NASA
Engineering Directorate
Materials Science Division
Kennedy Space Center, Florida

November 18, 2011

KSC-MSL-2011-0149

SUBJECT: Post STS-135 Evaluation of Main Flame Deflector Witness Materials

CUSTOMER: Wulf Eckroth / United Space Alliance (USA) / USK-800

1. ABSTRACT

NASA and USA design engineers submitted witness materials from the solid rocket booster (SRB) main flame deflector for evaluation after the launch of STS-135. The following items were submitted for analysis: HY-80 steel witness rods, 304 stainless steel caps, and tungsten pistons. All of the items were photographed in order to document their condition after the launch of STS-135. The submitted samples were dimensionally measured in order to determine the amount of material lost during launch. Microstructural changes were observed in the HY-80 witness rod metallographic samples due to the heat of the launch.

2. FOREWORD

Materials tested on the SRB main flame deflector at Launch Complex (LC) 39B during the launch of STS-135 on July 8, 2011, were submitted for evaluation. The materials were analyzed in order to determine their suitability for use in the main flame deflector as an alternative to the refractory material currently used on the flame deflector during launch. The purpose of the investigation was to evaluate the condition of the material after being subjected to the SRB plume during launch. The requested analyses included photodocumentation, dimensional measurements, and metallography in order to determine the wear profile and mechanism for the different materials. A customer-supplied matrix of the submitted samples and the requested objectives are listed in Table 1. For each sample type, a different sample was submitted for each of the locations listed in Table 1, which indicates their relative testing location on the SRB main flame deflector. Metallography of the 304 stainless steel cap was not requested since the material was determined to have melted in a prior analysis after STS-133 (ref. KSC-MSL-2010-0344). The customer reported that the STS-135 top stainless steel cap was not submitted for analysis because it was installed ¼ inch below the surface and no erosion occurred.

Table 1. Testing matrix and objectives for each of the samples submitted.

Sample Type	Sample Locations	Objective
HY-80 Witness Rods	Top Middle Bottom	Determine erosion profile Determine if erosion or melting of material occurred
304 Stainless Steel Caps	Middle Bottom	Determine erosion profile
Tungsten Pistons	Top Middle Bottom	Determine erosion profile Document cracks Measure hardness

3. PROCEDURES AND RESULTS

3.1. The submitted samples were photographed, as received (Figures 1-10). The amount of erosion varied by sample and by location on the flame trench. The bottom and top locations of the HY-80 witness rods displayed visible erosion from STS-135 (Figures 1-3). The customer reported that the middle witness rod had previously been installed in the bottom location for STS-133 and rotated 180 deg for STS-135. Therefore the erosion seen in the photos for the middle witness rod are from STS-133, not STS-135. Both of the 304 stainless steel caps displayed significant material loss, which exceeded the erosion observed on the HY-80 witness rods (Figures 4 and 5). The tungsten pistons did not have a considerable amount of erosion, but cracks were observed on the sides of the pistons (Figures 6-10). The 6 o'clock position is noted for each sample and was designated by the customer.

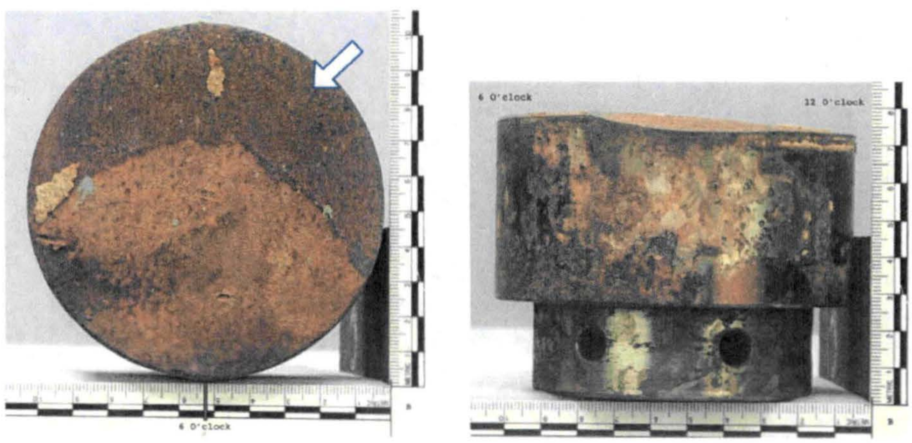

Figure 1. Bottom HY-80 witness rod, as-received. The arrow indicates the eroded region. Scale is in centimeters.

