it as a "blunt body". The proposed dimensions of the test article are shown on the right in inches. A poster-board form in the shape of the cone portion was prepared, and lined with waxed paper to assure release. The foam dispenser was kept indoors at about 70 F, per the manufacturer's directions, until immediately prior to dispensing. The foam was dispensed as shown below, and the form was overfilled several cm to provide material to press into a backing square of Atlas foam. The cone was pressed into the backing square before it could set up significantly. Two steel pipe hanging straps holding the backing square became imbedded in the foam cone, helping hold it in place.

The foam dispensed in 33 seconds, set to a gelatinous semi-firmness in about a minute, and was quite firm by 112 seconds after dispensing was complete. The resulting cone was about 9 cm deep at the vertex. To test as quickly after dispensing as possible, we eliminated the pitot tube. The flame was lit 388 seconds after dispensing was complete.

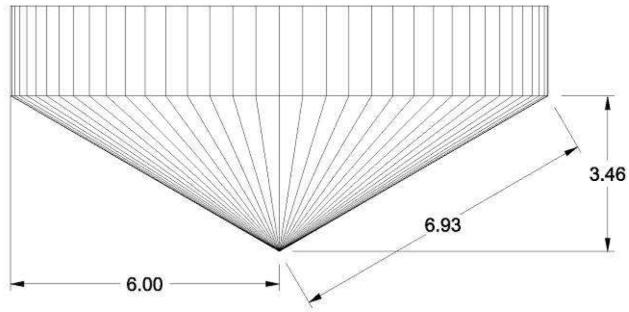



**Figure 24 The foam specimen shape was based on NASA's IRVE inflatable heat shield. The cone angle is 120 degrees. Art on the left courtesy of NASA.**


**Figure 25. Form for producing the cone-shaped specimen.**

**Figure 26. Backing foam piece with sandwich thermocouple.**

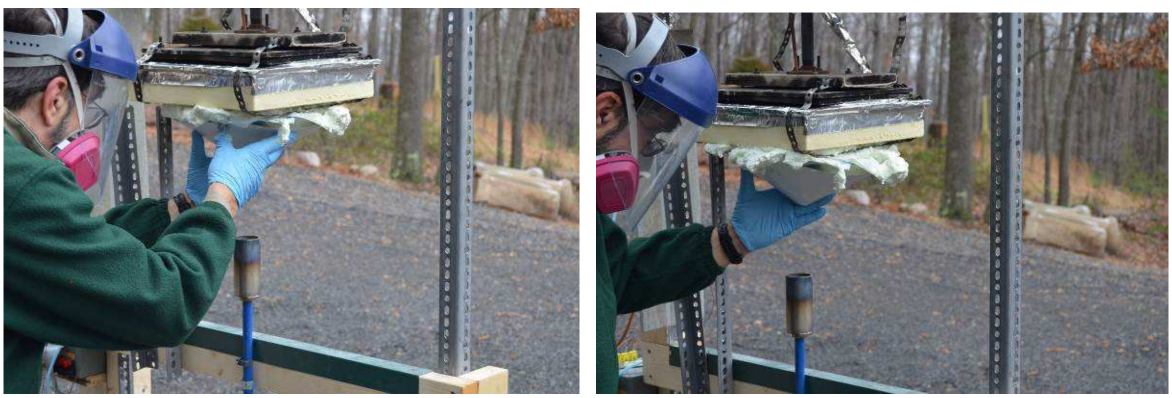


**Figure 27. Pressing foam cone specimen onto backing foam.**

**Figure 28. Foam cone ready to test. Some waxed paper remained on the cone but is unlikely to have affected the test significantly**

**Figure 29. Views of the foam cone after the test.**

**Figure 30. The foam cone was reduced to an open charred form during the test, but about 3 cm remained of the backing foam.**

For the two-component foam cone test, the pitot tube was not used. Data from the pitot tube had not been as reliable as desired, and it was felt that the time required to insert the tube through the test specimen would increase the time between dispensing the cone and starting the torch. However, an additional thermocouple was used on the top side of the backing foam piece. This is identified as the Backing thermocouple in the data. It is noteworthy that the backing thermocouple temperature barely budged during the test of the foam cone.

