SANDIA REPORT

SAND2017-5684
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Printed May 2017

Pipe Overpack Container Fire Testing: Phase I & II

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Abstract

The Pipe Overpack Container (POC) was developed at Rocky Flats to transport plutonium residues with higher levels of plutonium than standard transuranic (TRU) waste to the Waste Isolation Pilot Plant (WIPP) for disposal. In 1996 Sandia National Laboratories (SNL) conducted a series of tests to determine the degree of protection POCs provided during storage accident events. One of these tests exposed four of the POCs to a 30-minute engulfing pool fire, resulting in one of the 7A drum overpacks generating sufficient internal pressure to pop off its lid and expose the top of the pipe container (PC) to the fire environment. The initial contents of the POCs were inert materials, which would not generate large internal pressure within the PC if heated. However, POCs are now being used to store combustible TRU waste at Department of Energy (DOE) sites. At the request of DOE's Office of Environmental Management (EM) and National Nuclear Security Administration (NNSA), starting in 2015 SNL conducted a new series of fire tests to examine whether PCs with combustibles would reach a temperature that would result in (1) decomposition of inner contents and (2) subsequent generation of sufficient gas to cause the PC to over-pressurize and release its inner content. Tests conducted during 2015 and 2016, and described herein, were done in two phases. The goal of the first phase was to see if the PC would reach high enough temperatures to decompose typical combustible materials inside the PC. The goal of the second test phase was to determine under what heating loads (i.e., incident heat fluxes) the 7A drum lid pops off from the POC drum. This report will describe the various tests conducted in phase I and II, present preliminary results from these tests, and discuss implications for the POCs.

ACKNOWLEDGMENTS

The authors of this document would like to thank Mr. James O'Neil of NNSA and Dr. Robert C. Nelson of DOE EM for their close collaboration from the beginning of this test program. It was their motivation and knowledge of the facts surrounding this work which lead to funding and focus of this test program. We would also like to thank Matthew Q. Johnson of Los Alamos National Laboratories who collaborated closely with Sandia National Laboratories in all aspects related to operation and staging of POC drums at Los Alamos National Laboratories. We would also like to thank L. Wes Chilton and William L. Uncapher for assembling the Phase I test units; Danielle M. Michel for QA of Phase I tests; Vincent A. Valdez for instrumenting the test units in Phase I tests; Richard B. Simpson for video recording and editing; Jerry J. Koenig for test setup and IR video recording; Brandon L. Servantes, for running the Phase I tests; and Shane M. Adee, and Chuan P. Banh for running the Phase II tests. Other test support was provided by Sylvia Gomez-Vasquez and the ECI TTC crew.

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NOMENCLATURE

ARF	Aerosol Release Fraction
DAQ	Data Acquisition
DFT	Directional Flame Thermometer
DR	Damage Ratio
DOE	Department of Energy
EM	Environmental Management
FLAME	Fire Laboratory for Accreditation of Models and Experiments
HFG	Heat Flux Gauge
IR	Infrared
LANL	Los Alamos National Laboratories
MIDAS	Mobile Instrumentation and Data Acquisition System
MOD	Modifications
NNSA	National Nuclear Security Agency
NQA	Nuclear Quality Assurance
PC	Pipe Container
POC	Pipe Overpack Container
RFP	Rocky Flats Plant
SNL	Sandia National Laboratories
TGA	Thermogravimetric Analysis
TRU	Transuranic
TC	Thermocouple
TTC	Thermal Test Complex
WIPP	Waste Isolation Pilot Plant

1. INTRODUCTION

The Pipe Overpack Container (POC) was developed at Rocky Flats to transport plutonium residues, with higher levels of plutonium than standard TRU waste, to the Waste Isolation Pilot Plant (WIPP) for disposal. The POCs consist of an inner Pipe Container (PC) surrounded by fiberboard (Celotex®) and plywood dunnage inside of a 7A drum (see Figure 1). The PC was designed to maintain separation of fissile material and to provide shielding from radiation. In 1996 Sandia National Laboratories (SNL) conducted a series of tests to determine the degree of protection POCs provide during storage accident events. These tests were conducted to support use of POCs by Rocky Flats Plant (RFP) to package and ship plutonium residues. One of these tests exposed four of the POCs to a 30-minute engulfing pool fire, resulting in one of the drums generating sufficient internal pressure to pop off its lid and expose the top of the PC to the fire environment. The PC contents in this test were inert materials that would not generate significant pressures within the PC. Even if the O-rings and filter failed, only a small fraction of the radioactive material contained within the PC is predicted to be released. These test results were reported in 1997 for the RFP (Ammerman, Bobbe, Arviso, & Bronowski, 1997) and are also available in DOE STD-5506-2007 (DOE, 2007).

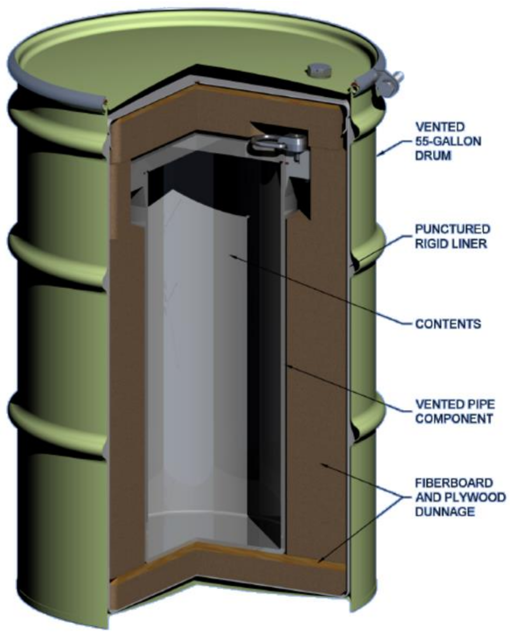


Figure 1. POC Assembly

Further review of ongoing use of POCs showed that current generating facilities were utilizing the POC for storage, and subsequent shipment to WIPP, of reactive salts and combustibles. The use of the POCs for combustibles was not considered an appropriate extension of the 1996 SNL tests and the aerosol release fractions (ARFs) could be significantly different for this application and from what is quoted in DOE STD-5506.

The generating facilities, as well as WIPP, would like to be able to claim some level of protection is provided by the POC for thermal assaults that could occur within DOE storage facilities. To gather information to support this claim, a storage drum test program headed by the DOE Office of Environmental Management (EM) and the National Nuclear Security Agency (NNSA) was established for the POCs with combustible contents. In 2015, SNL started conducting fire tests with POCs in support of the EM/NNSA test program.

This report describes the various tests conducted between October of 2015 and April of 2016 as part of the initial effort of this test program. Specifically, the goal of this fire test series was to examine performance of POCs with combustibles inside. This report presents results from these tests, and discusses implications.

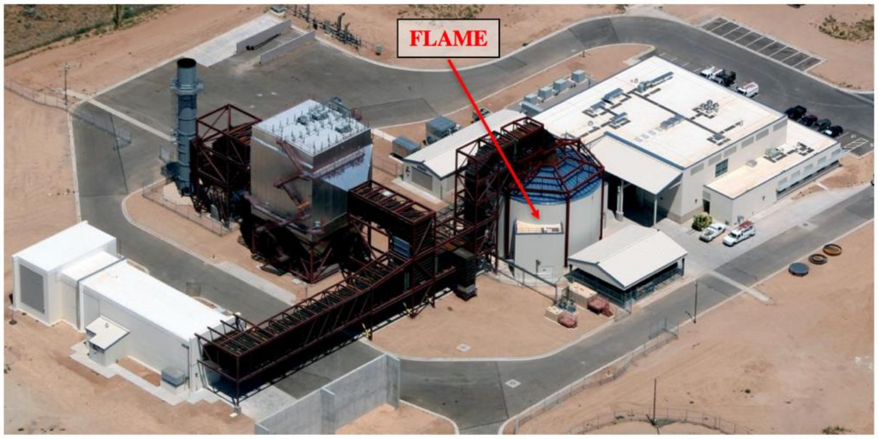
2. OVERVIEW OF FIRE TESTS

The primary goal of the 2015-2016 test series was to see if the PCs filled with inert material inside the POCs would reach temperatures that would result in the generation of sufficient gas to cause over-pressurization of the PC and subsequent release of its aerosol contents when engulfed in a fire. If so, future tests, as part of this test program, would be conducted with combustibles inside the PC to determine damage ratio (DR) and aerosol release fractions (ARF) from PCs under the same conditions. Ideally the POC tests would have been conducted with combustibles, but at the time it was not known if the fire would cause over-pressurization of the PC and subsequent violent failure, jeopardizing the test facilities. Thus, obtaining temperature response of the PC, both inside and outside the fire, would be a first step in understanding the likelihood of combustibles decomposing in or near the fire and the possibility for PC failure.

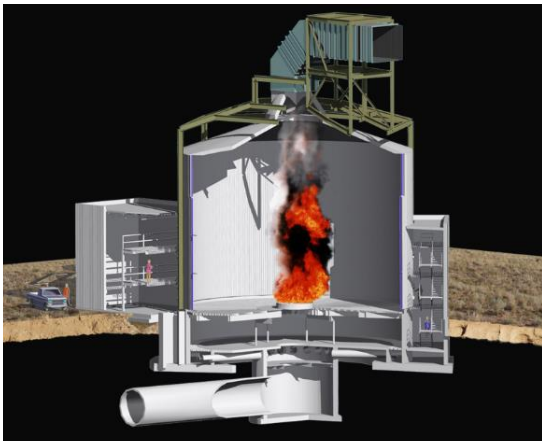
Test Facility

In all, four tests were performed at SNL between October of 2015 and April of 2016. All tests were conducted inside the Fire Laboratory for Accreditation of Models and Experiments (FLAME) test cell located in SNL’s Thermal Test Complex (TTC) (see Figure 2). FLAME is a vertical wind tunnel design for conducting pool fires tests under calm conditions. The test cell has an inner diameter of 18.3 m and is 12.2 m tall along its perimeter walls. The walls are made of steel channel sections and are filled with water to keep the perimeter of the facility cool. At the top of these perimeter walls, the ceiling slopes upwards (~18º) from the end of the walls to a height of 15 m over the center of the facility. A round hole 4.9 m in diameter at the top of the test cell transitions to a chimney duct, allowing fumes to escape the test cell.

Most of the test cell floor is made up of metal grid panels. At the center of the grid floor of the test cell is a fuel pan or gas burner. FLAME works with either a 3 m diameter gas burner (H_2, CH_4, etc.) or a liquid fuel pool (JP8, Jet-A, methanol, etc.) For this test, only the liquid fuel pool was used. Air channeled vertically through the grid floor, via a vent ring several feet below the floor and adjacent to the perimeter walls, allows air to be entrained naturally into the fire, as it would be in an outdoor fire.



(a)



(b)

Figure 2. (a) Location of FLAME within the TTC and (b) interior of the FLAME facility.

General Test Layout

Figure 3 shows the typical test layout in this test series. The 3 m circular pool shown at the center of the pool was initially filled with Jet-A fuel in all tests. A remote refueling system added fuel to the pool in discrete amounts during tests to keep the POC fully engulfed. To limit the fire to the desired time, the pool has a drain system that dumped all remaining fuel at the end of the test, almost immediately terminating the fire. Typical fuel consumption rate for these tests was 0.3 kg/sec. All tests in this series consisted of one POC placed at the center of the pool, with additional drums placed on the grid floor outside of the fuel pan at various distances, as depicted Figure 3. The POC at the center of the pool was always resting on a square-grid table, 1 m above the fuel pool surface and directly above an empty 55 gallon drum. This vertical configuration is typical of what is seen in storage facilities, where drums are stacked on top of each other, typically in a drum-array arrangement within a single drum level, as seen in Figure 4. In these tests, there were no drums adjacent to other drums as depicted in Figure 4 and the stack was only two drums high. This test configuration, without the third stack of drums above the POC drum or adjacent drums within the same level as the POC drum, exposes the POC drum to higher thermal loads than would be experienced within the typical drum-array arrangement depicted in Figure 4.

Figure 3. Typical fuel-pool/drum layout inside of FLAME.

Figure 4. Drums in a typical storage configuration at LANL

In all tests, the top center drum was instrumented with at least four thermocouples (TCs), while the lower empty drum was never instrumented. The empty drum was there to block the flames and to partially insulate the top POC, as occurs in an actual stacked-drum configuration. The lower drum was also used in some tests to route TC lines from outside the fire to the interior of the top POC. The reason for loading and instrumenting just the upper drum is that this is the drum that will experience the highest temperatures in a typical storage fire should there be a fuel pool accumulated at the base of the bottom drum. Fires typically contain a relatively cold region adjacent to the surface of the pool. Near the edge of the base of a quiescent pool fire, where the plume diameter is largest, air entrainment deep into the plume at this height is limited. Thus, combustion is efficient only near the edges of the fire but not inside the plume, which results in a cooler interior region. Further up from the fuel pool, air entrains more readily further into the plume, creating hotter regions deeper into the fire. The extent, height wise, of the cold region is greatest at the center of the fuel pool and decreases towards the edge of the pool. Thus, the shape of the cooler region resembles a dome. Objects submerged within this dome, such as the bottom drum, experience lower heat fluxes than other objects outside of this region within the fire (Gritzo, Nicolette, Murray, & Moya, 1995).

All drums outside the fire were located on the floor of the facility at distances ranging from 1.7 to 4.3 m from the center of the pool, all spaced at an angular distance of approximately 45 to 90 degrees from each other, depending on the test. Some POCs outside the fire were instrumented with TCs, as will be indicated.

3. SUMMARY OF FIRE TESTS

For technical/historical reasons and for discussion herein, the four tests were conducted in two separate phases. Table 1 shows a breakdown of each tests by phase.

Table 1. Summary of Tests

Phase	Test #	Drum Label	Type	Lid (Y/N)	Contents 55-Gallon Drum/PC	Radial Location (m)	Heat Flux (kW/m^2)	PC TCs (Y/N)
1	1	A	POC	N	Standard/Cerablanket®	0	~80	Y
		B	POC	Y	Standard/Cerablanket	1.7	55	Y
		C	POC	Y	Standard/Cerablanket	2.75	30	Y
		D	POC	Y	Standard/Cerablanket	4.3	16	Y
	2	A	POC	Y	Standard/Cerablanket	0	~80	Y
		B	POC	Y	Standard/Cerablanket	2.0	45	Y
		C	7A	Y	Celotex®/NA	2.75	30	NA
		D	POC	Y	Standard/Cerablanket	3.2	23	Y
		E	7A	Y	Celotex®/NA	3.2	23	NA
2	1	A	POC	Y	Standard/Empty	0	~80	N
	2	B	POC	Y	Standard/Empty	0	~80	N
		C	POC	Y	Standard/Empty	1.7	55	N
		D	POC	Y	Standard/Empty	2.0	45	N
		E	7A	Y	Standard/Combustibles	1.7	55	NA
		F	7A	Y	Standard/Combustibles	2.0	45	NA

The first two tests were part of Phase I, and the last two were part of Phase II. Phase I focused primarily on determining the thermal response of the PCs, while Phase II focused on the performance of the drum lid and drum filter. Other details shown in the table include the type of drum, the drum configuration (drum lid vs. no drum lid plus other components inside the drum), the radial distance of the drum from the center of the fire, the equivalent heat flux distance, and the PC instrumentation.

All tests in Phase I were conducted using Nuclear Quality Assurance (NQA-1) processes to collect quality temperature measurements. Routing TCs to the interior of the POC was particularly challenging and required rigorous instrumentation checks to make sure all TCs and TC channels in the data acquisition (DAQ) system were recording data accurately per NQA-1 standards. As part of NQA-1, the drums were weighed before and after each test. In addition, after each test, each POC drum lid was inspected for damage on the drum filter or the drum seal, and each accompanying PC was leak tested. This leak test only verified the leak rates through the PC filter gasket and the PC flange O-ring. Note that leak rates through the PC filter were not obtained. PC filters are designed to release gases generated inside the PC (i.e., hydrogen) during normal storage conditions; therefore, the leak rate is not zero before or after the test if the PC filter remains in good condition. Therefore, if the PC filter looked intact after the test, it was assumed that the PC filter still functioned as designed.

In Phase II, no temperature data were collected and no leak tests were conducted. Recall that these tests were primarily conducted to assess the performance of the drum lid. As such, the tests only required documentation of the test layout and weigh-in of the drums before the tests, extensive use of videos and cameras during (videos only) and after the tests, and weigh-in of the drums and inspection of PC filters after the drums were removed from the test cell.

Details of Phase I Tests

As noted in Table 1, two fire tests were conducted in the first phase, each lasting 60 minutes. Figure 5 and Figure 6 show the location of the drums relative to the fuel pool in these tests. For reference, the door of the FLAME test cell is located on the northeast side of the test cell. The azimuthal origin was aligned with the edge of one of the floor grid panels at the entrance to the facility. Drum distances from the center of the pool are given in Table 1. Four standard POCs (drums A, B, C, and D) were used in the first test, while three standard POCs (drums A, B, and D) were used in the second test. Drum D in the second test was the same POC drum labeled D in the first test, but rotated 180° about its axis to expose the undamaged side of that drum to the fire in the second test. Drum D contained all standard POC components, except that some of the plastic liner was degraded during the first test. Two 7As (drums C and E) were added to the second test at the request of EM/NNSA. Both these drums were filled with combustibles, i.e., chipped Celotex® inside a plastic bag (see Figure 7).

As noted in Table 1, one significant difference between these two tests was that in the first test the center POC (i.e., drum A) was installed without: (1) the drum lid, (2) the plastic liner cover, (3) the Celotex® cover, and (4) the wood board attached to the Celotex® cover. The reason for testing without these components was that the 1996 SNL tests suggested that for drums inside the fire these components would be ejected. In one of those tests, the POC drum lid flipped over onto the side of the drum, the top covers were then ejected, and afterwards the rest of the Celotex® material remaining inside the drum burned completely. A test without these components was considered the worst possible scenario from the standpoint of recording the highest temperatures on the PC. In the second test, the center POC included all these components from the beginning of the fire to see if the drum lid would fail again for a POC inside the fire, as happened in the 1996 SNL tests.

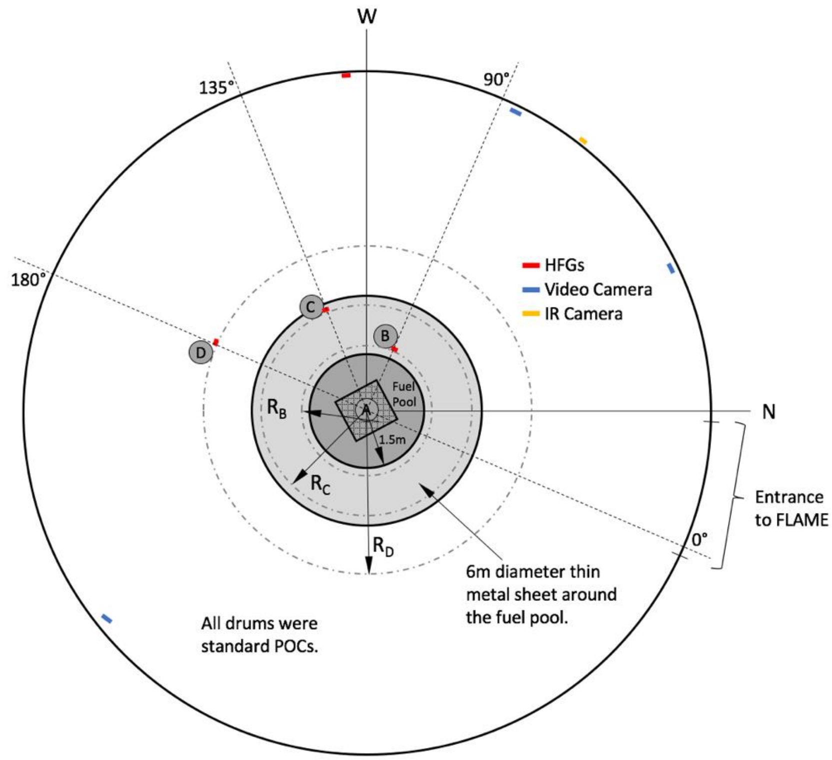


Figure 5. Test layout for Test #1 in Phase I.

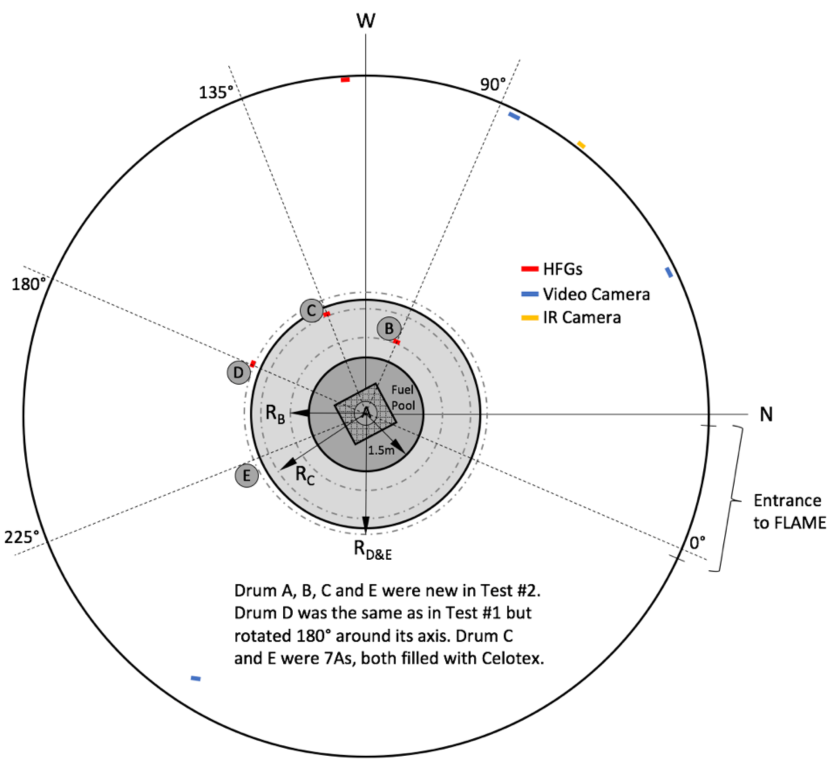


Figure 6. Test layout for Test #2 in Phase I.

Figure 7. Drums outside the fire filled with chipped Celotex.

In a storage environment, there is a high probability that at least some drums will only be exposed to an offset fire, as reported in WHC-SD-SQA-ANAL-501, (Baylor, Guttok, & Bucci, 1996). Distances and heat fluxes for these drums in the Phase I tests are given in Table 1 relative to the center of the axis of the fire pool to the closest point on the drum. The heat fluxes were obtained from correlations found in (Drysdale, 2007). This correlation was also used to corroborate heat flux measurements obtained with heat flux gauges (HFGs) deployed during the experiments, as will be described later in this section.

As shown in Figure 8, TCs were installed in several locations inside the POCs to measure the temperature responses of the internal components in Phase I for drums inside and outside the fire. These images demonstrate how POCs were first instrumented and then assembled: starting from the top left where the drum is laid down for instrumentation, proceeding through the middle with instrumentation of the POC components and the PC, and finalizing on the lower right where the PC is shown inside the POC after assembly is complete. Note that color sensitive markers were also placed inside the PCs as shown in the third row, second image in Figure 8. Also Cerablanket® was used as a substitute for typical combustible materials because its thermal conductivity is about the same as the average thermal conductivity for typical combustibles stored in PCs based on data obtained from TA-55 at Los Alamos National Laboratory (LANL).

All TCs were type K, mineral insulated, and sheathed with a 1/16 inch outside diameter. The tables in Appendix A show the exact location of the TCs in these drums. As shown in those tables, the TCs were distributed every 90 degrees inside and throughout the height of the POC. TCs were placed on the interior plastic liner, and on the outer surface and on the interior of the PC. TCs were also placed outside of the POC drum to measure flame temperatures outside of the fire to ensure that flames fully covered the top and sides of the drum. Instrumentation of the POCs required modifications to the design of the POCs. Appendix B shows a drawing detailing this modification in addition to some pictures showing the results of the modifications.

Figure 8. Series of images showing the process of instrumenting and assembling POCs in preparation for Phase I test. Images are from the first test.

Because the TCs were inserted inside the PC, these containers were checked for leaks prior to the test. This was done to make sure the PC could be pressurized during the test, and for comparison against post-test leak tests. If the PC filter was not clearly ruptured after post-test examination, the

PC could be checked to make sure the leak rate through the filter gasket and the flange O-ring was still as expected (below 10^{-2} std·cm^3/sec).

As shown in Figure 5 and Figure 6, HFGs were placed adjacent to the POCs outside the fire to measure the incident heat flux on the hottest part of the drum (see Table 1 for radial distances). The type of HFGs used in these tests was a Directional Flame Thermometer (DFT) (see Figure 9.) These HFGs consist of two 1/16 inch thick plates separated by 1 inch Cerablanket insulation. The plates are painted with Pyromark® and then baked to give the plates' surfaces a stable emissivity prior to the test. This process is required since the inverse heat transfer calculations used to obtain the incident heat flux (Q_{inc}) to the plate are based on the temperature of the TCs, the geometry, and the material properties that make up the HFG, including the emissivity of the sensing plate and the equivalent convective coefficient of the flow passing through the plate. Calculations are particularly sensitive to the emissivity of the plate. Uncertainties can be up to 20% of the calculated heat flux (Figueroa, 2005). The inverse heat flux calculations were performed using the IHCP1D computer program. Note that one additional HFG was placed near the wall of the facility (~9 m from the center of the pool), as shown in these figures, also facing the center of the pool.

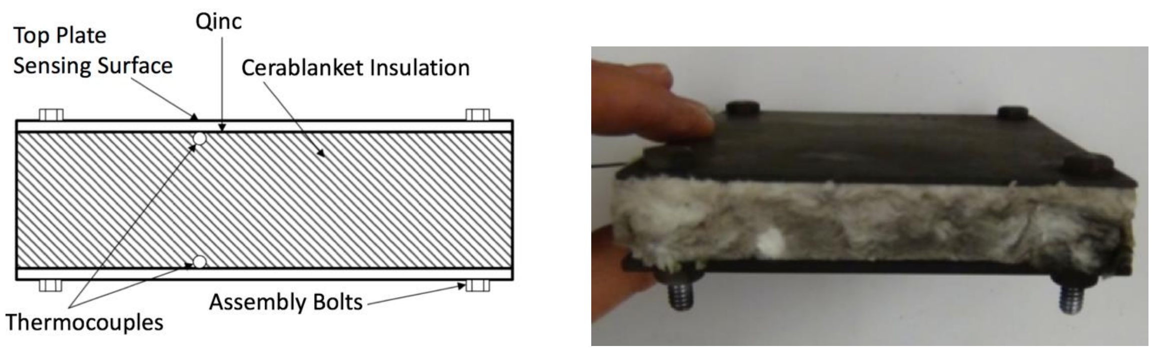


Figure 9. Heat Flux Gauge (HFG) used in POC and 7A fire tests.