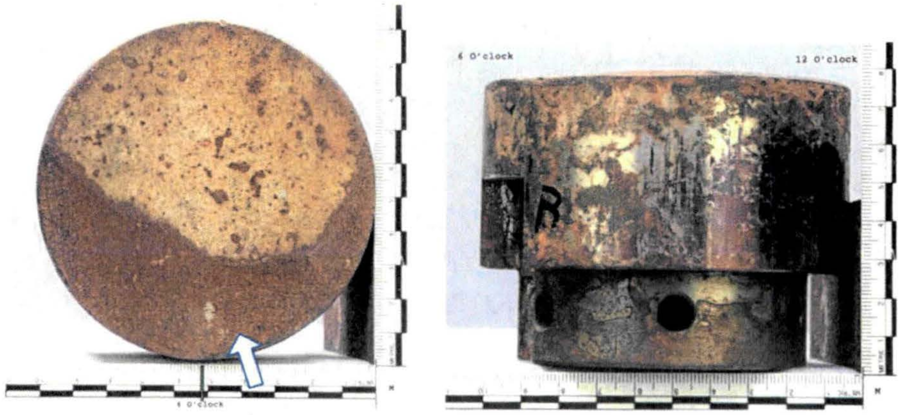

Figure 2. Middle HY-80 witness rod, as-received. The arrow indicates the eroded region from STS-133. Scale is in centimeters.

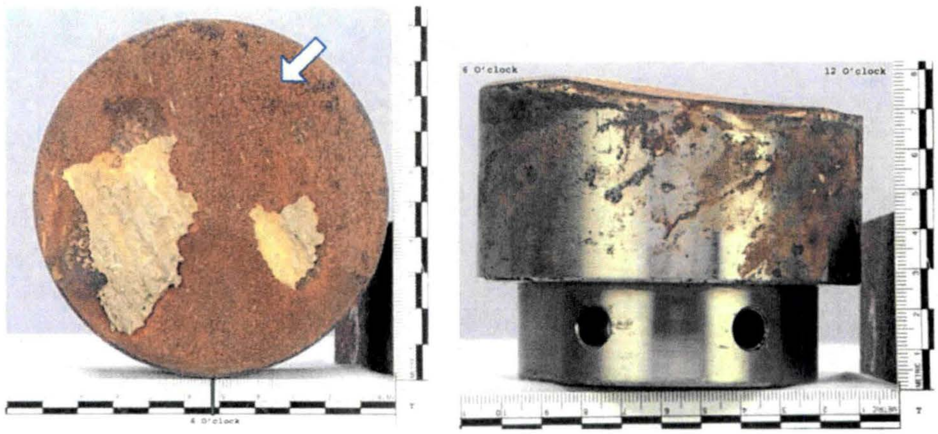

Figure 3. Top HY-80 witness rod, as received. The arrow indicates the eroded region. Scale is in centimeters.

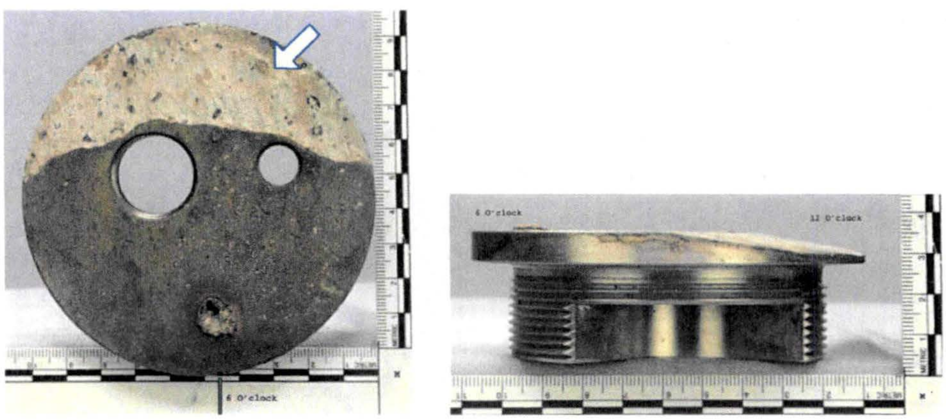

Figure 4. Middle 304 stainless steel cap, as received. The arrow indicates the eroded region. Scale is in centimeters.

