PAD A MAIN FLAME DEFLECTOR SENSOR DATA AND EVALUATION

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ABSTRACT

Space shuttle launch pads use flame deflectors beneath the vehicle to channel hot gases away from the vehicle. Pad 39 A at the Kennedy Space Center uses a steel structure coated with refractory concrete. The solid rocket booster plume is comprised of gas and molten alumina oxide particles that erodes the refractory concrete. During the beginning of the shuttle program the loads for this system were never validated with a high level of confidence. This paper presents a representation of the instrumentation data collected and follow on materials science evaluation of the materials exposed to the SRB plume. Data collected during STS-133 and STS-134 will be presented that support the evaluation of the components exposed to the SRB plume.

INTRODUCTION

Refractory concrete is currently used on the main flame deflector at KSC's Launch Complex 39. It has been in use since 1966, when it was determined to be a suitable design solution to protect the main flame deflector steel structure. During the STS-124 MIT Flame Trench Failure Investigation, the team recommended that the space shuttle program should instrument the flame trench area as soon as possible. This information is critical for understanding the dynamics environment of the flame trench and to improve current computational fluid dynamic models for both the space shuttle program as well and the constellation program. [1,2]. In addition, an observation was presented which cited that "the MIT noted numerous recorded refractory concrete liberation events". Both of these report findings established the basis for the initiation of a project to capture the induced loads on the flame deflector and flame trench.

The predicted environments the refractory concrete should be qualified to the Specification for Refractory Concrete, KSC-STD-P-0012. This standard required a material to be subjected to 3300 Btu/ ft2-sec for 10 seconds[8], while a later publication required 5880 Btu/ ft2-sec for 10 seconds [7]. Microstructure evaluation of the refractory concrete revealed the presence of a synthetic fiber (T_m ~ 340 Deg F) which remained intact on the hot face post launch. Based on the predicted heating rates and post heat treatment microscopy should form a melt phase in the pore space, which was not observed.

Measuring the induced loads on the main flame deflector to the calculated loading environment required a custom designed instrumentation suite to collect the required data in the remaining shuttle flights to provide valuable date to future programs. United Space Alliance was contracted to design, build, implement and report data on the LC39 Pad A, main flame deflector. The environmental data collected included heat rates, temperatures, pressures, accelerations and witness rod samples from specific locations on the deflector. This paper presents some preliminary environmental data collected by USA and material investigations performed to date by the NASA KSC Materials Science Division[6].

SENSOR SUITE OVERVIEW

The sensor suite consists of a custom designed tungsten calorimeter, commercial off the shelf sensors (COTS), and witness rod at each of the 3 locations shown in figure 1. All the sensors are in the centerline, with the top suite centered directly under the solid rocket booster. Sensors were added at the bottom left and right or flame fence of the flame deflector just after STS-124, with the bottom and middle sensors spaced equidistant along the centerline between the solid rocket booster center-center position and the flame fence location. The typical detail for the sensor arrangement is shown in figure 2.

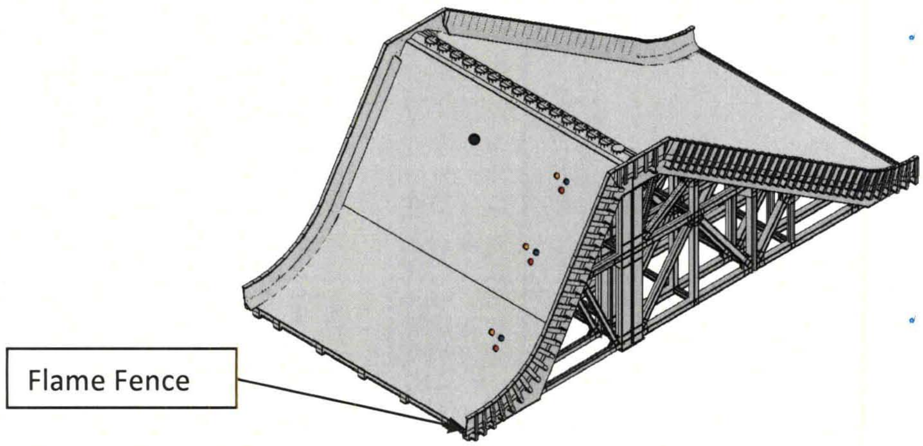

Figure 1. Main Flame Deflector Sensor Arrangement.

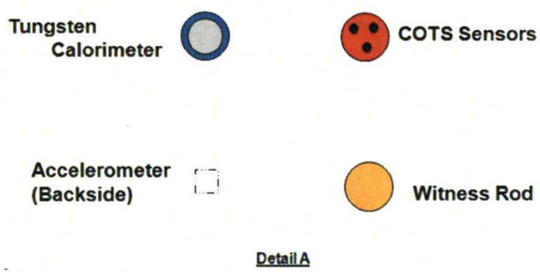

Figure 2. Typical Sensor Arrangement for each location.

MEASURED ENVIROMENT

The COTS sensor suite consisted of a Medtherm gardon gage calorimeter [5], Kullite pressure transducer and Nanmac erodible thermal couple. In figure 3, data from the erodible thermocouples show erratic inconsistent data, with data drop outs. The top and bottom sensors are non-functioning, while the middle senor shows a peak temperature of 1800 °F. The temperatures appear to low for gas temperatures, but are the same order of magnitude of thermocouple responses in the Tungsten Calorimeter.

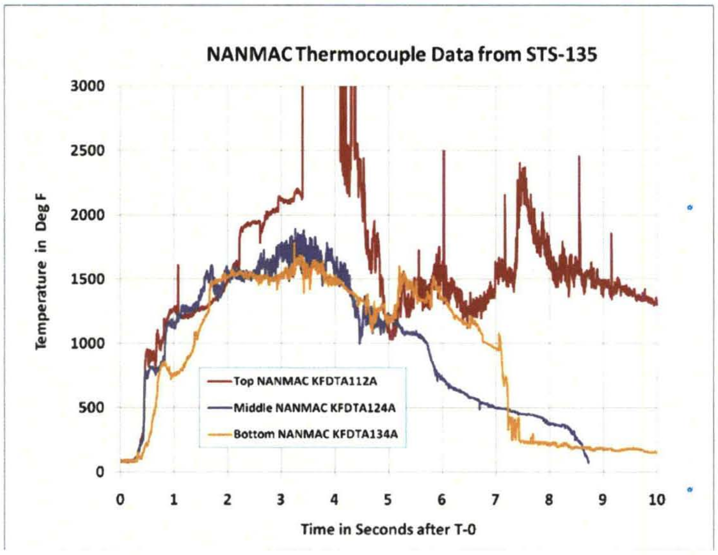

Figure 3. STS-135 Erodible Thermocouple Response.

The gardon gage response shows a consistent dynamic response with short duration spikes. For STS-133 the body temperatures exceeded the recommended limit of 400 °F, data was not corrected for this effect. The body temperatures were highest at the top and lowest at the bottom.

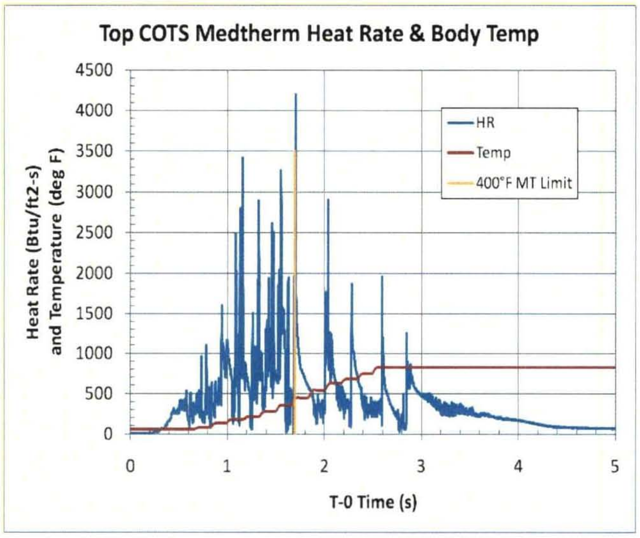

Figure 4. STS-133 Top Gardon Calorimeter Response.

Data spikes appeared once the time step was reduced, figure 5. The data spikes are theorized to be from the molten alumina particles solidifying on the small sensor area. The profiled response was consistent with all gardon gage calorimeters for all three flights during this program.

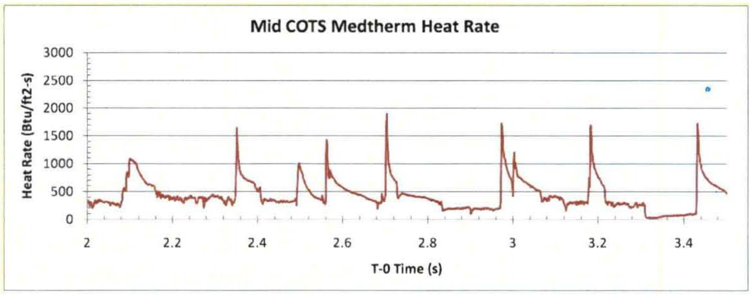

Figure 5. STS-133 Middle Gardon Calorimeter Response.

Data reduction was completed via 100 moving point average for the gardon gage calorimeter data as shown in figure 6. Heat rates range from 1000 (top) to 500 (bottom) Btu/ ft2-sec. This results in thermal loads that are 1/3 to 1/5 the original requirement as documented in thermal and pressure environmental specification.