Beside the temperature response of POC components, one additional aspect of interest was the performance of the drum seal, drum filter, and drum lid. Does gas start to vent through the drum seal before the drum filter ruptures; does the drum lid open before the drum filter ruptures; if the lid opens, when does it open; etc.? To help answer some of these questions, three video cameras and one IR camera were deployed to monitor the tests in real time and for closer post-test examination of test events. Video cameras provided coverage of the entire flame region and of specific drums, and an infrared (IR) camera was used to observe the center POC through the flames. Figure 10 shows the four views taken with three video cameras and the one IR camera in Phase I. The top left image was taken with a camera set on the floor of the facility and looking up at the fire with a wide-angle view. This camera was located in the northwest quadrant of the facility, close to the IR camera. The top right image was also taken with a second camera in the northwest quadrant, but looking closer at the fire. The lower left image was taken with the camera located in the southeast quadrant. This camera was directed mostly at the drums outside of the fire, with the edge of the fire visible to the right. The last image was taken with an IR camera, and shows the center POC inside the fire.

Figure 10. Camera views used in Phase I.

Phase I tests were controlled and documented using NQA-1 plans and procedures. As mentioned before, temperature responses of the POCs were collected using NQA-1 procedures. As part of these procedures, TC data was collected using the Mobile Instrumentation and Data Acquisition System (MIDAS), which is designed and accredited to meet the requirements of NQA-1 processes and procedures. Additional data collected with MIDAS includes audit trail containing information on how the MIDAS was configured for the test. An estimate of total uncertainty in the temperature measurements is expected to be ±(2-3) % of the reading in Kelvin, which includes error contributions by the MIDAS DAQ, instruments, and mounting to 95% confidence as reported in (Nakos, 2014).

To conduct the leak tests post-test, the PC filter was first sealed with a rubber piece placed at the outlet of the carbon media. The pressure and temperature inside the PC were then monitored for 5 minutes, recording the internal pressure and temperature every minute. This process was repeated a second time with the filter and filter gasket removed and the four holes on top of the PC lid sealed. The following equation was then used to estimate the leak rate through the gasket/O-ring combination and/or through the O-ring only:

$$LR = \frac{V_T T_S}{t_f P_S}\left(\frac{(P_f)_{af}}{(T_f)_{af} + 273.15} - \frac{(P_i)_{af}}{(T_i)_{af} + 273.15}\right)$$

where V_T is the total free internal PC volume with the PC contents; t_f is the total monitoring time; P_s and T_s are the standard reference pressure (14.7psia) and temperature (298K), respectively; P_i and P_f are the initial and final internal PC pressures, respectively, measured during the monitoring time t_f and after (af) the PC was exposed to the fire test; and T_i and T_f are the initial and final internal PC temperatures, respectively, during that same period. V_T was calculated using the following formula:

$$V_T = \frac{(P_f)_{bf} - (P_i)_{bf}}{P_A - (P_i)_{bf}} V_E$$

where V_E is the empty volume of the PC; P_A is the atmospheric pressure at the location of the test, and P_i and P_f are the initial and final internal PC pressures, respectively, measured before (bf) the PC was inserted into the POC during initial drum setup.

Details of Phase II Tests

As noted above, one goal in Phase I was to collect evidence on the effects of the fire on the performance of the POC and 7A drum lids, both for the POC with the lid inside the fire on the second test, and for the drum outside the fire in both tests. Particularly, the drum lid filters used in the current test series were different in design than the ones used in the 1996 SNL tests, but served the same purpose [i.e., allow release of gases (e.g., volatile organic compounds and hydrogen) from inside the drum during normal operating conditions as a result of long term degradation of internal materials, while maintaining radioactive aerosol materials inside the drum]. How does the drum lid perform with this filter design, inside the fire and outside the fire? It was expected that at least the drum lid would get ejected on the POC inside the fire in the second test. This did not happen, and although this outcome was plausible, additional tests, as outlined in this section, were required to confirm this result. Information obtained later from TA-55 at LANL drum torqueing procedures reveal that the drum lids were not torqued sufficiently. This, however, did not invalidate temperature measurements collected in Phase I.

As noted above, the main goal of the second phase of tests was to see how the POC and 7A drums would perform when the drum lid was torqued appropriately. To ensure this goal, staff from LANL were used during the second phase to demonstrate the procedure for tightening the drum lids in TA-55 at LANL. During that demonstration, it was learned that to achieve the required 60 ft-lb torque, the lid ring must be hammered with a mallet all around the drum ring every so often to readjust the lid gasket before continuing to tighten the lid to prevent damage to the drum ring or ring bolt. This procedure is repeated several times until the drum ring bolt is torqued to 60 ft-lb. To verify that the lid is properly torqued, at the end of the procedure when the 60 ft-lb torque has been reached, the spacing at the end of the ring should be checked to make sure it is about 3mm, as indicated in Figure 11. Although this was followed in earlier tests, the ring was not hammered with sufficient force to readjust the drum seal and drum ring, preventing torqueing to proceed until the 3mm gap was reached. That is, the torque specification is not sufficient to guarantee proper closure of the drum lid.

Two fire tests were conducted in Phase II; both fires lasted 30-minutes. As noted in Table 1, all POCs used in this phase contained empty PCs. All 7As tested contained typical combustibles (i.e., plastics, rubber gloves, etc.) as opposed to chipped Celotex®. The first test had only one standard POC at the center of the fuel pool. The second test included three standard POCs and two 7As and was the only test in Phase II with drums outside the pool. As shown in Figure 12, one POC and one 7A were placed at a radial distance of 1.7 m (or 55 kW/m^2 equivalent distance); the remaining drums were placed at a radial distance of 2.0 m (45 kW/m^2 equivalent distance). In this test, the drums were spaced 90° apart. Note that the azimuthal origin was shifted when compared to the previous layout figures; this new origin has no special significance.

Figure 11. Gap that remains in the drum ring after torqueing to 60 ft-lb. Image taken from the first test in phase II.

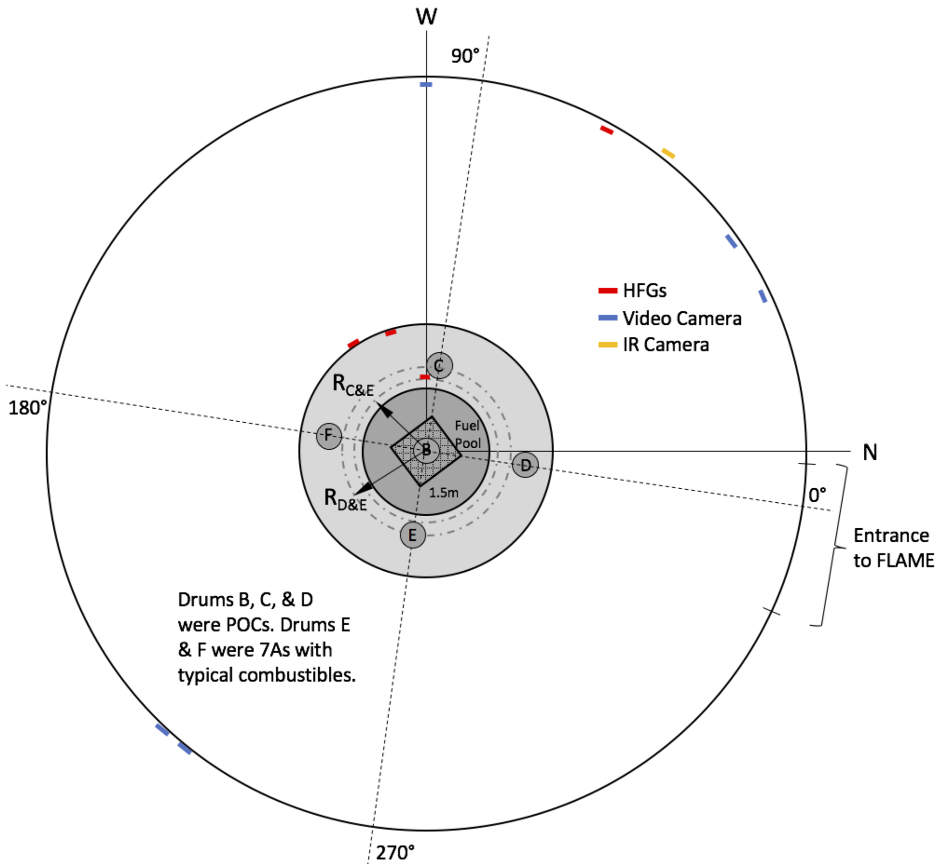


Figure 12. Test layout for Test #2 in Phase II.

In all tests, the POCs inside the fire were instrumented on the outside of the drum with four to five TCs (one TC on top and three to four TCs on the sides spaced equally apart) to assure fully engulfing conditions, as was done in the first phase. However, additional sacrificial TCs were added to the center drum in Phase II to detect the time when the lid popped open (see Figure 13). What was unique about the sacrificial TCs is that the metal cover (i.e., the sheath) was deliberately sliced at a location downstream from the top of the drum (just around the table top) to induce a mechanical failure when the lid either popped open but remained attached to the drum or was completely ejected. Some slack was left in the TC line to discount possible bulging of the lid, without opening or ejecting. During the test, these TCs recorded temperatures just before the lid popped open, at which time a sharp rise/drop would be noted in the temperature trace, indicating the time at which the lid came off.

Figure 13. Sacrificial TCs routed through the top of the POC to detect the time when the lid popped open or was ejected.

As in Phase I, HFGs were used in these tests to confirm previous heat flux measurements and the heat flux correlation. One of the HFGs was placed 2.2 m from the center of the pool and the other two HFGs were moved to the edge of the solid floor, one just inside the solid flooring and the other just beyond this flooring. These remained at this location in both tests.

In the first test in Phase II, the southeast video camera was changed to the west side of the facility. Results of the first test indicated that additional cameras may be necessary to capture events of interest in the second test. Therefore, after the first test, video camera coverage was expanded to observe ejection of materials from the POC (see Figure 12.) Two cameras were added to the lower instrumentation port and one to the middle port on the southeast side of the facility. As will be shown in the results, the camera in the middle port with a downward angled view of the setup, was key in capturing venting through the drum filter in the second test of Phase II. As in Phase I, the IR camera was used to view what was happening inside the fire during all the tests.

4. TEST RESULTS

Table 2 shows the conditions of POC drums in these test series. The mass loss is based on the total weight of the POC with content. Typical initial weight of a POC was 317 lbs, but this weight did not include the weight of additional components such as instrumentation, insulation, and fittings. Rows with red color text highlight cases where the PC filter ruptures. Note that except for drum A at the center of the fire in Test #2 of Phase I, in other red cases the drum lid, and the top plastic liner, Celotex®, and wood board covers were ejected. Recall that in Test #1 of Phase I, the drum lid, and the top plastic liner, Celotex®, and wood board covers were left out of the POC purposely. Rows with blue color text highlight cases where PC filter rupture was expected based on results highlighted in red but did not. In Test #2 of Phase I, and as alluded to before, the lid in drum A was not torqued to the drum manufacturer's specifications. In the case of drum A in Test #1 of Phase I, it can be argued that since the drum lid and the top covers were ejected early into the fire test in all other cases highlighted in red, this test is still representative. Although Test #2 of Phase I did not include a properly torqued lid, it did provide information that if the drum lid stays attached even in a 1-hour engulfing fire, the PC maintains confinement of its contents.

Table 2. Summary of Test Results

Test #	Drum Label	Drum Lid Ejected	Drum Filter/Seal	PC Filter/O-ring	POC Mass Loss (%)
1	A	NA	NA	Rupture/Damaged	25
	B	No	Rupture/Damaged	Intact/ Intact	5
	C	No	No Rupture/ Damaged	Intact/ Intact	>1
	D	No	No Rupture /Undamaged	Intact/ Intact	>1
2	A	No	Rupture/ Damaged	Intact/ Intact	17
	B	No	Rupture/ Damaged	Intact/ Intact	2
	D	No	No Rupture /Damage	Intact/ Intact	>1
1	A	Yes	Rupture/ Damaged	Rupture/Damaged	30
2	B	Yes	Rupture/ Damaged	Rupture/Damaged	30
	C	No	Rupture/ Damaged	Intact/ Intact	2
	D	No	Rupture/ Damaged	Intact/ Intact	1

Looking at Table 2, two outcomes are clear: (1) for standard POC configurations inside the fire, the table indicates that the lid will be ejected when the lid is properly torqued; and (2) for POCs and 7As outside the fire, the table indicates the drum lid will remain in place. Although as will be seen later in this section, in the latter case there is clear evidence that for drums near the fire (≤2 m or at distances with equivalent heat fluxes ≥ 45kW/m^2) lid bulging or drum mechanical deformation occurs due to the pressure build-up inside the drums resulting from air expansion and plastic liner/Celotex® material degradation inside the POC. For drums at the edge of the fire (≤1.7 m or at distances with equivalent heat fluxes ≥ 55kW/m^2), it is not inconceivable that continued testing under these conditions could result in the POC drum lids being slightly open since, for example, not all drum orientations were tested (e.g., drum at 1.7 m with the drum filter rotated about the drum axis by some amount that is different from what was tested). Other data presented in this section strongly suggests that for POCs outside the fire, the risk for a PC DR and a PC ARF greater than zero should be below the bounding estimates established in (DOE, 2007) given that a great majority of the Celotex® insulation survived, and the temperatures measured were far below what is expected for degrading the combustible material inside the PC when this insulation remains.

Additional results will be described in the following sections using post-test observations, post-test PC leak tests, and TC data. The latter two are limited to results obtained from Phase I tests. All evidence will be presented separately for each test. Discussion of results and additional relevant data (e.g., heat flux measurements) will be presented in the discussion section.

Phase I

The primary purpose of this phase was to obtain the temperature response of components inside the POC at the center of the fire and at various distances from the edge of the fire. This would allow determination of whether combustibles inside the PC would reach high enough temperatures to decompose in a fire accident scenario inside a storage facility. Inside the fire it was expected that the drum lid would be partially opened or ejected consistent with the 1996 SNL test for POC fully submerge in the fire. Outside the fire, it was believed this would not happen, but tests were needed to confirm this hypothesis.

Test 1

Figure 14 shows a series of images of the first test setup taken before the first fire test in Phase I. Recall this test lasted one hour, and it included four POCs: one at the center and three other POCs around the perimeter of the pool spaced 45° apart.

The image in Figure 14(a) was taken from the southeast quadrant of the test facility looking towards the west. As noted in Figure 14(b), the POC at the center of the fuel pool had the drum lid, and the top plastic liner, Celotex®, and wood board covers removed. POCs outside the fire were configured with all the standard components of a POC. Also, as noted in Figure 14(b) and (c), each one of these POCs had one HFG next to the drum. This was the case in all tests in Phase I for the three closest drums to the fire. The top-center POC was instrumented with TCs around the drum perimeter and inside the drum at various component locations as noted in the previous section and detailed in Appendix A. As shown in Figure 14(d), the TC wires from inside the top POC were routed down through the empty drum, and through a hole on its side to the outside of the pool. All instrument TC wires, including those on other POCs, were routed to the outside of the FLAME facility through a port on southwest side of test cell and connected directly to MIDAS. HFG wires were routed to a standalone DAQ system beneath the floor of the test cell. All wire bundles were covered with Cerablanket insulation to protect them from the fire heat. In addition, Cerablanket material was placed over the top of the bundles outside the fuel pool (see Figure 14(e)).

Fully engulfing conditions occurred between 25 and 30 seconds after ignition. This was typical in all tests inside of FLAME and is typically the point at which fire tests for certification of radioactive material waste packages are considered to begin as stated in NRC 10CFR71. Therefore, all times stated herein to describe the sequence of events observed in this fire are given with respect to initiation of fully engulfing conditions, which begins the test. This also includes the time stamps given in some of the images.

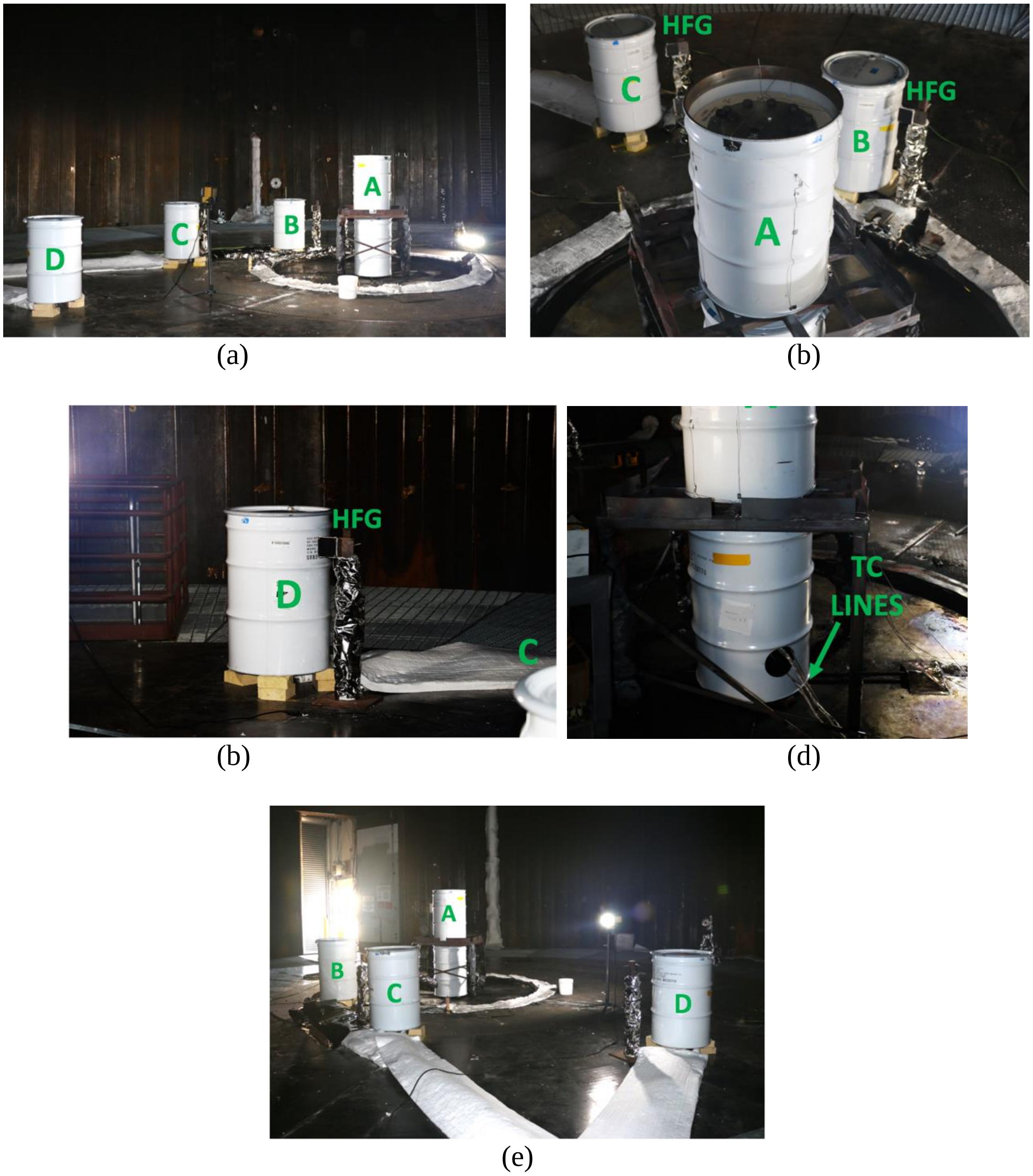


Figure 14. Images of drums before Test #1 in Phase I: (a) view from southeast side of the test cell, (b) view from above the center drum looking southwest, (c) HFG adjacent to drum D, and (d) image showing instrumentation cables from inside the center drum routed through the bottom drum, (e) view from the southwest side of the test cell.

Figure 15 shows video-screen captures 17 minutes into the test; the time stamp is synchronized with initiation of fully engulfing conditions. In drums B and C, light smoke first appears on the drum side facing the fire. The initial smoke is due to paint burning on the drums and some rubber degradation on the seal. In drum B, the smoke is first visible in the videos approximately 30 seconds into the test but quickly propagates around the lid. Shortly after 5 minutes into the test, flames begin jetting around the lid of drum B. It appears that once the drum seal is mostly burned on the outside of the drum and partly through the drum lid, gases from inside begin escaping the drum and combusting with the hot air outside, which leads to the flames observed around the lid in the top image of Figure 15.

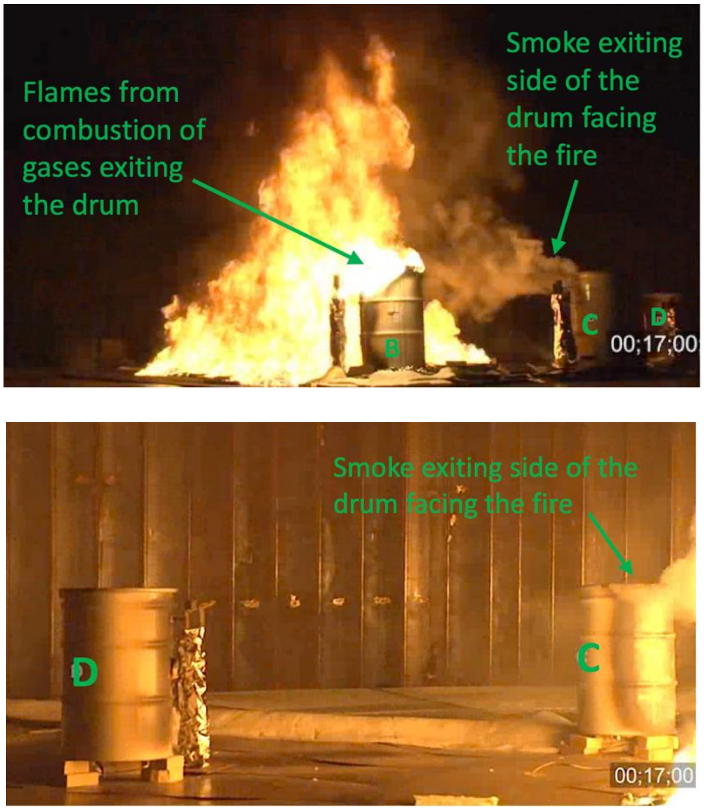


Figure 15. Screen capture of videos 17 minutes into the test showing flames around the lid of drum B and smoke on the lid of drum C.

The heavy smoke observed in Figure 15 on the hot side of drum C appeared 12 minutes into the test and was limited to the side facing the fire throughout the test. Flames were never visible in the video in this drum. Also, at no point during this test was any smoke observed coming out of drum D (due to the resolution of the videos). The one noticeable event on this drum was gradual burning of the paint, as observed in the lower image of Figure 15.

Figure 16 shows post-test images of the test. The center POC is full of heavy soot through the top one-quarter of the drum, but a large, thinner soot patch is also visible near the center of this drum in these images. Other than the paint being consumed in drum A, the drum appeared to be in good condition externally. Outside the fuel pool, drum B sustained the most damage to the drum; the lid bulged slightly upward on the flame side and the top of the drum bulged slightly on one side (not visible in these images). On drums D and C, the paint was damaged mostly on the fire side of the drum due to the intense heat, but no real indication of metal structural deformation was observed on these drums after the test.

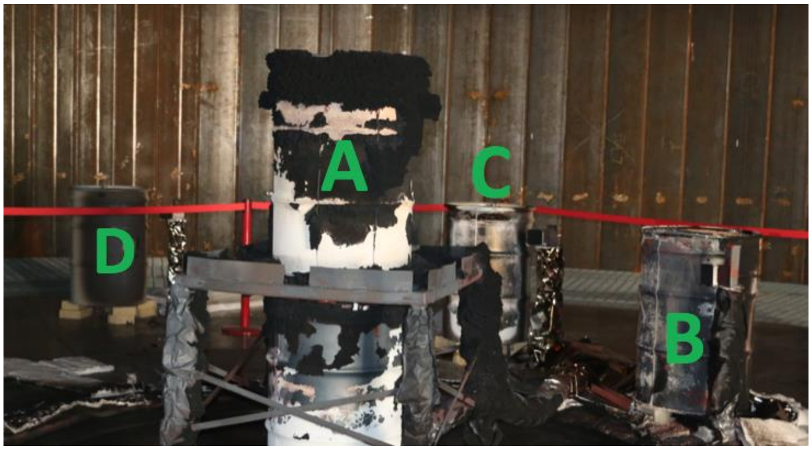
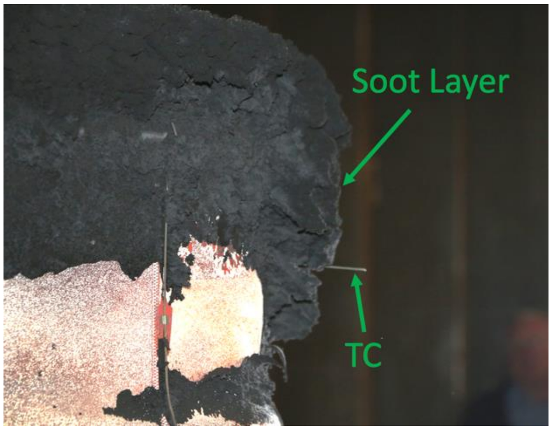


Figure 16. Post-test view of drums in Test #1.

Figure 17(a) and (b) shows a close-up of the top of drum A and B, respectively. In drum A, the top side profile shows a thick layer of soot. The lack of any wind within FLAME allows soot to settle on the upper surfaces of the drum. In drum B, the lid is warped upward to the right of the drum seam, and the drum body is bulged on the left side of the image. The lids on drum C and D were removed inside the facility, but not the lid on drum B. After these pictures were taken, the drums were taken to SNL's building 6630 for further inspection, weighing, and to test the PC for leakage. The lid on drum B was subsequently removed there.



(a)

(b)

Figure 17. (a) Soot layer on top of the drum A, (b) bulging on drum B.