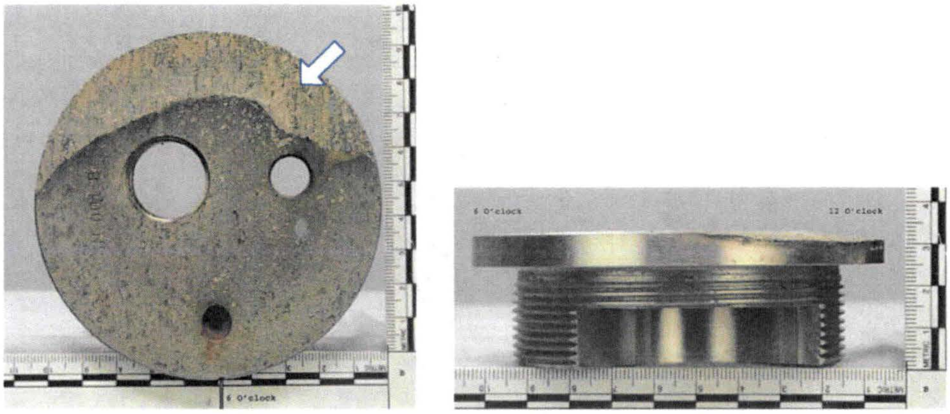

Figure 5. Bottom 304 stainless steel cap, as received. The arrow indicates the eroded region. Scales is in centimeters.

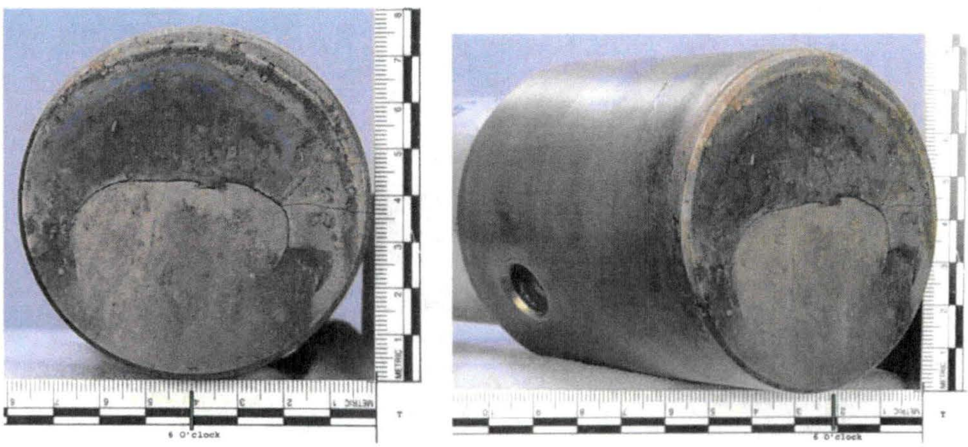

Figure 6. Top 100% tungsten piston, as received. Scale is in centimeters.

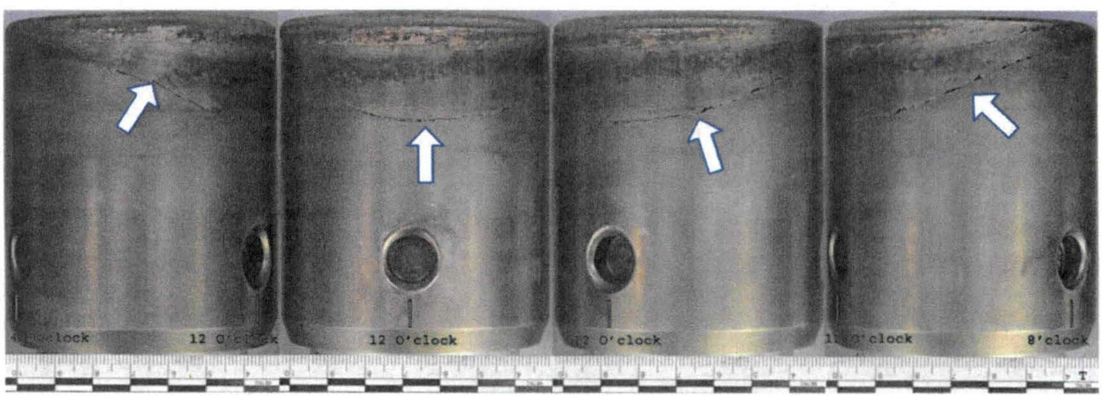

Figure 7. Series of images, rotated 45° per image, around the side of the top 100% tungsten piston, showing the crack around the outer surface (arrows). Scale is in centimeters.