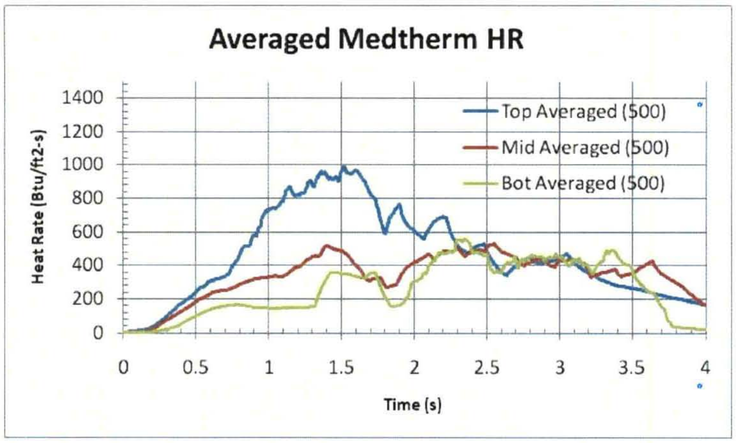

Figure 6. STS-133 Middle Gardon Calorimeter Response.

The gardon gage style calorimeters were included to gain insight into the lower temperature transient environment with the tungsten calorimeter expected to take the upper heating loads and particle impingement. Since calibrations testing to the upper limit of the requirements were not available, a dual approach to collection of heat rate data was included in the project. By comparing the response of the two calorimeters the performance of the tungsten calorimeter could be base lined. Comparisons of the heat rate data collected by both these methods are shown in figure 7.

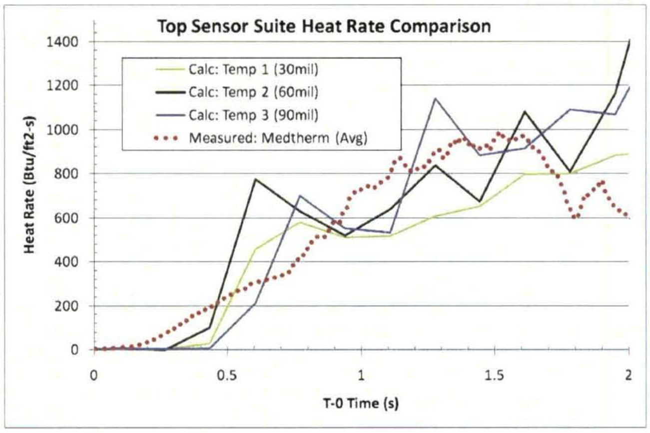

Figure 7. STS-133 Comparison of Tungsten to Averaged Gardon Calorimeter Heat Rates at Top Location.

The tungsten calorimeter is 3" in diameter and 3.5" tall, manufactured from 99.9 % pure tungsten. This material was chosen due to the high melting temperature and hardness values. The material selection was based on a parametric study of materials modeled in SingaG to the requirement heat load of 5880 Btu/ ft2-sec.

SENSOR MATERIAL EVALUATIONS

As part of the data collection, post mortem inspections of the tungsten calorimeter noted numerous circumference cracks both on the top and sides, figure 8. The metallography did not indicate any signs of melting.

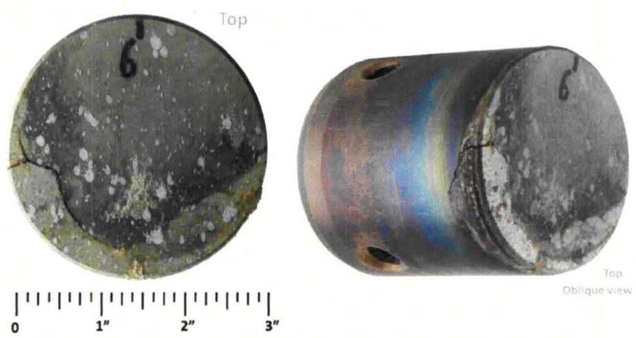

Figure 8. Top Tungsten Calorimter Post Launch.

In order to protect the sides of the tungsten calorimeter a A-286 sleeve was incorporated in the design. Figure 9 shows the top and isometric views of this piece. The tungsten calorimeter utilized an outer 17-4 housing to shield the tungsten calorimeter. The image is a micrograph of the 17-4 housing which was rotated 90° after STS-133 and reused for STS-134. At the time of this manuscript submittal the metallography and thermal response modeling data had not been completed.

Figure 8. Top A-286 Sleeve Post Launch.

The 304 stainless steel COTS caps house the gardon gage calorimeter, pressure transducer and erodible thermal couple, figure 9. By using the heat rates obtained from the tungsten calorimeter, the response of the caps could be obtained to support the microstructural investigation. The results show that the cap will reach the melting point of 2650 °F in approximately 2 seconds.

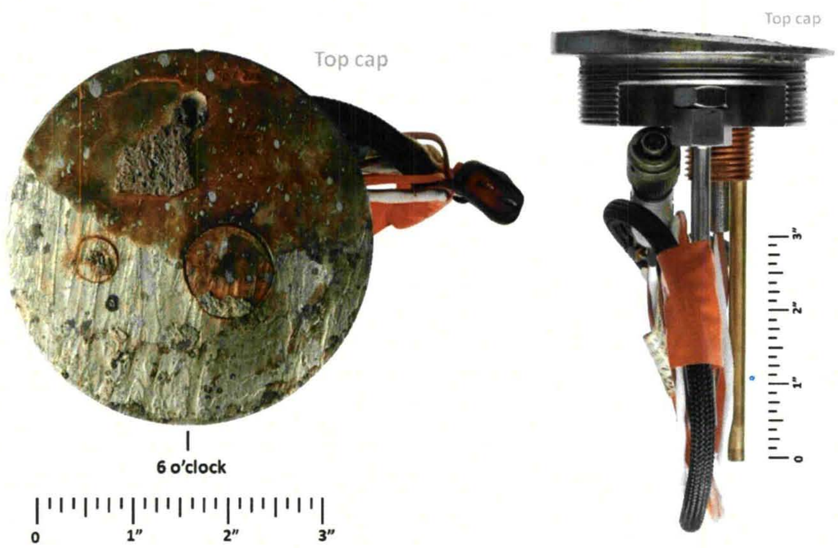

Figure 9. Top 304 COTS Cap Post Launch.

This analysis support the microstructural conclusion which show a layer of melted and 0.5 mm of resolidified metal as indicated by dendritic microstructure, while the base material is of austenitic grain structure with larger grain sizes than the parent material, figure 10.

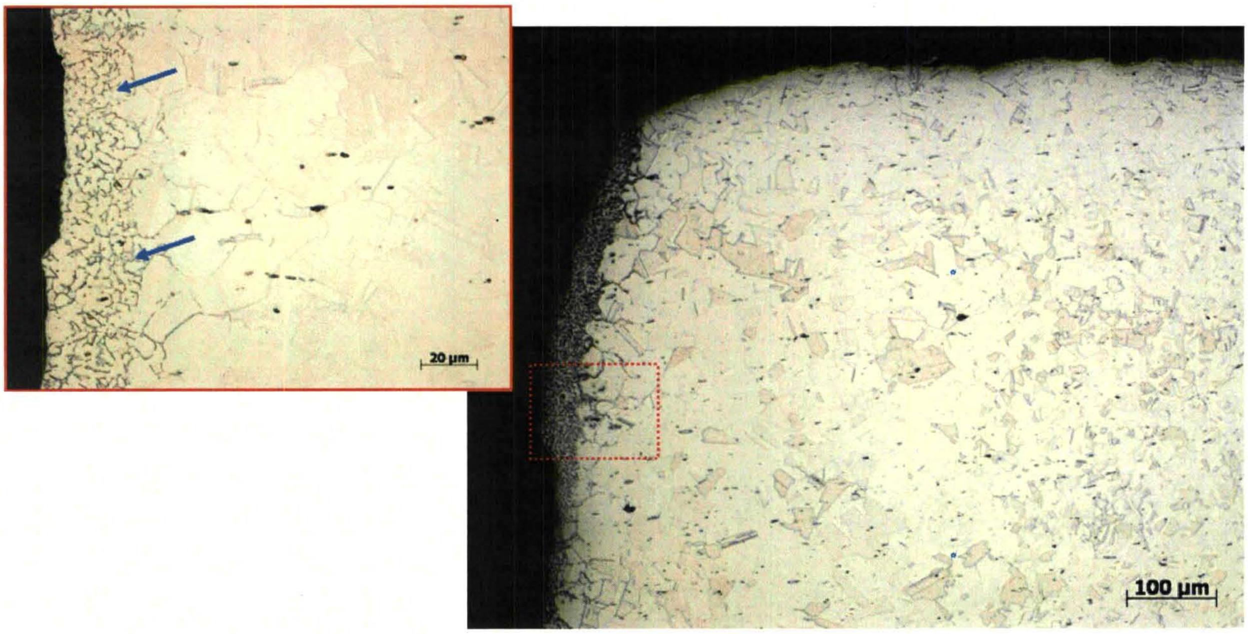

Figure 9. Top 304 COTS Cap Post Launch Original magnifications: 500X (boxed), 100X (right).

While the above materials were selected specifically to assure data integrity, HY-80 material was selected as a candidate material to replace the refractory concrete. This shift in methodology was based on previous examination of refractory concrete anchors which did not show any signs of melting. The top witness rod exhibited little erosion; the sample from the bottom location is shown in figure 10.

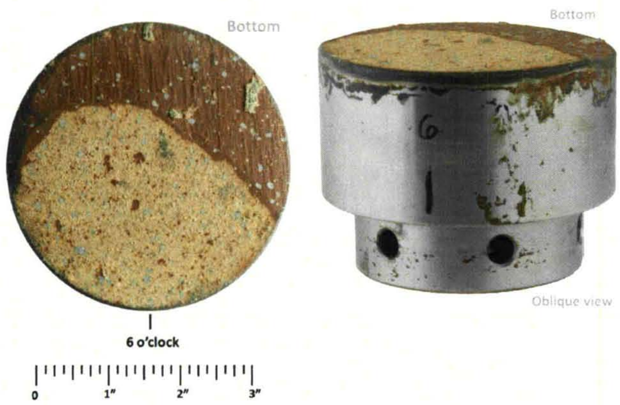

Figure 10. Bottom HY-80 Witness Rod Post Launch.

