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Pipe Overpack Container Fire Testing: Phase I, II, & III

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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. 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 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 were done in three 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. The goal of the third phase was to see if surrogate aerosol gets released from the PC when the drum lid is off. This report will describe the various tests conducted in phase I, II, and III, 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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A series of fire tests was conducted on the Pipe Overpack Container (POC) to determine the amount of protection provided in various thermal environments. The table below summarizes the results from these tests.

Environment	**Damage Ratio (DR)**
Offset fire – heat flux less than 45 kW/m^2	0
Fully engulfing fire < 3 min (<17 gallons of fuel)	0
Fully engulfing fire with drum lid retained	0
Fully engulfing fire > 3 min, drum lid ejected	Varies, up to 1

A 3-minute fire is sufficient to cause the drum lid to be ejected if there are no mitigating measures taken. For a 30-minute fire with no post-fire active cooling, the temperature of the Pipe Container (PC) gets hot enough for combustible contents to decompose/vaporize, leading to a damage ratio of 1. This is because the Celotex® that is between the drum and the PC continues to burn after the pool fire ends. The testing did not determine if there was a length of fire longer than 3 minutes, but less than 30 minutes, that would not lead to continued combustion of the Celotex®.

For POCs outside of the fire, the post-test leak rate is not significantly changed from the pre-test leak rate. The measured values are on the order of $1x10^{-3}$ std-cm^3/sec. For a 1-hour engulfing fire without the drum lid (or if the drum lid is ejected), the post-test measured leak rate was 39 std-cm^3/sec. For a 1-hour engulfing fire where the drum lid stayed in place, the post-test measured leak rate was about 1 std-cm^3/sec through the filter gasket and there was no change in the leak rate through the flange O-ring. The results from the leak rate tests are not significantly different from those reported by Ammerman et al. in SAND97-0368, so for POCs without combustible contents, the DR and Aerosol Release Fraction (ARF) provided in DOE-STD-5506-2007 are still valid.

A 30-minute fire test was conducted to determine if there could be release of nuclear waste aerosol from a fully engulfed POC after the lid gets ejected from the drum. Results from this test showed that indeed aerosol could be released from the POC; however, the exact value for the ARF is not given here because this test was only designed to sample aerosol in materials released from inside the PC during the test, and not to collect all aerosol released from the PC.

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 [1] and are also available in DOE STD-5506-2007 [2].

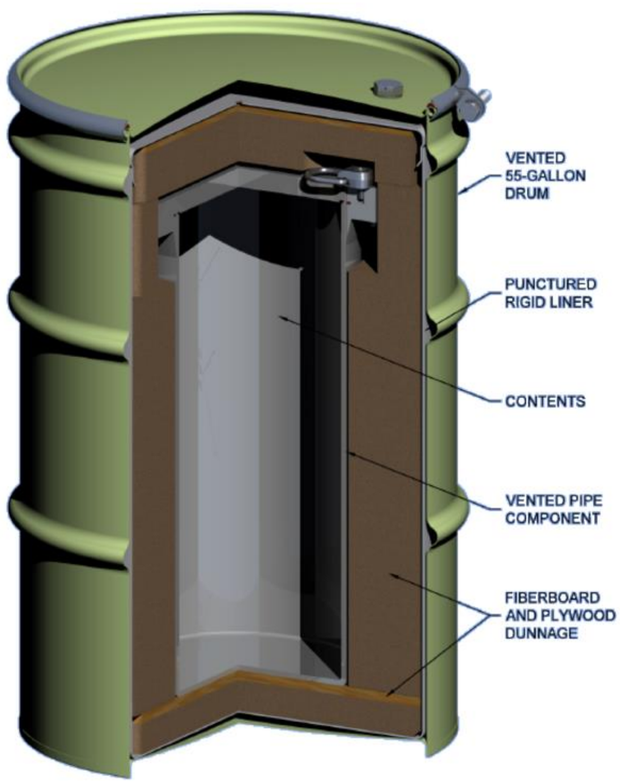


Figure 1. POC Assembly

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 July 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.

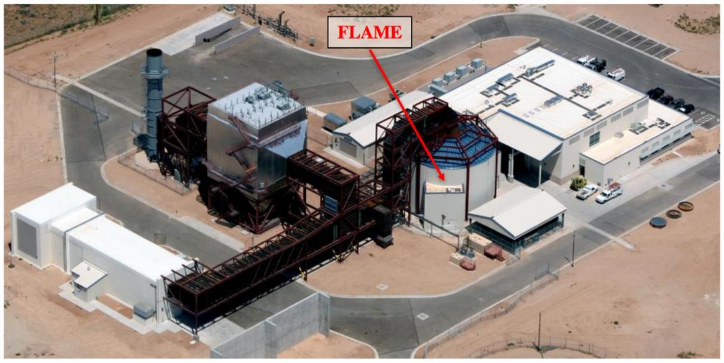
2. OVERVIEW OF FIRE TEST SETUP

The primary goal of the 2015 and 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 or at various distances from the edge of the 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 initially with combustibles, but it was not known if the fire would cause over-pressurization of the PC and subsequent violent failure, jeopardizing the test facilities and/or the aerosol collection system. 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. One test was conducted in an outdoor facility to study the possibility for PC failure and/or the release of aerosol from the PC.