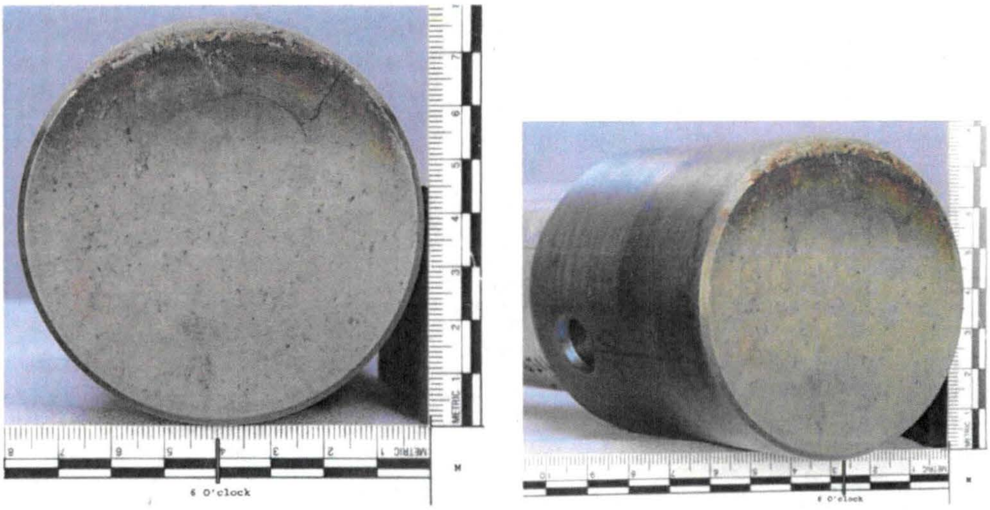

Figure 8. Middle 100% tungsten piston, as received. Scale is in centimeters.

Figure 9. Series of images, rotated 45° per image, around the side of the middle 100% tungsten piston, showing the crack around the outer surface (arrows). Scale is in centimeters.

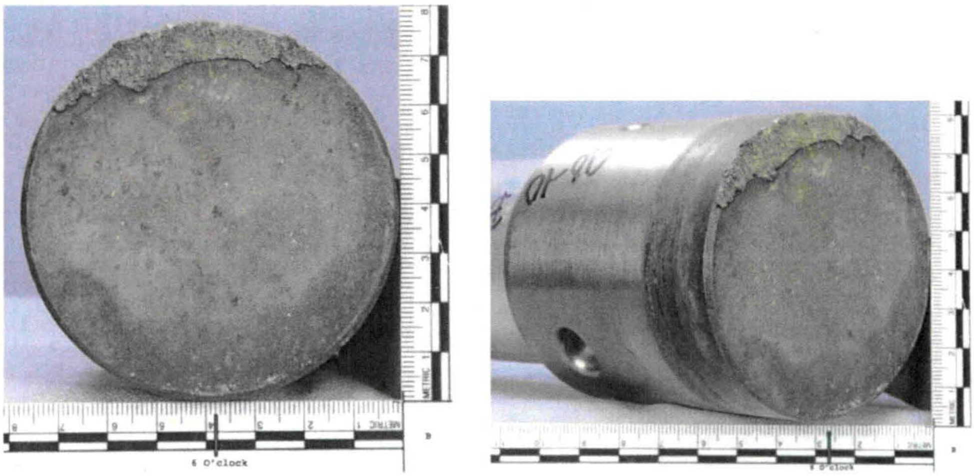

Figure 10. Bottom 90-10 tungsten piston, as received. Scale is in centimeters.