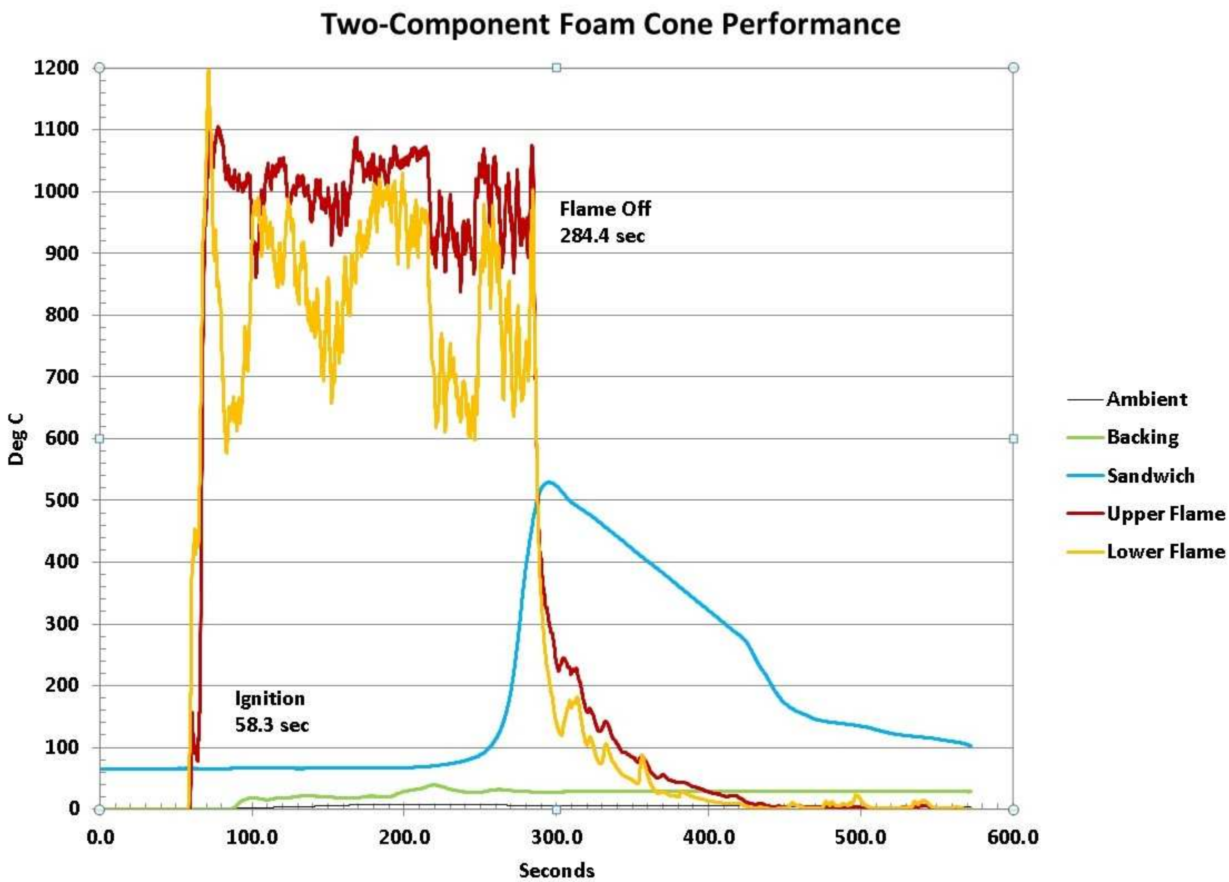



**Figure 31. Temperature performance of the two-component foam cone.**

The test duration for the two-component foam cone was 226 seconds, somewhat longer than the unprotected Atlas foam. The amount of heat penetration was comparable. Without a doubt, a covering of the silica fabric would have provided similar benefits for the cone, but that test will have wait for a later opportunity, hopefully with some funding.