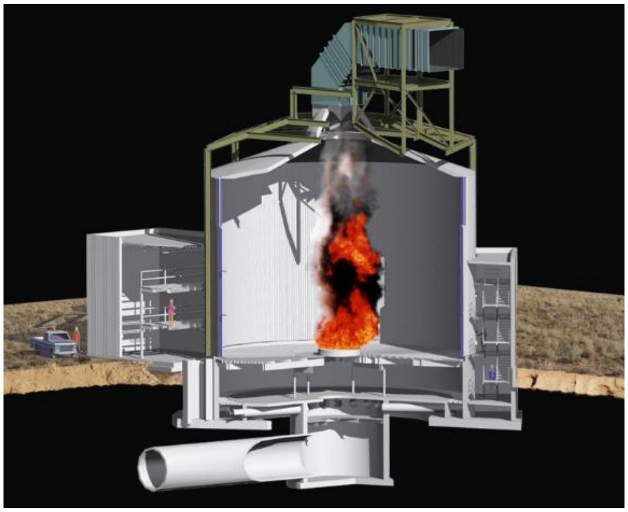
Test Facility

In all, five tests were performed at SNL between October of 2015 and July of 2016. The first four 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 the first four tests, a 3m 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 fifth test was conducted at Sandia's outdoor burn site facility; see Figure 2(c). The fire test cells at the burn site usually have a circular or rectangular fuel pool. Circular pools are typically between 3 to 8m in diameter. The largest pool is rectangular and is approximately 9x18m. For this test, a 4m fuel pool was used. Wind data has been collected over the years at the site to determine the best time to conduct quiescent fuel pool fires. Calm wind conditions (less than 1m/s) that guarantee a vertical fire plume covering a test article typically occur in the early morning, shortly before sunrise. However, experience has shown that even during this time wind conditions are unpredictable, changing in a matter of minutes from less than 1m/s to upwards of 4m/s. To guarantee test articles are fully engulfed during the entire test time, fuel pools are typically enclosed inside steel chain link fences, as observed in Figure 2(c). Insulation and/or other porous materials are placed on the fence to control wind flow into the test cell. The extension of these fences around the perimeter of the pool and the height of the fences varies with the size of the pool and the test article.



(a)



(b)

(c)

Figure 2. (a) Location of FLAME within the TTC, (b) interior of the FLAME facility. and (c) Sandia's outdoor burn facility.

General Test Layout

Figure 3 shows the typical test layout inside the FLAME facility for the first four tests. The 3-m circular pool shown at the center of the facility was initially filled with Jet-A fuel in all tests. Jet-A fuel fires behave similar to a diesel fire. Little difference in heat flux to objects inside and outside of the fire are expected between these two fuel fires. A remote refueling system added fuel to the pool in discrete amounts during tests to keep the fire going. 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. The 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 in 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 a third drum stacked above the POC drum or adjacent stacked POC drums) exposes the POC drum to higher thermal loads than would be experienced in the typical drum-array storage arrangement, where the energy released from the fire would be shared with additional drums.

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

In all indoor 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 used to block the flames and to partially insulate the top POC, as it 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 heat fluxes in a typical storage fire should there be a fuel pool accumulated at the base of the bottom drum. One additional drum stacked above this top drum would shield this drum from the top flames.

Figure 4. Drums in a typical storage configuration at LANL

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 is limited at this height. 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 deeper into the plume, creating hotter regions inside 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 outer surface 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 [3]. Further up in the fire, at some distance above the top POC drum, flame necking progressively exposes the interior of the fire to the cool environment. For larger diameter fires than used in these tests, the height of the dome region and necking width of the fire is larger. However, if the fuel amount is the same but spread over a larger area, the fire lasts a shorter amount of time. The key factor is the heat flux to the top POC drum, which in these indoor tests was believed to be conservative (80-100kW/m^2 to an object at the center of the fire for 30 to 60 minutes depending on the test).

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.

Figure 5 shows the test layout for the outdoor fire test. The 4.2-m circular pool was initially filled with Jet-A fuel. As in previous tests, a POC rested on a table with an empty 55-gallon drum placed underneath it. The table is the same one used in the indoor tests. The bottom of the POC was 1-m above the top of the fuel surface. The drum lid of the POC and all POC components above the PC lid were removed since they were assumed already ejected from the

POC. The drum lid and these components were ejected around 3 minutes in the fire when the POC was at the center of the fire in the indoor test. As shown in this Figure 5, an aerosol collection system was placed over the top of the drum, and consisted of an T-shape pipe system with the bottom of the vertical pipe covering the PC vent. The system was designed to collect material released through the PC vent. Samples of released material were analyzed for the presence of surrogate aerosol material. Details of the aerosol collection system are provided in the next section.

Figure 5. Outdoor fire test cell with the POC drum.

