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ABSTRACT

This paper presents the experimental results of the third and final phase of a cookoff model validation effort. In this phase of the work, two generic Heavy Wall Penetrators (HWP) were tested in two heating orientations. Temperature and strain gage data were collected over the entire test period. Predictions for time and temperature of reaction were made prior to release of the live data. Predictions were comparable to the measured values and were highly dependent on the established boundary conditions. Both HWP tests failed at a weld located near the aft closure of the device. More than 90 percent of unreacted explosive was recovered in the end heated experiment and less than 30 percent recovered in the side heated test.

INTRODUCTION

A slow cookoff model validation effort has recently been completed. The effort involved researchers from the US Navy working under support from the Office of Naval Research, and from the Department of Energy (DOE) laboratories working under the DOD/DOE memorandum of understanding. This paper describes the final experiments performed as part of an effort to provide appropriate data for verification of DOE predictive models. The effort was used not only to verify these models, but to identify areas of deficiency (both experimental and analytical) which might impede the realization of the modeling effort. The prediction of not only the time and temperature a cookoff reaction will occur, but also the level of violence that can be expected in a cookoff reaction was the goal of this study. This work represents the third and final phase of an effort lasting for about 3 years. Continuation of each phase of the project was contingent on the accomplishment of established success criteria.

Phase I experiments were performed with the well characterized explosive PBXN-109. Variables such as confinement, ullage, and heating profile were investigated relative to the degree of reaction violence.[1] Changes in the heating profile generated the greatest amount of change in the experimental results; however, none of the variables studied provided the modelers with anything beyond a mild reaction. Experimental complexity was increased in Phase II of the project with the addition of two additional explosive materials, LX-10 and PBX9501, to extend the level of cookoff reaction violence to the detonation regime.[2,3]

A full scale heavy wall penetrator (HWP) was used as the full scale test vehicle for Phase III of this work. Cookoff tests with both inert and live explosive fills were examined. Two heating configurations were selected based on the calculated predictions of ignition in the HWP configuration. A side heated configuration akin to that used in standard IM testing and an additional end heated configuration were selected in order to test the modeler's ability to predict the ignition location.

BACKGROUND

Cookoff is a complex and costly hazard that has an impact over a broad range of disciplines, impacting the munitions design, testing, transportation, and storage, as well as fire fighting tactics. Shipboard fires are a major concern in the US Navy, especially for the large aircraft carriers where the potential for fire is extremely high and the potential for weapons to be caught in fire is also high. There are many cookoff hazards situations to be considered, but the focus has been on the two ends of the spectrum: fast cookoff, where the item is subjected to direct fire such as a fuel fire; and slow cookoff, where thermal exposure of the item is indirect. In reality, the cookoff hazards threat spans the two extremes, where little data exist. With the advent of the Threat Hazards Assessment (THA), as allowed in MIL-STD 2105B, a cookoff testing regime can be selected that reflects the potential hazards environments that a weapons system is likely to experience, the stimulus levels, event probability, and likely outcome. Unfortunately, these kinds of data are rare, often difficult to obtain, and costly to generate for each specific weapons system. The implementation of a THA scheme which incorporates fully validated modeling tools will reduce design costs and increase developmental efficiency.[4]

It is neither practical nor affordable to generate the data describing ordnance response with respect to the shipboard fire threat for every ordnance item loaded. Ship commanders require accurate answers to a number of fire-related questions: (1) How long do their sailors have to fight a fire? (2) What are the most vulnerable munitions in a shipboard fire? (3) Can the munitions be loaded in the magazine in such a manner as to reduce their vulnerability? (4) What are the consequences of a cookoff reaction? These questions should be considered in the design of more sophisticated fire protection systems that incorporate part or all of the cookoff model concepts.

EXPERIMENT

A full scale ordnance item was needed for Phase III of the cookoff model validation effort. A generic HWP was selected for this work. The HWP hardware was excess from the IMAD/HE program. Three units were obtained from J. Roquemore at China Lake. Details on the HWP are given in Figure 1.

• Dimensions	
Total Length	17.8"
Outer Diameter	8.0"
Wall	0.5"
Aft Plate	0.5"
Nose Plate	1.5"
Liner	0.06"
Interior Volume	573.6 in^3
• Weights	
Empty	81.2 lb
Typical Load	33.8 lb
Total	115.0 lb
• Material	**4130 steel**

FIGURE 1. Details of HWP used in Phase III of the Slow Cookoff Model Validation.

The HWP was nominally 8 inches in diameter and 18 inches in length. It was composed of Type 4130 steel with a 0.5 inch wall thickness. The original aft closure of the HWP was replaced with a more robust closure design of H. Sandusky. This modification incorporated an o-ring seal and is shown in Figure 2. It was selected to provide increased confinement and to support three internal thermocouple probes. The HWP was instrumented with both internal and external thermocouples that were used to map the temperature contours generated in the device during thermal exposure. Strain gages were used on the live experiments and a resistance wire technique was also included. An inert HWP was tested in both the side and end heated orientations to determine the thermal behavior in the device and to test the selected heater capabilities.

FIGURE 2. HWP with Modified Aft Closure.

The HWP were lined with a polyamide epoxy liner, as per the recommendation of Naval Surface Weapons Center, Indian Head (NSWC-IH).[5] It was found that the liner failed during the thermal treatment involved in the mounting of the strain gages to the cylinder. Further consultation with NSWC and others resulted in the removal of the liner and reapplication of the material that had been "thinned" to a lower viscosity after the installation of the strain gages.

Two heating profiles were selected for Phase III, end heated and a traditional side heating arrangement. Preliminary calculations suggested that the end heated arrangement would produce a different reaction response than that of the side heated test due to the difference in ignition locations. A Minco Model HR6485.4L12A 375 watt silicone rubber heater was selected for the side heating test as shown in Figure 3. The heater is rated to withstand temperatures to 220ºC. Each heater was 5 inches wide and 15 inches in length with an effective area of 69.7 in^2. Five heaters were installed to cover the circumference of the HWP and secured with #20 stretch tape. A Minco model HM6809 R32.7L12T2 mica heater rated to withstand temperatures to 593ºC at a watt density to 100 W/in^2 was selected for the end heated test, as shown in Figure 4. The end heater was 6 inches in diameter with a 24.7 in^2 effective area. Both test fixtures were wrapped with Siltemp; a thermal insulating fabric to decrease the level of heat loss to the environment. Two inert tests were performed in order to determine the heating capability of each heater and to obtain an understanding of the resulting temperature distribution throughout the grain.