3.2. The HY-80 witness rods, 304 stainless steel caps, and the tungsten pistons were dimensionally characterized in order to determine their erosion profiles. Each of the samples was measured using a Micro-Vu optical coordinate measuring machine (CMM) with an accuracy of ± 0.008 inch. The thicknesses were measured at four places around the periphery of the sample, at the 12, 3, 6, and 9 o'clock positions. The measurements are listed in Tables 2 through 4, along with the average thickness, maximum thickness, minimum thickness, and max-min difference. All measurements are listed in inches. The customer supplied original thickness measurements for the HY-80 witness rod samples.

Table 2. HY-80 Witness Rod Measurements

Measurement Location	Top Sample Thickness	Middle Sample Thickness	Bottom Sample Thickness
12 O'Clock	1.699	1.975	1.840
3 O'Clock	1.755	1.838	1.820
6 O'Clock	1.924	1.858	2.002
9 O'Clock	1.742	1.914	1.834
Average	1.780	1.896	1.874
Maximum	1.924	1.975	2.002
Minimum	1.699	1.838	1.820
Max-Min Difference	0.225	0.136	0.182

Table 3. 304 Stainless Steel Cap Measurements

Measurement Location	Middle Sample Thickness	Bottom Sample Thickness
12 O'Clock	0.112	0.227
3 O'Clock	0.334	0.306
6 O'Clock	0.317	0.321
9 O'Clock	0.298	0.318
Average	0.265	0.293
Maximum	0.334	0.321
Minimum	0.112	0.227
Max-Min Difference	0.222	0.094

Table 4. Tungsten Piston Measurements

Measurement Location	Top Sample Thickness	Middle Sample Thickness	Bottom Sample Thickness
12 O'Clock	3.481	3.475	3.499
3 O'Clock	3.481	3.487	3.495
6 O'Clock	3.493	3.482	3.512
9 O'Clock	3.484	3.475	3.496
Average	3.485	3.480	3.501
Maximum	3.493	3.487	3.512
Minimum	3.481	3.475	3.495
Max-Min Difference	0.012	0.012	0.017

3.3. The HY-80 witness rod samples were cross-sectioned in the area with the observed erosion, mounted in acrylic resin, and prepared for metallographic examination. All three samples displayed a transformed layer due to heating of the metal during launch, followed by quenching due to the water deluge (Figures 12-14). These heat affected zones in the bottom and top samples consisted of untempered martensite with possible minor amounts of bainite (Figures 12 and 14, left side of image). The heat affected zones displayed observable difference in the microstructure as a function of depth, which was likely due to differences in the amount of time spent in transition during quenching of the surface of the witness rod. The middle sample displayed some tempering of the martensitic grain structure, which would be due to the additional heating that this sample experienced since the erosion occurred during STS-133 and it was exposed to more launches (Figure 13). The difference in microstructure observed in the middle sample versus the top and bottom samples would be due to the additional heat from subsequent launches. The parent metal consisted of tempered martensite for all three samples (Figures 12-14, right side of image). The heat affected zone was approximately 0.11 inch (2.7 mm) deep in the bottom and middle samples and 0.09 inch (2.3 mm) deep in the top sample. High magnification observation at the surface of the witness rod revealed no apparent indications of melted metal, such as dendrites or distorted grains (Figures 15-17). The possibility of melting is not likely, but could not be eliminated because the melted metal could have been removed from the surface due to the launch blast.

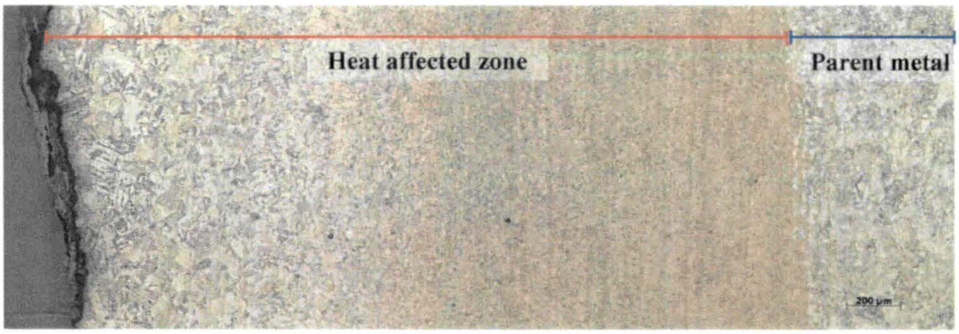

Figure 12. Micrograph of the surface (left) of the bottom sample HY-80 witness rod showing the untempered martensite in the heat affected zone and tempered martensite in the parent metal. The observable differences in microstructure in the heat affected zone are likely due to differences in the amount of time spent in the transition during quenching. Etchant: 2% nital. Original magnification: 100X