A polygonal-shaped fence was erected around the perimeter of the pool. The top of the fence extended 4 inches over the top of the POC drum. Insulation covered the fence on the pool-side. CFD-Fire simulations showed this fence height with insulation material was sufficient to guarantee the POC drum is fully engulfed when sitting on top of table. Each side of the fence had a separate thin-wall panel extending about a foot above the fuel pool (not clearly visible in this image) that swung open from the top with the aid of remotely controlled hydraulics. These panels allowed air flow to entrain naturally inside the test cell. Air flow is required to maintain the fire. The use of wind fences results in higher flame temperatures because the insulation covering the chain-link fence partially blocks the heat release that normally occurs from the sooty fire plume to the cooler environment surrounding the plume in the open fire configuration.

3. SUMMARY OF FIRE TESTS

For technical/historical reasons and for discussion herein, the five tests were conducted in three separate phases. Table 1 shows a breakdown of each test 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
3	1	A	POC	N	Standard/Combustibles	0	~80	Y

The first two tests were conducted in Phase I, the middle two were conducted in Phase II, and last test was conducted in Phase III. Phase I focused primarily on determining the thermal response of the PCs, while Phase II, with no instrumentation on the PC, focused on the performance of the drum lid and drum filter. Finally, Phase III focused on collecting and analyzing materials released from a PC loaded with typical combustibles. 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. The 80kW/m^2 at the center of the fire is an average value over the duration of the fire. Peak heat fluxes at the center are closer to 100kW/m^2.

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 PC 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.

In Phase III, typical combustibles were added to the PC, and material released from the PC was sampled and chemically analyzed for the presence of surrogate CeO_2 aerosol. Phase III was conducted using NQA-1 processes to collect PC temperatures and internal pressures. Based on Phase I and II test results, it was expected that the PC would reach high enough temperatures to decompose the combustibles inside it. Prior to the test, during the planning phase, it was estimated that at 900°C—close to the measured temperature of the top of the PC lid in previous tests—the pressure inside the PC would be ten times higher than at room temperature if the PC filter vent was completely blocked by condensing gases. Since at this temperature, stainless-steel yield strength is significantly diminished, there was a possibility the PC vessel would rupture. To protect the FLAME facility, it was decided that the test would be performed at SNL's outdoor burn facility.

Details of Phase I Tests

As noted in Table 1, two fire tests were conducted in the first phase, each lasting 60 minutes. Figure 6 and Figure 7 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 8).

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.

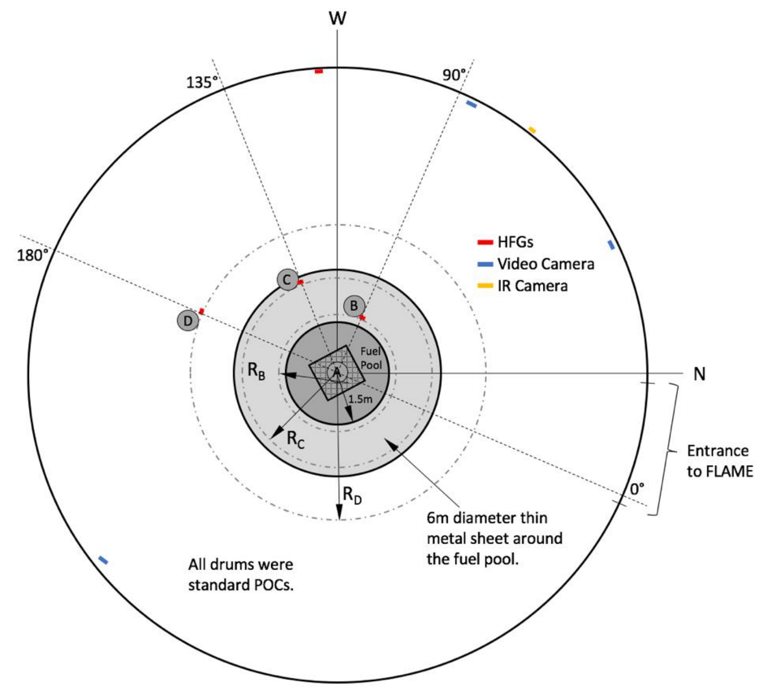


Figure 6. Test layout for Test #1 in Phase I.