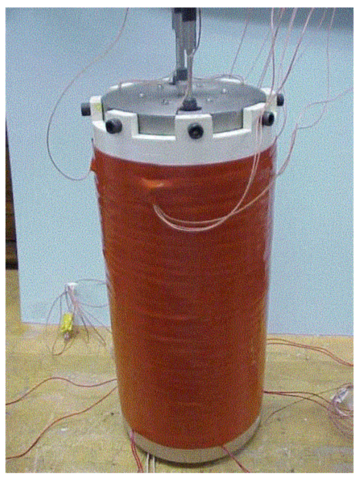

FIGURE 3. Silicon Rubber Heater for Side Heated HWP.

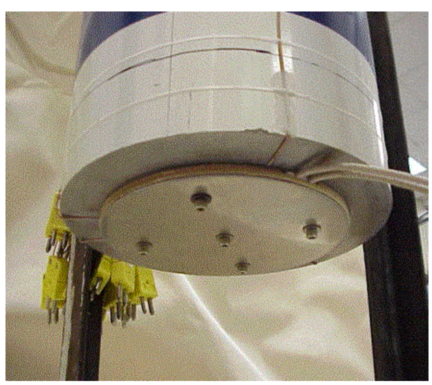

FIGURE 4. Mica Heater used in End Heated HWP

Heating was accomplished using an Omega CN8622TCA programmable process controller operated in time proportioned mode with 0-5 VDC output to a solid-state relay for delivery of pulsed 110 VAC to the heater. A "quick" ramp to 150ºC was selected with a 150 degree soak for 5 hours followed by the traditional 0.05ºC/min slow ramp to cookoff. A "quick" ramp of 3.3ºC/min was achieved for the side heater and 2.6ºC/min was reached for the end heater. Temperatures were monitored in the inert HWP with 52 type K thermocouples. Three internal probes were used each containing 10 thermocouples, 6 additional internal thermocouples were mounted on the walls of the cylinder. Sixteen thermocouples were mounted on the exterior of the HWP. The thermocouples were sampled every 0.5 seconds for a maximum of 64 hours during the inert tests. Two runs were made in each orientation. The live HWP were instrumented with 20 thermocouples, 9 or 10 strain gages, and the Sandia resistance wire.

Placement of the thermocouples for the "live" HWP tests was based on the analysis and recommendation of the modeling community. The thermocouples were concentrated near the end of the cylinder for the end heated configuration, as shown in Figure 5. Four external thermocouples (Omega GG-28) were located on the forward end next to the heater. The control thermocouple that provided feedback to the temperature controller was located in the center of the HWP. The remaining forward end thermocouples were located 2.5 inches from center at 30, 150 ,and 270 degrees. Three thermocouples were located on a plane 2.0 and 5.75 inches from the forward end at 90, 210, and 330 degrees. Two thermocouples were located on a plane 13.25 inches from the forward end at 90 and 180 degrees. One thermocouple was located on the aft end of the HWP, 0.2 inches from the center at 0 degrees.

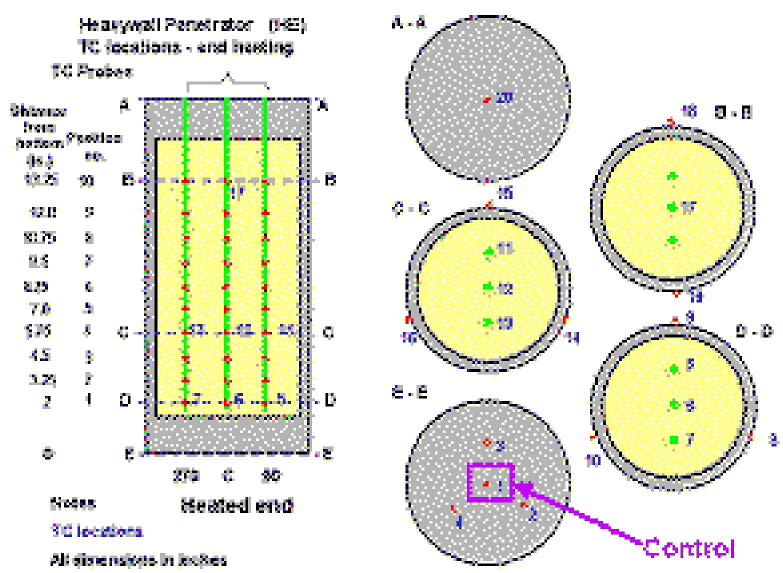

FIGURE 5. Thermocouple Locations for End Heated HWP Cookoff Test.

Three internal thermocouples (Omega PP10-36K-G-18-OST-M) were located along the center axis of the end heated HWP at 2 inches, 5.75 inches, and 17 inches from the forward end. Two internal thermocouples were located 2.5 inches from center at 90 degrees at a height of 2 inches and 5.75 inches from the forward end. Two internal thermocouples were located 2.5 inches from center at 180 degrees at a height of 2 inches and 5.75 inches from the forward end.

The thermocouples were distributed along the length of the cylinder in the side heated case, as shown in Figure 6. One external thermocouple was located in the center of the HWP at the forward end. Three thermocouples were located on a plane 4.5 inches from the forward end at 90, 210, and 330 degrees. Two thermocouples were located on a plane 9.0 inches from the forward end at 210 and 330 degrees. A thermocouple at the 90 degree location 8.8 inches from the forward end was used as the control thermocouple. The side heated HWP was tested in the horizontal position with 90 degrees at the top. Three thermocouples were located on a plane 13 inches from the forward end at 90, 210, and 330 degrees. One thermocouple was located on the aft end 0.2 inches from the center at 0 degrees.

Three internal thermocouples in the side heated HWP test were located along the center axis of the HWP at 4.5, 8.25, and 13.5 inches from the forward end. Three internal thermocouples were located 2.5 inches from center at 270 degrees at a height of 4.5, 8.25, and 13.50 inches from the forward end of the device.