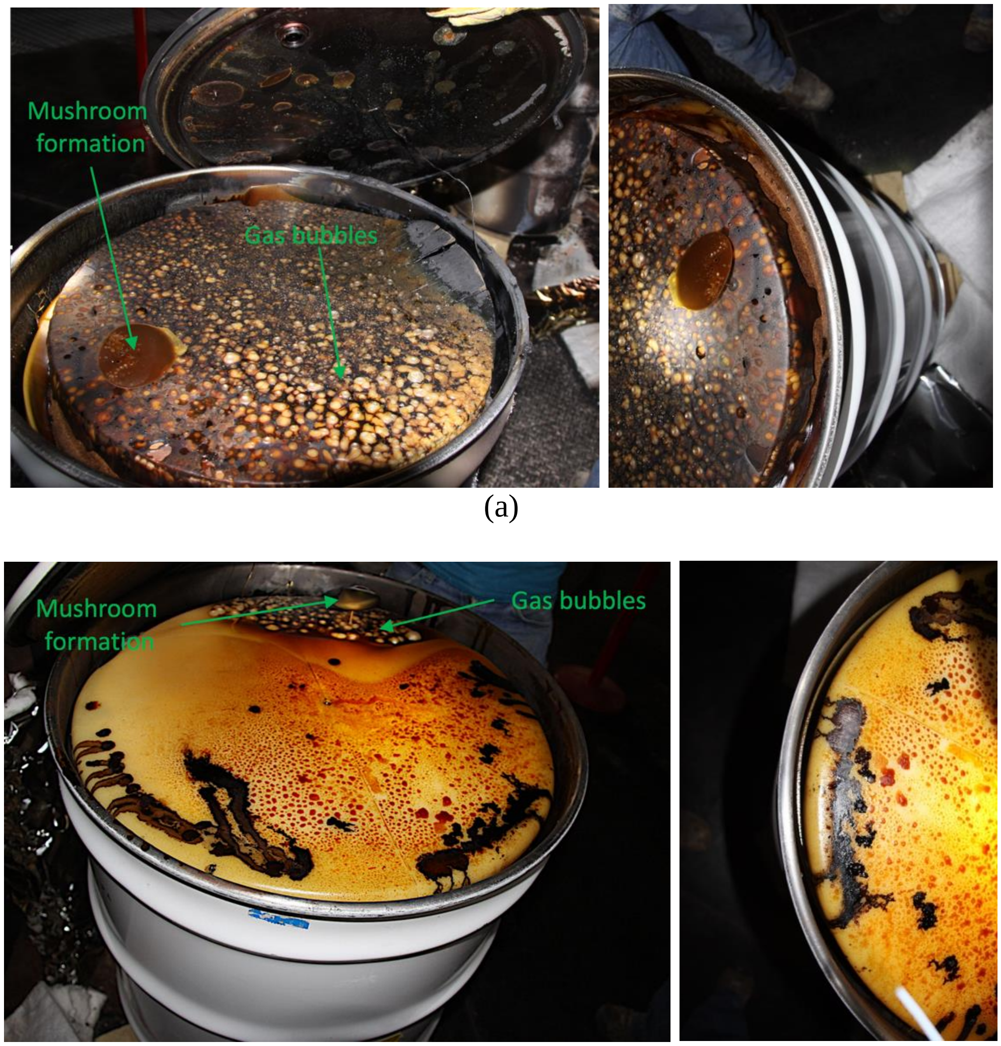
Figure 18 and Figure 19 show the interior of each POC after Test #1 of Phase I. In Figure 18(a), the images of Drum A only show the char material remaining after the fire, and after the PC had been removed for leak testing. The right image is a close-up of the same material (ignore the red cloth). Essentially the PC sat on top of this charred material with some of the charred remains filling the sides of the PC, but not much beyond the bottom of it as will be observed in later pictures taken in other tests. In Figure 18(b), the wrinkled material observed in the left image is the wood board piece that was attached to the top of the Celotex® cover in drum B. What is missing in the left image is the plastic liner which presumably vaporized during the fire. Although not quite clear in either image is that the Celotex® surrounding the PC survived. There are signs of charring on the outside, but overall the Celotex® structure remained in place. When the top Celotex® cover and PC were removed, the interior of the Celotex® components looked unburned as shown in the image on the lower right.

(a)

(b)

Figure 18. Internal remains of POC after Test #1: (a) drum A and (b) drum B with and without the PC.

Figure 19(a) and (b) show the partially melted plastic liner cover on drums C and D, respectively. Closer inspection of the drums revealed that the circumferential sides of the plastic liner remained; although, in drum C, it looked like the plastic wall liner had sagged down as a result of weakening of this component. In both drums, large bubbles were observed on the top plastic liner cover. It looked as though the plastic material was boiling and/or gas from evaporated moisture inside the Celotex® was rising through the plastic cover. In both cases, a mushroom like plastic growth was observed on the top cover, suggesting that burped molten material burst to the top of the lid, then slowly dripped down as it cooled until frozen in place, forming the mushroom shape.

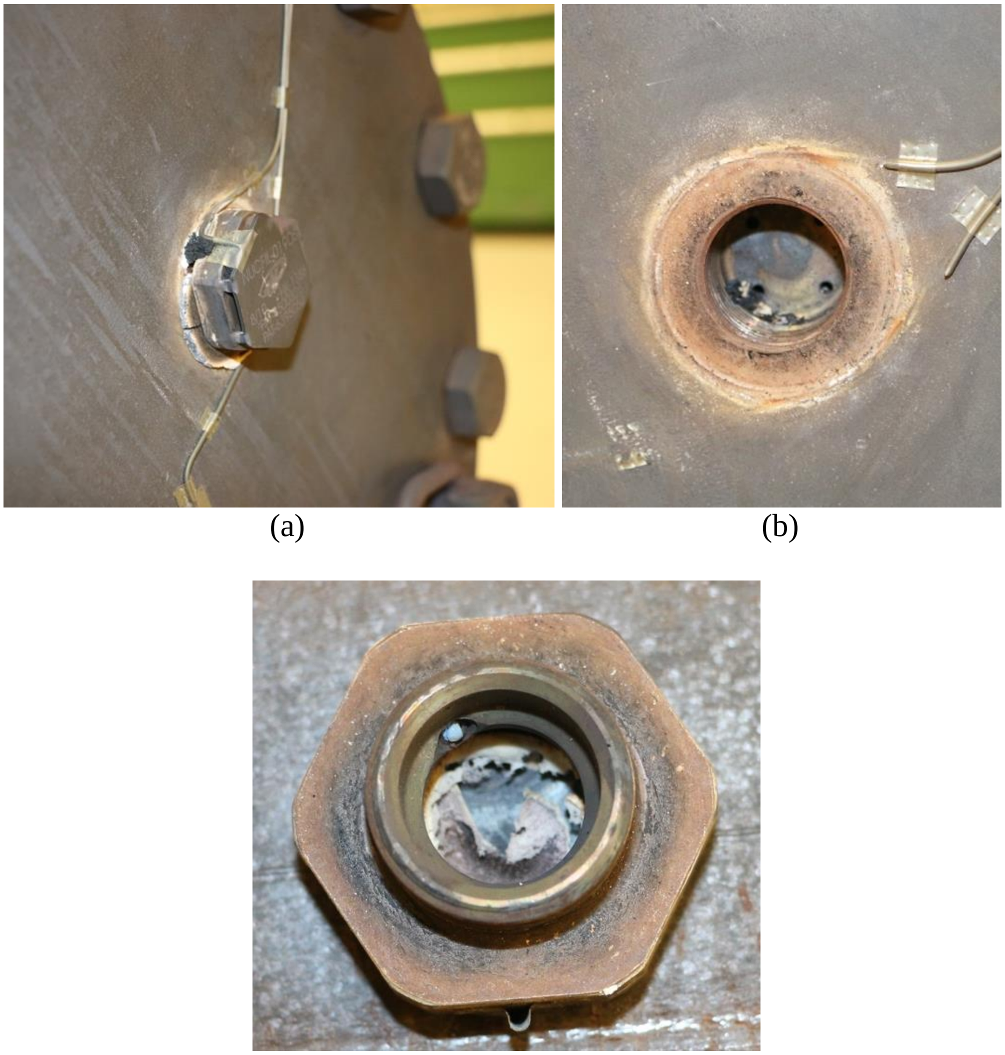


(a)

(b)

Figure 19. Internal remains of POC after Test #1: (a) drum C and (b) drum D.

Figure 20 shows the conditions of the top of the PC after it was removed from drum A. The steel has a dark gray color and looks as though it has been heat treated. The material beneath the filter is degraded on the edges and there was evidence of a char residue on one side of the filter as seen in Figure 20(a). When the PC filter housing was removed, additional charred remains were observed inside the threaded hole (see Figure 20(b)). The source of the charred residue is unknown. Visual inspection of the filter showed the carbon media was compromised (see Figure 20(c)). The filter port was then blocked to conduct a leak test through only the PC O-ring.



(a) (b)

(c)

Figure 20. PC lid with filter housing in place (a) and extracted (b), and the underside of the PC filter housing (c).

Leak tests and inspection of the PC filters and PC flange gaskets on the remaining PCs tested were done using a slightly different procedure. For PCs on POCs outside of the fire, the leak test was performed with the PC filter on the PC lid first, and then without it since it was found from visual inspection these PC filters remained in good condition. With this procedure, it could be quantitatively discerned if the PC filter gasket, the PC O-ring, or both had failed. Leak test results for all PCs in this test are shown in Table 3. Notice that drum D was not tested since the PC inside this POC looked intact and there was a desire to reuse it in the subsequent test of Phase I. For comparison, pretest leak rates measured on all PCs were less than 0.00181 std-cm^3/sec through the gasket and the O-ring. Clearly the leak rate on the PC inside drum A indicates gross failure of the O-ring.

Table 3. Summary of post-test PC leak rates (std·cm^3/sec) in Test #1 of Phase I.

Drum	PC Filter Gasket + PC Flange O-ring	PC Flange O-ring
A	**39.2**	—
B	0.00797	0.00100
C	0.00262	0.00099

Figure 21 through Figure 34 show the temperatures measured at various locations inside the POCs starting with drum A. Plots are presented from the outside of the drum towards the inside. For example, for drum A, the first figure shows temperatures outside the drum wall, the second shows the inner drum wall temperatures, the third shows the inner plastic liner temperature, the fourth shows the outer PC wall temperatures, and the fifth figure shows the inner PC temperatures. For all other drums, the temperature on the inner wall of the drum and the plastic liner are merged into one plot. Note that all plots extend to 1200°C and show eight hours of data. The legend in each plot shows a description of the location of the TCs on the drum, and the coordinates (angle around the drum, height with respect to the drum/PC, and radial location with respect to the center axis of the drum). The angle around the drum is based on the drum coordinate system, with 0° being the side of the drum facing the fire. The order in which the items are presented in the legend are from the top to the bottom of the drum/PC. Therefore, typically as one goes down each item in the legend, so do the magnitudes of the temperatures recorded on the POC at the center of the fire.

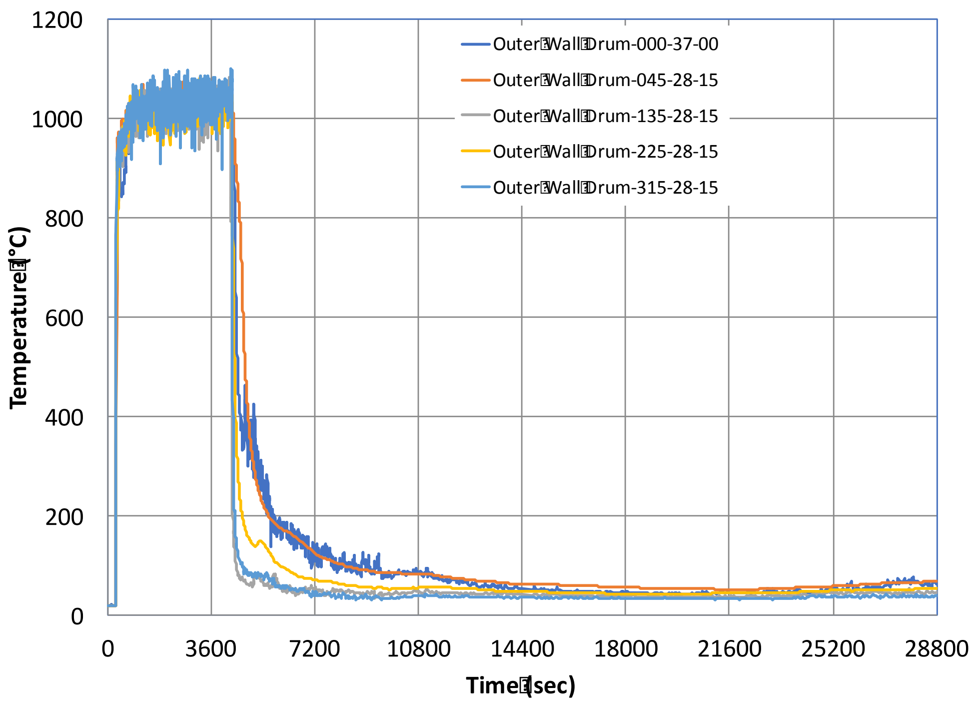


Figure 21. Temperatures on the outer wall of the drum (POC drum A).

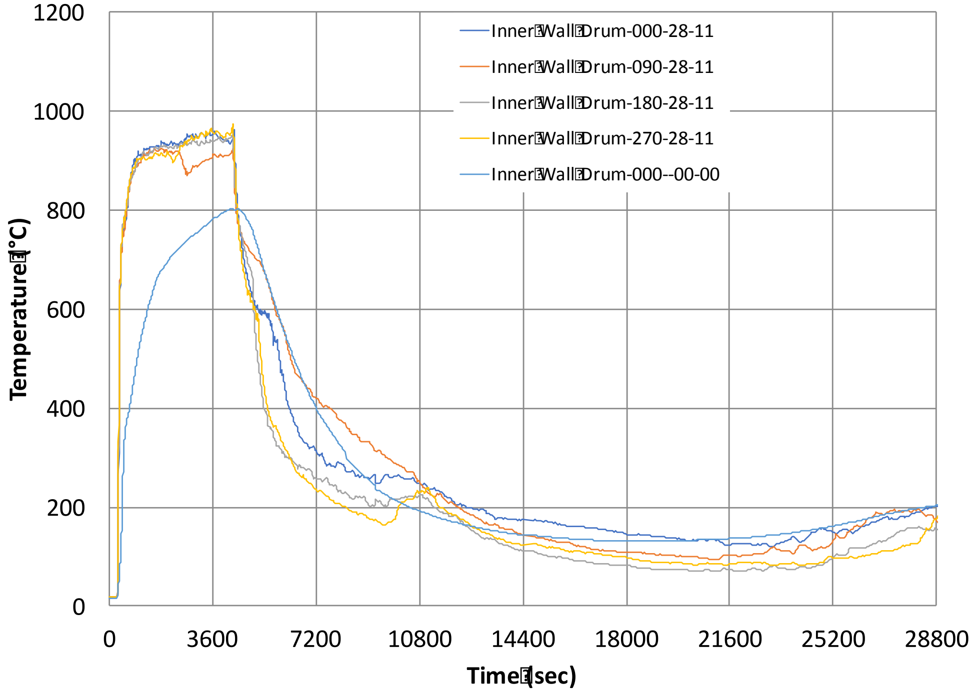


Figure 22. Temperatures on the inner wall of the drum (POC drum A).

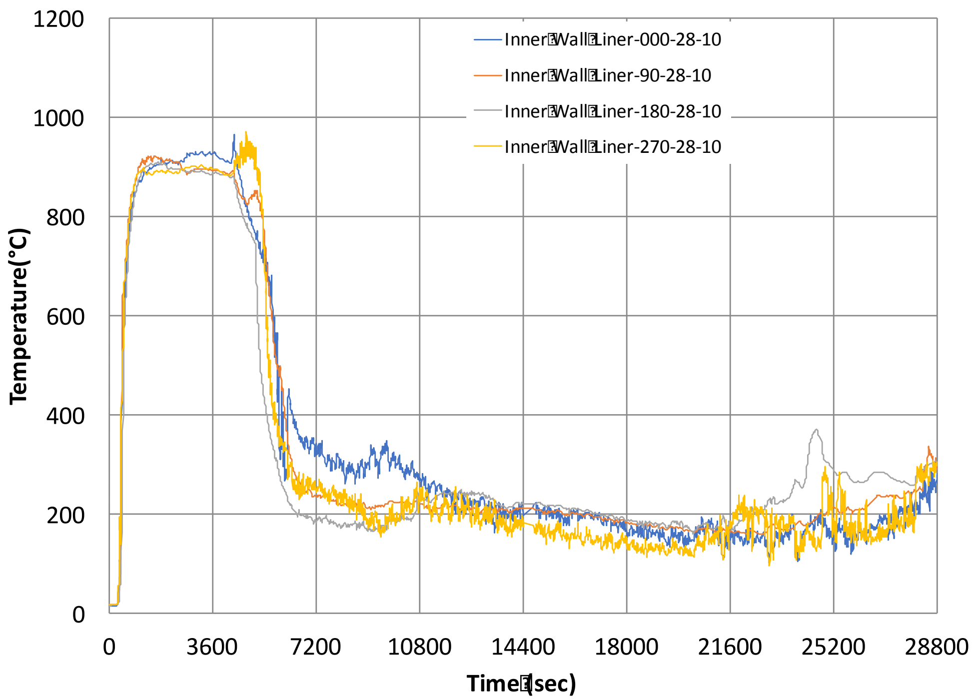


Figure 23. Temperatures on the inner wall of the plastic liner (POC drum A).

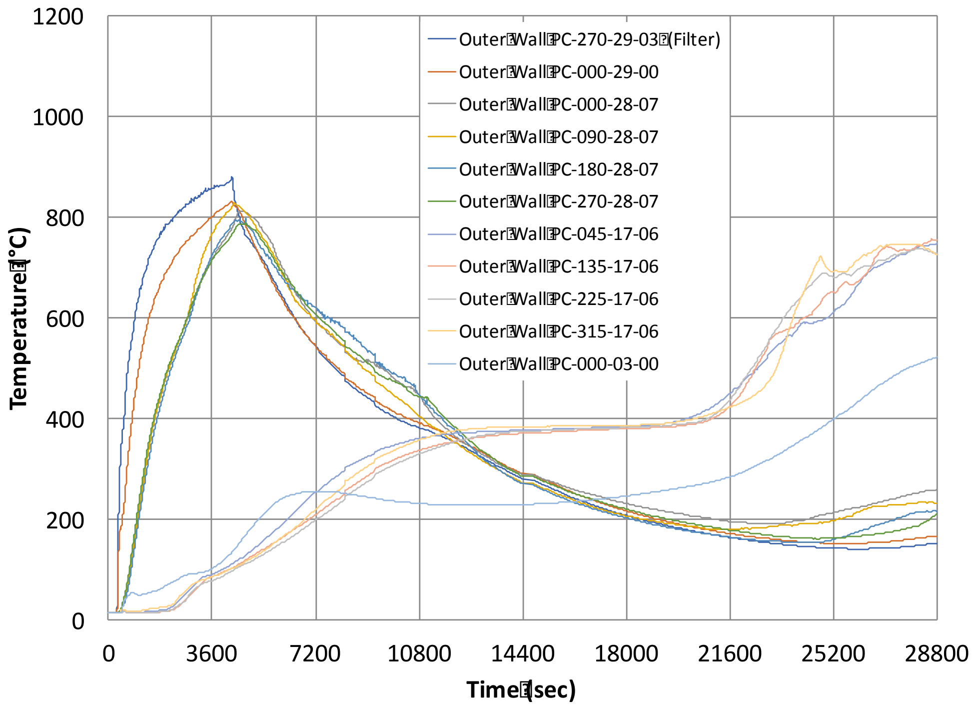


Figure 24. Temperatures on the outer wall of the PC (drum A).

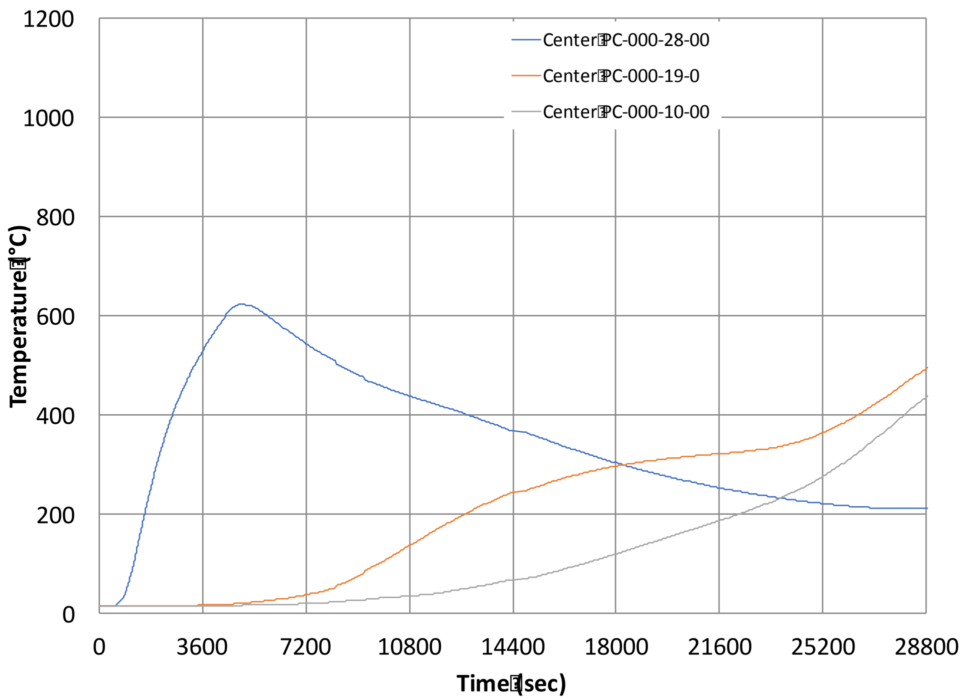


Figure 25. Temperatures in the center of the PC (POC drum A).

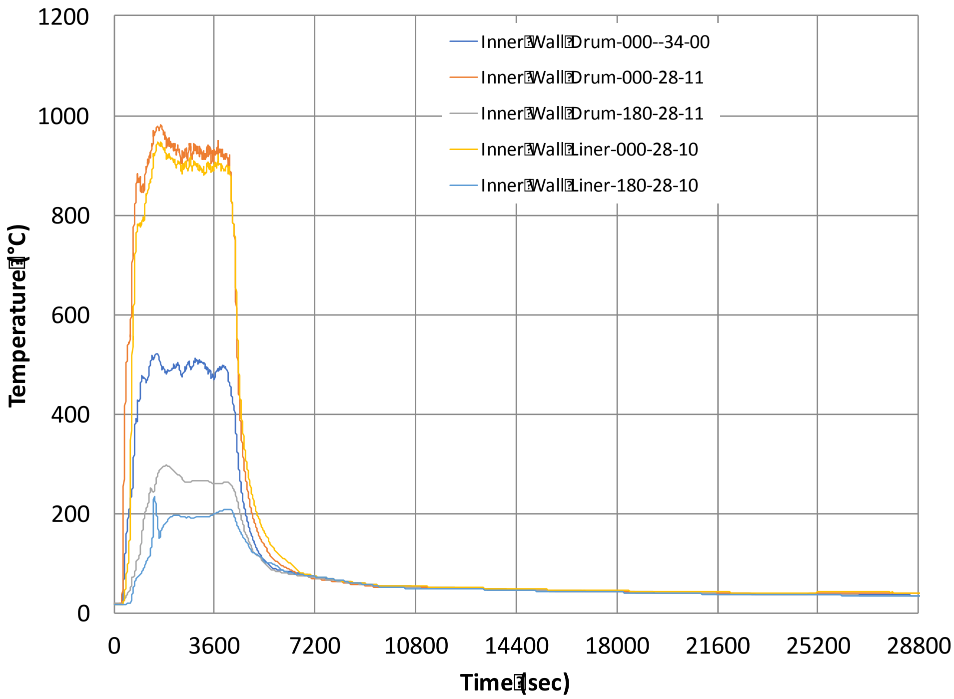


Figure 26. Temperatures on the inner wall of the drum and plastic liner (POC drum B).

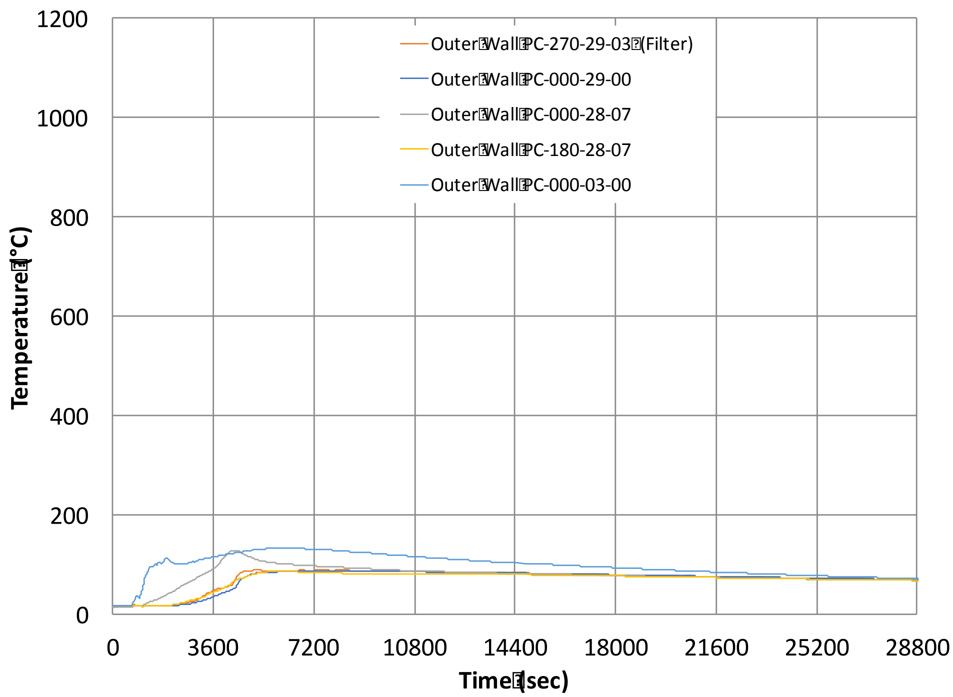


Figure 27. Temperatures on the outer wall of the PC (POC drum B).

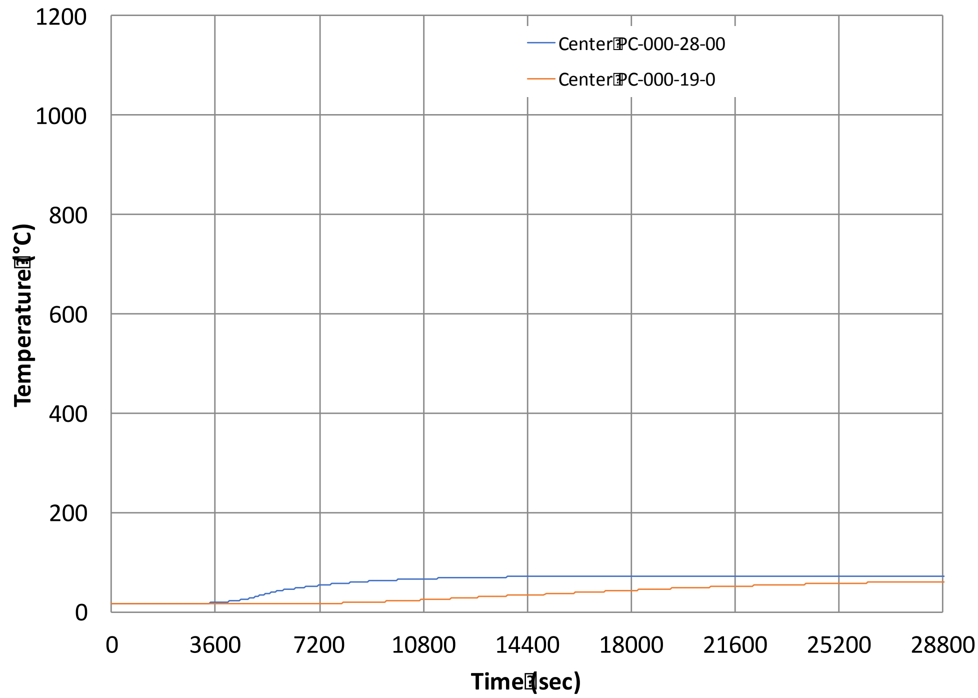


Figure 28. Temperature in the center of the PC (POC drum B).