It was inconclusive from the metallography due to the possibility of the alumina particles removing any evidence of melting. No indications of melting and resolidication of the material were present on the hot face, figure 11 and 12.

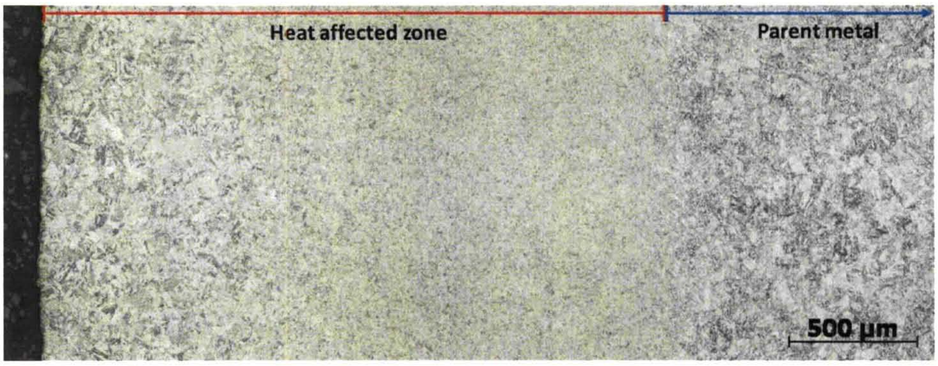

Figure 11. Micrograph of the surface of the top sample HY-80 witness rod. Original magnification: 100X.

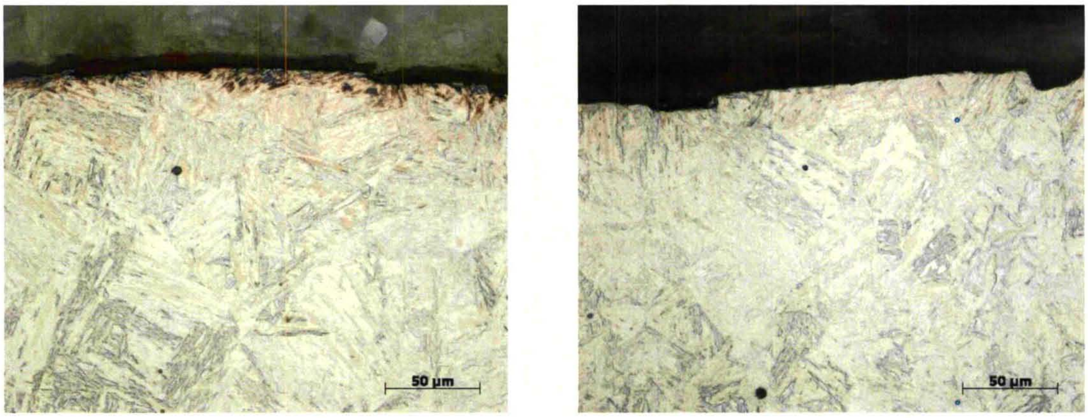

Figure 12. Micrographs at the surface of the bottom sample (left) and top sample (right) Original magnifications: 500X.

By using the method of evaluation previously described, the analysis showed the HY-80 reached 2000ºF in 2.3 seconds, which is well below the melting temperature of 2595 ºF. Erosion of 0.078" occurred with the heat affected zone turned to untemperated martensite while the hardness increased from HRC 22 to HRC 42.

During STS-134 the gardon gage calorimeter appears to have lost structural integrity fairly early in the launch event, figure 13. After failure of the sensor occurred the cooling water was ejected into the flow field at 150 psig, which protected the 304 stainless from melting or eroding downstream of the water port. This evidence is consistent with tests performed at Stennis Space Center which found that metal plates with holes drilled across the surface when cooling water is injected into the flow field[4].

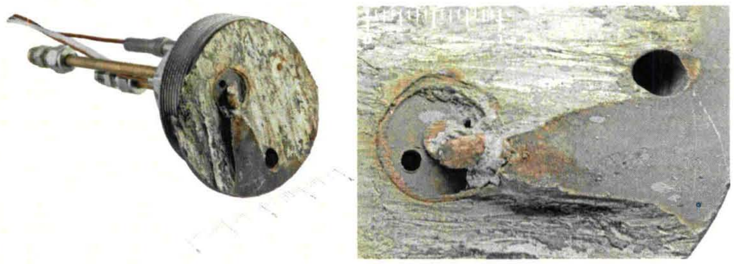

Figure 13. Bottom HY-80 Witness Rod Post Launch.

After the launch of STS-134 the material for the witness rod was changed to AISI 1018, based on the usage of the material in the solid rocket booster separation motors (BSM). These BSMs have a similar loading environment to data collected from STS-133. The material eroded 0.4 inches. The metallography and thermal analysis was not complete at the time of submission.

Figure 14. STS-134 1018 Top Witness Rod.

CONCLUSIONS

The collection of plume induced heat rates, pressures, temperatures and material witness rod materials in the space shuttle solid rocket booster environment was presented. The selection of materials for this environment can be performed by analysis, but often over constrains the design solution due to errors in the models. Verification of the environment in a solid rocket plume is possible by the use of a combination of techniques.

CONTACT

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7. National Aeronautics and Space Administration. Environment and Test Specification Levels Ground Support Equipment for Space Shuttle System Launch Complex 39, GP-1059 Volume IV, 1992

8. KSC-SPEC-P-0012, Specification for Refractory Concrete, National Aeronautics and Space Administration, 1979

Pad A
Main Flame Deflector (MFD)
Sensor Data & Evaluation

Presented By

Chris Parlier

Thermal & Fluids Analysis Workshop

TFAWS 2011

August 15-19, 2011

NASA Langley Research Center

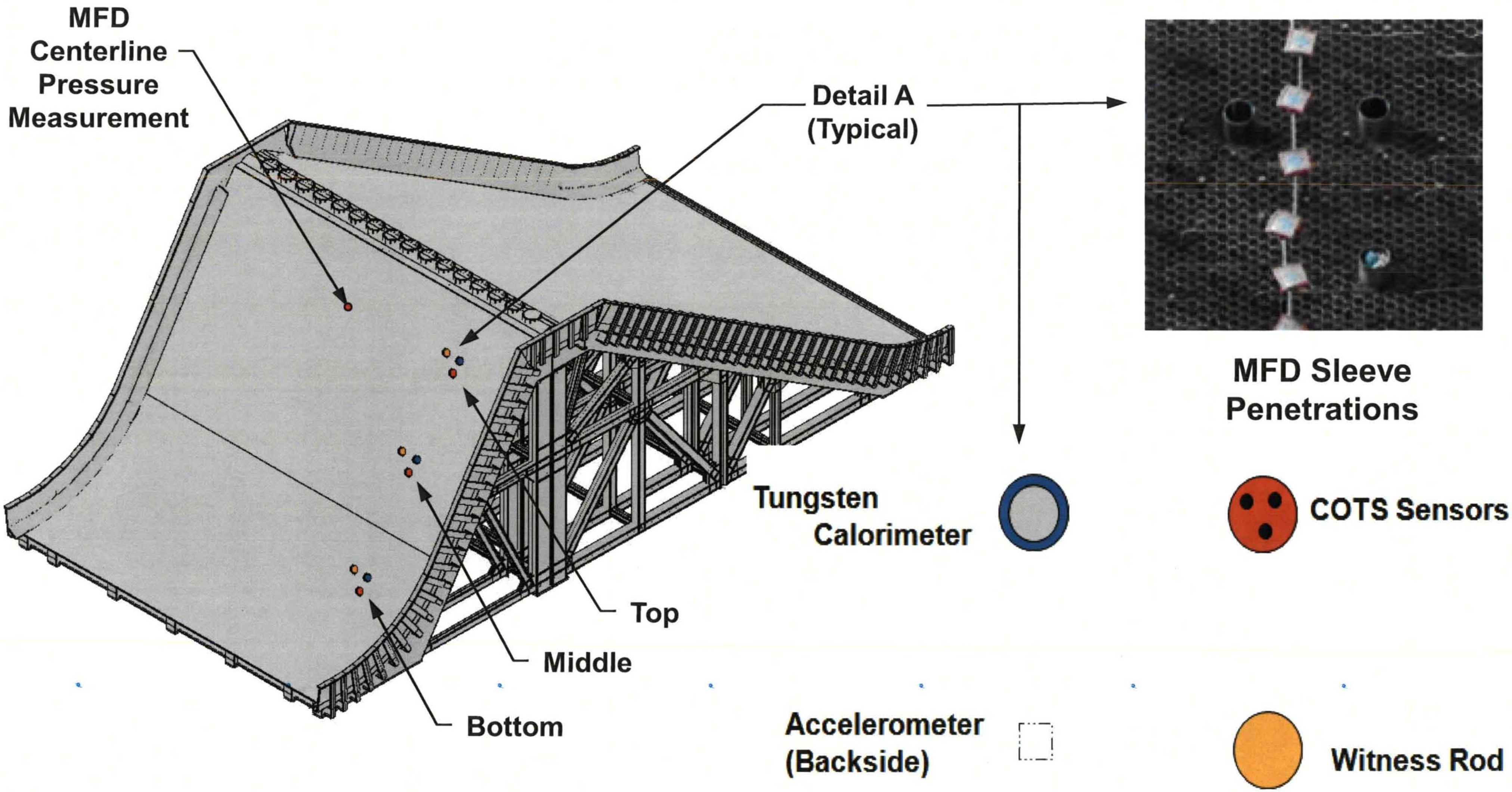
Newport News, VA

Project Purpose

- To determine loading environment, instrumentation was designed, fabricated, and installed on the SRB Main Flame Deflector
  - Heat Rates, Temperatures, Pressures, Accelerations are measured/calc
  - 'Witness Rods" installed flush for material wear evaluation

- Compare measured data to material response for increased confidence in selecting materials on the Main Flame Deflector for future programs