http://youtu.be/fwztkGGnAlg

Notice that the "Backing" thermocouple, installed above the foam backing sheet, barely heated up. While the backing sheet itself suffered the usual charring on the hot side, it retained sufficient insulating ability to prevent runaway heating. Just a little additional insulation (the ejection seat and a space suit, for example) would have been sufficient to protect a person for this duration of heat exposure.

This test demonstrated that a quick-setting two-component foam can set up quickly to sufficient firmness and provide comparable resistance to high heat flux to the Atlas foam. This was a key step to demonstrating the suitability of this type of product for the intended astronaut rescue application.

## Conclusions

Polyisocyanurate foam is remarkable stuff, and we recommend that it be considered, in conjunction with materials such as are being investigated for inflatable hypersonic decelerators, as a key component of Single Person Emergency Atmospheric Re-Entry Devices.

We have demonstrated the ability of off-the-shelf two-component insulating foam to form and set quickly. The resulting foam can, with no additional protection, withstand high heat flux and combustion temperatures, at modest dynamic pressure, far in excess of those so far encountered in IRVE flight tests, and close to those used in combustion-heated hypersonic wind tunnel tests of IRVE materials.

The Atlas foam tests demonstrate that these materials can be expected to perform substantially better with a modest layer of high temperature fabric.

We believe that 2-component polyisocyanurate foam may allow simplification of the IRVE layup schemes, providing the desired insulation while eliminating the need for a bladder. Filling the decelerator with rigid foam should reduce aeroelasticity and eliminate the threat of deflating the structure.

We believe that the SPEARED device is feasible, and urge its consideration for future crewed missions. While the tests documented above are certainly just a starting point, they seem sufficiently promising to be worth further investigation.

## Links

Stephanie Osborn

http://www.sff.net/people/steph-osborn/

Stephanie's Shuttle accident novel, Burnout, written prior to the Columbia accident, and remarkably similar to it:

http://www.sff.net/people/steph-osborn/burnout.html

Arlan Andrews:

http://www.amazon.com/gp/aw/d/B007Z5Y3R4/ref=redir_mdp_mobile?ref_=sr_1_6&s=books&qid=1335880566&sr=1-6
For my novel, VALLEY OF THE SHAMAN
http://www.amazon.com/gp/aw/d/B005BZKWTI/ref=redir_mdp_mobile/190-4958131-6132753
For my anthology, OTHER HEADS & OTHER TALES.

Tom Ligon: http://www.tomligon.com/

Analog Science Fiction and Fact: http://www.analogsf.com/

NASA HIAD and IRVE References

*Please note that we have no control over these external links, which may be subject to change. Our apologies if they fail to work. These resources are out there and may be located using their titles.*


"The Big Picture," NASA Space Technology Mission Directorate, http://www.nasa.gov/directorates/spacetech/game_changing_development/HIAD/big-picture.html

"IRVE-3: Inflatable Heat Shield a Splashing Success, 7/23/2012," NASA Space Technology Mission Directorate, http://www.nasa.gov/directorates/spacetech/game_changing_development/HIAD/irve3-success.html

"Inflatable Re-entry Vehicle Experiment (IRVE) Design Overview," NASA Langley Research Center, Hampton, VA, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050182124_2005183200.pdf

"Structural Analysis and Testing of the Inflatable Re-entry Vehicle Experiment," NASA Langley Research Center, Hampton, VA, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060013504_2006014732.pdf

"IRVE-3 Post-Flight Reconstruction," NASA Langley Research Center, Hampton, VA, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130013398_2013013188.pdf