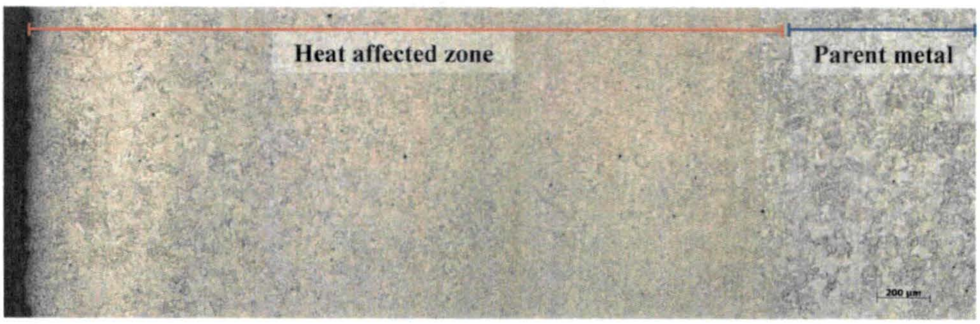

Figure 13. Micrograph of the surface (left) of the middle sample HY-80 witness rod showing the heat affected zone and the parent metal. Some tempering of the martensite in the heat affected zone has occurred. Etchant: 2% nital. Original magnification: 100X

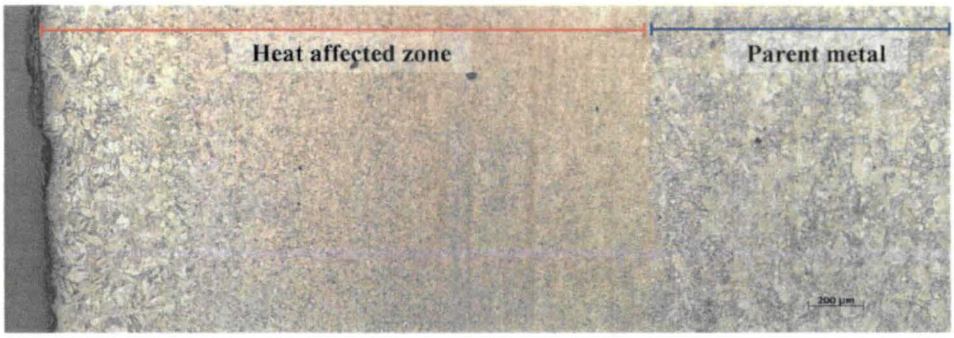

Figure 14. Micrograph of the surface (left) of the top sample HY-80 witness rod showing the untempered martensite in the heat affected zone and tempered martensite in the parent metal. Etchant: 2% nital. Original magnification: 100X

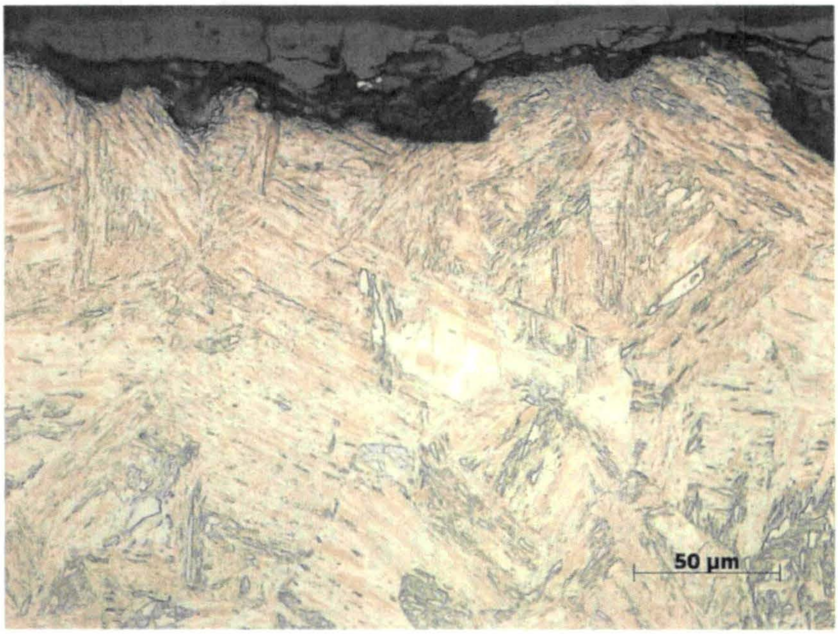

Figure 15. Micrograph of the surface of the bottom sample showing the untempered martensitic grain structure. No apparent indications of melting and resolidification of the metal are present. Etchant: 2% nital. Original magnification: 500X