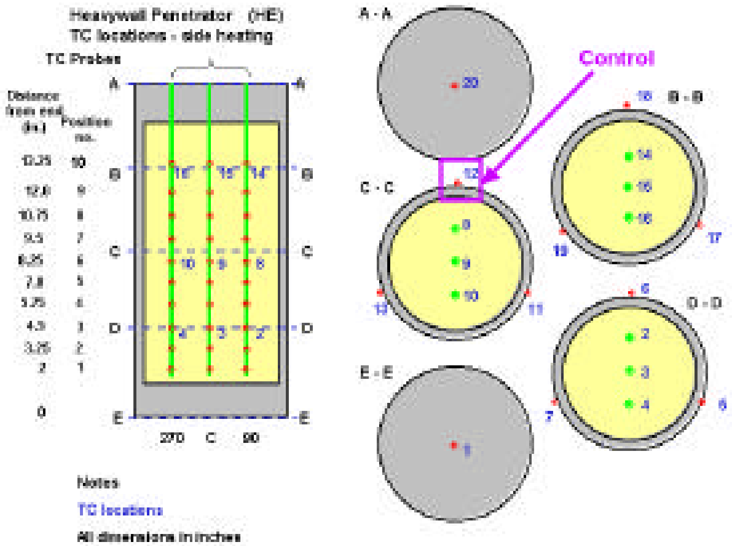

FIGURE 6. Thermocouple Locations for Side Heated HWP Cookoff Test.

All of the strain gages used in the two HWP experiments were type EA-060125BZ-350-LE. Nine strain gages were installed to measure hoop strain in the end heated HWP experiment. Three strain gages were installed on a plane at 90, 210, and 330 degrees at 1.75, 5.0, and 8.25 inches from the forward end. One strain gage was installed to measure longitudinal strain at 195 degrees and a distance of 5 inches from the forward end. A Sandia National Laboratory resistance wire was installed at 6.75 inches from the forward end.

Ten strain gages were installed to measure hoop strain in the side heated HWP experiment. Two strain gages were installed on a plane 5.25 inches from the forward end at 0 and 180 degrees. Four strain gages were mounted on a plane 9.0 and 13.0 inches from the forward end at 0, 90, 180, and 270 degrees, respectively. A Sandia National Laboratory resistance wire was installed at 9.875 inches from the forward end of the HWP.

The electronic thermocouple and strain gage data were recorded on a Nicolet Multipro multi-channel digitizer. The data were collected at two digitization rates. Thermocouple and strain gage data for the live tests were captured at 500 ms/point (2Hz) with a total sweep time of 1.5 days (260,000 points). Data collection was manually triggered for the 2 Hz data. Data was also captured at 1 microsecond/point (1 M Hz) for a total sweep time of 2 seconds (2,000,000 points). A pre-trigger time of 1.98 seconds (98%) allowed the acquisition of data to be triggered by the output of any strain gage.

The live HWP cookoff experiments were performed at the barricade 5 test site of area R of the Pacific Ranges and Facilities, Ordnance Test and Evaluation Division. An outdoor test pad was constructed as shown in Figure 7.

FIGURE 7. HWP Penetrator on Area R Test Pad – End Heated Configuration.

SAMPLE

INERT

A HWP fixture was filled with an inert explosive in which two tests were performed in each heating profile. The composition consisted of an R45 binder system filled with glass beads to simulate the solid fill. There was no aluminum added to this mix. The inert formulation was composed of 13.06 weight percent R-45HT, 14.05 weight perent hydrocarbon process oil, 71.3 weight percent glass beads (53-105 microns), 0.01 weight percent blue dye and 1.58 weight percent polymeric isocyanate.

EXPLOSIVE

The RDX-based explosive, PBXN-109, was selected for study in the validation experiment. This explosive was selected as the baseline explosive for the model validation project because it was believed that there would be considerable thermal characterization data for a widely used explosive such as PBXN-109. Characterization data describing the thermophysical, mechanical, and chemical properties of the explosive are required as input into the models used for cookoff modeling. Unfortunately, little data of the type required for the modeling was located and a number of characterization tests were required in the early stages of the study.[6] These data were used in the modeling performed for the Phase III, full scale tests.

Two HWP units were vacuum cast from a 150 gallon production mix, lot 021105 (5 November 2002) and cured at 57ºC. Each unit was filled with 33.25 lbs of explosive. A 0.75 inch gap was left at the aft end of the HWP as shown in Figure 8, to allow for thermal expansion during the test. Chemical and mechanical analyses of lot 021105 verified compliance with the PBXN-109 specification. The compositional analysis of the formulation is listed in Table 1. The average solid density of the formulation was 1.6704 ± 0.0015 gm/cm^3.

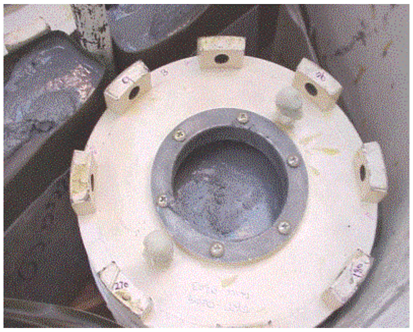

FIGURE 8. HWP Filled to Within 0.75 Inch of Top with PBXN-109 Explosive.

TABLE 1. PBXN-109, Lot 021105 Formulation.

Ingredient	Weight percent
RDX	64.87
Binder	15.62
Aluminum	19.51

MODEL PREDICTIONS

Prior to release of any live HWP results, the DOE modelers were asked to make predictions of the outcome of the two tests. An analysis of the experiment was performed using a 2-D axisymmetric finite element model of the HWP by Sandia National Laboratory.[7] Details of the analysis can be found in Reference 8. Various cases were considered that included original and modified chemistry, convective versus adiabatic heat loss, and the contribution of the liner. The predicted temperature and time to reaction are listed in Table 3 for the end heated case and in Table 4 for the side heated experiment. Case 9 was selected as the "best" prediction in each case as these simulations were the closest in predicting the temperature profiles of the inert HWP tests. These simulations showed that the liner contribution was minor, while chemistry and heat losses had a significant effect on the simulations.

TABLE 2. End Heated HWP Predictions.

Case	Description	Control Temp at Cookoff (ºC)	Time to Explosion (min.)
1	baseline,	176.6	864.3
2	baseline, with 8” heater	174.1	815.6
3	baseline, with original chemistry	181.2	956.5
4	baseline, without liner	176.4	859.7
5	baseline, with no heat losses.	171.6	765.3
6	baseline, without liner, no heat losses	171.5	762.9
7	baseline, 4x heat trans. coeff.	184.8	1028.2
8	baseline, 1.5x heat trans. coeff.	178.4	901.6
9	baseline, spatially varying heat trans. coeff.	178.1	894.9

TABLE 3. Side Heated HWP Predictions.