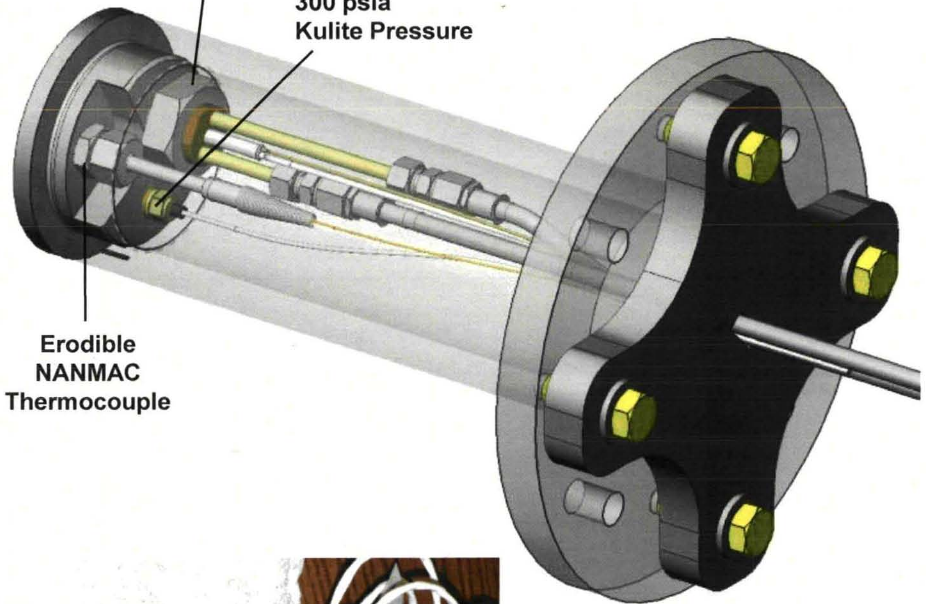
MFD Sensor Arrangement

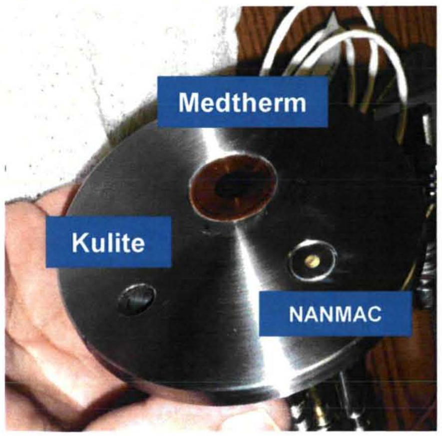


Detail A

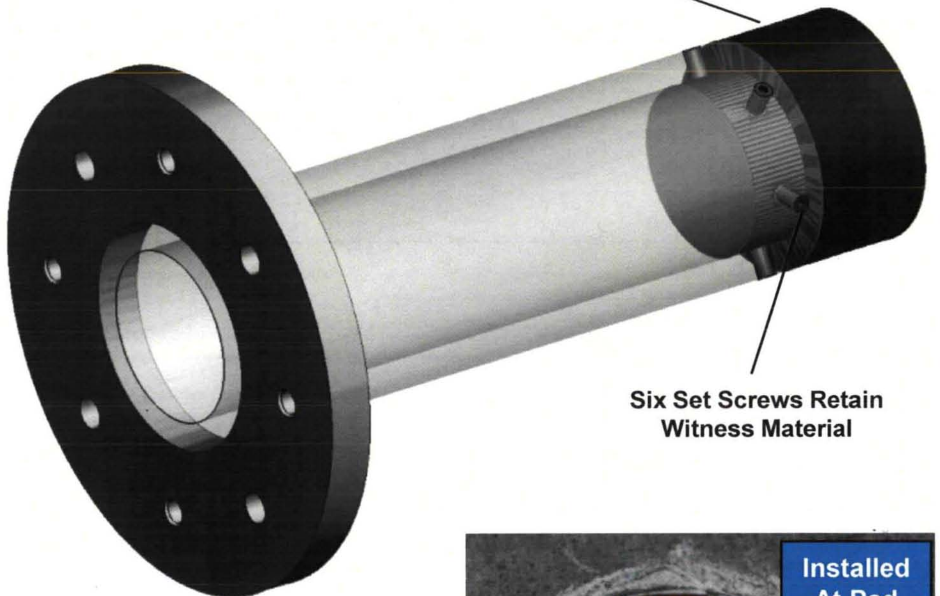
COTS and Witness Rod Assemblies

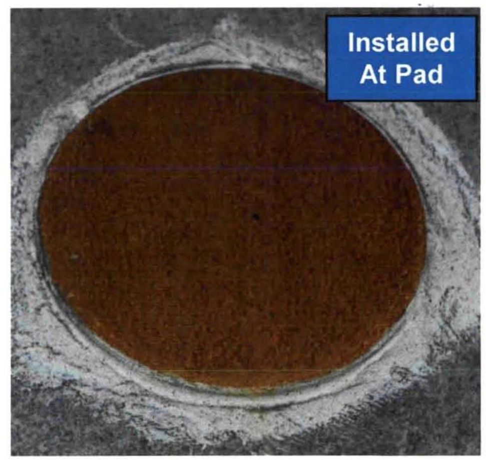
COTS Sensors





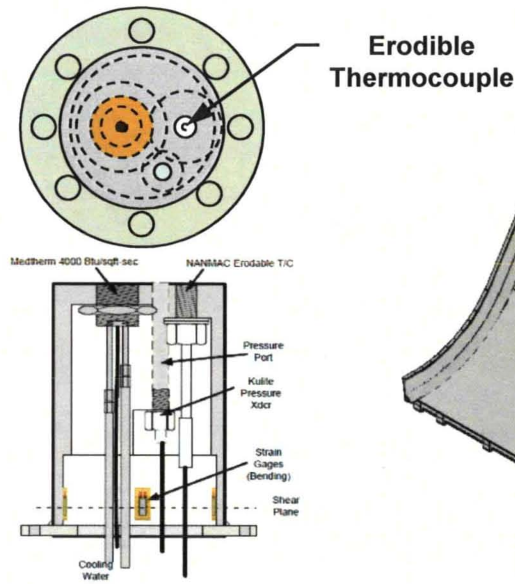
Witness Rod Sensor

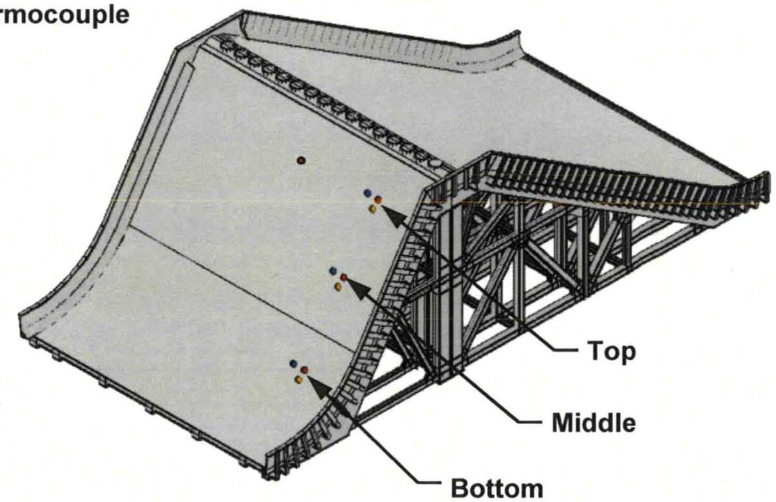


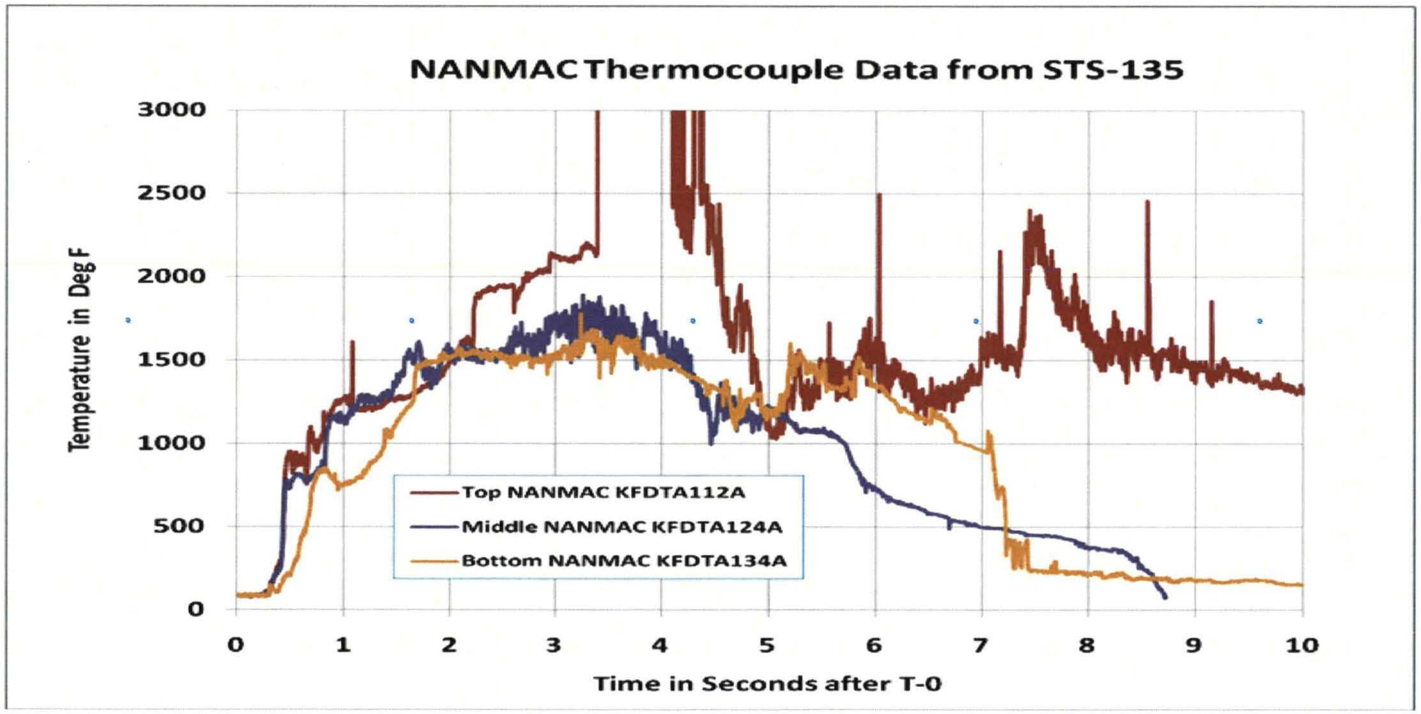


COTS NANMAC Erodible Thermocouple Response

- Top and Bottom COTS Erodible thermocouple non- functioning
- Middle thermocouple response indicates 1800 °F peak temperatures from STS-133
  - Temperature appears to be to low for gas temperatures
    - On same order as tungsten temperatures