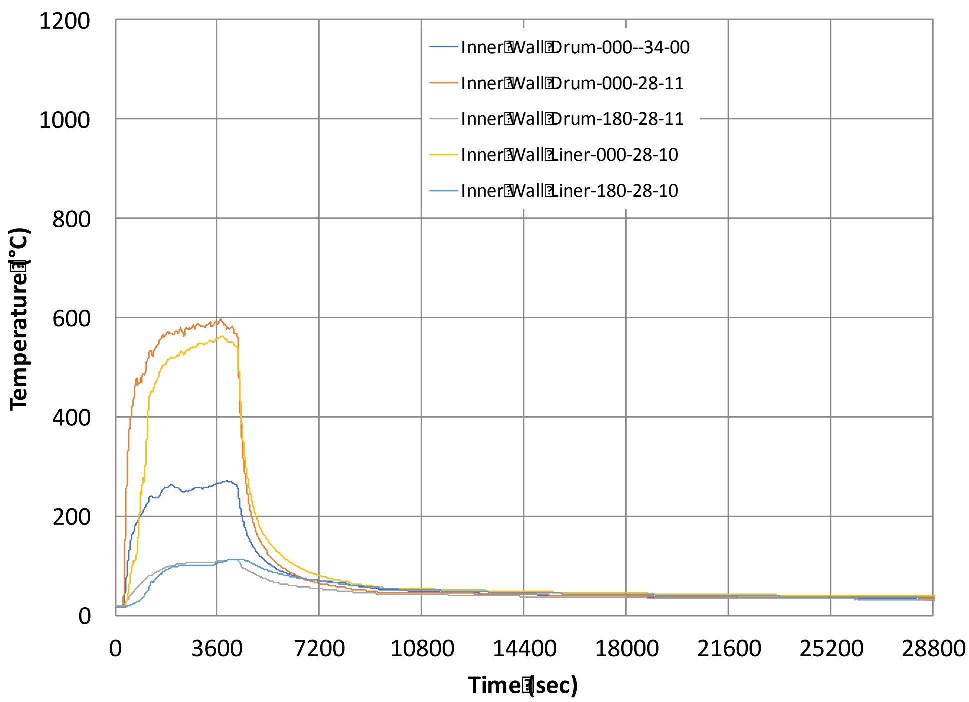


Figure 29. Temperatures on the inner wall of the drum and plastic liner (POC drum C).

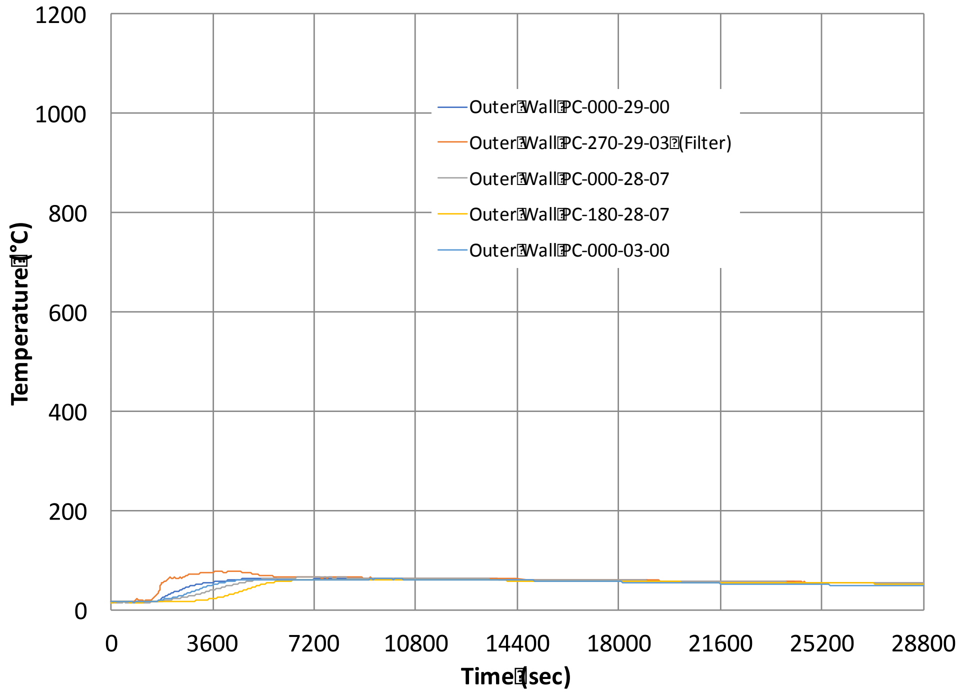


Figure 30. Temperatures on the outer wall of the PC (POC drum C).

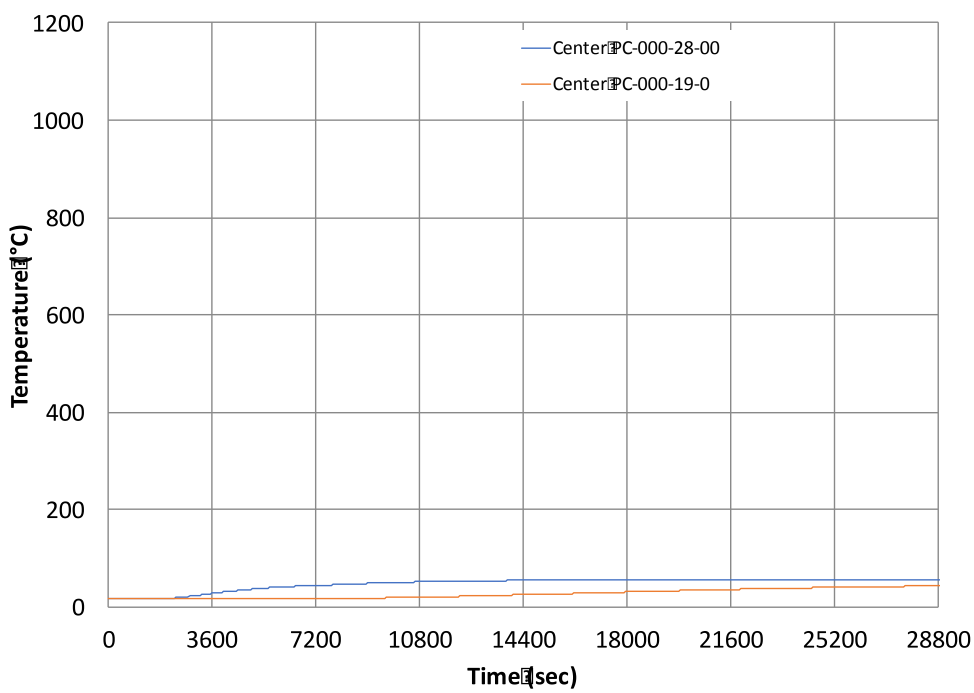


Figure 31. Temperatures in the center of the PC (POC drum C).

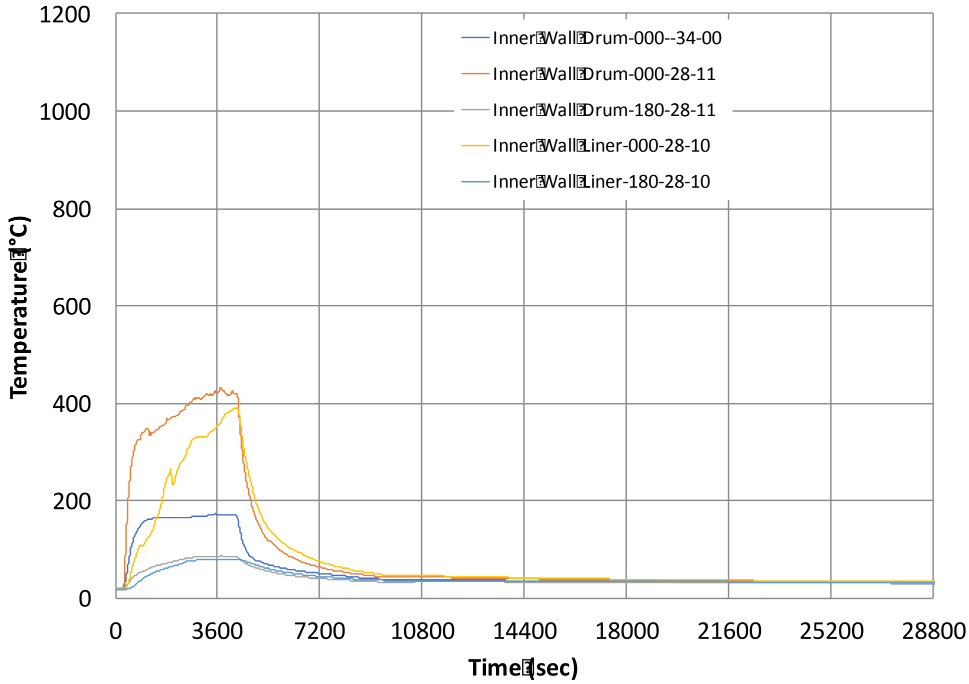


Figure 32. Temperatures on the inner wall of the drum and plastic liner (POC drum D).

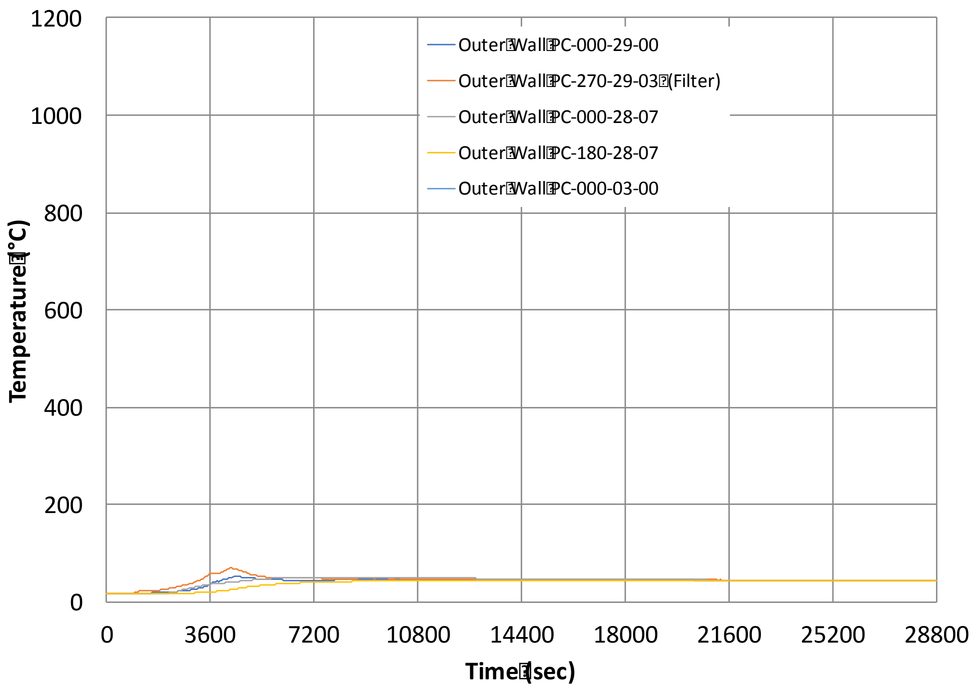


Figure 33. Temperatures on the outer wall of the PC (POC drum D).

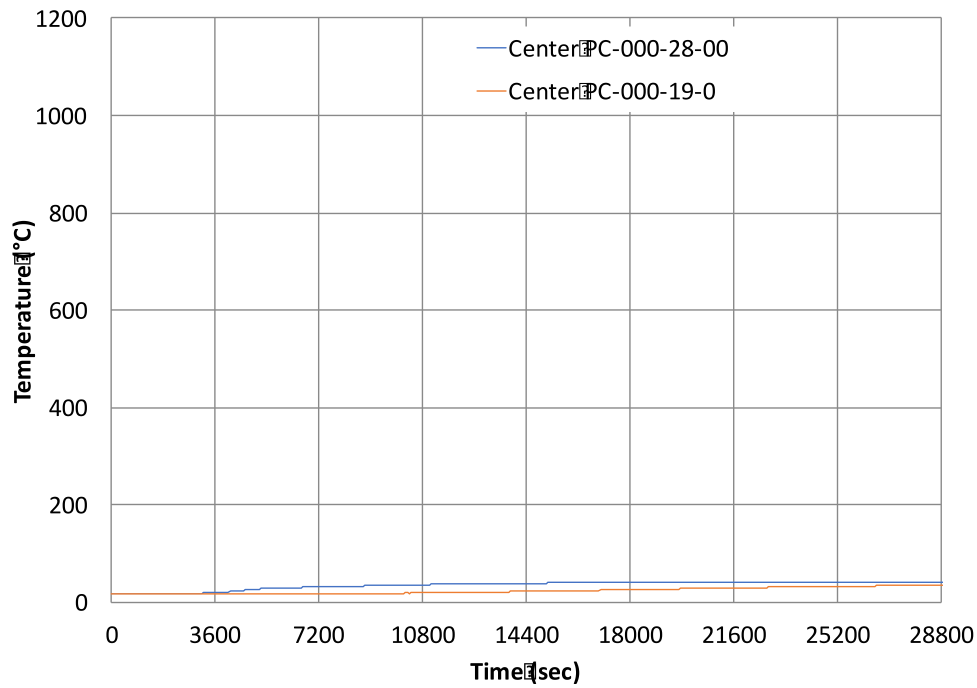


Figure 34. Temperatures in the center of the POC (POC drum D).

Two interesting trends can be observed in the plots for POC drum A: (1) the temperatures on the inner wall of the drum, the plastic liner, and the top of the PC rise near the very end of data collection possibly because the Celotex® remaining inside the drum continue to burn well beyond the end of the test, and (2) the temperatures in the center of the PC exceed 400°C at more than one location at some point during the eight hours shown. For all other POCs, as expected, temperatures on the outside of the drum are hottest on the side facing the fire, followed by the top, and then the side opposite the fire. Of these POCs, the temperatures on the outside wall of the PC remain below 135°C and in the center of the PC remain below 100°C. Temperatures on the inner wall of the plastic liner have to be interpreted with caution in drum A and drum B. Recall that in these drums, the plastic liner melted. The question is then, when does the plastic liner melt and what temperature are the TCs on the plastic liner measuring after that? On drum A, very small differences were observed between the inner wall of the drum and the inner wall of the plastic liner; therefore, it's likely that temperature gradients in the gap between the inner wall of the drum and the outer wall of the Celotex® are not steep, and the eventual location of the TCs originally attached to the wall of the plastic liner does not make a large difference in the results so long as they remain vertically around the same location, which is what is observed in the plots of the inner wall of the plastic liner.

Test 2

The second test in Phase I was not an exact repeat of the first test. For one, the POC inside the fire was configured with all standard components, including the drum lid, from the beginning of the test. Outside the fire, drum B and D were configured with standard components as in the first test; however, drum B was moved slightly further back (2.2 m or 45 kW/m^2) and drum D was moved much closer to the fire (3.2 m). Drum C and E, the additional drums added in this test, were both

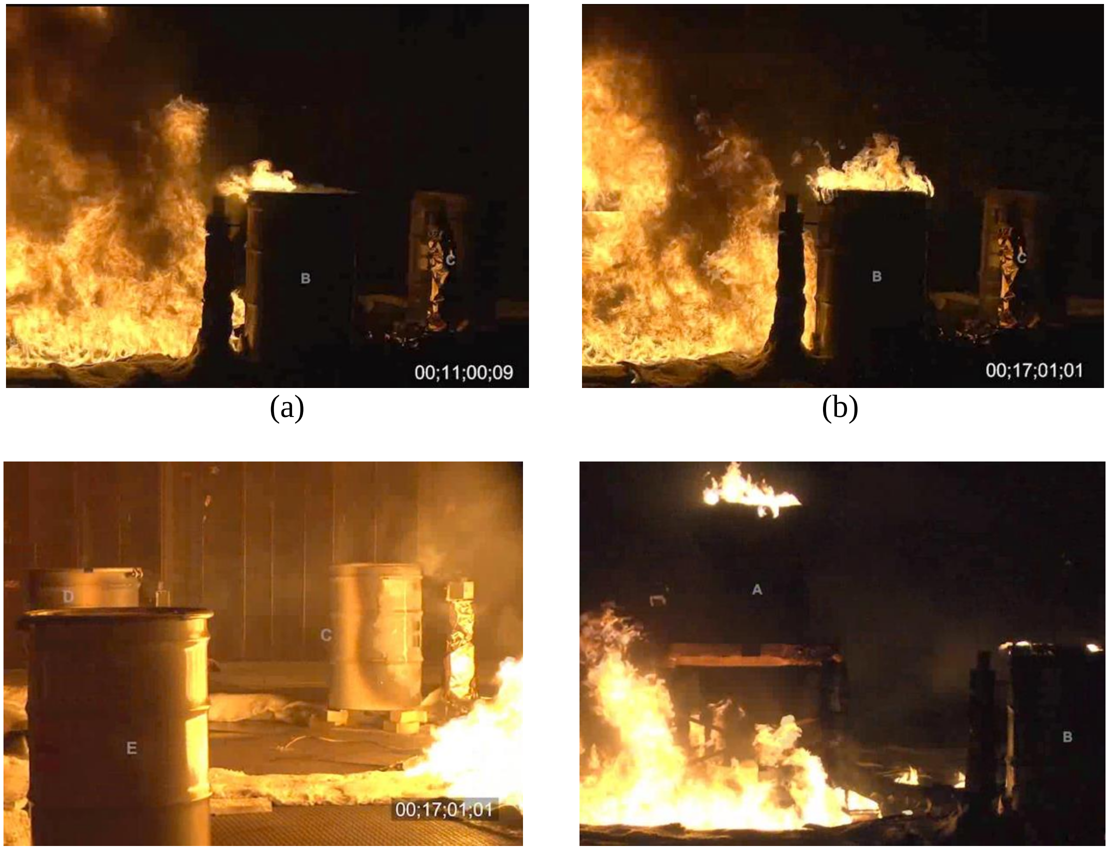
7As with chipped Celotex® material inside, as shown in Figure 7. Drum C was in the same location as POC drum C in Test #1, and drum E was placed at the same distance from the fire as POC drum D.

Figure 35 shows images taken before the second test. Figure 35(a) shows drums A through D in place, while Figure 35(b) shows drum E right as it was being added to the test cell. Drum D is seen further back in the image. Since damaged to drum D had been limited in the first test, the same POC was used in the second test, this time with the damaged paint side of the drum facing away from the fire as observed in Figure 35(a). As in Test #1, the TCs lines from the center drum were routed through the bottom of the empty drum to the outside of the pool, where all TC lines, including those from the other drums, were routed out to MIDAS. Insulation to protect the TC lines was added just like in the first test. HFGs were aligned with the front edge of drums B, C, and D; there was no HFG on drum E, but since this drum was at the same radial distance from the fire as drum D, the heat flux should be the same.

(a) (b)

Figure 35. Images of test layout in Test #2: (a) looking northeast towards the entrance of the test cell and (b) looking southwest just to the left of the pool.

Videos of the second test showed similar trends observed in Test #1 with delays on the initiation of certain events in that test. As in the first test, initial light smoke was observed on drum B 30 seconds into the test. The smoke is likely coming from burning of the paint and or initial decomposition of the rubber seal. Twenty seconds later, a large pop is heard in the video but no observable changes occur at this point in the fire or on the drums around it; therefore, it is believed that the sound came from expansion of the metal floor adjacent to the pool, or from expansion of the metal floor and/or walls of the fuel pool, which is common in this facility. Heavy smoke from drum B begins around 7.5 minutes into the fire, with flames visible from the front of this drum just after 9 minutes (see Figure 36(a)). Compared to the first test, flames were visible in this test on drum B four minutes later, and were initially localized to the front of the drum. These flames begin to propagate sporadically to the back of drum B just after 11.5 minutes. By 17 minutes, they are continuously visible all around this drum (see Figure 36(b)). Flames around the lid in this test were more buoyant in nature, as opposed to the first test where they seem to be jetting out of drum B, suggesting that pressure buildup inside this drum is less severe here due to the increased distance of this drum from the fire in this test.



(a) (b)

(c) (d)

Figure 36. Screen capture showing various conditions of the drums during and immediately after Test #2: (a) drum B showing flames on the side closest to the fire, (b) drum B with flames all around the lid, (c) light smoke is observed on the hot side of drum C, and (d) flames observed around the lid of drum A just after the fire test was over.

By 17 minutes, the other drums show mostly evidence of paint damage on the side of the drums facing the fire and some light smoke visible around the top of them, especially on the hot side of drum C facing the fire (Figure 36(c)). By 30 minutes, denser smoke is evident on the hotter side of the lid of drum C, reminiscent of what was observed in the first test (see the bottom image in Figure 15). From then on, the smoke pattern remains the same in these two drums until the end of the test. Shortly after the hour test is over and drum A, at the center of the fire, is no longer engulfed, flames can be seen around the lid (see Figure 36(d)) for quite a long time. This is evidence that internal combustion continued on this drum well beyond the end of the test.

Figure 37(a) shows the state of all the drums after Test #2. As shown in Figure 37(b), drum A was heavily coated with soot; however, the lid did not appear to bulge significantly, as seen in Figure 37(c) after the soot was removed.

(a)

(b)

(c)

(d)

Figure 37. (a) All drums after Test #2, (b) and (c) close-ups of drum A, and (d) close up of drum B.

Outside the fire, drum B sustained the most damage, but it was significantly less than in the previous test (see Figure 37(d)). Particularly, the drum lid and the rest of the drum body did not show the level of bulging as observed in Test #1. The other drums appeared to have similar external damage to drum C in Test #1.

The more interesting cases in Test #2 are shown in Figure 38. Not shown are the internals of drum B and E. The close-up image of drum A shown in Figure 38(a) shows the plastic liner in this POC was completely consumed, but the Celotex® remained up to about half the height of the PC. Drum B sustained nearly the same damage internally as drum B in the first test. Figure 38(b) shows the interior of drum C, the closest 7A to the fire. The thin plastic bag shown in Figure 7 holding the chipped Celotex® melted inside this drum at the start of the fire and the Celotex® shows signs of burning. Some Celotex® pieces near the walls of the drum show a significant amount of char. It's very likely that Celotex® burning continued beyond the end of the test.

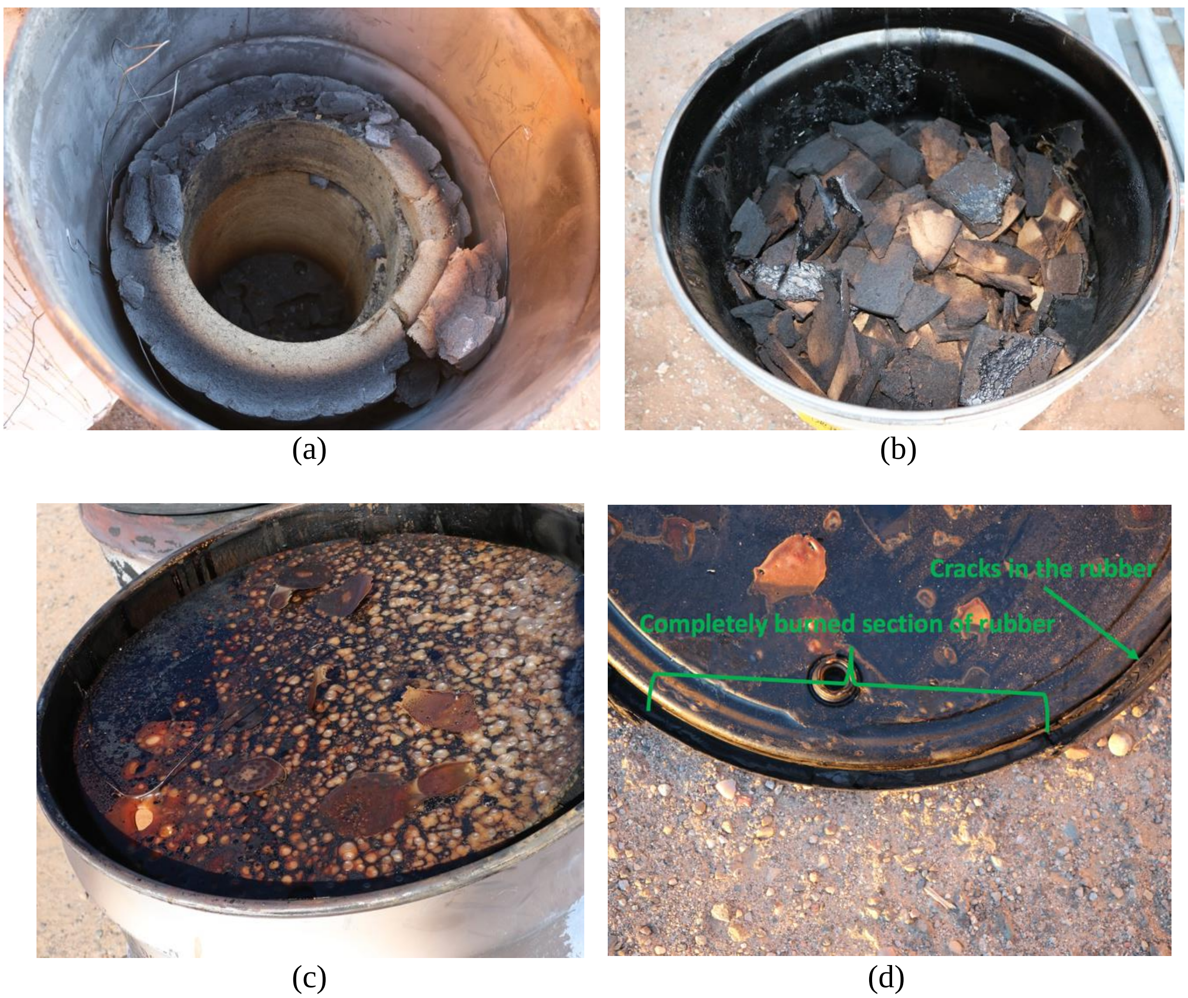


Figure 38. Internal conditions of drum A, C, and D after Test #1: (a) drum A, (b) drum C, and (c) and (d) drum D.