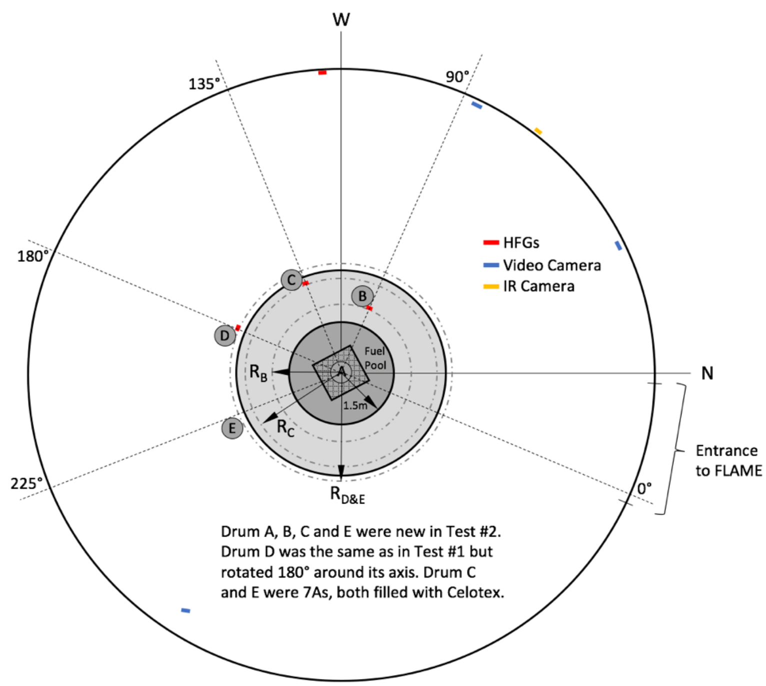


Figure 7. Test layout for Test #2 in Phase I.

Figure 8. Drums outside the fire filled with chipped Celotex®.

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.

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, [4]. 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 [5]. 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 9, 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 9. 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.

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 9. 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 6 and Figure 7, 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 10.) 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.

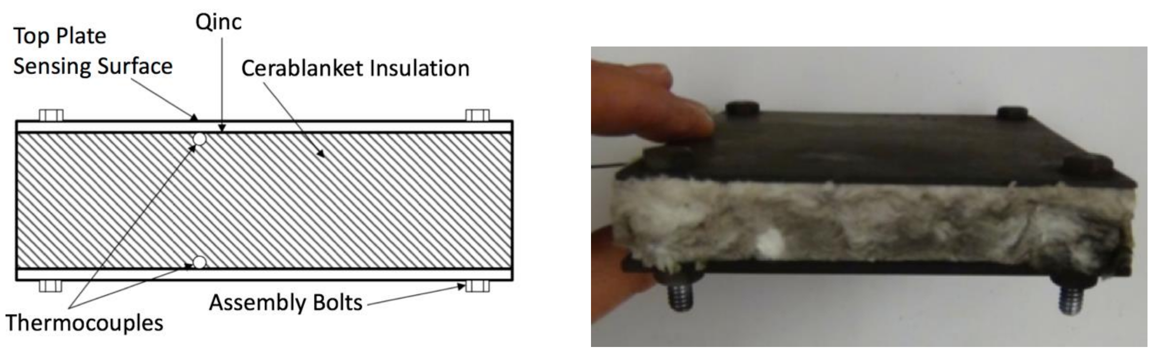


Figure 10. Heat Flux Gauge (HFG) used in POC and 7A fire tests.

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 11 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 11. 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 [6].

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 12. 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 13, 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 12. Gap that remains in the drum ring after torqueing to 60 ft-lb. Image taken from the first test in

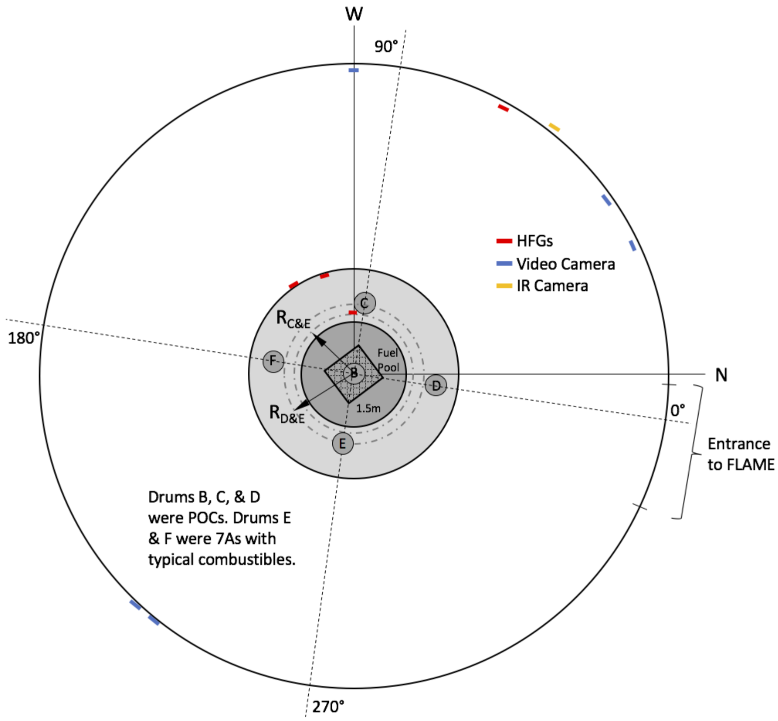


Figure 13. Test layout for Test #2 in Phase II.

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 14). 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 14. 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 13.) 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.

Details of Phase III Test

The goal of Phase III was to determine if the surrogate aerosol (CeO_2) is released from the PC after the drum lid gets ejected from a fully-engulfed POC. Therefore, typical combustibles were added to the PC. A secondary goal was to measure the pressure inside the PC during the test. Since in Phase II the drum lid, the top plastic liner, plywood and Celotex® components of the POC were ejected in all drums inside the fire early in the tests (i.e., less than 3 minutes into the test), these components were not included in this test.