Figure 16. Micrograph of the surface of the middle sample showing the martensitic grain structure in this location. No apparent indications of melting and resolidification of the metal are present. Etchant: 2% nital. Original magnification: 500X

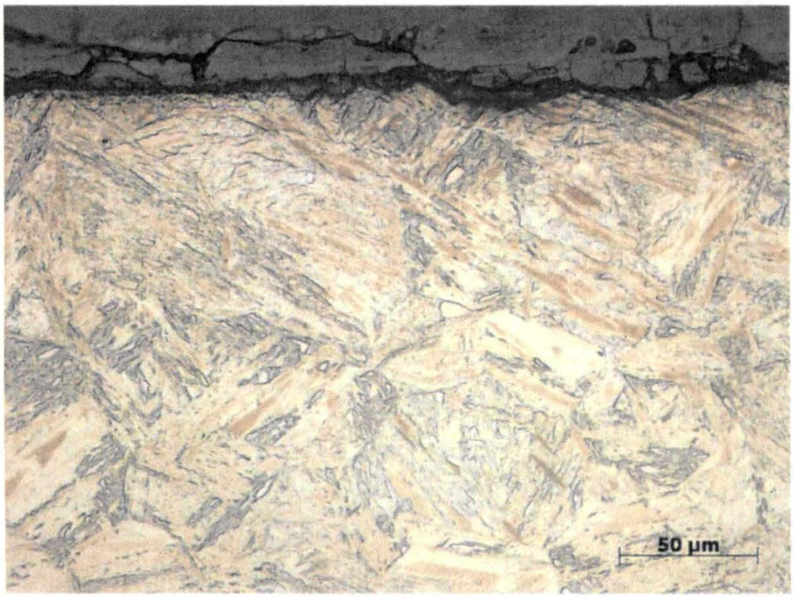

Figure 17. Micrograph of the surface of the top sample showing the untempered martensitic grain structure. No apparent indications of melting and resolidification of the metal are present. Etchant: 2% nital. Original magnification: 500X

3.4. In order to confirm the microstructural changes that were observed in the HY-80 witness rods, microhardness measurements were taken on the metallographic specimens using a Vickers indenter with a 500 g load every 0.5 mm, starting near the surface of the witness rod. The measurements were then converted to Rockwell C scale (HRC) per ASTM E 140, *Standard Hardness Conversion Tables for Metals.* The average hardness in the heat affected zone for the bottom and top samples was 42 HRC, which is typical for untempered martensite in HY-80 steel. The hardness profile in the middle sample varied more as a function of the depth than in the top and bottom samples, which is an indication that the middle sample witnessed different thermal conditions. The average hardness in the parent metal was 23 HRC, which is typical for tempered martensite in HY-80 steel. The hardness values were distinctly different in the transformed region versus the parent material with a sharp difference in hardness right at the transition line in the bottom and top samples (Figure 18). The hardness values correlated with the metallographic observations.