Figure 38(c) shows the inside of drum D, the only other POC outside the fire. Note that this drum was slightly further back from the fire than POC drum C in Test #1. Internally this drum showed similar damage to drum C in the first test. As shown in the figure, bubbles again appeared on top of the plastic liner cover in drum D. Closer inspection of the interior of the drum showed the plastic liner walls still remained, although the top of the liner wall appears to sag down. Figure 38(d) shows a close-up of the interior side of the lid in drum D. Damage to this lid is interesting because in the previous test the rubber seal in this same drum showed almost no damage. At the new location (3.2m), complete decomposition of the seal can be seen on the side facing the fire. In general, for drums closer to the fire, the drum seal suffered more damage than in drum D, with the rubber decomposing and cracking further to the back relative to the fire side of the drum. Within 2.2 m, which includes both POC drums B in the first two tests, the drum ring seals were almost if not all decomposed. 7A drum E showed similar damage observed inside of 7A drum C; the difference is that the Celotex® pieces in drum E were less burned.

Figure 39 shows the PC extracted from drum A after the test. Drum A in the second test is critical because it was the drum that sustained the most Celotex® decomposition with the lid still on throughout the fire test, and because it was the only drum inside the pool fire that kept the lid on throughout the test. As such, this PC suffered a greater thermal insult relative to POCs outside of the fire, which also kept their lids.

As noted in Figure 39(a) and (b), this PC was heavily coated with a black/brown tar substance on the top. Around the PC flange sides, the same tar substance was observed but with less accumulation. In the rest of the PC body (see Figure 39(b)), it looked like the tar substance dripped while the PC was still hot. This tar substance was not analyzed, but it’s probably condensed plastic material from the decomposed plastic liner with soot created by the burning Celotex®. The color of the substance is similar to the color of the melted plastic observed on the top of the POC drums outside of the fire. Note the tar material was also observed in PCs recovered from POCs outside of the fire. In particular, the PCs recovered from the POCs furthest from the fire had the least accumulation. Figure 40 shows the PC extracted from drum C. Accumulation of tar is limited to the top of the PC. A similar condition was observed in drum D of this test.

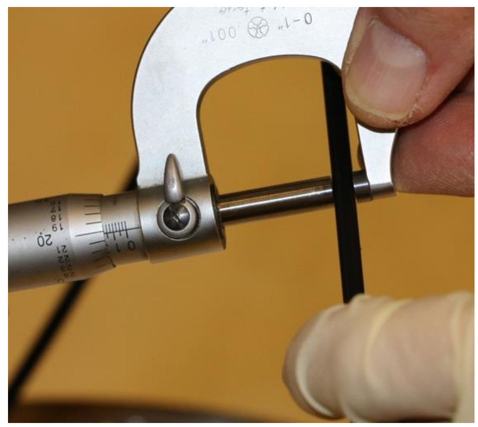
Interestingly, in Test #1, the PC at the center of the fire did not show the tar accumulation observed in all other PCs. Recall that in that test the lid and components covering the PC were removed from the POC from the start of the test. Since the lid was open and the interior components were exposed to the fire environment, any accumulation of gas material from the molten or from charring of the plastic and the Celotex® would likely leave the drum under buoyancy forces. This may explain why in that test there was no accumulation of tar on the PC, but also the top of this PC was at a very high temperature and any tar that could have been present would have been burned off.

Figure 39(c) and (d) show the PC filter and the PC flange O-ring that were extracted from the PC in drum A. Surprisingly the filter and the O-ring were found in good condition. Although hard to see in Figure 39(c), the carbon media is still in the vent housing. Typically, when the PC filter fails, the carbon media is displaced further down when the filter is placed upside down and not visible from the angle shown in this image, and in some cases when looked at straight down the center of the housing from the point of view of the side shown here, the carbon media shows signs of cracking on the surface. Other PC filters and the PC flange O-rings recovered from the other POCs outside the fire in this test and in Test #1 show similar conditions depicted in Figure 39(c) and (d).

(a)

(b)

(c)



(d)

Figure 39. PC extracted from the center drum (A) after Test #2: (a) and (b) show black tar substance on the outer walls of the PC, (c) PC filter, and (d) PC O-ring.

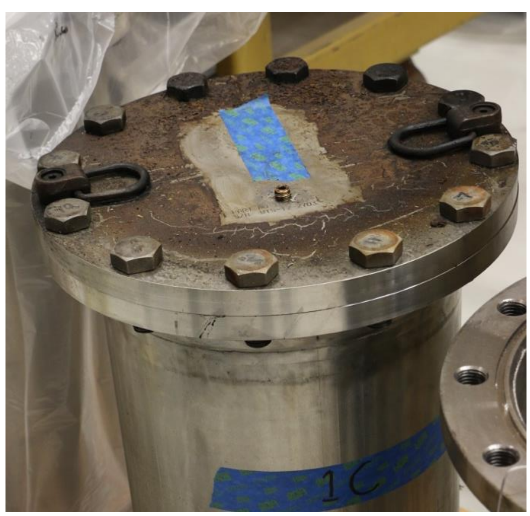


Figure 40. PC extracted from drum C.

Results of leak test on POC drums used in Test #2 are shown in Table 4. For comparison, pre-test leak rates measured on all PCs were less than 0.00181 std-cm^3/sec through the gasket and the O-ring. There is a noticeable increase in the leak rate through the PC filter gasket after Test #2 on the center drum.

Table 4. Summary of post-test PC leak rates in Test #2 of Phase I.

Drum	PC Filter Gasket + PC Flange O-ring	PC Flange O-ring
A	**0.940**	0.00099
B	0.00163	0.00101
D	0.00121	0.00081

Figure 41 through Figure 54 show the temperatures measured at various locations inside the POC starting from the outside and working towards the PCs on and inside the drums, as before. In this set of figures, the POC data is shown before the 7A data, which only includes temperature from the outside of the drum. The same conventions used in the plots shown in Figures 21 through 34 are used in these figures; however, there are a number of changes to the sequence shown in the legends due to minor changes in TC locations and quantities used in this second test.

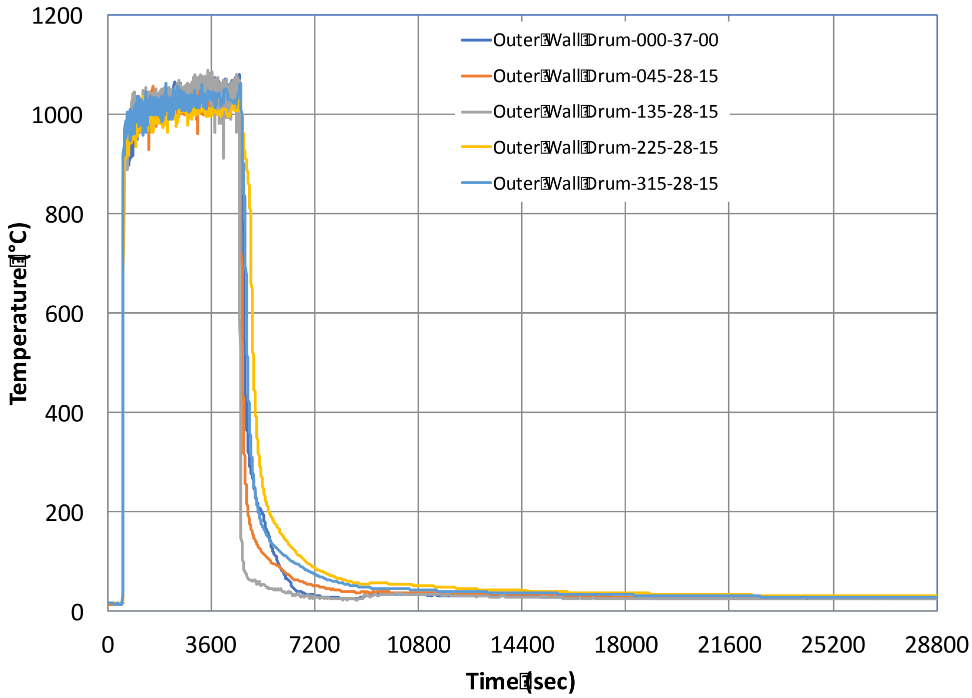


Figure 41. Temperatures on the outer wall of the drum (POC drum A, Test #2)

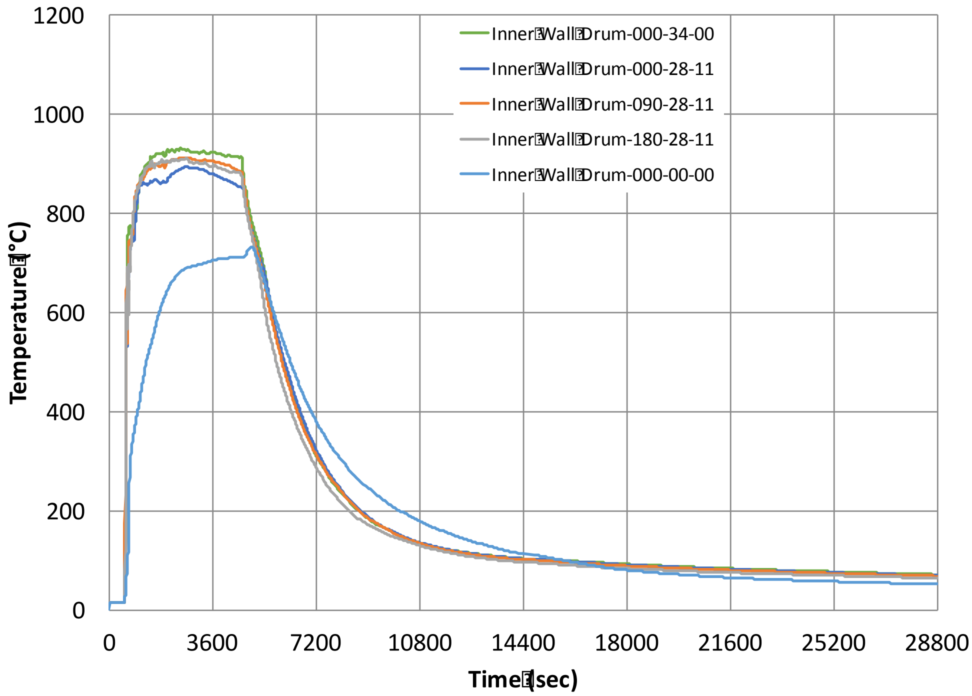


Figure 42. Temperatures on the inner wall of the drum (POC drum A, Test #2)

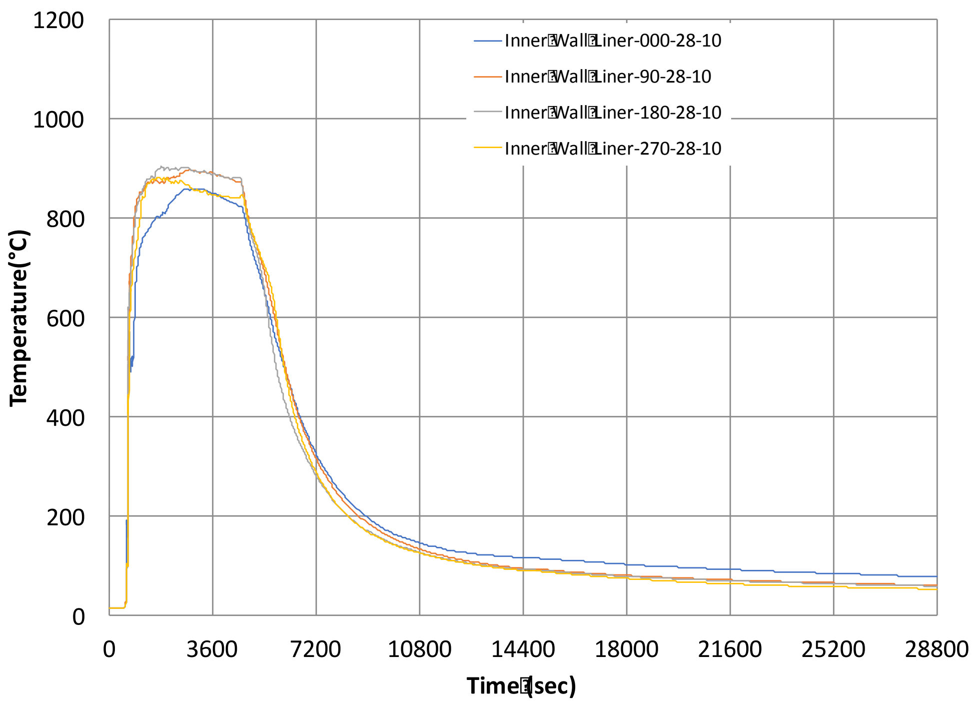


Figure 43. Temperatures on the inner wall of the plastic liner (POC drum A, Test #2)

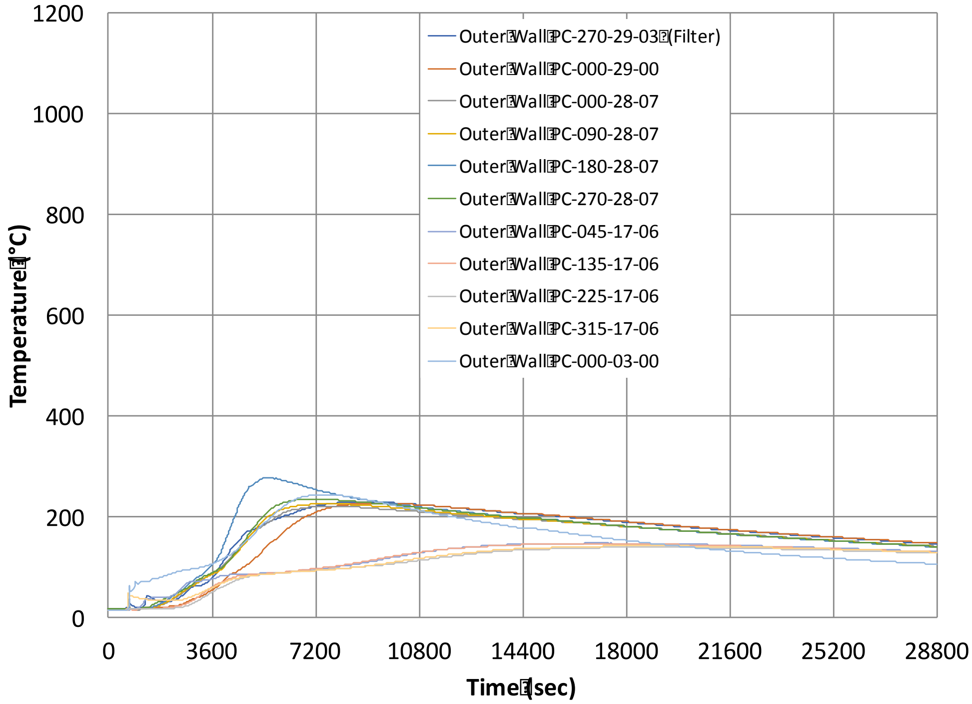


Figure 44. Temperatures on the outer wall of the PC (POC drum A, Test #2)

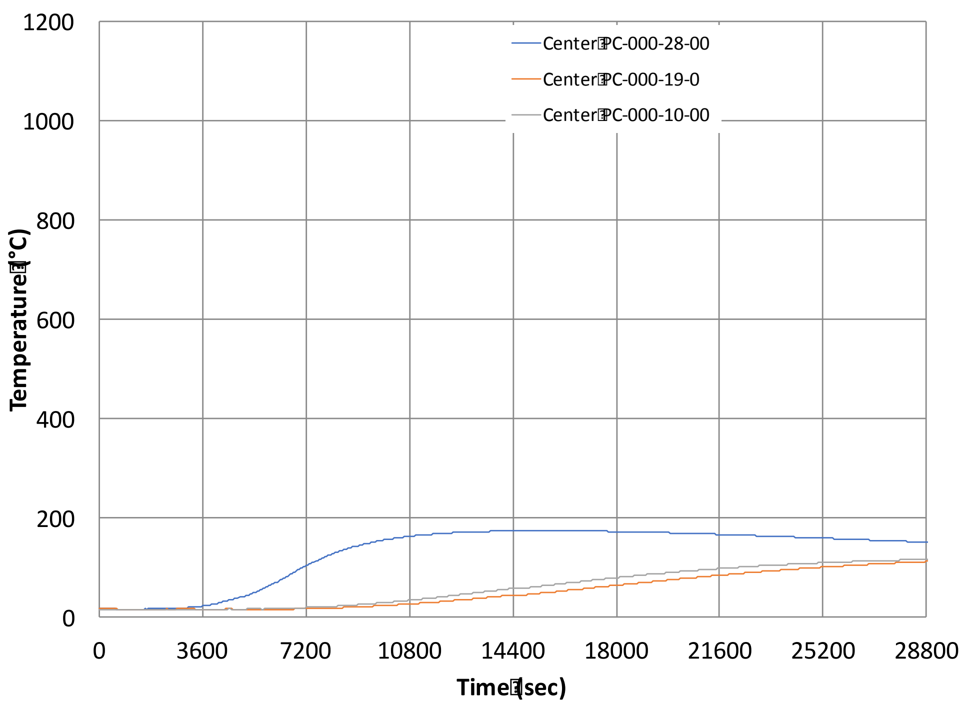


Figure 45. Temperatures in the center of the PC (POC drum A, Test #2)

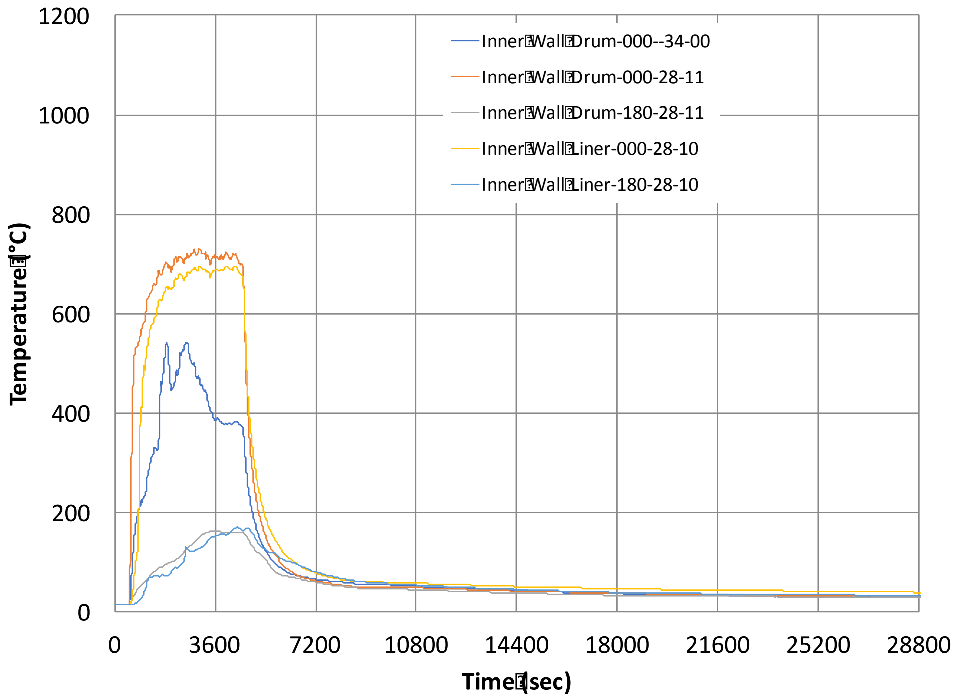


Figure 46. Temperatures on the inner wall of the drum and plastic liner (POC drum B, Test #2)

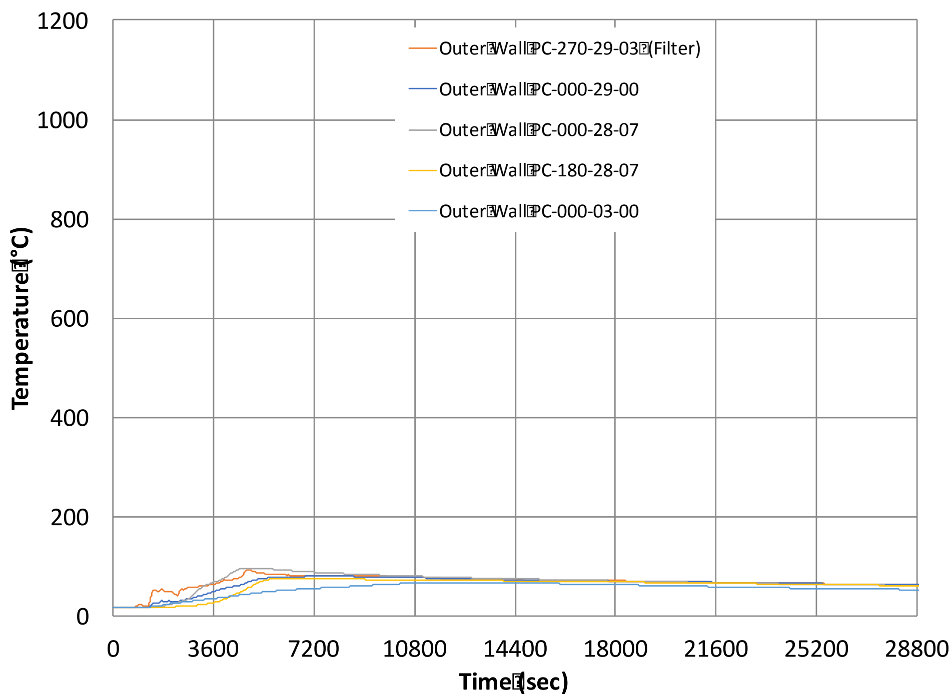


Figure 47. Temperatures on the outer wall of the PC (POC drum B, Test #2)

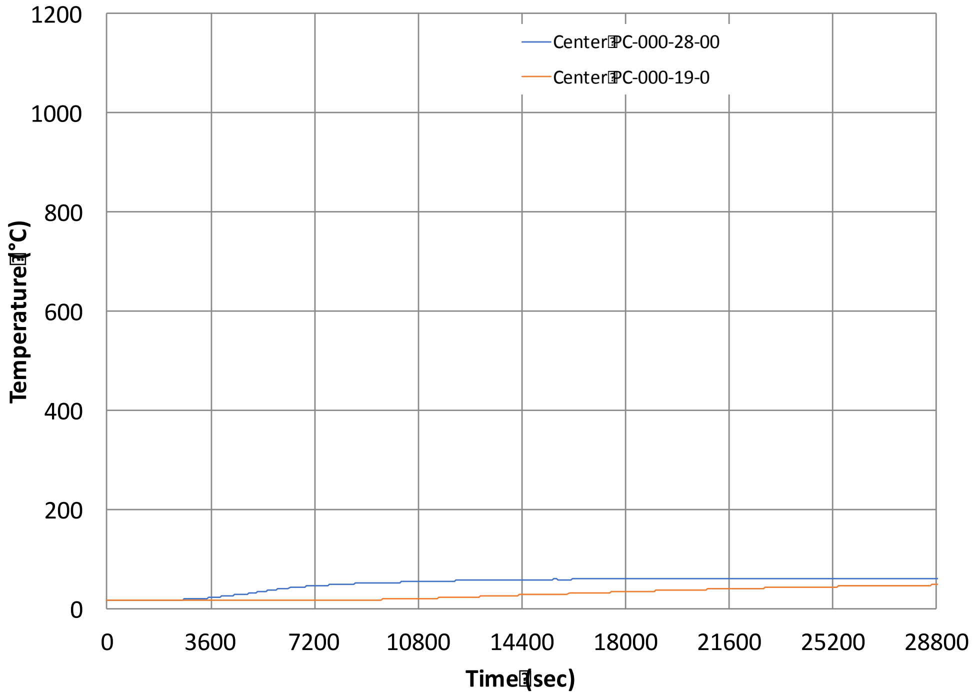


Figure 48. Temperatures in the center of the PC (POC drum B, Test #2)

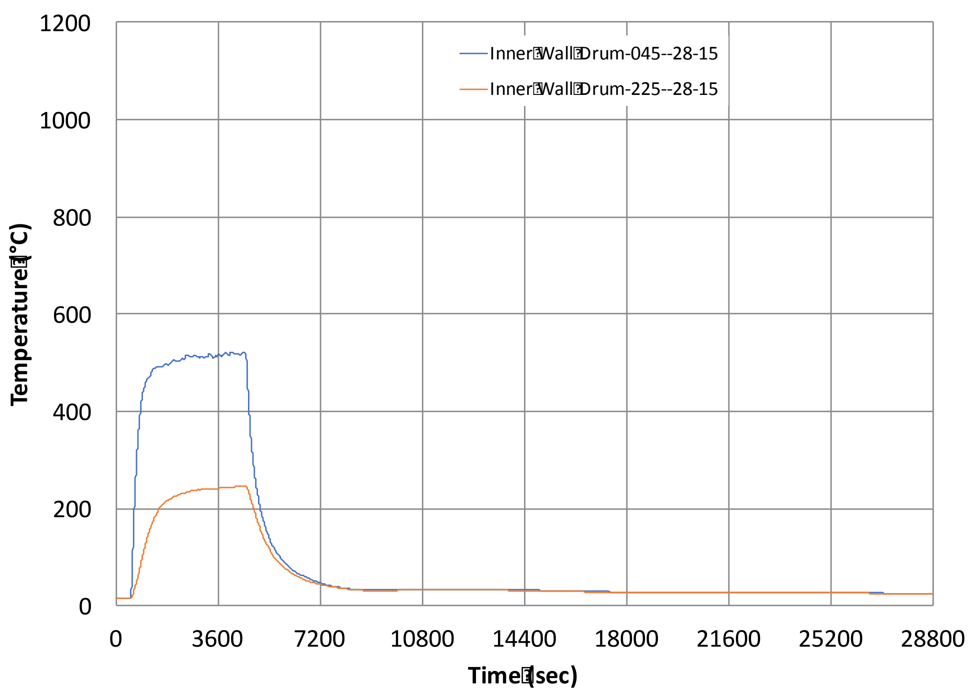


Figure 49. Temperatures on the outer wall of the drum (POC drum D, Test #2)

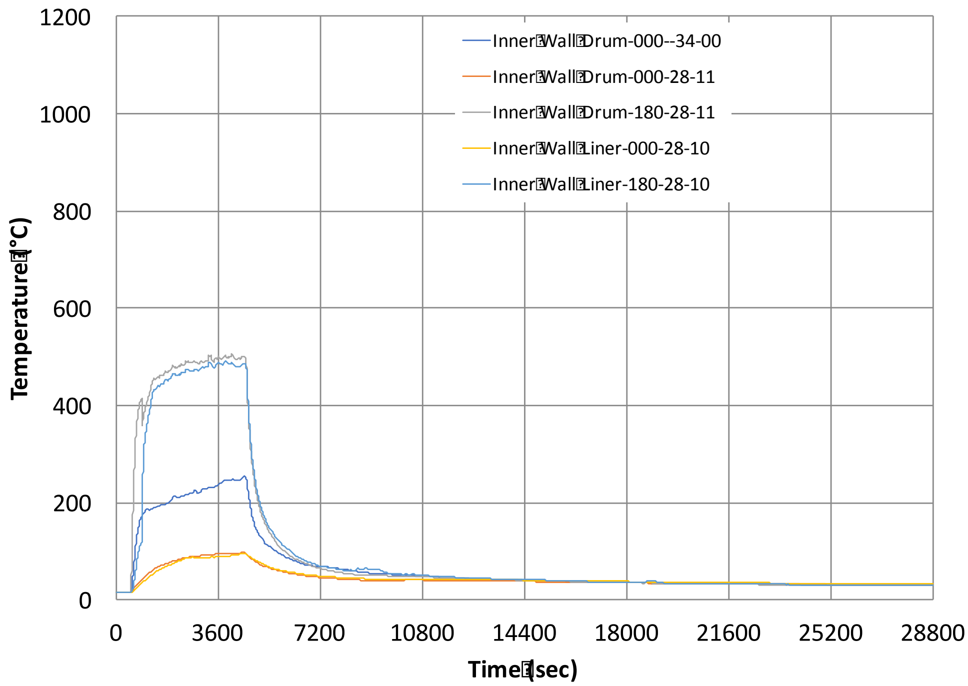


Figure 50. Temperatures on the inner wall of the drum and plastic liner (POC drum D, Test #2).