Table 2 shows the combustibles and their corresponding masses placed inside the PC for this test. CeO_2 powder acts as a surrogate material for the plutonium in the waste. The quantity of CeO_2 powder is close to the maximum allowable inside a PC. The size of the CeO_2 particles was between 0.6 and 1micron. An inventory of typical materials placed inside the PC was obtained from TA-55 nuclear-waste processing facilities in LANL and from this list a representative combustible material load was determined. By far most of the combustibles in this list were plastic and cellulose materials. The mass of the plastics and cellulose material in this table is based on an average mass over a number of PC load configurations. The source of the plastic material used for this test was the plastic bag-out bags that hold the waste material inside the PC. These bags were provided by TA-55 personnel. Kimwipes® and cheesecloths, the source of most of the cellulose material, and Fantastik® (or similar all-purpose cleaners) are used to wipe clean surfaces where nuclear waste material is processed and contain particle traces of radioactive contaminants, represented here by CeO_2 powder. The wiping materials are dried afterwards for an extended period to release excess moisture from the Fantastik® in the wiping materials before they are placed inside a bag-out bag, which then goes inside the PC. The bag-out bag is inspected for the presence of moisture before loading. At LANL, the entire process described above is done under vacuum conditions to prevent release of aerosol waste outside the waste processing area.

Table 2. Mass of combustibles inside the PC in the Phase III test

PC Combustibles	Mass (kg)
CeO2 Powder	0.178
Kimwipes® (Kimberly Clark Wipeall Model L40)	1.60
LANL Bag-14-PVC (bag-out)	0.68
LANL-Bag-3-SPVC	1.94
Fantastik® Cleaner	1.52
Total Mass	5.92

The amount of CeO_2 and Fantastik® shown in this table is higher than what is typically found inside a PC. Therefore, the combustible inventory was deemed conservative from the standpoint of maximizing release of CeO_2 during the test. That is, at elevated temperatures a larger amount of liquid inside the PC generates higher pressure due to the added moles of evaporated liquid in the gas. Higher pressure is expected to lead to more release of CeO_2 material from inside the PC when the carbon-media filter fails. Note however that the release of aerosol from the PC is not only dependent on the moisture content inside the PC but also on other factors such as the types of materials present inside the PC, how these materials decompose, and resulting size of particles generated from decomposing material, how these particles interact with already present CeO_2 aerosol, etc.

The procedure for loading the combustibles inside the PC was as follows:

1. Individual mass components were first weighed.
2. Ten Kimwipes® were sprayed with sufficient Fantastik® over a table (The wipes were damp but not dripping.)
3. A generous amount of CeO_2 powder was sprinkled over the top of the Kimwipe®. Each Kimwipes® was folded carefully to keep the powder from falling.

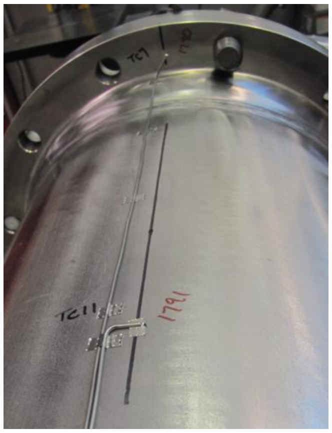
4. The ten Kimwipes® were placed into the bag-out bag (the standard bag used to hold waste content inside a PC).
5. One layer of plastic (cut from bag) is placed over the 10 Kimwipes®.
6. Steps 2 through 5 are repeated until all the Kimwipes® are used.
7. Any excess CeO_2 was sprinkled over the top of the contents inside the bag-out bag.
8. The bag-out bag was then closed (some excess air was let out slowly) and weighed.
9. The bag-out bag with the combustibles was placed inside the PC and pushed gently all the way to the bottom of the PC vessel.
10. The PC lid was placed over the PC vessel, and the PC was closed using appropriate torqueing procedures.

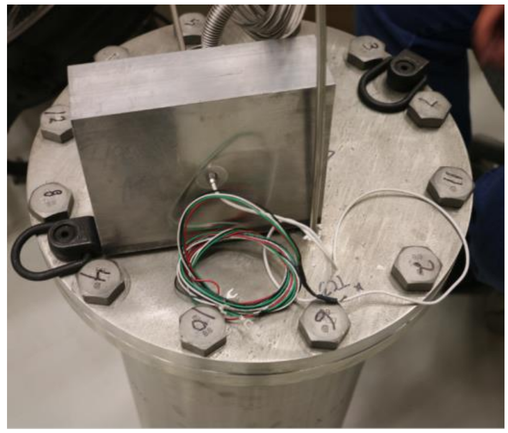
The prescribed amount CeO_2 powder was placed inside a hand-held spice dispenser initially. The dispenser was weighed before and after the powder was added, and after the sprinkle procedure, when the dispenser was visibly empty. Very little difference was detected between the initial bottle mass and the final mass after all the powder was sprinkled over the contents of the bag-out bag. During the sprinkle step, some agglomeration of the powder was observed inside the dispenser. No attempt was made to measure the size of these agglomerated particles once on top of the Kimwipes®. Figure 15 shows the combustibles and the PC with the contents inside.