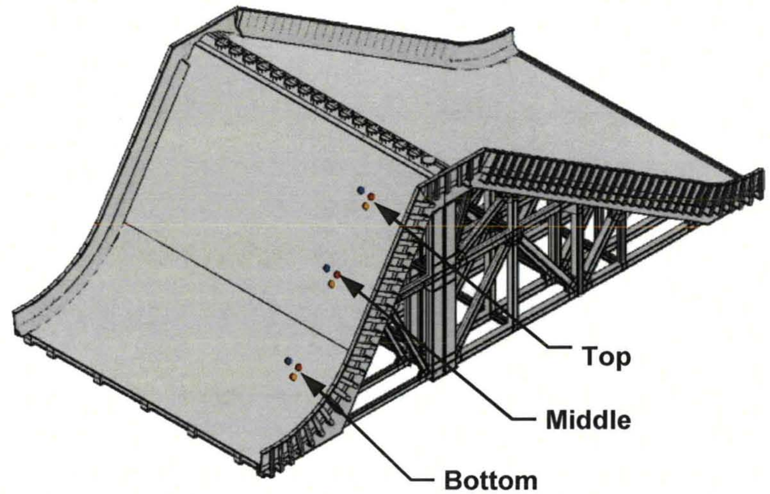




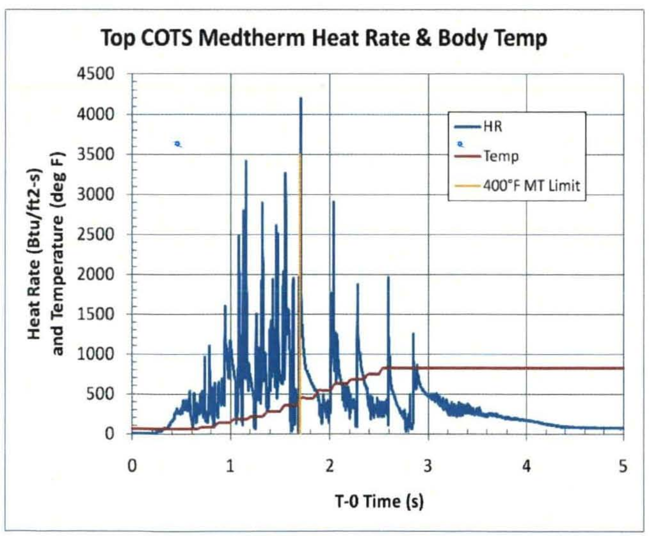


Top, Middle and Bottom Calorimeter Heat Rate Response

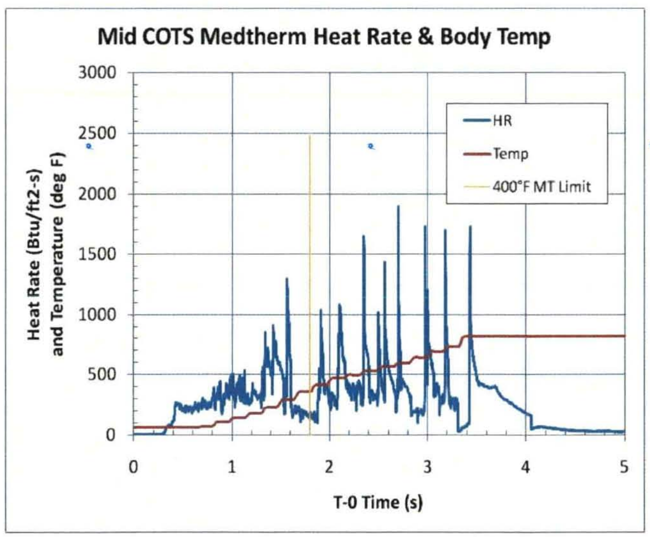
- **Comparison of Top, Middle and Bottom heat rates and body temperatures (STS-133)**
  - **Heat rates show consistent type response**
    - **Random 'spike' profiles**
  - **Body temperatures exceed recommended limit of 400°F**
    - **Highest Body Temperatures starts from top to bottom sensor**



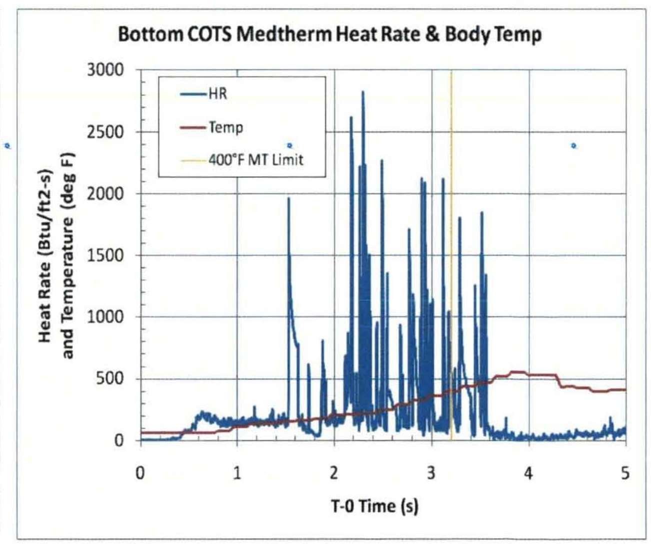
Top



Middle

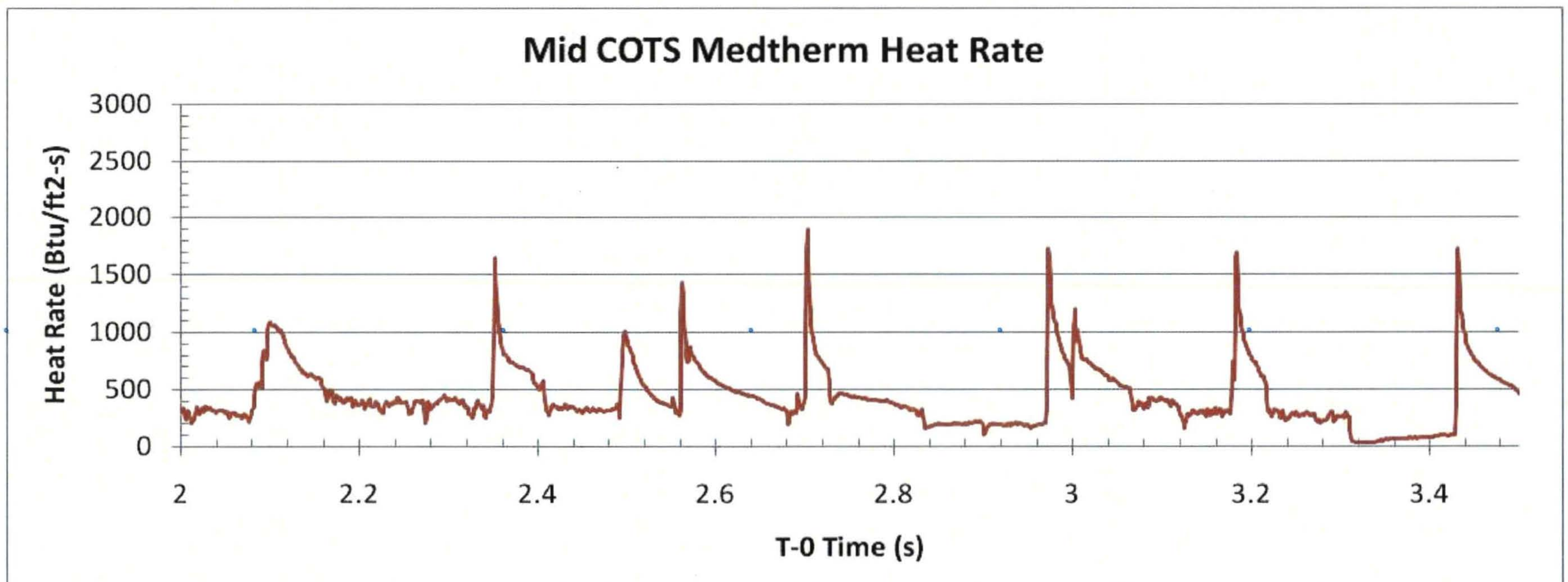


Bottom



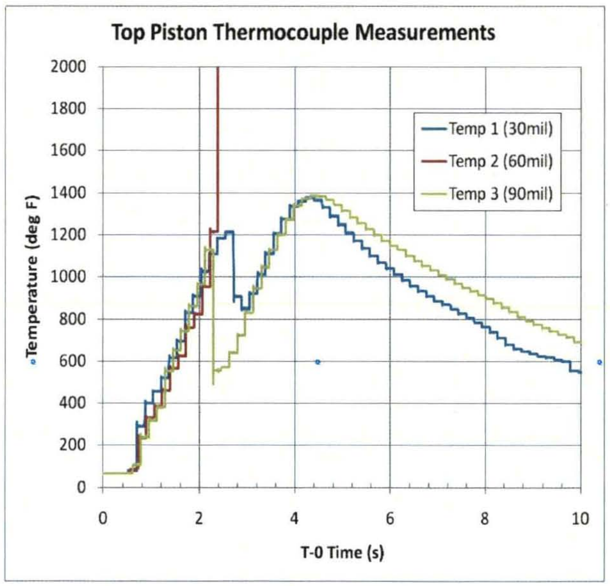
Calorimeter Heat Rate Response Characteristics