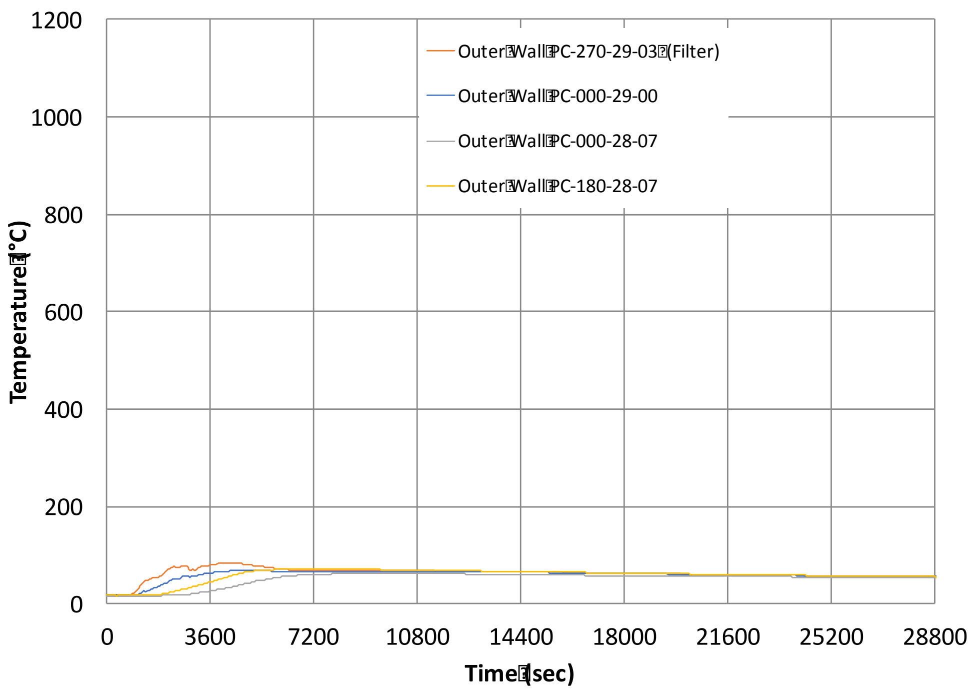


Figure 51. Temperatures on the outer wall of the PC (POC drum D, Test #2)

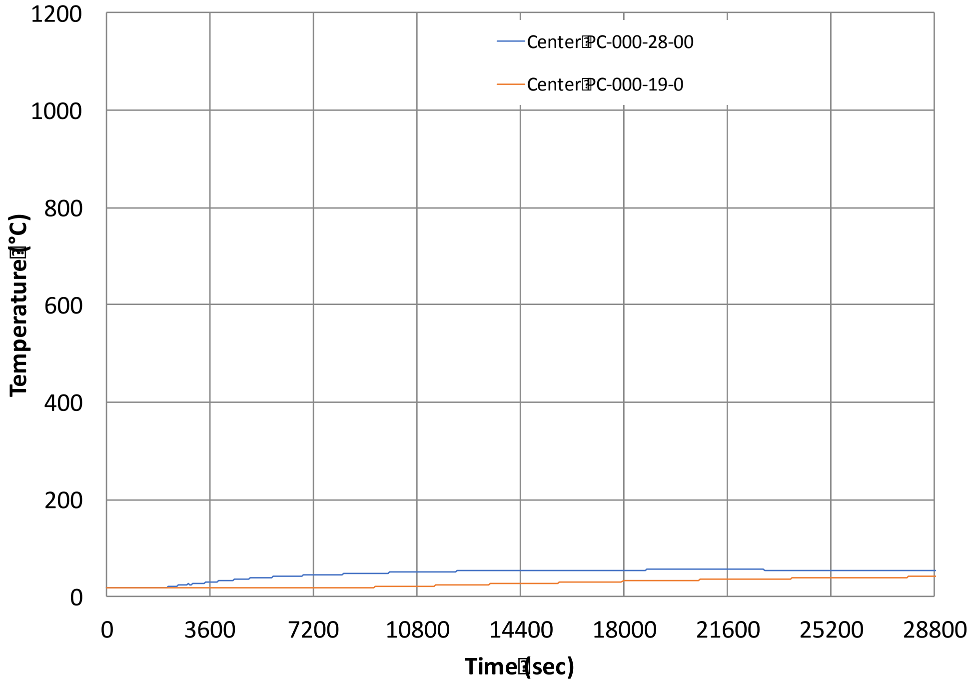


Figure 52. Temperatures in the center of the PC (POC drum D, Test #2)

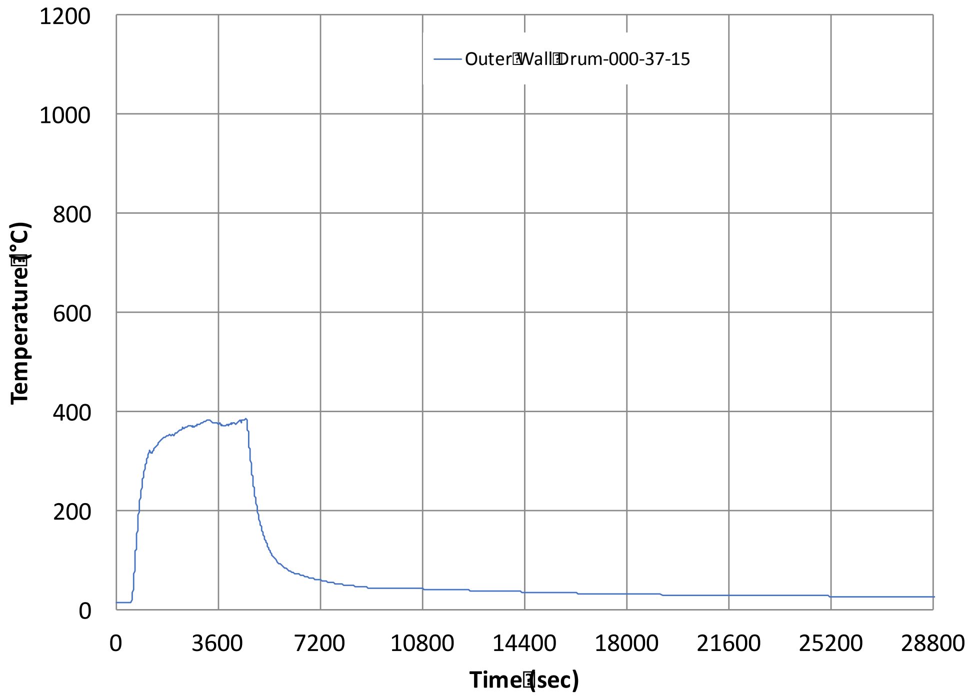


Figure 53. Temperatures on the outer wall of the drum (7A drum C, Test #2)

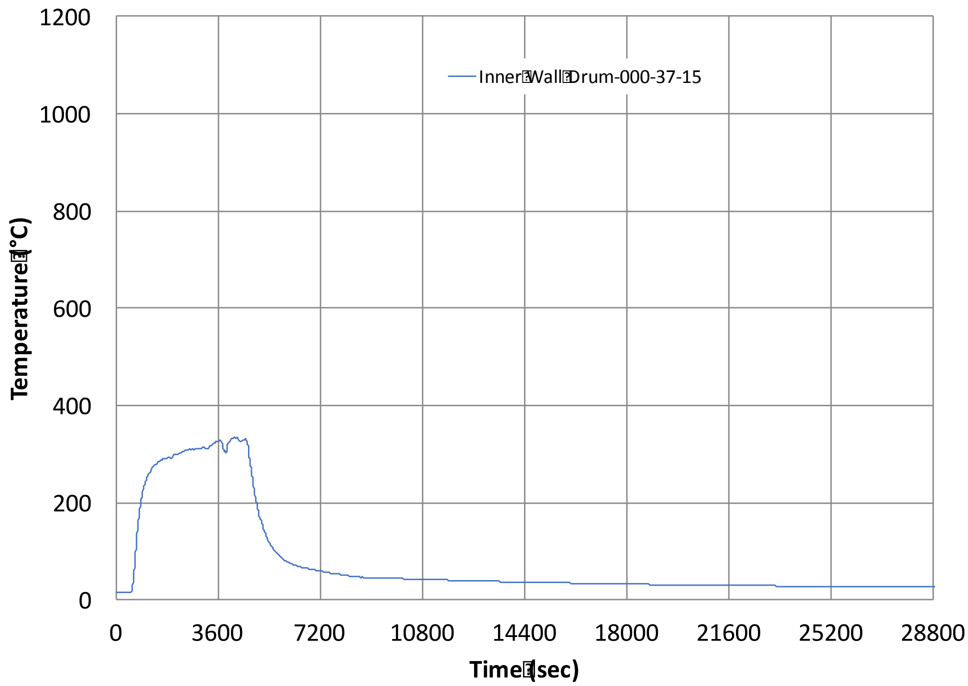


Figure 54. Temperatures on the outer wall of the drum (7A drum E, Test #2)

Similar trends are observed for the POC drum A at the center of the fire, except that the temperatures below 200°C on the wall of the PC and in the center of the PC, significantly lower than the +500°C temperature peaks observed in Test #1 on the PC. Notice also that the plots don't show the upward rise in temperature that was observed in the same drum in Test #1. As shown in Figure 38(a), the Celotex® did not burn all the way down to the bottom of the drum in this test. Keeping even half the insulation caused the temperatures in the PC at the center of the fire to be significantly lower. The fact that the lid did not come off and that the Celotex® survived in this drum shows the impact of keeping the lid on the drum. Outside the fire, compared to Test #1, the temperatures on the POC components shown in the current plots are similar. Peak temperatures on the outer wall of the PC are below 135°C, and in the center of the PC, they are also below 100°C. On the 7As, the peak temperature on the side of the drum facing the fire is over 400°C. This temperature was high enough to burn some of the combustibles inside this drum as previously described (see Figure 38(b)).

Phase II

Results from Phase I Test #2 did not show the drum lid opening or getting ejected for the drum inside the fire. One reason why this may not have happened was inappropriate torqueing of the lids. To address this hypothesis, Phase II was added to this test series.

Table 2 shows the state of the PC filters and the PC flange O-ring after the Phase II tests. Note that all the PCs used in Phase II were empty and no leak test were performed on them since tests in this phase were strictly designed to look at the performance of the drum lids when properly torqued. The following sections describe the results of these two tests in more detail.

Test 1

The first test in Phase II was initially the only test planned in this phase. Since the purpose of the test was to see if the POC drum lid would get ejected from the center of the pool, only one POC was used. The POC was a standard POC with the drum lid on. There was no instrumentation inside it, but TCs were attached to the outside of the drum to monitor the temperature of the flames, which helped corroborate that the POC was getting heated evenly during the fire. HFGs were not required for this test, but were already in the facility. Thus, they were used to verify pervious heat flux data. Figure 55 is an image taken prior to the test.

Figure 55. Test layout in Test #1 of Phase II.

Figure 56 shows two images from this test. The test images are screen captures from videos taken just after the lid was ejected from the drum. In Test #1 of Phase II, the drum lid, the plastic liner, Celotex®, and wood board covers were ejected from the fully engulfed POC 3 minutes after the POC was fully engulfed. The time stamp shown on the bottom right corner of the images corresponds to the time elapsed since fully engulfing conditions where reached. The left image shows the lid in midair shortly after getting ejected from the drum, and the right image shows a section of burning Celotex® coming down on the pool after it had risen beyond the viewing area of the video camera. Note the difference in time in between images, which gives an indication of the time the Celotex® piece in the right image was airborne above the camera view. Although not show in this figure, images obtained from IR video screen captures also showed the entire PC flange momentarily raised above the edge of the drum soon after the lid and the other components were ejected.

Figure 57 shows the test area the day after the test. Figure 57(a) shows char remains of various Celotex® pieces inside the pool. The Celotex® lid is by the corner of the table and the Celotex® ring shown towards the bottom of the image (originally wrapped around the PC flange). The remains of the plywood and traces of molten plastic were observed near the table on the pool floor.

Figure 56. Videos screen captures of Phase II Test # 1 showing ejection of lid.

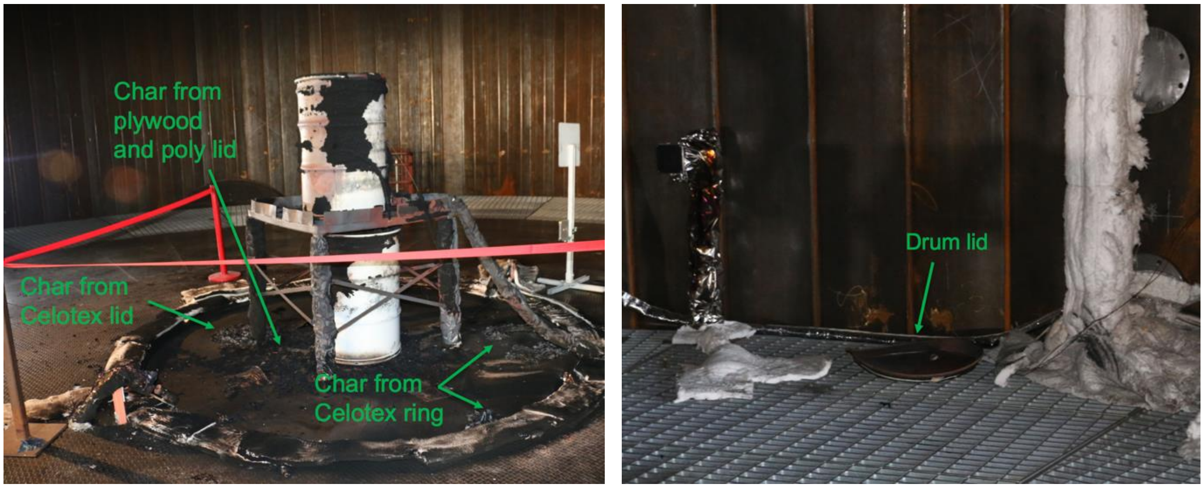
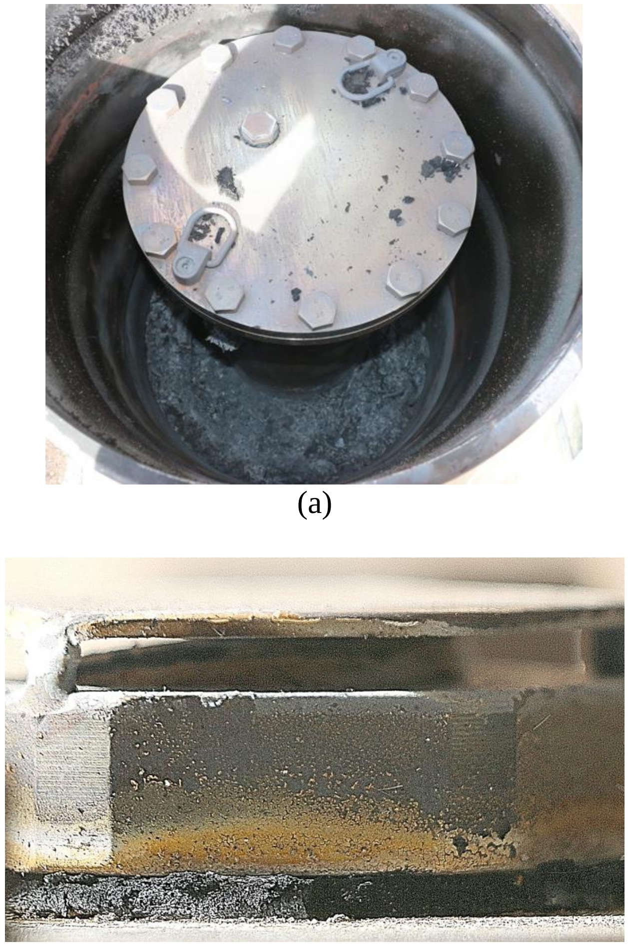


Figure 57. Test remains after Test #1 in Phase II. (a) center of the pool and (b) lid by the wall of the test cell.

Figure 57(b) shows the final location of the drum lid; it's next to the HFG placed by the wall of the test cell, roughly 9 m away from the center of the pool. The lid was severely bowed and landed with the bottom side facing up. The ring was still attached to the drum with no signs of the seal, which had been completely consumed during the fire.

As in the first test of Phase I, all that remained inside the POC were the remains of burned Celotex® beneath and just to the side of the POC (see Figure 58(a)). The PC filter was examined in place (i.e., while attached to the lid) and the carbon material inside the vent housing was found pushed out from where it normally sits, with some evidence of gray discoloration on the sides of the carbon media (see Figure 58(b)). Without a leak test it's difficult to quantify the state of the filter. However, given the conditions observed and what was observed in the first phase, it's almost certain that the PC filter was compromised.



(a)

(b)

Figure 58. Remains of the POC in Test #1 of Phase II.

Test 2

The second test was initially designed to be a replicate of the first test in this phase. However, given the force with which POC materials were ejected in the first test, as noted by the weights of the materials ejected and the height attained by these materials after ejection, release of the drum lid from a properly torqued drum adjacent to the fire was deemed a possibility. Therefore, in this second test, the POCs and 7As were also added adjacent to the pool.

Figure 59 shows an image of the test layout. One POC and one 7A were placed 1.7 m from the center of the pool and the other POC and 7A were placed 2.0 m from the fire, slightly closer to the fire than the POC in the Test #2 of Phase I. The POCs were located on the north and west side of the facility and the 7As on the opposite side as shown in Figure 12. As noted in that figure, the drum labeling scheme changed in this test but this had no special significance. In Figure 59, the 7As are the two closest drums (E and F), while the remaining drums shown towards the back are POCs.

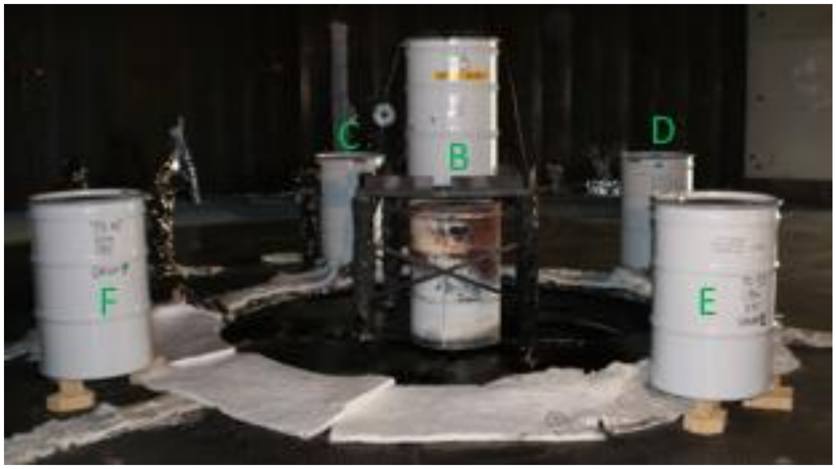
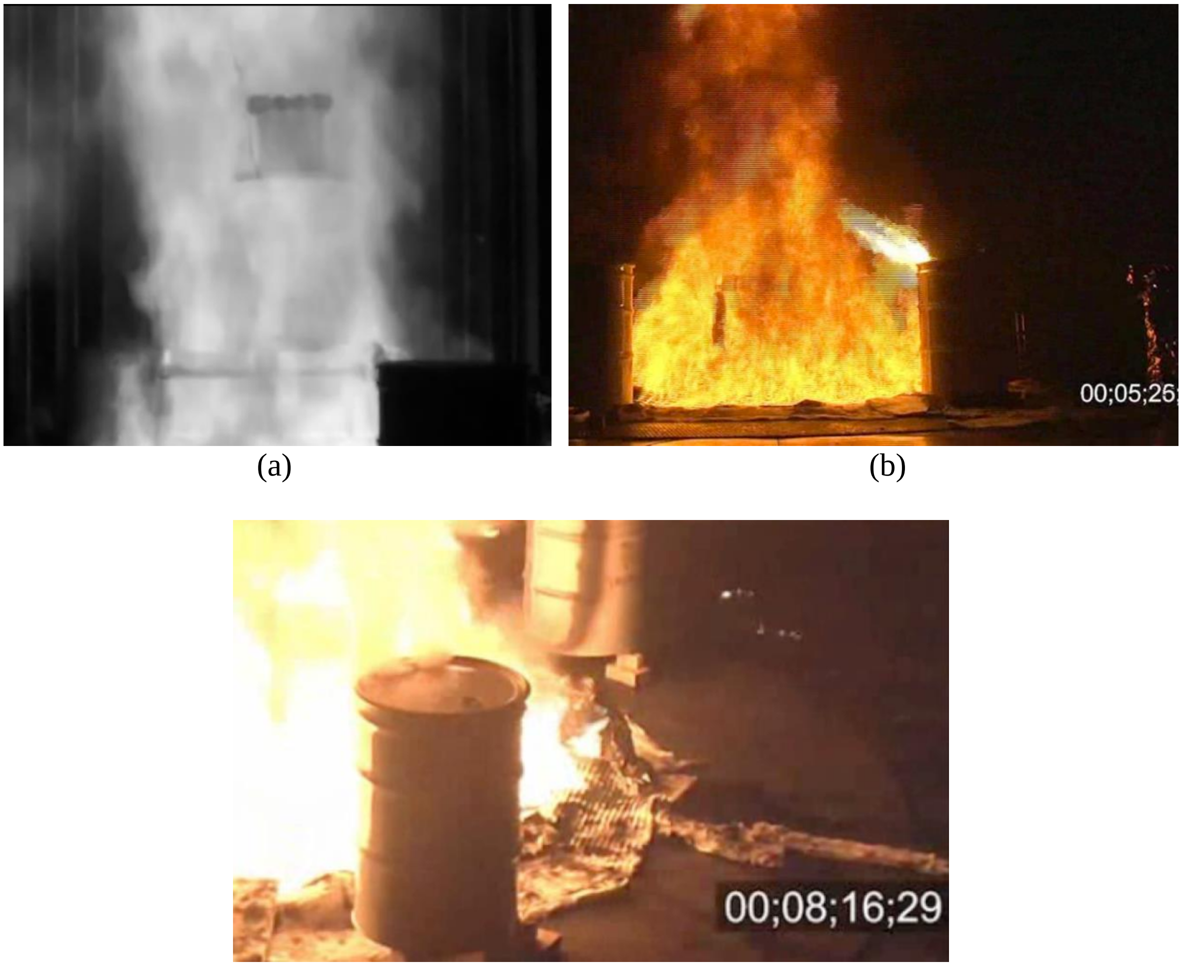


Figure 59. Image of the test layout in Test #2 of Phase II taken from the southeast corner of the facility.

The PCs on the POCs were empty, but the 7As were filled with typical combustible materials (gloves, plastics, etc.) to the top (see Figure 60). Except for the center drum B, none of the other drums had TCs. The TCs on the center drum were all attached on the outside of the wall of the drum to make sure the drum was fully engulfed.

Figure 60. Typical contents of 7As in Test #2.

As in the first test of this phase, the same components were ejected from the fully engulfed POC and at about the same time (~3 minutes). However, in this test, the PC was propelled upwards higher than in the first test. Figure 61(a) shows a screen capture of the IR video when the PC reached its maximum height. Close to half of the PC is out of the drum based on the diameter of the flange shown in the image and the total length of the PC. Differences in the lid torque or the mass inside the POC (e.g., additional moisture in the Celotex®), and even the fire conditions could account for the differences in the force with which these components were ejected. Figure 61(b) and (c) are screen captures showing venting from the closest POC and 7A. Venting from this POC and 7A started shortly after 5 and 7 minutes, respectively. Note that while smoke was observed around the lid of these drums prior to and during the outgassing observed in these images, possibly suggesting some outgassing through the lid, the vast majority of the outgassing appears to come from the vent.

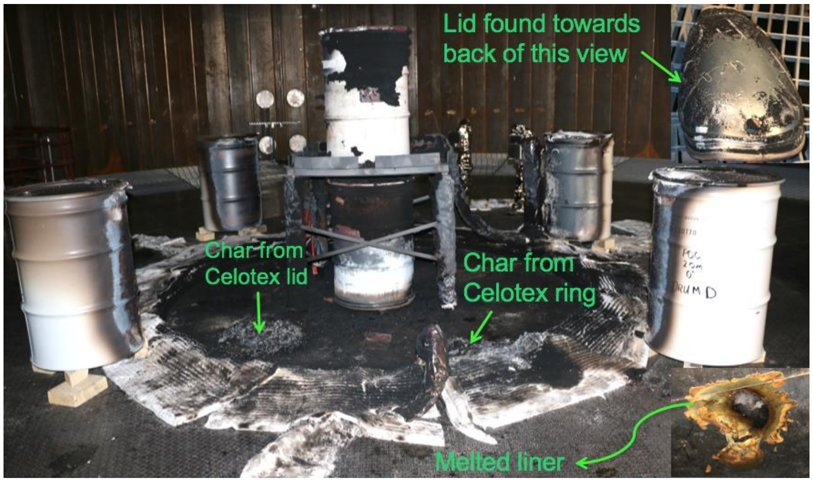


(a) (b)

(c)

Figure 61. Screen captures of videos taken during Test 2: (a) PC at the center of the fire protruding just above the POC drum, (b) closest POC to the fire venting gas (flames) from the drum filter, (c) closest 7A to the fire venting gas from the drum filter.