(a) (b)

Figure 15. (a) Combustibles and (b) PC with combustibles (Phase III, Test 1).

Figure 16(a) shows two TCs attached to the PC in Phase III: one beneath the flange and the other at the vertical center of the vessel. The procedure used to attach TCs to the PC in Phase I was used in this test. For this test, the TCs were mounted only on the outside surface of the PC. The TCs were the same type used in previous tests. The exact locations of the TCs on the outer surface of the PC are shown in Appendix C. TCs were also installed on the wall of the Celotex® insulation and on the outside of the POC drum, as shown in Appendix C. To measure pressure, a 1/8” through-hole had to be drilled on the PC lid (Appendix D shows the location of the hole on the PC lid). A tube was inserted through this hole and welded to the top of the PC. The other end of the tube was attached to one side of a rectangular-aluminum-block via a threaded hole and connector. A pressure gauge was in turn attached to the other end of this block to sense the pressure in the tube line (see Figure 16(b)). The aluminum block was used to reduce the temperature rise of the pressure gauge during the fire, which prevents bias in the pressure reading. The pressure gauge was calibrated before the test by SNL’s standard measurements laboratory. Figure 16(b) and (c) shows the diagnostic system used to verify the pressure readings before the test.


(a)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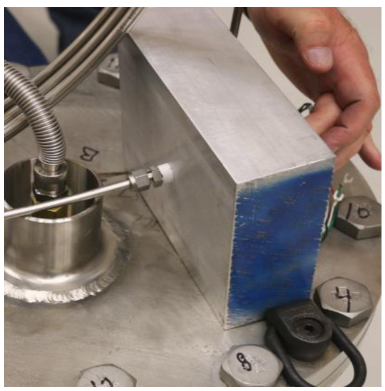
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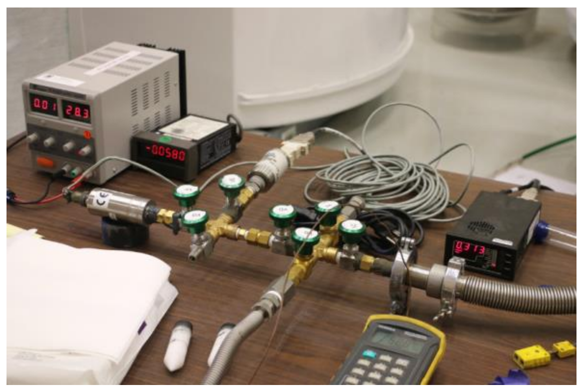

(d)

Figure 16. (a) TCs on the PC vessel, (b) pressure gauge attached to the aluminum block and the pressure tube welded to the PC lid, (c) flexible metal hose threaded to the PC vent port and used to pressurize the PC and pressure tube attached to the other side of the aluminum block, and (d) system used to verify a correct pressure reading.

As in Phase I tests, modifications were made to POC components to route TCs from the surface of the PC and the Celotex® down through the bottom of the POC. Modifications to the POC are shown in Appendix D. The TC lines were then routed through a hole on the side of the bottom drum and then through a pipe that led to the underside of the fuel pool. The top of the pipe was above the fuel line. Once below the fuel pan, the TC lines were routed directly to MIDAS. TCs were checked once the entire TC circuits were attached to the MIDAS patch panel. Insulation was wrapped around the TC lines starting from the outer surface of the bottom of the POC drum all the way to just outside of MIDAS, which was over a hundred feet away and mostly shaded by a concrete bunker. Because the top plastic liner and Celotex® components were not included, no POC modifications were required to route the pressure tube to the aluminum block. The tube line was routed from the top of the POC, around the fence, to the bottom of pool with no insulation wrapped around it to keep the line hot and prevent moisture from condensing in the line.

Figure 23 is a CAD rendition of the POC drum inside the fuel pool test cell used at SNL's outdoor burn site with the front-access fenced door hidden (left) and the chain-linked fenced hidden (right). This entire test cell fixture sat inside the 9x18m rectangular pool in the burn site. Note below the sides of the polygon fence the thin-wall panels. Recall these panels opened and closed with the aid of remotely control hydraulics to allow a controlled amount of air flow into the fire test cell. A pipe was routed beneath the fuel pool to add fuel to the pool with the use of a remotely-controlled fuel pump sitting outside the test area.