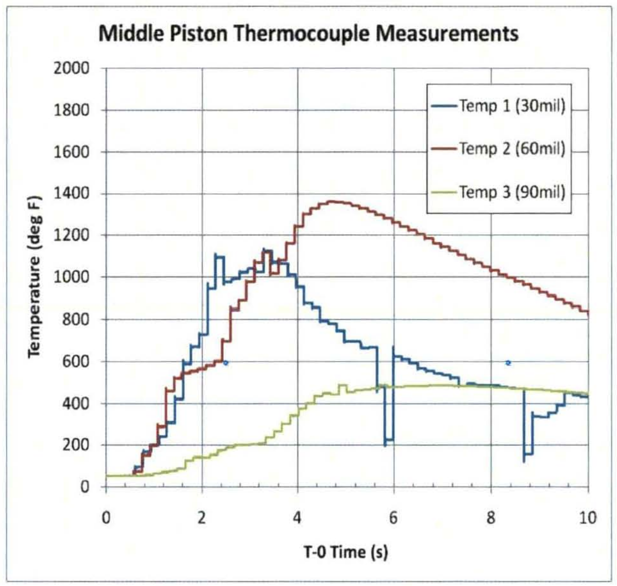
- Data spikes are theorized to be from molten $Al_2 0_3$ solidifying on the small Medtherm sensor area – then shed to the flow field with the process repeated
  - GP-1059 addresses particle heat flux phenomena
  - NASA "Therm 1-D" Program and the ATK "Slag Code" developed for US Air Force both take into account the $Al_2 0_3$ deposition
- Duration of spikes range from .03 to .10 seconds (STS-133)
  - Profiles show consistence
- Causality of the data behavior is unknown

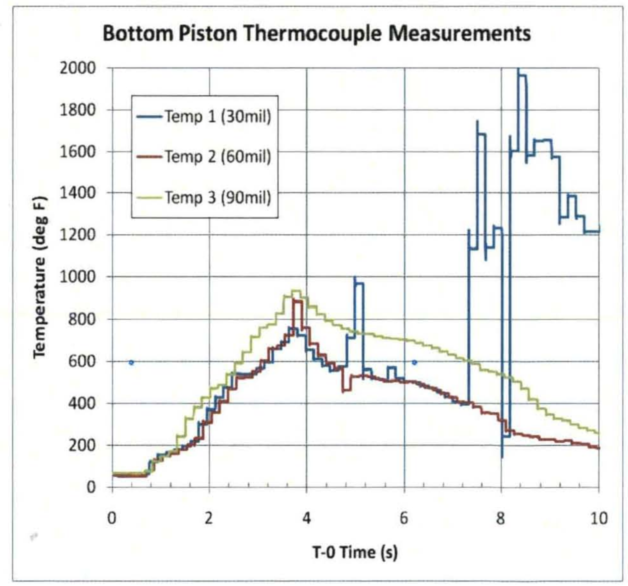


Tungsten Temperature Responses

- Temperature response of TPLCC shows high initial temperature change (STS-133)
  - Proportional to heat rates
- Indication of temperature drop out at ~ 1,200 °F for Top TPLCC
  - Brazing temperature 1,200-1,400 °F
    - Indication of melting
- Sampling rate limited to 6 samples per second with indication of some drop out

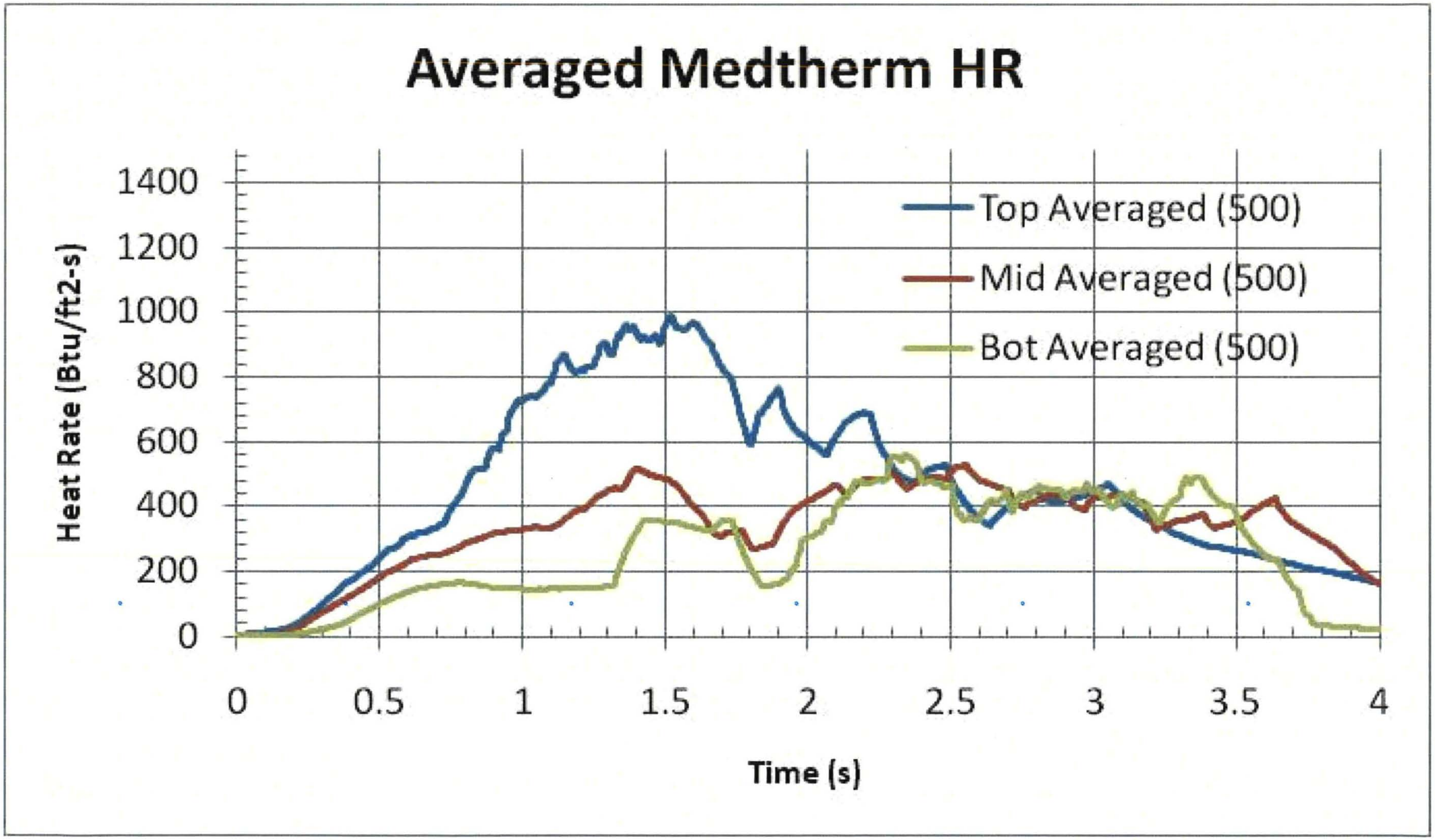






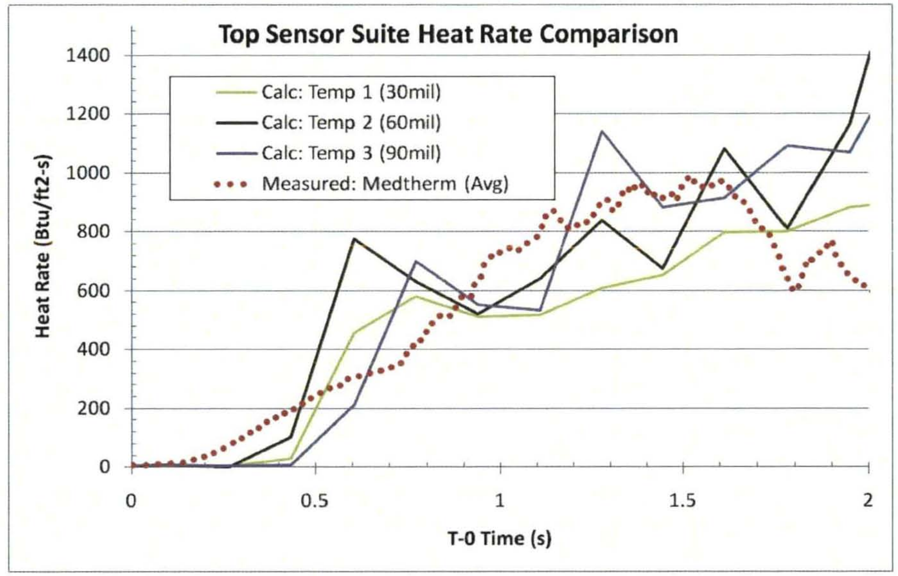
Averaged COTS Calorimeter Heat Rates

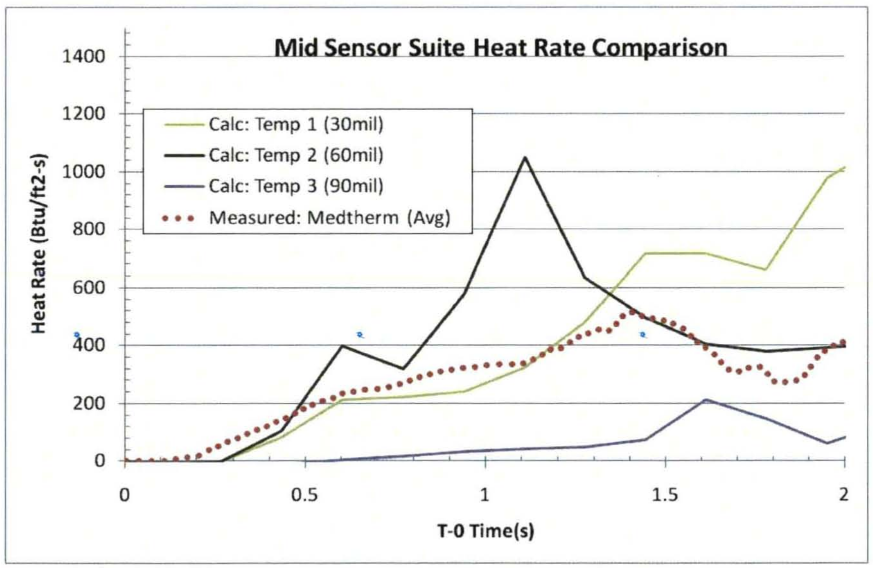
- Highest heat rates range from 1,000 (top) to 500 (bottom) Btu/ ft2-sec for STS-133