Figure 62(a) shows the overall state of the POCs and 7As after the fire. As before, Celotex® material ejected from the center drum fell on the pool. The drum lid was found on the grid floor of the test cell towards the back of the setup (from the point of view of this image), as shown on the cutaway at the top right of this image. The lid was much more severely deformed than in the previous test. Molten plastic from the liner was also found, this time on the north side of the test cell, as observed on the cutaway image on the lower left of this figure. Figure 62(b) shows the PC filter recovered from the PC in drum A. Figure 62(c) and (d) show close-ups of the drum lids of the closest to the fire POC and 7A drum.



(a)

(b)

(c)

(d)

Figure 62. Conditions of the POC and 7As after completion of Test #2 in Phase II: (a) extent of damage to the center drum, (b) PC filter recovered from the center POC, and (c) and (d) damage on the lid of the POC and 7A drums closest to the fire.

Overall, the 7A drum underwent very little damage; however, the POC drum shows significant bulging on the lid on the side facing the fire. Damage on the POC located at 2 m was less than shown in Figure 62(c), but more extensive than the damage observed on drum B in both the first and second test of Phase I. Based on these results, it appears that when the lid is torqued properly, bulging of the POC drum lids closest to the fire (<2.2m) is more severe. Still, both POC drum lids stayed on with no sizable gaps found between the lid and top edge of the drum. Damage to the 7A drum at 2m was less than that from the 7A that was closer to the fire.

Inside the POCs, the interior looked similar to the interior of drum B of the first and second test. Figure 63 shows an image of what was left inside one of the 7A drums. More than half the combustible material originally placed inside the drum was decomposed.

Figure 63. Left over material inside one of the 7As in Test #2 of Phase II.

5. DISCUSSION OF RESULTS

The primary goal of this test series was to obtain the temperature response of POCs with PCs filled with inert material, both inside and outside the fire, and to assess the performance of POC and 7A drum lids inside and adjacent to the fire. Combustibles and inert material were used in the 7As and POCs, respectively, and were considered typical and/or deemed acceptable for reproducing the thermal response of these packages. Initial Phase I tests were originally designed to meet both goals; however, as already mentioned, only the first goal was met. To address the second goal, additional tests were added to the test series and conducted in a subsequent phase. Phase II did not include instrumentation inside the POCs or 7As. Both Phase I and II show consistent results as will be discussed in this section.

As demonstrated in the previous section, variations in the location of the POCs with respect to the fire in both Phase I and II produced a wide variety of results, from minor decomposition of the drum seal to ejection of the drum lid and other POC components above the PC and subsequent melting/burning of the plastic liner, Celotex® and wood material left inside the POC. Particularly, for the POCs at the center of the fire, decomposition of the Celotex® gradually exposed the PC directly to the hot fire environment and to the high temperatures produced by the smoldering Celotex®, which persisted hours after the test was completed based on temperature recorded on the outside of the PC. Despite these intricacies, two aspects controlled the temperature response of the PC. The first was the impact of the location of the drum with respect to the fire, and the second was whether the drum lid and other components sitting on top of the PC got ejected from the POC as a result of internal pressurization of the POC.

Inside the fuel pool, results from Phase I and II test clearly suggest that there is a very good likelihood the drum lid will be ejected when the lid is properly torqued and with the current drum filter design. With this design, there isn't sufficient way to release gases from inside the POC to prevent over pressurization even after the drum ring seal has burned off. After the drum lid gets ejected, the Celotex® remaining inside the POC will burn at a much faster rate compared to when the drum lid remains in place. It is almost certain that burning/decomposition of the Celotex® left inside the POC will continue after the fire without an external intervention. As shown in Figure 24 and Figure 25, temperatures near the bottom of the PC continue to rise well beyond the end of the fire as a result of the continued combustion of the Celotex®.

Table 5 shows the maximum temperatures recorded on the outer wall of the PC, and in the center of the PC contents (maximum is not always at the same height) for POCs inside the fire in both tests conducted in Phase I for three periods of time: (1) during the first 7200 seconds of data recording, which include the fire period, (2) during the middle of the cooling period (10800-18000 seconds), and (2) during the last 7200 seconds of data recording in the plots shown in the results section. Close attention should be paid to the POC without the lid at the center of the fire (i.e., Test #1, Phase I), where the difference in the maximum temperature between the first and last period on the outer wall of the PC is less than 10% and at the center of the PC is about 20%. During the first period, maximum temperatures occur on the top of the PC, while during the end period the maximum temperature occurs on the bottom of the PC. In between these end periods, the maximum temperatures were lower. Note however, with combustibles inside the PC, there exists the possibility that the temperatures are higher through the middle period and even increase with time beyond that if there is material pyrolysis occurring. In contrast, when the lid stays on the center POC (i.e., Test #2, Phase I), maximum temperatures at every location on the outer wall of the PC and inside the PC are significantly lower with a tendency for the peak temperature to occur in the initial period on the wall of the PC and in the middle period inside of the PC.

Table 5. Maximum PC temperatures observed in drum A in Phase I tests.

		Max Temperatures (°C)		
Test	Location	Up to 7200 sec.	10800-18000 sec	Last 7200 sec.
Test #1	Outer Wall of PC	827	447	756
	Center of PC Contents	623	438	496
Test #2	Outer Wall of PC	278	225	149
	Center of PC Contents	105	175	152

Clearly, for POCs outside the fire, maximum temperatures on the inner wall of the drum and the plastic lid, and on the outer wall of the PC tended to occur at the end of the fire. Inside the PC, the temperature peaked much later. However, since these POCs were outside of the fire, the maximum temperatures on the wall of the PC and in the center of the PC were much lower than shown in Table 5. The maximum temperature on the outer wall of the PC and inside the PC at any time for the closest POC to the fire (drum B in Test #1) were below 100°C and 60°C, respectively. There is no temperature data for POCs outside and adjacent to the pool without a drum lid, but results of these tests indicate that drum lids in these locations would not be ejected.

Figure 64 shows results of Thermogravimetric Analysis (TGA) done on the plastic and cellulose materials obtained from TA-55 at LANL. These are typical materials placed inside the PC and by far they account for the largest mass inside the PC based on the material inventories obtained from TA-55 at LANL. In the presence of air, the high-density polyethylene plastic begins to decompose around 400°C. The cellulose material analyzed, Kimwipes, typically start to decompose in air at around 250°C and by about 400°C it is more than 70% decomposed. The initial mass loss at lower temperatures is due to the release of moisture inside the Kimwipes.

In argon, decomposition of these materials starts at lower temperatures, as shown in Figure 65. Even using the more conservative temperatures shown in this figure, these materials never reach the point where they start to decompose if the drum lid is not ejected.

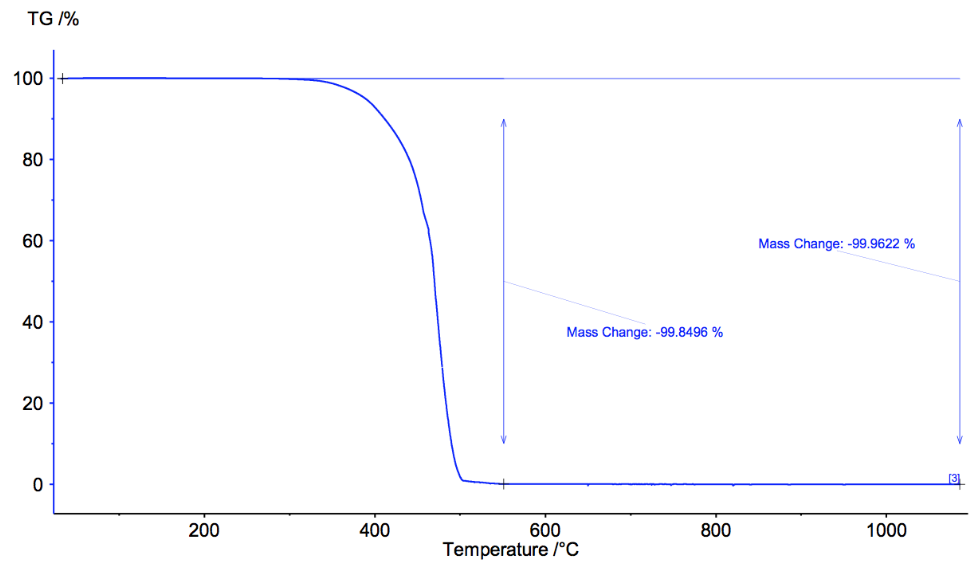
Given the temperatures on the outside walls of the PC and at the center of the PC and the TGA results, it is likely that inside the fire, when the lid remains in place, there will be no melting of the high-density polyethylene and no decomposition of the cellulosic material inside the PC. When the drum lid and other POC components inside the PC get ejected, melting of the high-density polyethylene and decomposition of cellulosic material is certain given that the peak and sustained high temperatures observed during and after the fire are higher than the temperatures required to melt or decompose these materials. Based on the temperature history of the outer wall of the PC and at the center of the PC, it is likely that melting and decomposition occurs from the top of the PC down and later from the bottom of the PC up. Thus, a DR of one is certain for POCs inside the fire when the lid and the top plastic liner, Celotex®, and wood board covers get ejected early in the fire.

In this test series, all POCs inside the fire had PCs with inert materials. Therefore, these results do not account for possible pyrolysis of materials which can exacerbate the amount of material decompose inside the PC and that potentially gets released. As such, it is difficult to predict based on data obtained from Phase I and II the approximate ARF value. Subsequent tests, which include typical combustibles, should be conducted.

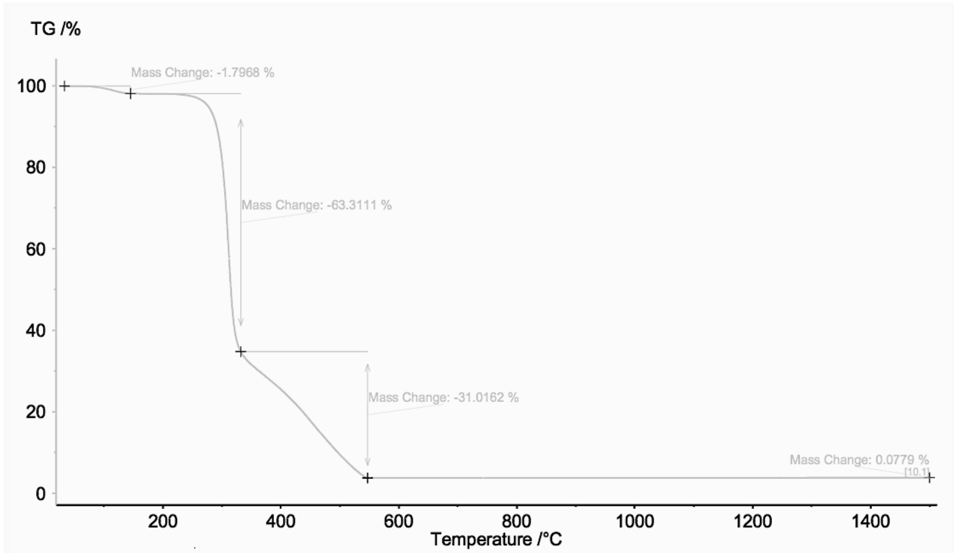
Outside the fire, the performance of the drum lid in Phase II and the temperature data obtained in Phase I on POCs outside the fire suggest that the drum lids will remain in place. As noted in Table 5, with the lid in place the maximum temperature at any point on the wall of the PC and inside the PC remains below 100°C, much lower than the temperature required to decompose the high-density polyethylene and the Kimwipes. Moreover, examination of PC filters and results of leak testing showed that, for POCs outside the fire, the PC filter, PC gasket, and the PC flange O-ring remain in good condition. Therefore, a DR of zero is expected for POCs outside of the fire. As previously mentioned, the PCs in these test series were filled with inert material or were empty, thus pressurization of the PC is expected to be lower than when the PC is loaded with typical combustibles. However, given that the temperatures recorded were low enough to prevent decomposition of the high-density polyethylene and Kimwipes analyzed, these results should remain valid even when the PC is loaded with typical combustibles.

Figure 66 shows a plot of some of the heat fluxes recorded with HFGs at various locations around the test cell, including locations where the closest to the fire part of the POC and 7A drums were located. As noted, the correlation given in (Drysdale, 2007) compares well with the data collected, which gives confidence on the heat flux measured with the HFGs deployed in this tests. This data is only applicable when Jet-A is used as a test fuel and under the conditions of these tests in FLAME.

The closest POCs to the fire were 1.7 m from the center of the pool. At this distance, the heat flux to the front of the drum is approximately 55kW/m^2. The errors presented in this plot are based on residuals from the inverse heat flux calculations and do not take other sources of uncertainty into account. A more rigorous uncertainty analysis is given in (Figueroa, 2005), which suggests errors can be up to ±20% of the predicted value using inverse heat flux methods. Therefore, at 55kW/m^2 equivalent distance, the heat flux could be as low as 45kW/m^2 or as high as 65kW/m^2. To be conservative, for POCs outside of the fire, the above DR conclusions should be valid starting from an equivalent distance of approximately 45kW/m^2.

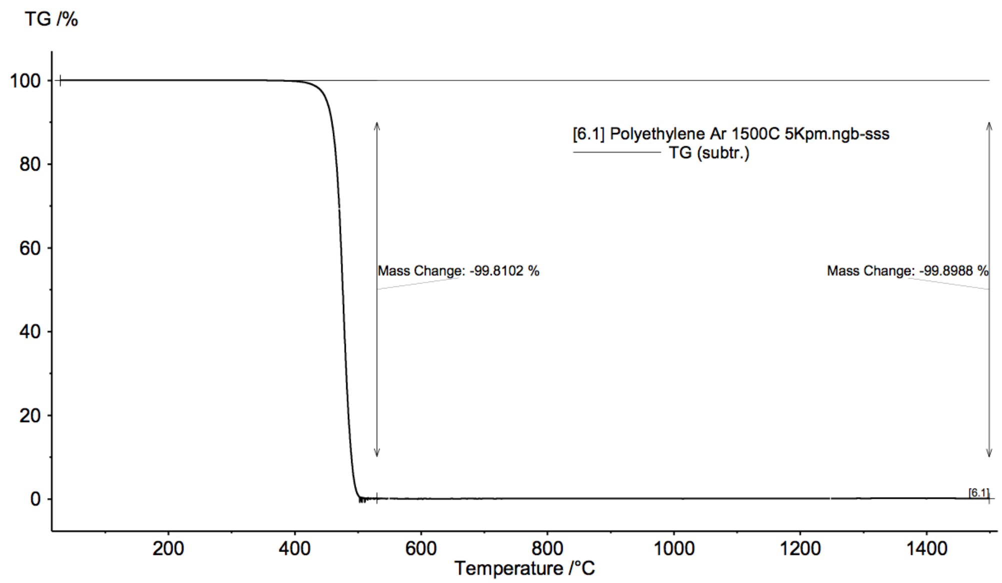


(a)

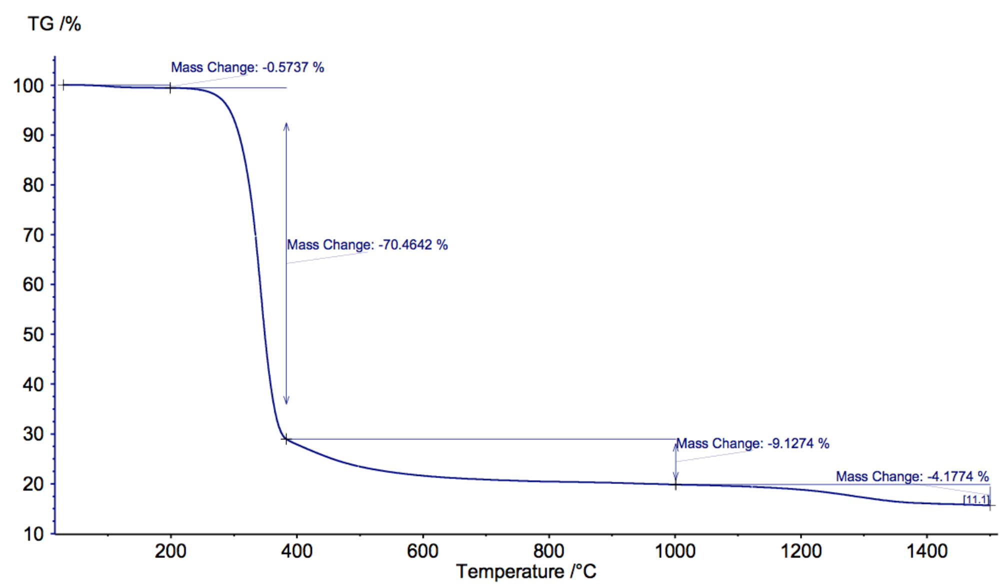


(b)

Figure 64. TGA results in air from typical materials inside the PC: (a) high density polyethylene and (b) Kimwipes®.



(a)



(b)

Figure 65. TGA results in argon from typical materials inside the PC: (a) high density polyethylene and (b) Kimwipes®.

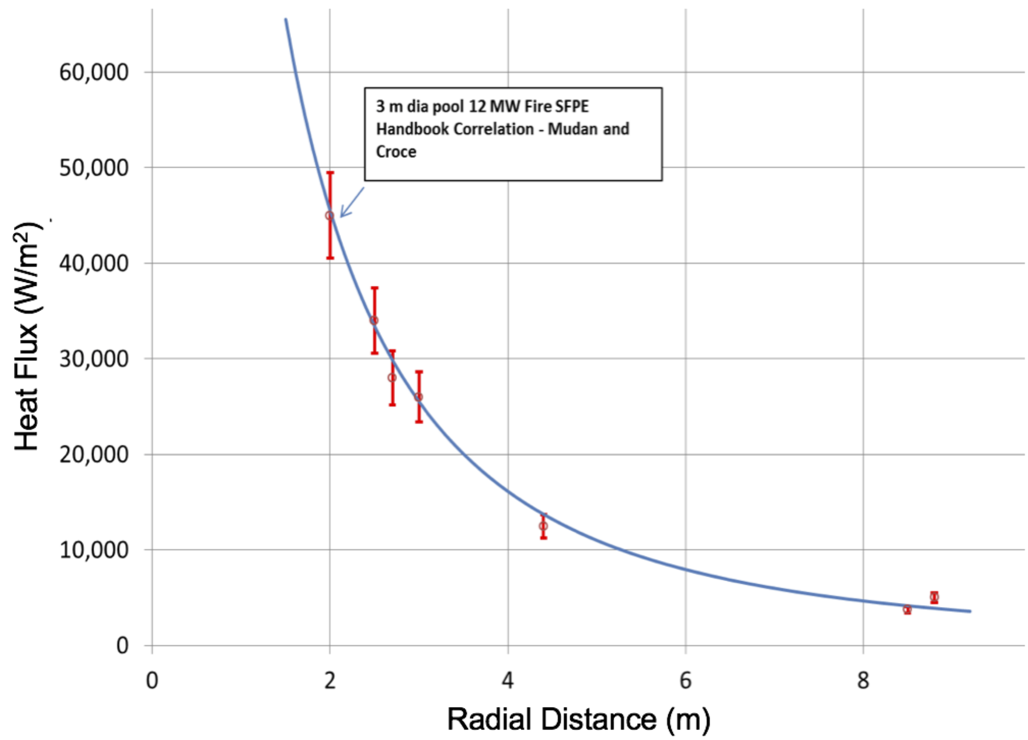


Figure 66. Heat fluxes measured inside the test cell using HFGS. The solid line represents results from the correlation given in (Drysdale, 2007).

Predicting the ARF is more difficult from this data because the ARF will depend not only on the temperature response of the PC, but also on the condition of the PC filter, PC filter gasket, and the PC flange O-ring, the burning characteristics of the materials inside the PC, and the total mass and mass distribution of the radioactive aerosol material inside the PC. For POCs inside the fire in Test #1 of Phase I, the PC filter and PC flange O-ring were heavily damaged when the lid and other components on top of the PC were absent. In addition, post-test leak testing conducted on this PC showed much higher leak rates through the PC filter gasket and through the PC O-ring than for pristine PCs. This suggest that for POCs inside the fire the possibility exists that the ARF will be greater than zero. More fire tests with POCs under fully engulfing conditions and with PCs filled with combustibles are needed to determine the ARF under this condition. In contrast, for POCs outside the fire, all post-test examination of their PC filters and PC O-rings showed (based on visual inspection) these components remained in good condition after the fire test. Moreover, leak tests conducted on these PCs showed leakage rates through the PC filter gasket and through the PC O-ring to be consistent with the those of pristine PCs. Therefore, under these conditions the ARF should be zero.

Finally, Phase I and II have shown that the 7A drum lids performed as expected outside the fire, with the drum filter effectively relieving the pressure built up inside the drum during the fire, and preventing the lid from getting ejected. Post-test observations of material left inside the PC after Test #2 in Phase I show evidence of charring, so the DR=1for 7A drums at radial distances equivalent to 45kW/m^2, and the ARF may not be zero for these drums because there was noticeable off-gassing from these drums past the drum lid gasket.

6. CONCLUSIONS

In 2015, SNL started conducting fire tests of POCs in support of the EM/NNSA test program. This report describes the various tests conducted between October of 2015 and April of 2016 as part the DOE EM and NNSA storage drum test program, which was established for POCs under the loading conditions typically being employed at TA55 at LANL. In addition, 7A storage drums filled with combustibles were included in some of the tests. Specifically, the goal of this fire test series was to examine performance of POCs with inert materials inside the PCs, and secondarily, the behavior of 7A drums with combustibles inside. This report presents results from these tests, and discusses their implications in terms of the DR and ARF ratios, both for POC and 7A drums.

For the POCs, results included temperature measurements of the exterior and interior of POC components and leak test rates through the PC filter gaskets and PC O-rings, as well as qualitative data that showed the state of the POC components after the fire. For the 7As, results included temperature measurements of the exterior of these drum and qualitative data that showed how the drum filter and drum seal performed outside of the fire and the state of the combustible materials inside the drums after the test.

Based on these data, it appears that for POCs inside the fire with appropriately torqued lids, the lids and some of the components sitting on top of the PC get ejected approximately 3 minutes into the fire. In these tests, the fuel consumption rate was 0.30kg/s; therefore, in 3 minutes the fire would have burned approximately 54kg (17gal) of fuel. Slow burning of the Celotex® results in gradual exposure of the PC to the fire and smoldering of the Celotex® after the fire leads to higher thermal insult to the PC than would be the case if the smoldering Celotex® were extinguished at the end of the fire environment. In all, temperature data collected for this scenario show temperatures inside the PC that can melt or decompose typical materials (i.e., high-density polyethylene and cellulosic material) inside it. Therefore, for POCs inside the fire the DR=1. Moreover, post-test examination of PC components and leak testing conducted on the exposed PCs suggest an ARF greater than zero. More tests are needed to determine the approximate ARF value for POCs loaded with combustibles under fully engulfing conditions. Outside the fire, the POC drum lids remained in place with the Celotex® insulation undergoing some decomposition, but not enough to cause a significant rise in the temperature of the PC and subsequent melting and/or decomposition of typical materials inside the POC. Accordingly, outside the fire the DR and ARF values should be zero for POCs at a distance experiencing a heat flux of $45kW/m^2$ or less under the fire conditions described in this report.

For the 7As, tests showed that at least for drums at a distance experiencing a heat flux of $45kW/m^2$ or less, the drum filter releases the pressure inside the drum and, as a result, the drum lids remain in place. Some burning and charring of combustible materials inside the 7A was observed, suggesting the DR=1 for these drums.

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APPENDIX A: LOCATION OF TCs ON THE PC

TCs on POC in drum A in Test #1 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[4]	Axial Location (inches)[5]	TC Location Description
1AT01-A000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
1AT02-A000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
1AT03-A000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT04-A000-29-00	0	0	26.50[2]	Top Center of PC Lid
1AT05-A180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
1AT06-A180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
1AT07-A180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
Not used in Test 1	0	0	34.18[1]	Center Inner Wall of Drum Lid[3]
1AT09-A000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
1AT10-A000-00-00	0	0	-2.30[1]	Center Inner Wall of Drum Bottom
1AT11-A000-28-00	0	0	24.55[2]	Center of PC
1AT12-A000-19-00	0	0	16.00[2]	Center of PC
1AT13-A000-10-00	0	0	7.00[2]	Center of PC
1AT14-A045-17-06	45	6.18	14.00[2]	Outer Wall of PC
1AT15-A225-17-06	225	6.18	14.00[2]	Outer Wall of PC
1AT16-A090-28-11	90	11.18	27.70[1]	Inner Wall of Drum
1AT17-A090-28-10	90	11.09	27.70[1]	Inner Wall of Liner
1AT18-A090-28-07	90	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT19-A270-28-07	270	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT20-A270-29-03	270	3.43	26.50[2]	On Lid Filter
1AT21-A270-28-11	270	11.18	27.70[1]	Inner Wall of Drum
1AT22-A270-28-10	270	11.18	27.70[1]	Inner Wall of Liner
1AT23-A135-17-06	135	6.18	14.00[2]	Outer Wall of PC
1AT24-A315-17-06	315	6.18	14.00[2]	Outer Wall of PC

[1] Axial Location Measured from the Base of the Drum
[2] Axial Location Measured from the Base of the Containment Vessel
[3] This gage location not used for Test #1
[4] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC
[5] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

TCs on POC in drum B in Test #1 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[3]	Axial Location (inches)[4]	TC Location Description
1AT25-B000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
1AT26-B000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
1AT27-B000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT28-B000-29-00	0	0	26.50[2]	Top Center of PC Lid
1AT29-B180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
1AT30-B180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
1AT31-B180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT32-B000-34-00	0	0	34.18[1]	Center Inner Wall of Drum Lid
1AT33-B000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
1AT34-B000-28-00	0	0	24.55[2]	Center of PC
1AT35-B000-19-00	0	0	16.00[2]	Center of PC
1AT36-B270-28-03	270	3.43	26.50[2]	On Lid Filter

[1] Axial Location Measured from the Base of the Drum
[2] Axial Location Measured from the Base of the Containment Vessel
[3] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC
[4] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

TCs on POC in drum C in Test #1 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[3]	Axial Location (inches)[4]	TC Location Description
1AT37-C000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
1AT38-C000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
1AT39-C000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT40-C000-29-00	0	0	26.50[2]	Top Center of PC Lid
1AT41-C180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
1AT42-C180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
1AT43-C180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT44-C000-34-00	0	0	34.18[1]	Center Inner Wall of Drum Lid
1AT45-C000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
1AT46-C000-28-00	0	0	24.55[2]	Center of PC
1AT47-C000-19-00	0	0	16.00[2]	Center of PC
1AT48-C270-29-03	270	3.43	26.50[2]	On Lid Filter

[1] Axial Location Measured from the Base of the Drum

[2] Axial Location Measured from the Base of the Containment Vessel

[3] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

[4] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

TCs on POC in drum D in Test #1 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[3]	Axial Location (inches)[4]	TC Location Description
1AT49-D000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
1AT50-D000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
1AT51-D000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT52-D000-29-00	0	0	26.50[2]	Top Center of PC Lid
1AT53-D180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
1AT54-D180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
1AT55-D180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT56-D000-34-00	0	0	34.18[1]	Center Inner Wall of Drum Lid
1AT57-D000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
1AT58-D000-28-00	0	0	24.55[2]	Center of PC
1AT59-D000-19-00	0	0	16.00[2]	Center of PC
1AT60-D270-29-03	270	3.43	26.50[2]	On Lid Filter

[1] Axial Location Measured from the Base of the Drum
[2] Axial Location Measured from the Base of the Containment Vessel
[3] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC
[4] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

TCs on POC in drum A in Test #2 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[4]	Axial Location (inches)[5]	TC Location Description
2AT01-A000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
2AT02-A000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
2AT03-A000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
2AT04-A000-29-00	0	0	26.50[2]	Top Center of PC Lid
2AT05-A180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
2AT06-A180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
2AT07-A180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
2AT08-A000-34-00	0	0	34.18[1]	Center Inner Wall of Drum Lid[3]
2AT09-A000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
2AT10-A000-00-00	0	0	-2.30[1]	Center Inner Wall of Drum Bottom
2AT11-A000-28-00	0	0	24.55[2]	Center of PC
2AT12-A000-19-00	0	0	16.00[2]	Center of PC
2AT13-A000-10-00	0	0	7.00[2]	Center of PC
2AT14-A045-17-06	45	6.18	14.00[2]	Outer Wall of PC
2AT15-A225-17-06	225	6.18	14.00[2]	Outer Wall of PC
2AT16-A090-28-11	90	11.18	27.70[1]	Inner Wall of Drum
2AT17-A090-28-10	90	11.09	27.70[1]	Inner Wall of Liner
2AT18-A090-28-07	90	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
2AT19-A270-28-07	270	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
2AT20-A270-29-03	270	3.43	26.50[2]	On Lid Filter
2AT21-A270-28-11	270	11.18	27.70[1]	Inner Wall of Drum
2AT22-A270-28-10	270	11.18	27.70[1]	Inner Wall of Liner
2AT23-A135-17-06	135	6.18	14.00[2]	Outer Wall of PC
2AT24-A315-17-06	315	6.18	14.00[2]	Outer Wall of PC

[1] Axial Location Measured from the Base of the Drum
[2] Axial Location Measured from the Base of the Containment Vessel
[3] This gage location not used for Test A
[4] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC
[5] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

TCs on POC in drum B in Test #2 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[3]	Axial Location (inches)[4]	TC Location Description
2AT25-B000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
2AT26-B000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
2AT27-B000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
2AT28-B000-29-00	0	0	26.50[2]	Top Center of PC Lid
2AT29-B180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
2AT30-B180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
2AT31-B180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
2AT32-B000-34-00	0	0	34.18[1]	Center Inner Wall of Drum Lid
2AT33-B000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
2AT34-B000-28-00	0	0	24.55[2]	Center of PC
2AT35-B000-19-00	0	0	16.00[2]	Center of PC
2AT36-B270-28-03	270	3.43	26.50[2]	On Lid Filter

[1] Axial Location Measured from the Base of the Drum

[2] Axial Location Measured from the Base of the Containment Vessel

[3] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

[4] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

TCs on POC in drum D in Test #2 of Phase I.