Case	Description	Control Temp at Cookoff (ºC)	Time to Explosion (min.)
1	baseline,	166.8	668.7
2	baseline, with entire sidewall heated	166.5	662.8
3	baseline, with original chemistry	173.7	806.0
4	baseline, without liner	166.7	667.5
5	baseline, no heat losses at all.	169.0 *	642.4
6	baseline, without liner, no heat losses at all	170.1 *	641.4
7	baseline, no heat losses from ends	165.5	643.1
8	baseline, 4x heat trans. coeff.	167.5	682.7
9	baseline, 1.25x heat trans. coeff	166.9	670.3

*With no heat losses, ramp heating profile is not maintained during exotherm; outer wall temperature is higher than expected.

Predicted ignition locations are shown in Figure 9 for both test orientations. It was predicted that the end heated sample would ignite along the center axis about 0.6 cm into the explosive and that the side heated sample would ignite on the side wall near mid plane about 1.6 cm into the explosive. Both simulations indicated that a significant portion of explosive would be at a relatively low temperature, thus indicating a mild reaction in both tests.

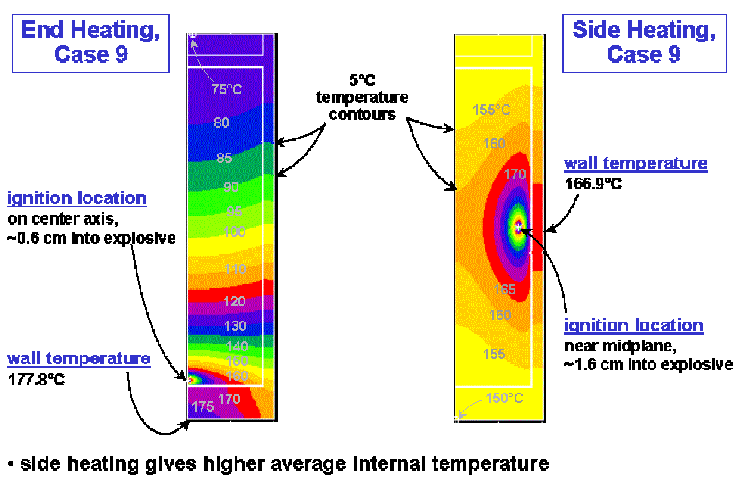

FIGURE 9. Predicted Temperature Profiles at Time of Ignition.

RESULTS

INERT FILLED HWP

Temperature contours are plotted in Figure 10 for the end heated inert HWP experiment after 30 hours. As mentioned two tests were run in this orientation, the duplicate tests were performed in order to obtain temperature data over a larger number of locations, since different locations were sampled for each test. It can be seen that the temperatures obtained from this test were sufficiently high to ignite the PBXN-109 and that the highest temperature is located at the center on the heated plane.

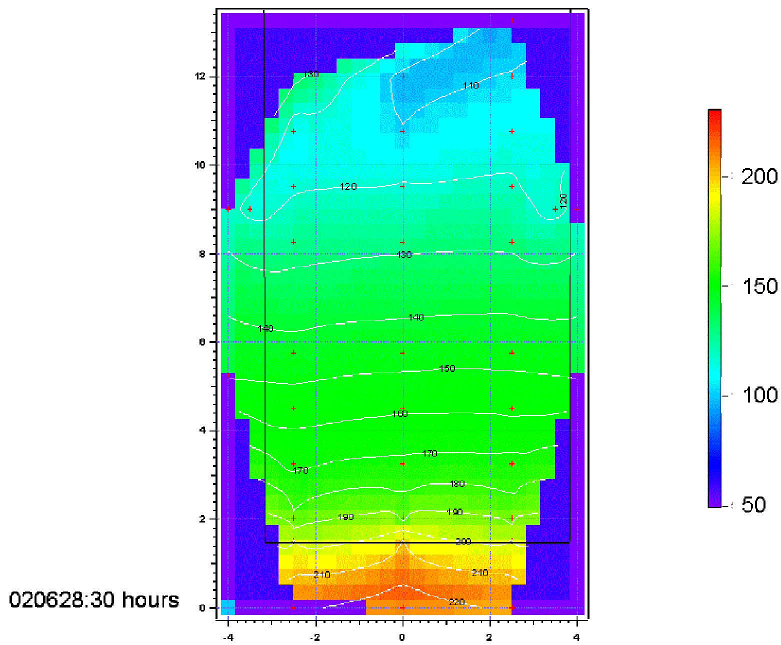

FIGURE 10. Temperature Contours for Inert HWP End Heated at 30 Hours.

Temperature contours are plotted in Figure 11 for the side heated inert HWP experiment after 16 hours of heating. Temperature measurements from two tests were combined to obtain these data. The data show that there is a sufficient heater output to ignite the explosive and the highest temperature location is on the top facing side wall.

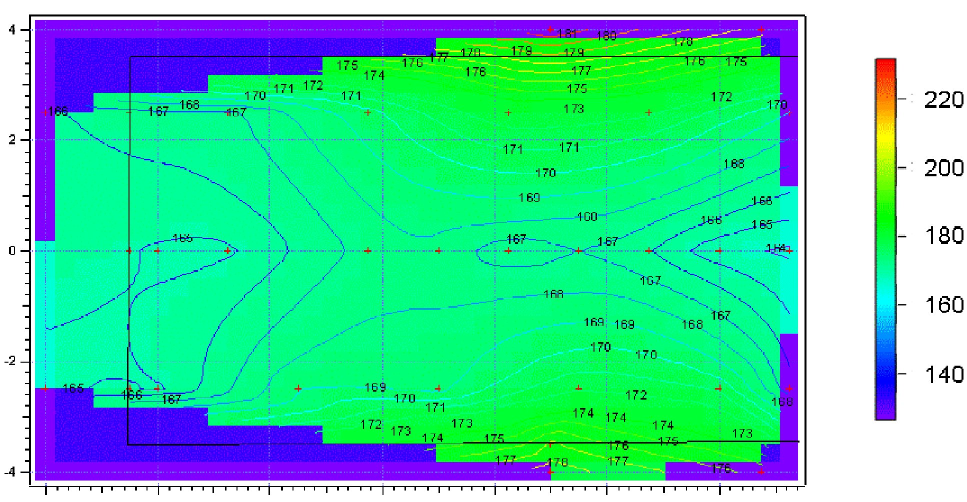

FIGURE 11. Temperature Contours for Inert HWP Side Heated at 16 Hours.