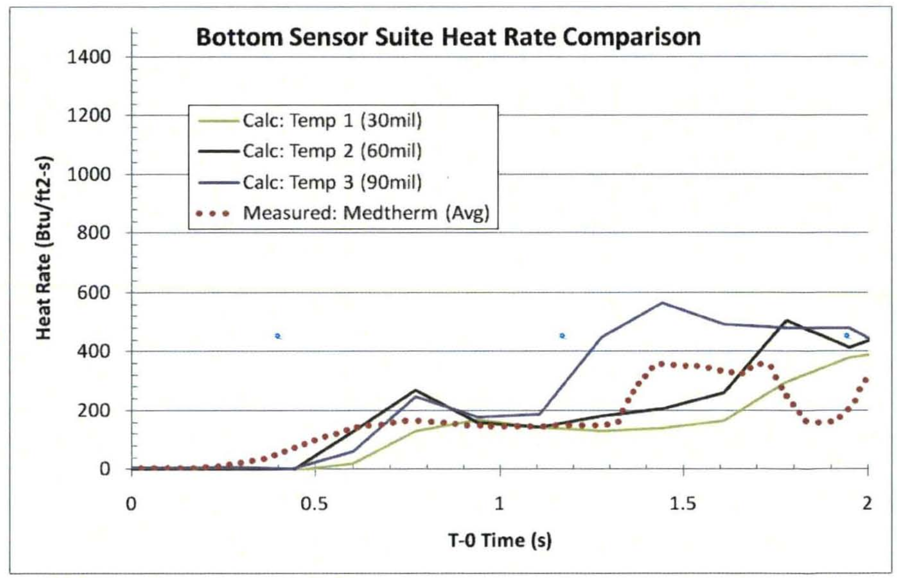


Comparison of Heat Rates

- **Average COTS calorimeter heat rates comparable to tungsten calorimeter calculated heat rates**







Top Tungsten Calorimeter

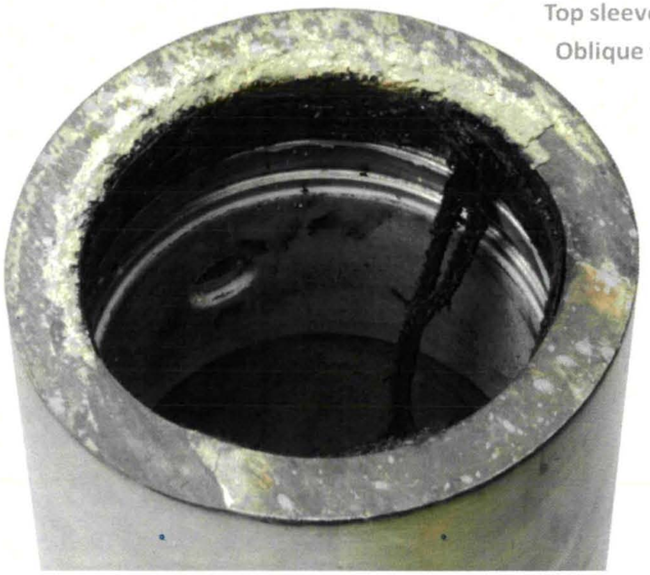
- Noted cracks on the tungsten post launch
- Metallography is in work
- Thermal analysis is in work

Top

Top
Oblique view

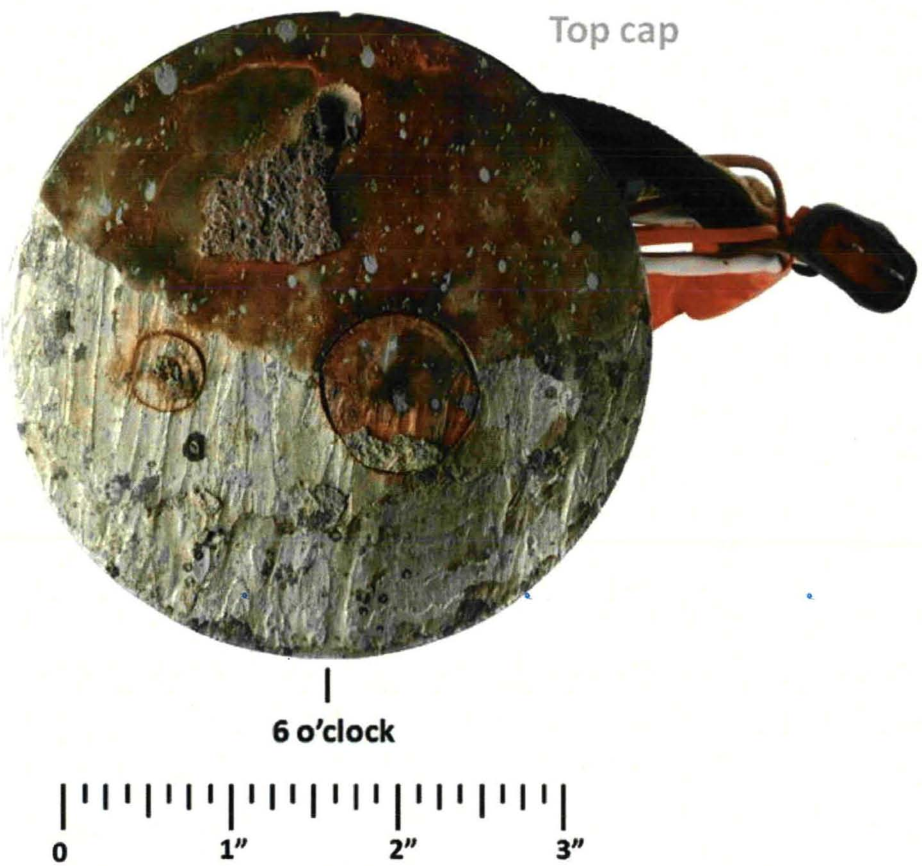
Top A-286 Tungsten Calorimeter Sleeve

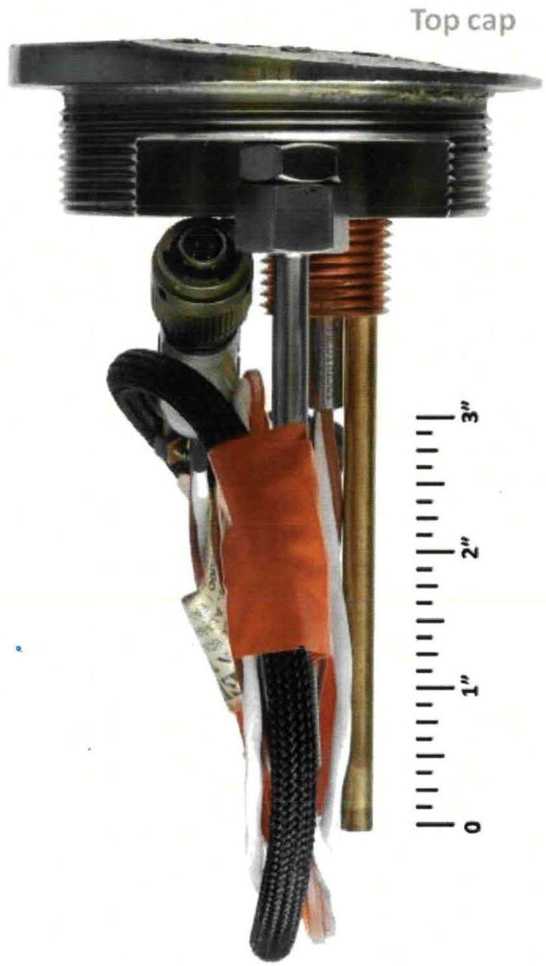
- Metallography is in work
- Thermal analysis is in work