A differential pressure gauge was installed in the pool to monitor the fuel level during the fire

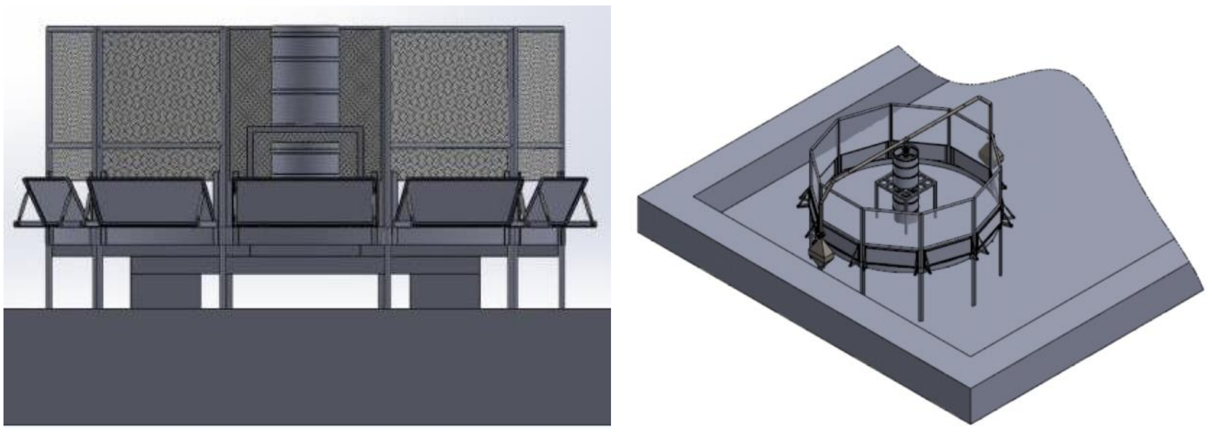


Figure 17. Side view of the fire test cell. The front door used for access to the interior of the pool is not shown.

and to control when the fuel pump was turned on and off to add more fuel to the pool, as desired. A second pipe with a remotely controlled valve fitting was welded to the bottom of the pool on one end of the pipe and connected to a large tank at the other to dump all the fuel remaining inside the fuel pan at the end of fire test. The tank rested on the floor of the rectangular pool. The pipes and the tank are not shown in this figure. These systems of refueling and dumping fuel were necessary because the evaporation rate of the fuel varies significantly with environmental condition, making it difficult to predict the amount of fuel needed to burn for the required amount of fire time, which was 30 minutes in this test. With this system in place, the fire duration can be controlled to ±3-minutes. Figure 18 shows the tank below the fuel pool and the underside of the fuel pool. The pipe systems are visible underneath the pool.

(a) (b)

Figure 18. (a) Fuel collection tank and (b) pipe systems below the fuel pan

Figure 19 shows a detail CAD rendition of the aerosol collection system. The fence details have been omitted on the front side to view the location of the drums with respect to the aerosol collection system. Although the right side of the system is not shown completely, it is identical to the left, including the filter housing (i.e., the pipe system is symmetrical about the center cross section of the vertical pipe.) Note also that POC components are not shown inside the top POC 55-gallon drum.