PBXN-109 FILLED HWP

The end heated HWP penetrator cookoff time was 1015 minutes (16.9 hours) at a maximum control temperature of 181.4ºC. Ignition appeared to occur on the center line at the forward end as predicted. Temperature contours are plotted for 1015 minutes in Figure 12. The hottest temperature occurred at the center of the grain, which was tested with the forward end facing down. It can be seen that at least half of the grain was below 100ºC at the time of cookoff. The post test collateral damage of the test pad is shown in Figure 13 where the cylindrical portion of the HWP can be seen. The aft portion of the HWP was located at a distance of about 50 feet from the test pad. The failure of the HWP occurred at a weld located near the end of the aft closure as shown in Figure 14. A total of 30.56 lbs of unreacted explosive was recovered from the test site (about 92 percent of the original sample weight).

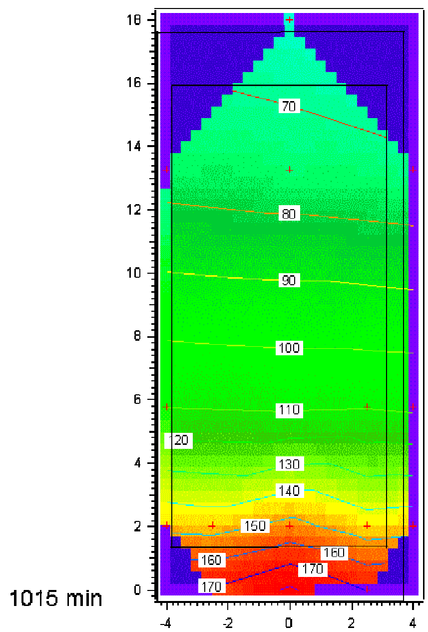

FIGURE 12. Temperature Contours for End Heated HWP at Time of Cookoff.

FIGURE 13. Post Test Damage to Test Site After End Heated HWP Cookoff Test.

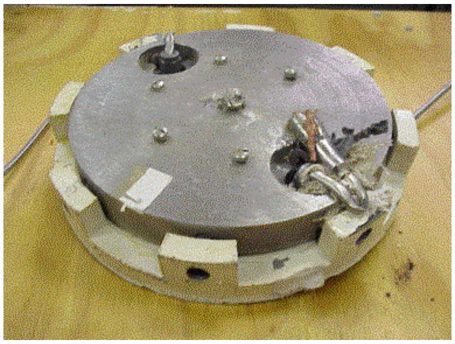

FIGURE 14. Aft End Piece Showing Failure at Weld.

Microstrain versus time data for the end heated HWP are plotted in Figure 15. The strain data exhibit a trend of slowly increasing strain, but no extreme changes occurred during the test. Since the HWP did not fail in a region near the strain gage locations, these data are not surprising.

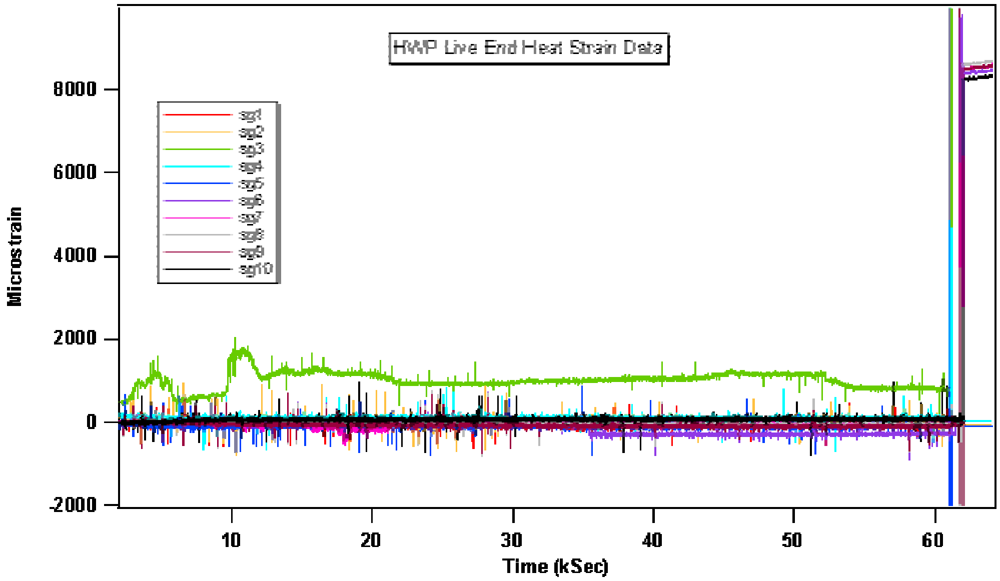

FIGURE 15. Strain Gage Data for End Heated HWP Test.

The side heated HWP penetrator cookoff time was 654.4 minutes (10.9 hours) at a maximum control temperature of 163.8ºC; however, the highest temperature recorded at cookoff was measured at the internal thermocouple located one inch in the explosive from the wall at the center position. The internal thermocouple reported 176.6ºC. The side heated HWP was tested in the horizontal orientation as shown in the temperature contours of Figure 16. It is assumed that ignition occurred at the location of highest temperature, which corresponds to the predicted location. The self heating, which occurred in the propellant, can be seen in the plot of the control and internal thermocouples of Figure 17. Only one thermocouple reported an exothermic event. Failure of the HWP occurred at the aft weld as described for the end heated test; however, in this case, the damage to the test site was extensive (Figure 18) with a fire resulting from the ejection of burning explosive. The cylindrical portion of the HWP was recovered about 550 feet from the test pad and the aft end fragment was located at about 415 feet from the test site in the opposite direction. Only 9.44 lbs of explosive was recovered from this test; however, much of the desert was covered with fine particulate explosive debris.

Microstrain versus time are plotted in Figure 19 for the side heated HWP test. Again, no extreme changes in strain were observed during the cookoff test since failure of the vessel occurred at the aft weld.