Top 304 Stainless Steel COTS Caps

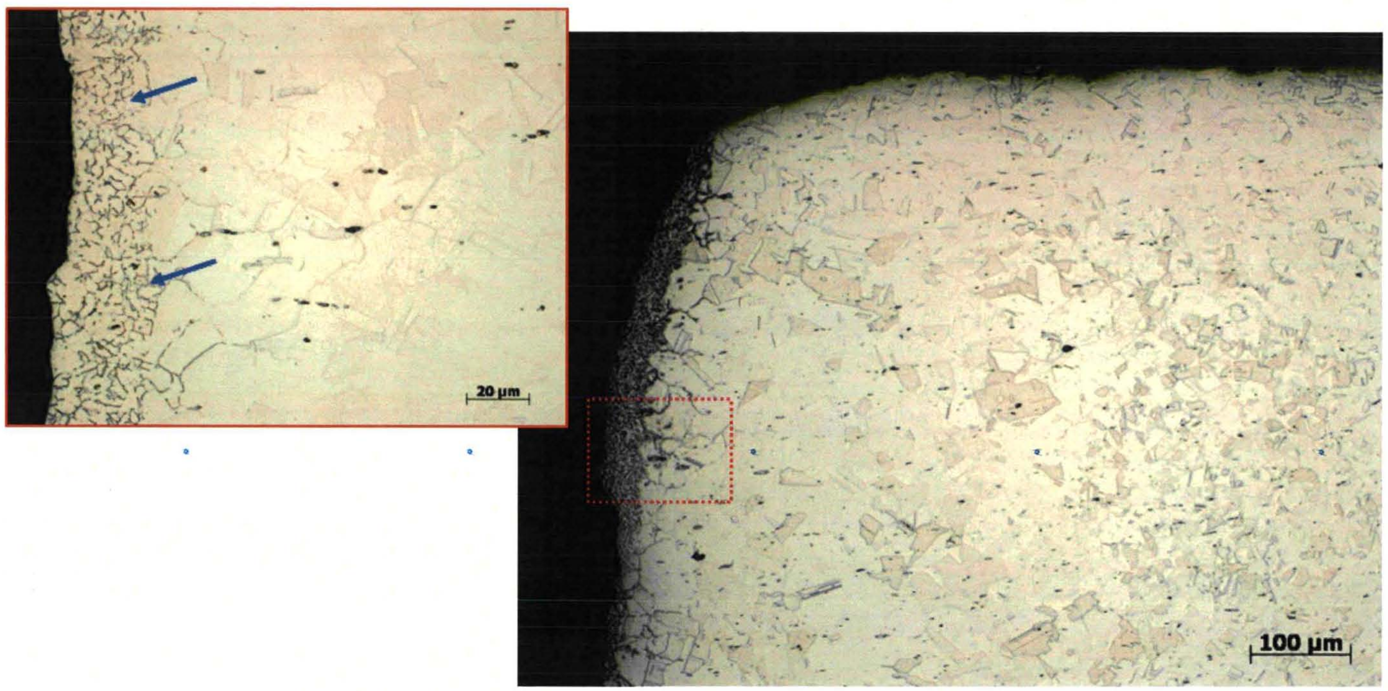
- Analysis shows that a COTS cap (304 stainless) will reach the melting temperature of (T_m = 2650 °F) in about 2 seconds using the measured heat rates





Top 304 Stainless Steel COTS Caps

- Layer of melted and 0.5 mm of resolidified metal as indicated by dendritic microstructure
- Base material – austenitic grain structure with larger grain sizes than the parent material
- Original magnifications: 500X (boxed), 100X (right).

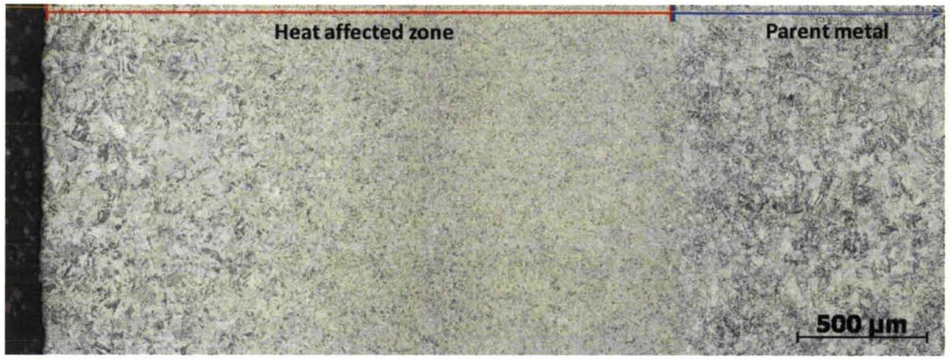


STS-133 HY-80 Top Witness Rod

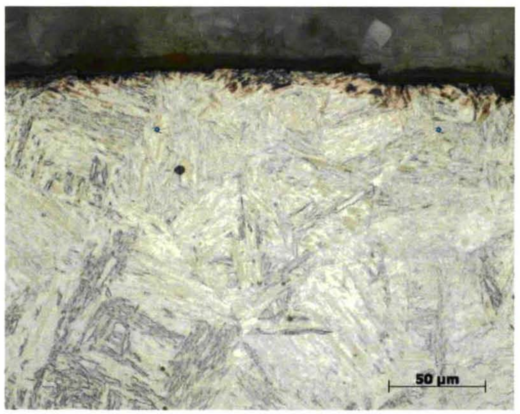
- Thermal analysis using the total measured heat rates shows that the HY-80 reached 2000°F (Tm = 2595 °F) in 2.3 seconds
- Erosion on the order of 0.078" occurred
- Heat affected zone turned into untempered martensite while the hardness increased to HRC 42
- Sample shown below is from the bottom location

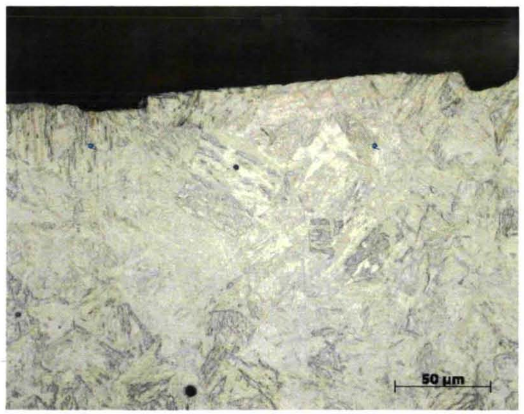
STS-133 HY-80 Top Witness Rod

- Metallography shows material probably did not melt and re-solidify
- No apparent indications of melting and resolidification of the metal are present.



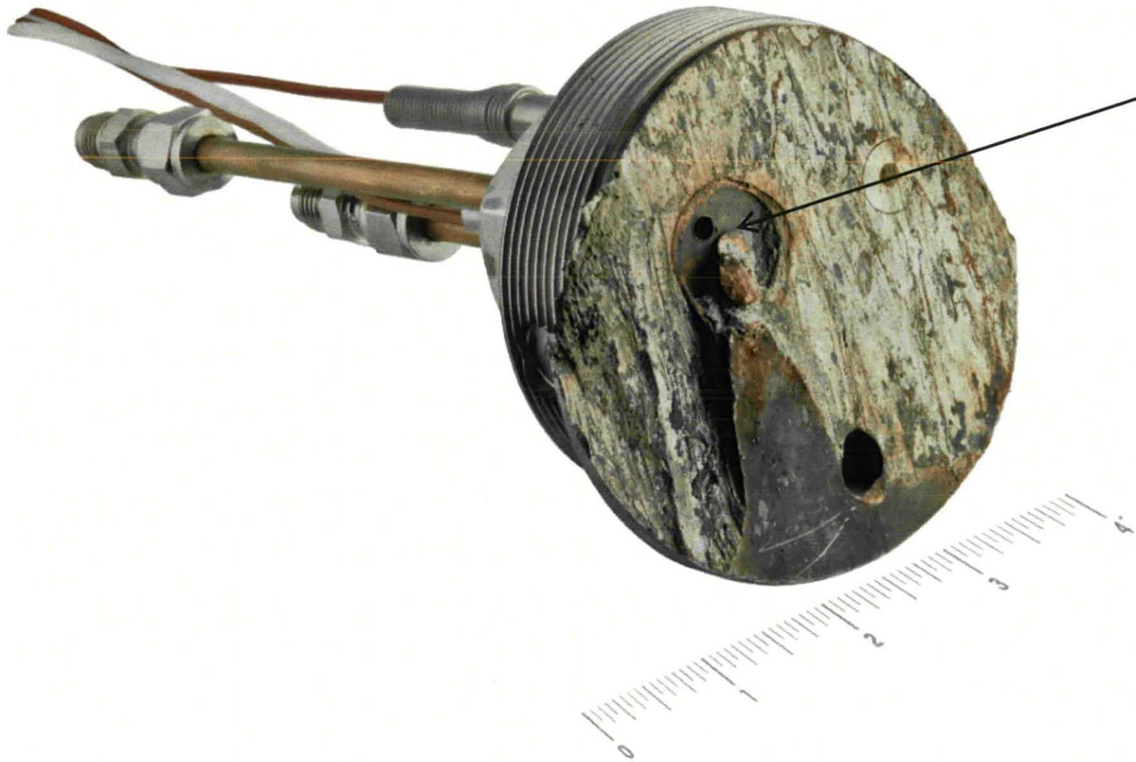
Micrograph of the surface (left) of the top sample HY-80 witness rod showing the untempered martensite in the heat affected zone and tempered martensite in the parent metal. Original magnification: 100X





Micrographs at the surface of the bottom sample (left) and top sample (right) showing the grain structure in these locations. Original magnifications: 500X

STS-134 Top 304 stainless COTS Cap



Water was being ejected from this hole at 150 psig

Medtherms are water cooled. This transducer eroded thru and the cooling water ejected into the flow field protected the 304 stainless from melting and eroding

STS-134 1018 Top Witness Rod

- Metallography is in work
- Thermal analysis is in work
- Erosion on the order of 0.4" occurred
- Material selected because of its use in BSM (booster separation motor) nozzles

STS-135 Top Tungsten Calorimeter

- Removal from the pad scheduled 7/21/11
- Metallography TBD
- Thermal analysis TBD
- Erosion TBD

Summary and Conclusions

- Induced environment on the flame deflector was presented for STS-133
- Selection of results were presented to demonstrate the relative performance of the materials in the SRB environment
- Selection of heat rate data using different methods for STS-133

Future Work

- Flame Trench Instrumentation
  - Complete erosion, microscopy and other investigations
  - Determine if any chemical reactions occurred on the surface of the samples
  - Release Report
- General
  - Determine the contribution of SRB slag to gardon type calorimeter data
  - Determine the material and geometry key performance parameters for sustainability in the SRB environment for longer firing times
  - Reduce size/cost of the tungsten calorimeter for broader use