TC Designation	Radial Orientation (degree)	Radial Location (inches)[3]	Axial Location (inches)[4]	TC Location Description
1AT49-D000-28-11	0	11.18	27.70[1]	Inner Wall of Drum
1AT50-D000-28-10	0	11.09	27.70[1]	Inner Wall of Liner
1AT51-D000-28-07	0	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT52-D000-29-00	0	0	26.50[2]	Top Center of PC Lid
1AT53-D180-28-11	180	11.18	27.70[1]	Inner Wall of Drum
1AT54-D180-28-10	180	11.09	27.70[1]	Inner Wall of Liner
1AT55-D180-28-07	180	6.18	24.55[2]	Outer Wall of PC Below Flange Collar
1AT56-D000-34-00	0	0	34.18[1]	Center Inner Wall of Drum Lid
1AT57-D000-03-00	0	0	0[2]	Bottom Center Outer Wall of PC
1AT58-D000-28-00	0	0	24.55[2]	Center of PC
1AT59-D000-19-00	0	0	16.00[2]	Center of PC
1AT60-D270-29-03	270	3.43	26.50[2]	On Lid Filter

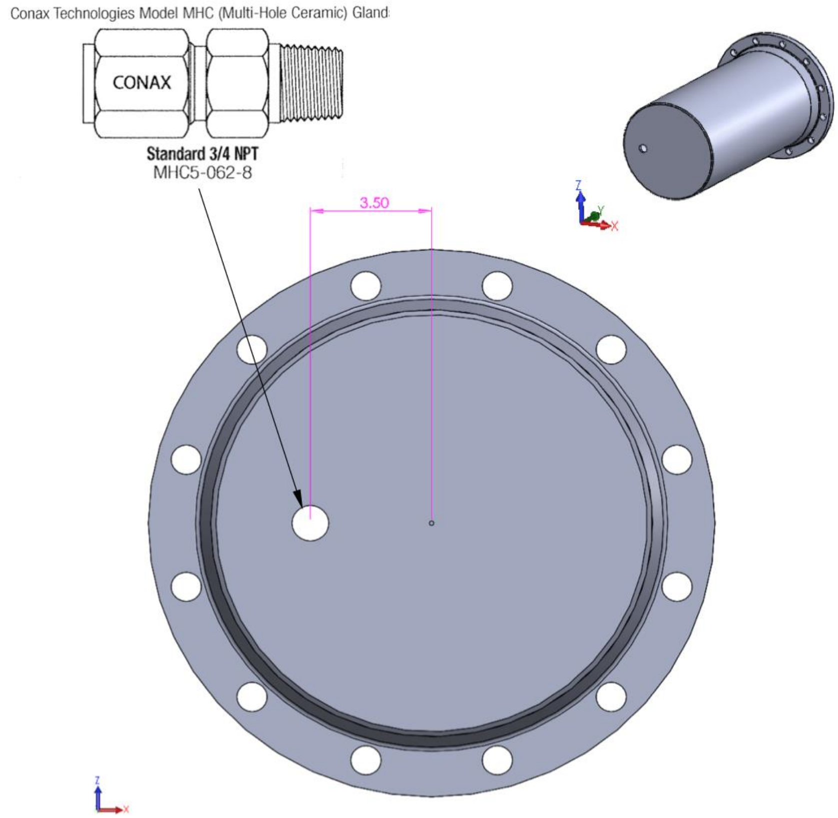
[1] Axial Location Measured from the Base of the Drum

[2] Axial Location Measured from the Base of the Containment Vessel

[3] The radial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

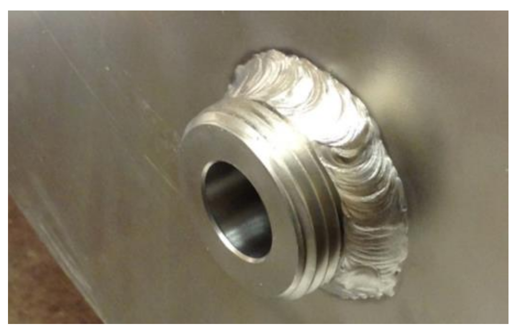
[4] The axial location tolerance is ±0.25 inches for all gauges mounted to a surface and ±0.5 inches for the gauges within the contents of the PC

APPENDIX B: MODIFICATIONS TO THE POC FOR INSTRUMENTATION IN PHASE I



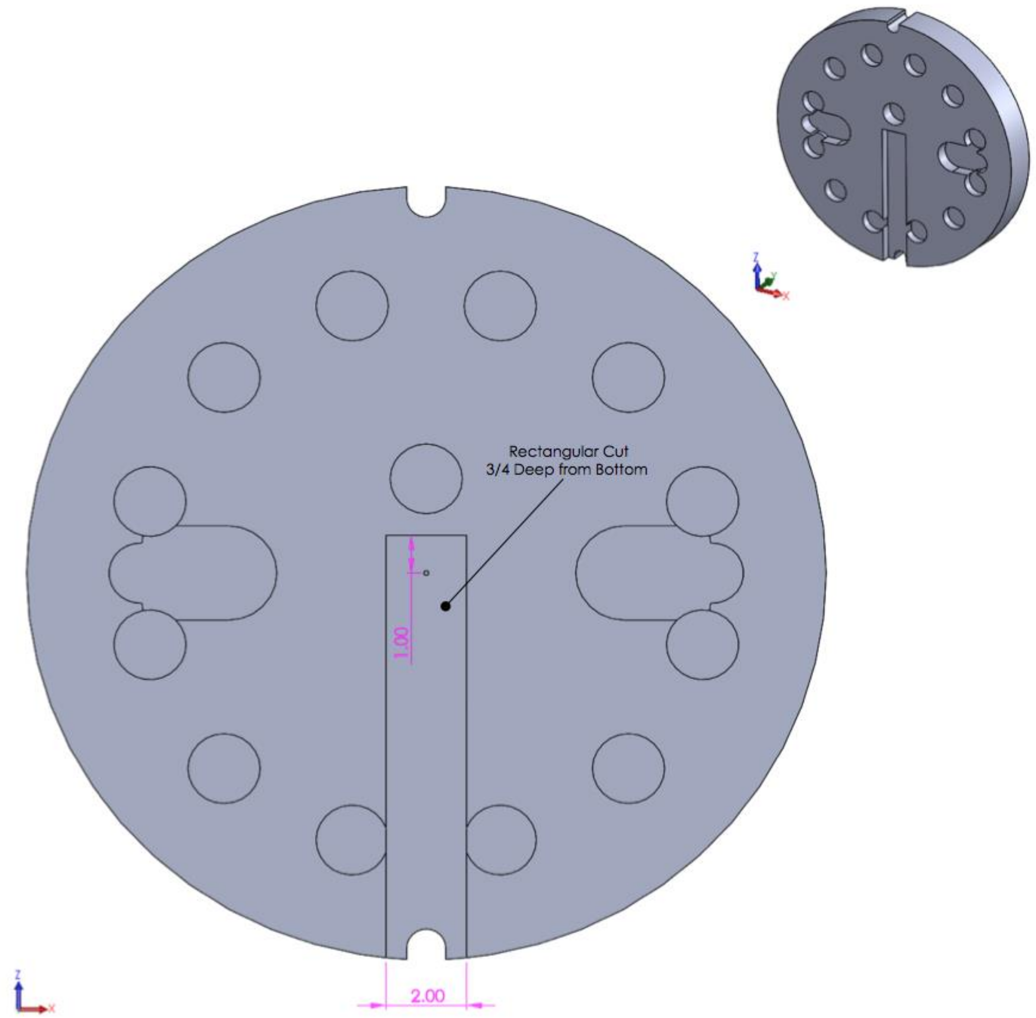
(a)

(b)

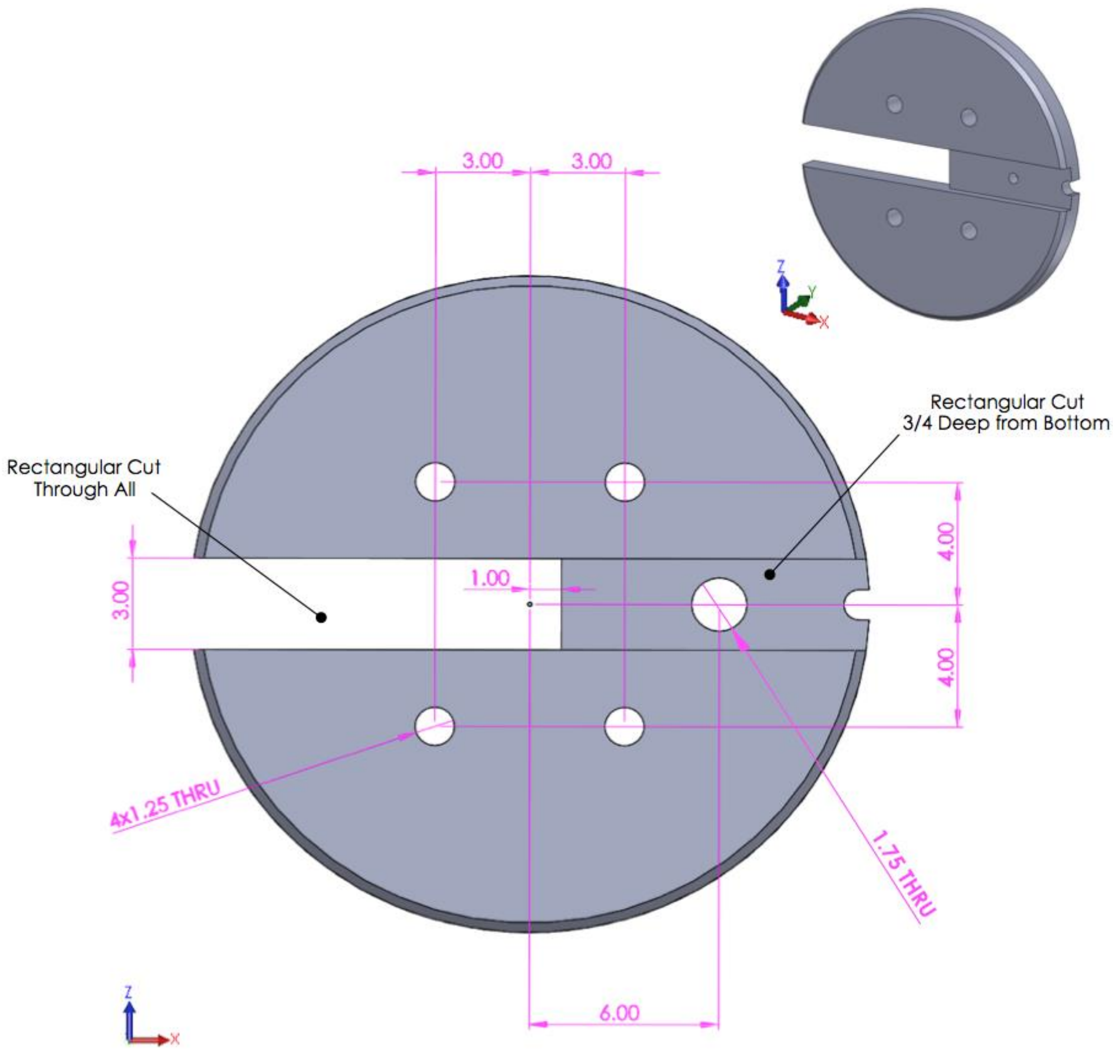


(c)

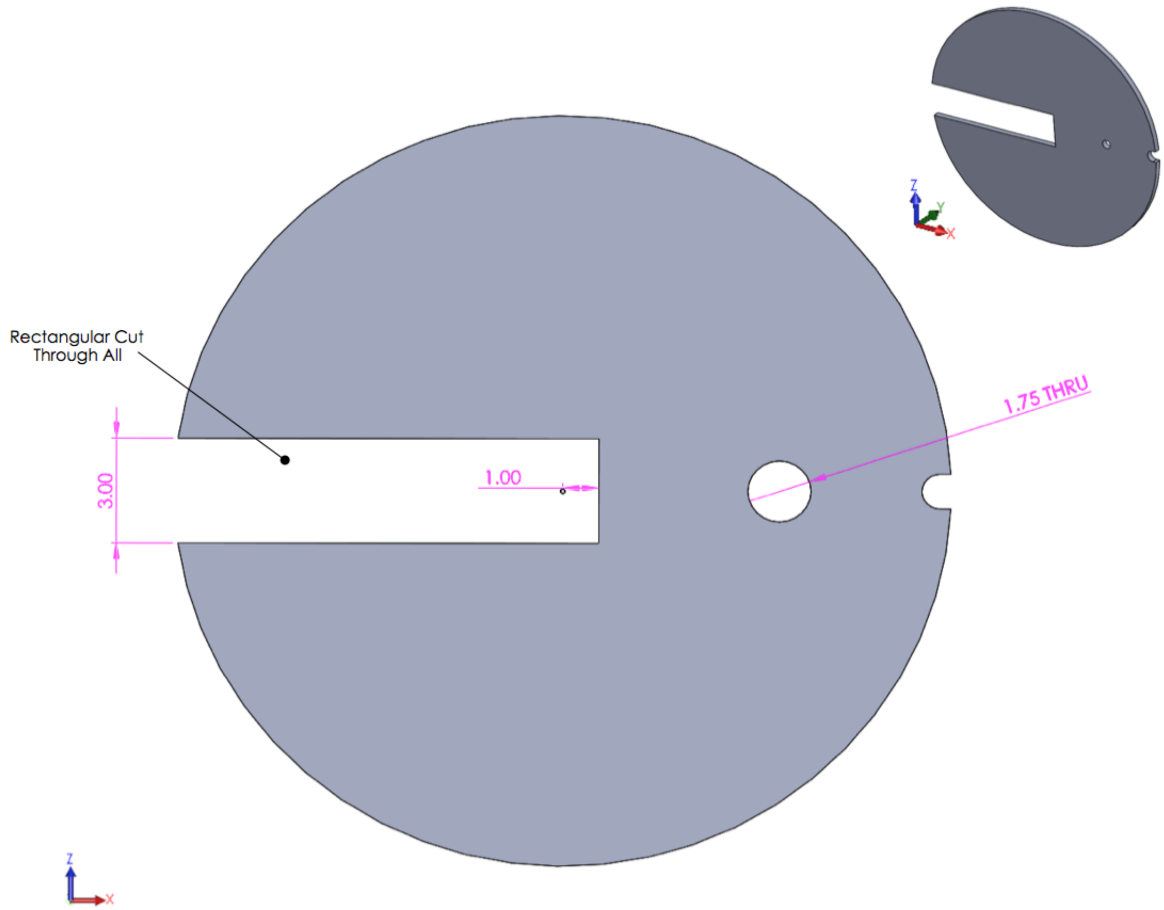
POC-DWG-0006-MOD: (a) One hole on the bottom of the PC at the locations shown. The hole is aligned with the seam on the –x axis. The hole has a Conax Multi-Hole Ceramic Gland seal as shown in the figure. The pipe thread side of the Conax feed-through goes through the hole and is welded outside of the PC. (b) View of Conax from the inside of the PC. (c) Conax pipe thread side welded to the outside of the bottom of the PC.



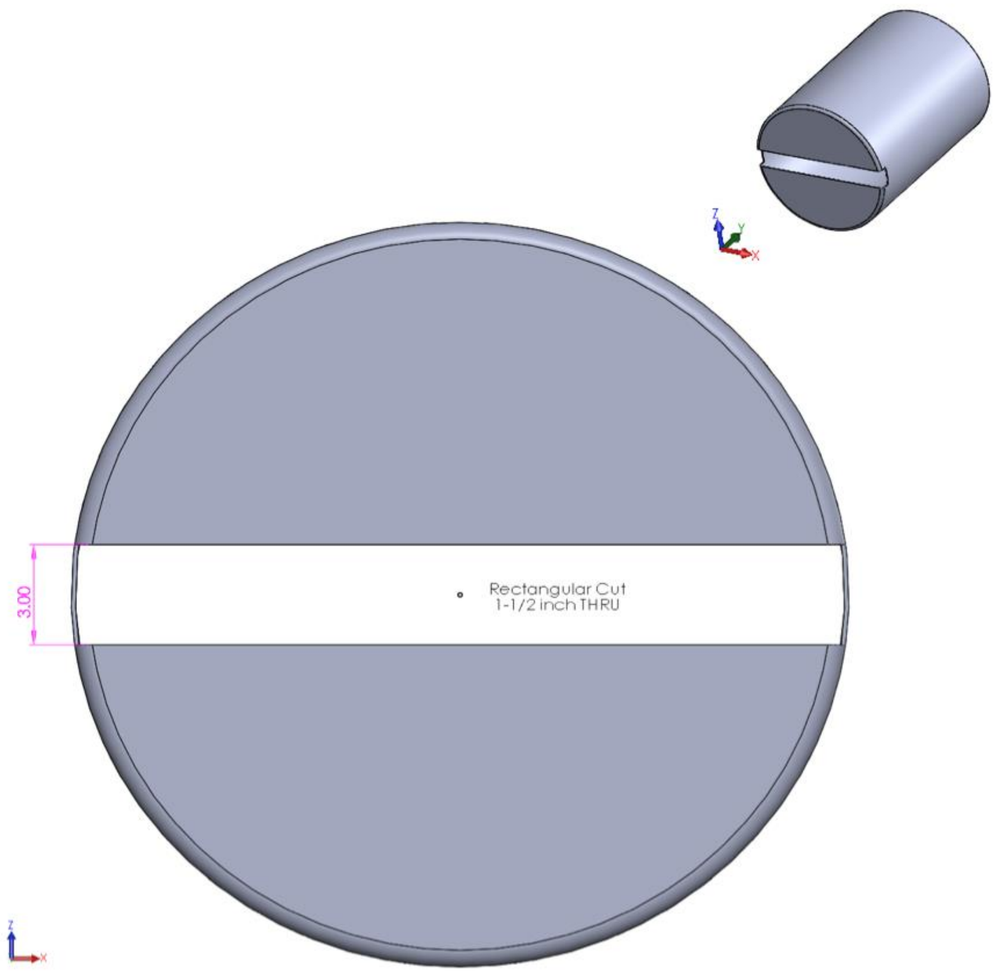
POC-DWG-0007-MOD, Part 2: One rectangular cut on the top fiberboard as shown. The cut is at the 270-degree axis with respect to the seam (0 degree or at +x axis.) The partial cut (3/4" deep) is on the bottom of the fiberboard.



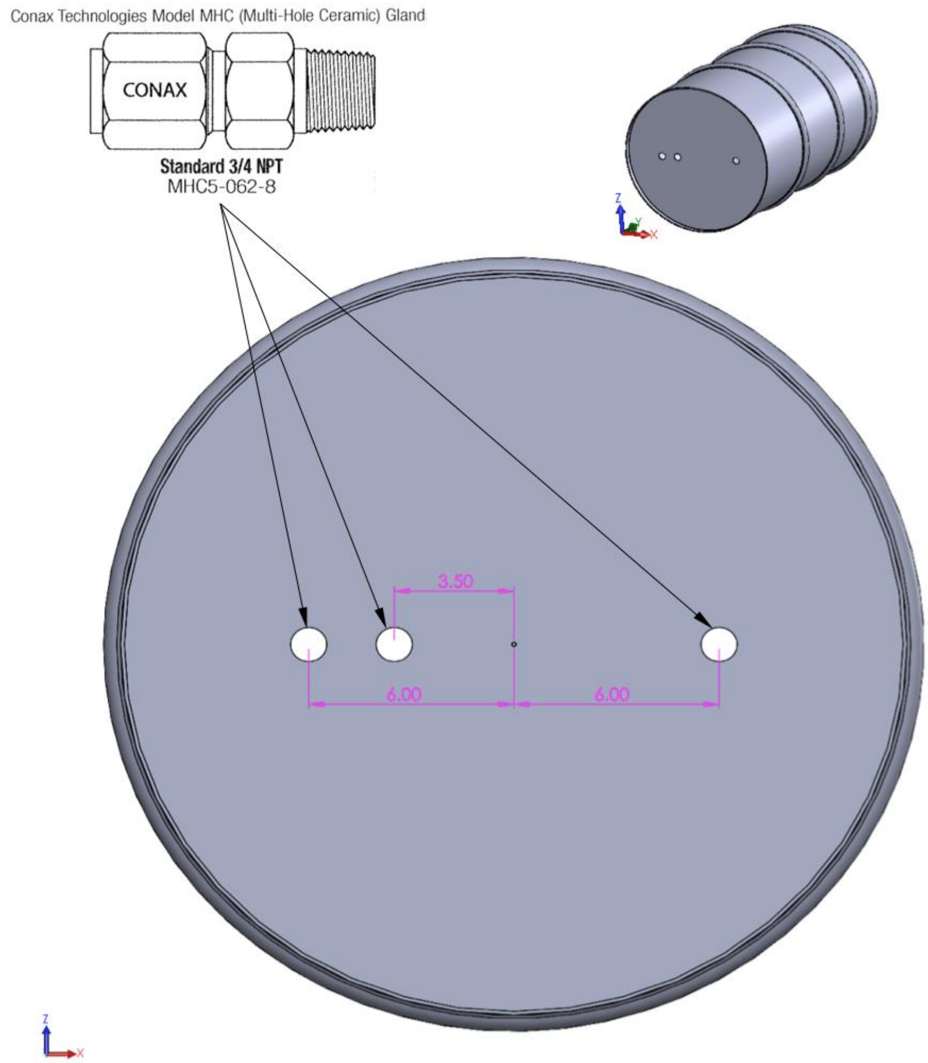
POC-DWG-0007-MOD, Part 7: Holes and rectangular cuts through bottom fiberboard. Each 1-1/4" hole is filled with a 1-1/4" DIA x 1-7/8" steel rod flush with the bottom of the fiberboard (opposite side, not shown). The 1-3/4" hole is for visual inspection of the TC cable leads. The partial rectangular cut (3/4" deep) is on the seam side (+x). The rectangular cut on the opposite side (-x) is through the entire fiberboard. This cut extends nominally 1" beyond the center of the fiberboard.



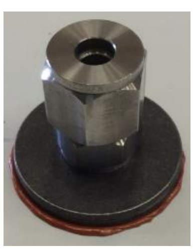
POC-DWG-0007-MOD, Part 8: Hole and rectangular cuts on the bottom plywood. The rectangular cut and the 1-3/4" hole are the same as in the fiberboard. This cut extends nominally 1" beyond the center of the fiberboard. As in the fiberboard, the hole is used for visual inspection of the TC cable leads.

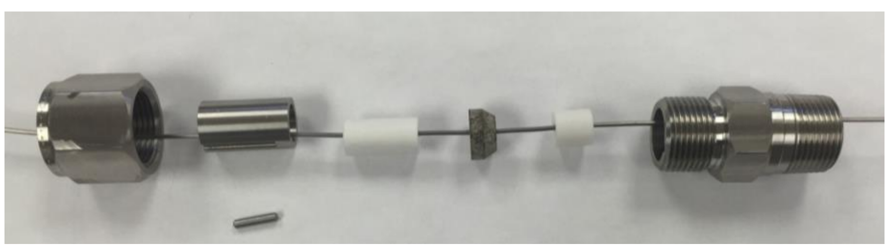


POC-DWG-0011-MOD: Rectangular cut 1-1/2" (nominal) deep through the bottom of the plastic liner.



(a)





(b) (c)

7A-DRUM-MOD: (a) Three 1-1/16" holes on the bottom of the drum aligned with the seam. The isolated hole is on the 0-degree side (+ x-axis). Each hole has a Conax Multi-Hole Ceramic gland seal. A conduit lock ring on the interior of the drum secures the Conax in place. (b) View of Conax from on the outside of the drum. (c) Assembly of Conax showing one TC wire passing through.

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