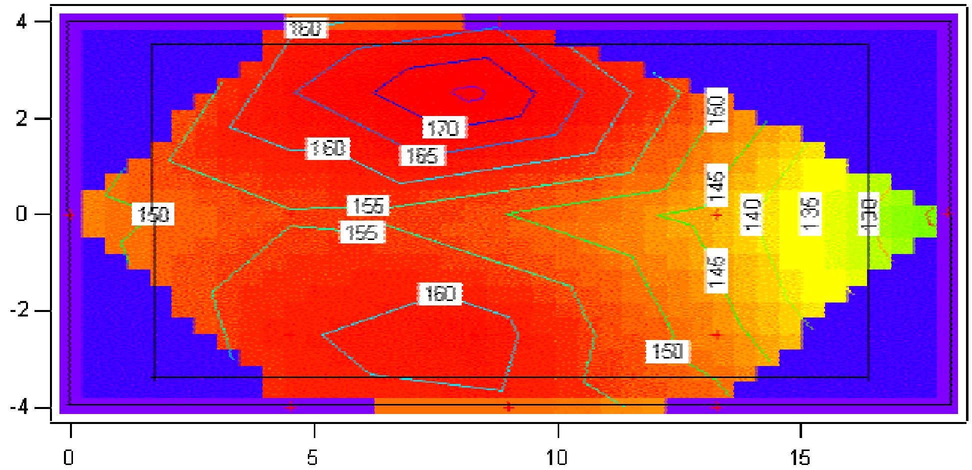

FIGURE 16. Temperature Contours for Side Heated HWP at Time of Cookoff.

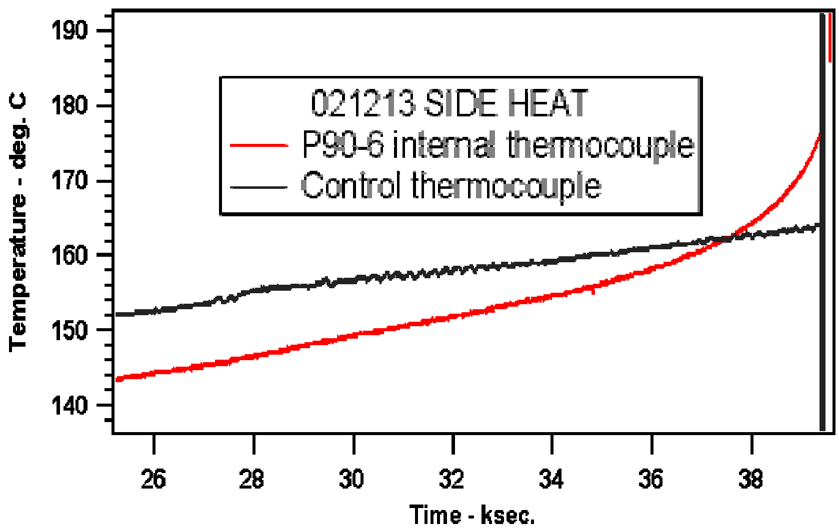

FIGURE 17. Temperature versus Time for Control and Internal Thermocouple from Side Heated Cookoff Test.

FIGURE 18. Post Test Damage to Test Site Following Side Heated HWP Cookoff Test.

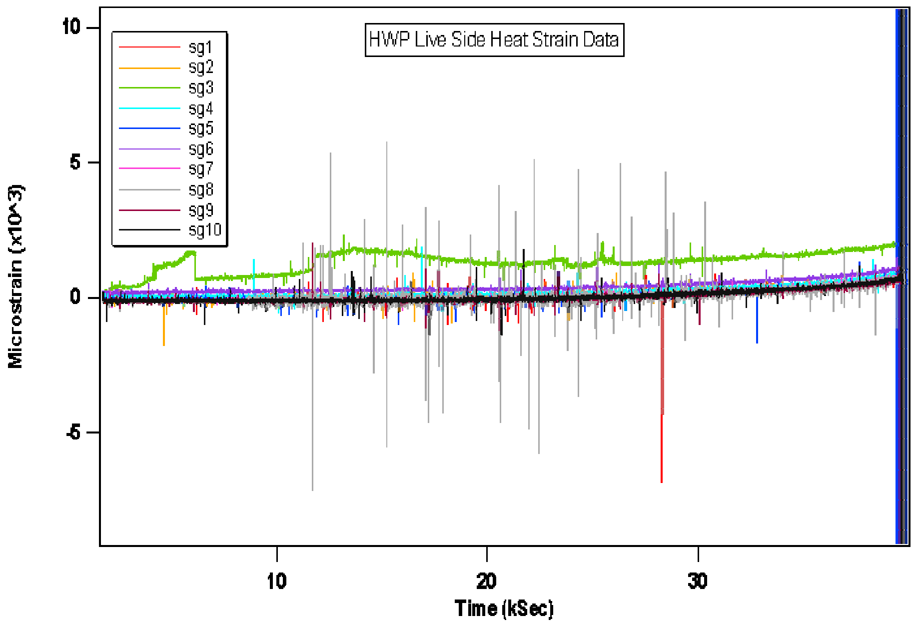

FIGURE 19. Strain Gage Data for Side Heated HWP Test.

COMPARISONS

A comparison of temperatures at the time of cookoff for end heated HWP to the inert test is presented in Figure 20a and b. The differences between the two experiments increase as distance away from heater is increased, for example, at 12 inches there is a 10 degree difference between the two tests.

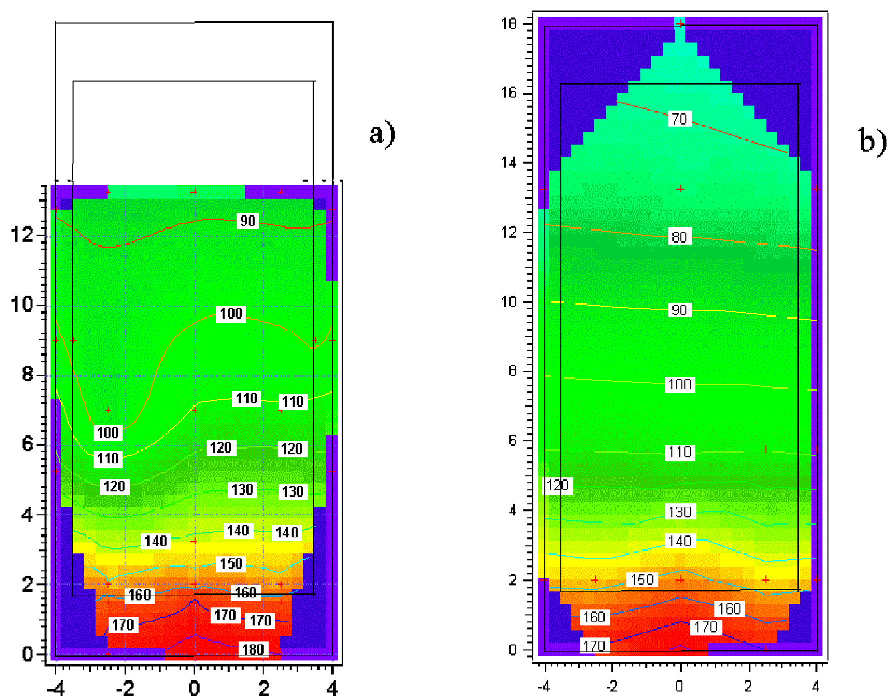

FIGURE 20. Temperatures of (a) Inert and (b) Live End Heated HWP after 1015 Minutes.