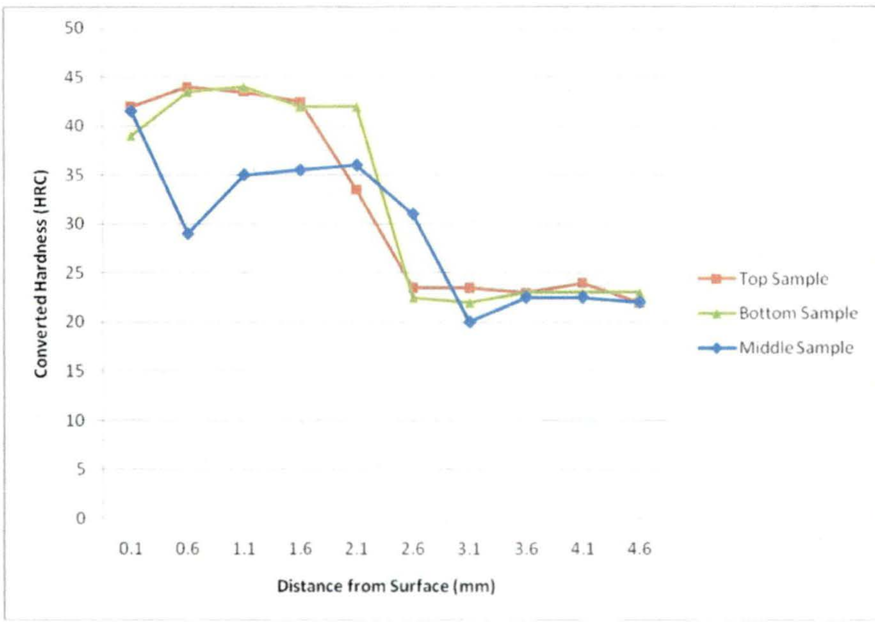

Figure 18. Converted hardness values as a function of depth in the HY-80 witness rods.

3.5. Hardness measurements were taken per ASTM E 18, *Standard Test Methods for Rockwell Hardness of Metallic Materials*, on the tungsten piston samples in the eroded area and on an undamaged area and are reported in the Rockwell A scale (HRA) in Table 5. The hardness values reported are the average of several trials. In accordance with standard practice, the average hardness is reported to the nearest whole number. The hardness values indicate a minor decrease in the material hardness at the location beneath the most erosion. Due to the geometry of the pistons, these hardness measurements should only be interpreted as relative to each other.

Table 5. Rockwell A Scale (HRA) hardness test results

Tungsten piston	Top (100% W)	Middle (100% W)	Bottom (90W-6Ni-4Cu)
Worst area under the burned surface, tested on the diameter, approx. 1/8—1/4 inch from the burned edge	62	64	62
Clean, undamaged area on the diameter, near the base	69	66	63
Calibration verification: 9/2/2011 Sun-Tec Calibration Standard Test Block, S/N 102722, 64.3 HRA ±1.0	64.7	64.9	64.9

4. CONCLUSIONS

4.1. The HY-80 witness rod samples were photographed, measured for dimensional changes, evaluated for microstructural differences, and tested to determine their microhardness profiles. The bottom and top witness rod samples had visible erosion occur on the exposed surfaces of the witness rods. The HY-80 witness rod samples exhibited a transformation of the microstructure to untempered martensite in the heat affected zone at the surface of the witness rod due to heating during launch and quenching during water deluge. This transformation was confirmed by a significant increase in the hardness of the heat affected zone compared to the hardness of the tempered martensite in the parent metal. The middle witness rod sample showed that some tempering of the martensite structure occurred in the heat affected zone. This is likely due to the additional heat that this sample experienced since the damage occurred during the launch of STS-133 and was removed after STS-135. The bottom and middle samples had heat affected zones that were approximately 0.11 inch (2.7 mm) deep and the top sample had a heat affected zone that was approximately 0.09 inch (2.3 mm) deep. No apparent indications of melting were observed in the microstructure; however, the launch blast could have removed any evidence of melting.

4.2. The 304 stainless steel cap samples were photographed and measured for dimensional changes. Metallography of the 304 stainless steel cap was not requested since the material was determined to have melted in a prior analysis following STS-133 (ref. KSC-MSL-2010-0344).

4.3. The tungsten pistons were photographed in order to document their condition and were dimensionally measured in order to document the amount of erosion.

EQUIPMENT: Micro-Vu Optical CMM Excel, ECN-2237258
Zeiss Z1m metallograph, S/N 3837000175
Struers Duramin microhardness tester, S/N 5640020
Wilson/Rockwell hardness tester, S/N 81987709

RELATED DOCUMENTATION: KSC-MSL-2010-0344

KSC-MSL-2011-0148

ASTM E 18, *Standard Test Methods for Rockwell Hardness of Metallic Materials*

ASTM E 140, *Standard Hardness Conversion Tables for Metals*

CONTRIBUTORS: L. Batterson/NE-L1
D. Lubas/NE-L1
P. Marciniak/NE-L1
P. Richiuso/NE-L1

PRIMARY INVESTIGATOR: V. Long/NE-L1