A comparison of temperatures at the time of cookoff for side heated HWP to the inert test is presented in Figure 21a and b. The differences in these two tests are more subtle, due to the development of the exotherm in the upper portion of the grain.

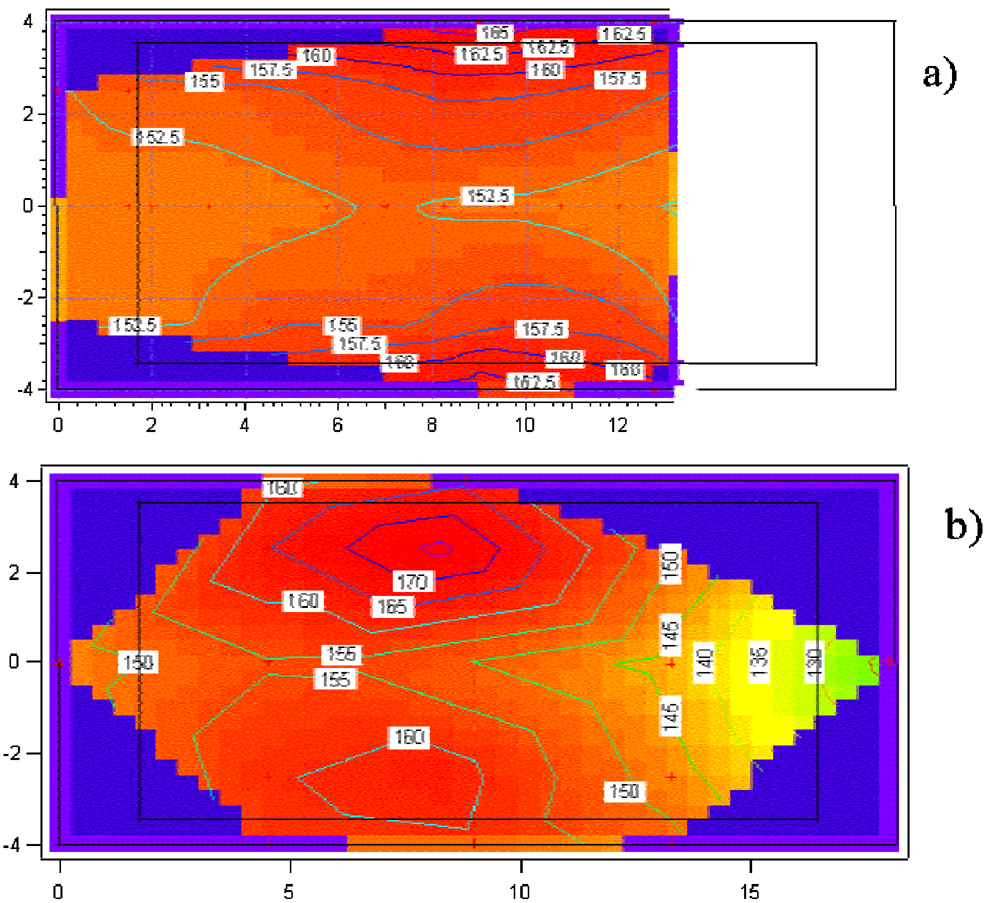

FIGURE 21. Temperatures of (a) Inert and (b) Live End Heated HWP after 654 Minutes.

Maximum instantaneous strain (MIS) is the analysis of large changes in strain over a short period of time using the raw data acquired from the strain gages.[1] In the small scale cookoff tests, MIS has been calculated to identify and verify reaction location and, combined with post-test photographs, used to obtain the degree of reaction violence with varying values of MIS.

In order to calculate MIS, the raw data from strain gages attached to the test vessel is compiled to reflect a point-by-point collection. The strain data are differentiated and a strain rate versus time plot is generated, as shown in Figure 22, for a typical small scale cookoff test. Examination of the high strain areas and associated times in reference to the heating cycle give the general location of the initial reaction point and the relative level of violence by the strain rate. In the example of Figure 22, the first arriving curve is sg 3, which was located near the center of the test vessel, where the sample failed.

An attempt was made to use the MIS concept in the HWP tests. The predicted ignition point on the end-heated HWP was the center of the grain adjacent to the heater plate, with the cylindrical vessel standing on end. The side heated HWP was oriented horizontally, allowing modelers to predict the rupture point to be on the center wall near the top of the setup. The test results were not as predicted. Instead of a rupture, both orientations failed at the weld located where the a-109ft closure was attached. Strain data gathered for both tests with a few thousand microstrain recorded. It should be noted that the level of strain recorded for the HWP tests was at least five times less that that recorded for tests in the small scale experiments.

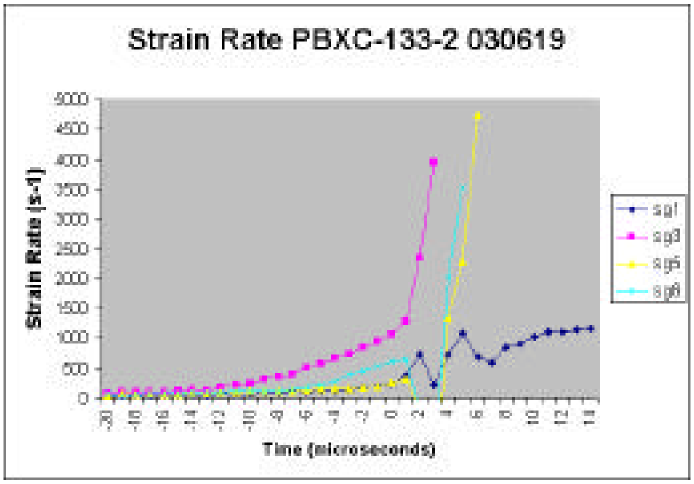

FIGURE 22. Strain Rate versus Time Data for a Typical Small Scale Cookoff Test.

In regards to the collected HWP strain data, the extreme changes in strain observed in the small scale experiments were not observed due to the location of the HWP failure; for this reason the concept of MIS could not be applied to these tests.

A comparison of the end heated and side heated predictions made to the experiment in Figure 23. It should be stressed that simulations 1-9 were real predictions made using the inert HWP tests to estimate heat loss boundary conditions for the live tests. All of the predictions fell within the range of the data. Simulations improved with a more thorough knowledge of the boundary conditions, as is illustrated by simulation A in the figure. Some of the observed differences in the predicted and observed response are due to the differences in the starting temperatures between the inert and live HWP tests. The inert experiments were performed in June at China Lake with a starting temperature at about 30ºC, while the live tests were performed in December with a starting temperature of about 12ºC.

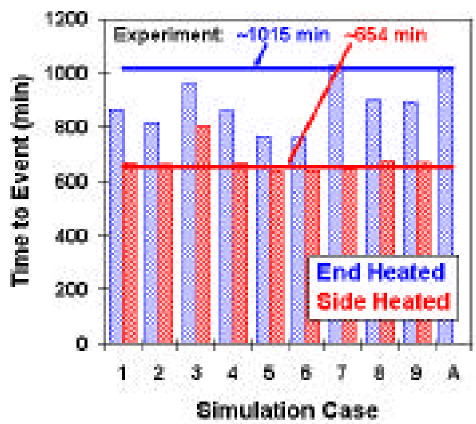

FIGURE 23. A Comparison of HWP Predictions of Sandia National Laboratory to Experimental Results.

A comparison of ALE3D calculated temperature fields at ignition are compared to both the end and side heated HWP experiments in Figure 24 and 25, respectively. These calculations were not “a priori” predictions, but were based on adjustment of the thermal boundary conditions to match the thermocouple output at selected locations. A cookoff temperature of 188ºC was calculated for the end heated experiment (181ºC measured) and 158ºC was calculated for the side heated experiment (164 degrees measured). There should be good agreement between the ALE3D simulations and the test since the calculations were based on the experimental measurements.

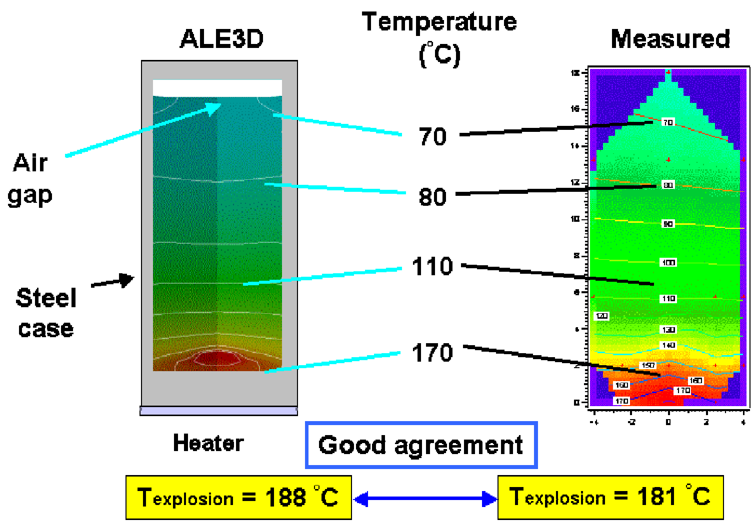

FIGURE 24. A Comparison of End Heated HWP Calculations of Lawrence Livermore National Laboratory to Experimental Results.

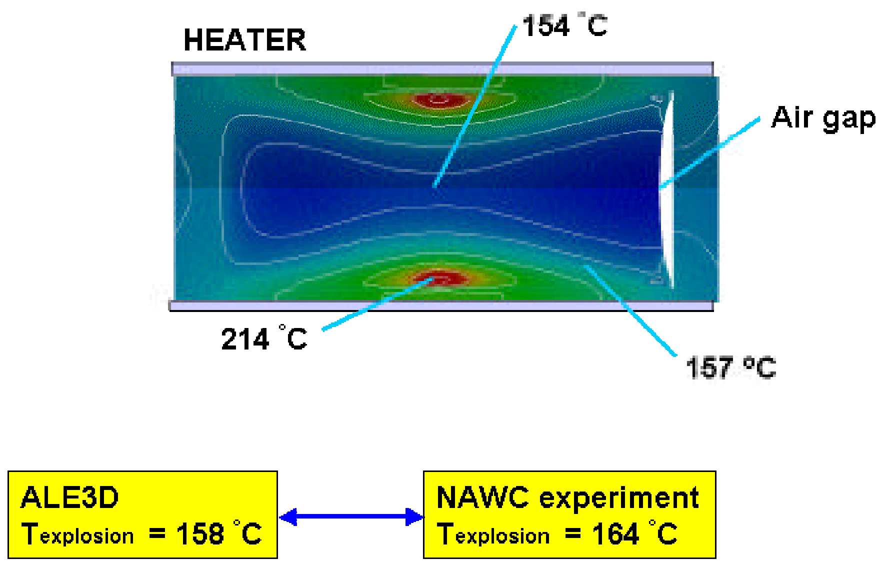

FIGURE 25. A Comparison of Side Heated HWP Calculations of Lawrence Livermore National Laboratory to Experimental Results.

CONCLUSIONS

The explosive PBXN-109 was vacuum cast and pressure cured in the HWP. Two tests were performed and, as predicted, the reactions were both mild. Differences in the two firings can be related to the amount of material at elevated temperature and in their firing orientation. Greater than 90 percent of the thermally damaged explosive weight was recovered in the end heated test, while only about 25 percent of the explosive was recovered in the side heated experiment.

Looking at the factors that impact strain gage data, the cause of the low levels of gage response was due to the HWP failure at the weld instead of a rupture of the tube wall, as was observed in the small scale tests. MIS can only be applied when a true failure occurs at the instrumented wall. The mode of HWP failure, while disappointing in its compromise of the experiments, represents an important element in the analysis of cookoff reactions. Careful attention to manufacturing and test details must be made in order for accurate predictions to occur.

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