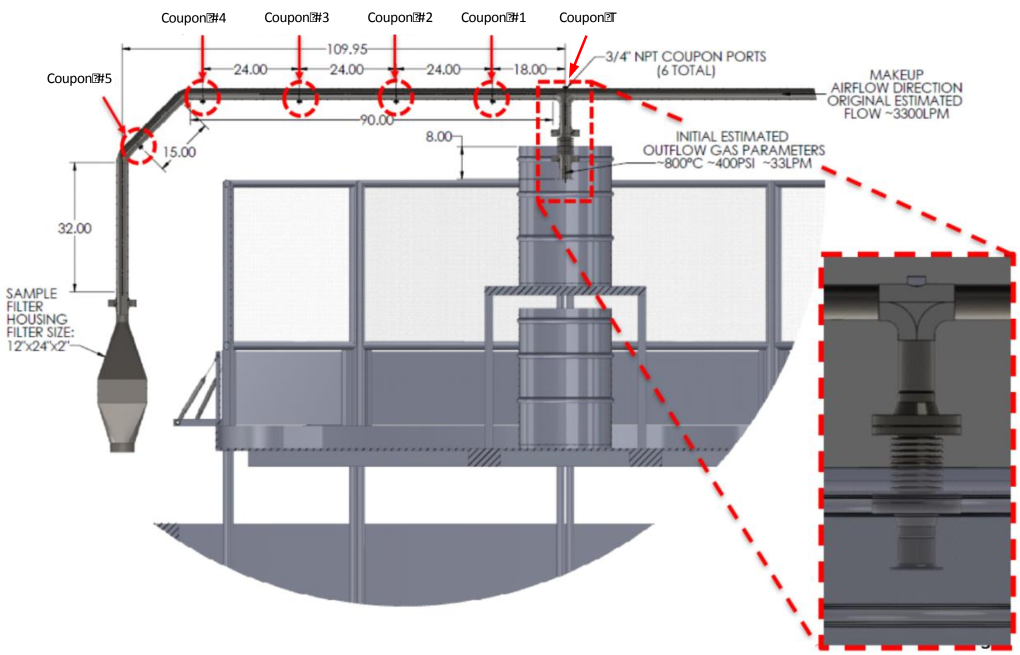


Figure 19. Aerosol collection system

This system was designed to collect surrogate aerosol material released exclusively from the PC filter. Tests conducted at room temperature showed gas flow through the O-ring of the PC was 20x less than the flow through the PC vent; therefore, the aerosol collection system was designed to collect only material released from the PC filter. The system consists of a section of vertical pipe connected at the lower end to the lid of the PC and at the other end to a horizontal section of pipe via a T-junction. The lower flange shown in the enlarged view on the lower right hand of the figure was welded to the top of the PC lid, concentric with the PC filter. As noted in this enlarged section, a bellows flange bolted to the lower flange was added to the vertical section of pipe to allow the PC lid to flex upward without lifting the rest of the pipe system in the case where the internal PC pressure was sufficient to deform the PC lid and the bolts securing the lid to the PC vessel. In all, six witness coupons (1-inch stainless steel pipe plug, Swagelok Co.) were screwed to the horizontal section of the pipe system, starting from the top of the T-junction, to collect samples of material deposited on the horizontal pipe walls. In Figure 19, coupons #2 through #5 were spaced approximately 24” apart, while coupons T and #1 were spaced at 18”. The witness coupons determined if deposition in the pipe occurred due to particle impaction and interception. Identical HEPA filters were placed horizontally at both ends of the pipe and inside the housing shown in this figure: on the left side to collect material released from the POC, and on the right side to clean dust debris from the inlet air. The HEPA filter was a 12” x 20” x 2” Koch filter (Model 102-700-009 MERV 13).

The entire aerosol collection system, including the filter housings, was insulated from the fire to keep the pipe temperature low. A small area around the flange welded to the drum was the only portion of the aerosol collection system that was not insulated, as shown in Figure 20. This was done to keep the PC lid and flange hot. The filter housings were placed outside of the insulated fenced area and close to the pool surface to keep flame radiation to the housing to a minimum.

(a) (b)

Figure 20. POC on the table at the center of the fuel pool and top of the PC lid with aerosol collection system welded covering the PC vent. Note that the top components have been removed from the POC.

Environment air was routed through the horizontal section of the pipe (from right to left) to create a venturi effect that would suction floating material from the vertical pipe out to the left side of the horizontal pipe. Air was also necessary to cool the hot gases and the aerosol released from the PC. It was estimated that at least 3300LPM of air were required to keep the gases cool enough to prevent the HEPA filter from burning. Initially one fan was attached to the outlet of the right housing to suction gases and aerosol material inside the pipe system. However, a mock test designed to test the refueling and aerosol systems showed that the one-fan air flow rate was insufficient to keep the gases sufficiently cool due to pressure loses. To remedy pressure losses, one additional fan was added to the inlet housing (the right side). The speed of this fan was set below the outlet fan to prevent the outlet HEPA filters from getting blown during the test.

In addition to the video taken during the test, an X-ray system was deployed to look at the top of the PC in-situ, in the flange region, to see if there was any deformation of the PC lid or the bolts during the test and/or to see if the aerosol collection system was compromised near the PC lid during the test. The X-ray was able to see details of the PC flange clearly, but it was not possible to see the combustibles inside the PC as clearly due to the low density of these materials and the viewing area. Figure 21 shows an image of the setup looking into the entrance to the test cell (taken from the west end of the burn site facility). The trailer to the right provided a secure area to store the X-ray generation equipment, preventing damage from the flames. The trailer was placed on top of large concrete blocks to raise the X-ray machine sufficiently high to see the top of the PC. The charge-coupled device (CCD) used for detecting the X-rays was located to the left of the test cell, between a large concrete wall and the test cell fence (not visible in this image). The concrete wall was required to attenuate X-rays passing beyond the CCD.

Figure 21. Fuel pool with X-ray trailer adjacent to the pool.

4. TEST RESULTS

Table 3 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 3. Summary of Test Results

Phase/ Test #	Drum Label	Drum Lid Ejected	Drum Filter/Seal	PC Filter/O-ring	POC Mass Loss (%)
1/1	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
1/2	A	No	Rupture/ Damaged	Intact/ Intact	17
	B	No	Rupture/ Damaged	Intact/ Intact	2
	D	No	No Rupture /Damage	Intact/ Intact	>1
2/1	A	Yes	Rupture/ Damaged	Rupture/Damaged	30
2/2	B	Yes	Rupture/ Damaged	Rupture/Damaged	30
	C	No	Rupture/ Damaged	Intact/ Intact	2
	D	No	Rupture/ Damaged	Intact/ Intact	1
3/1	A	NA	NA	Rupture/Damaged	>30

Looking at Table 3, two outcomes are clear from Phase I and II tests: (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 (≤1.73 m or at distances with equivalent heat fluxes ≥ 55kW/m^2), it is not inconceivable that continued fire exposure beyond the 30-minute tested, exposure to a larger diameter fire for the same duration, or exposure to the same fire with an alternate configuration (e.g., reradiating walls in close proximity to the drum) could result in the POC drum lids getting ruptured. However, additional data presented for Phase I and II 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 [2] 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.

In Phase III, the POC mass loss was greater than any of the fully engulfed drums in Phase II because the starting drum configuration in Phase III was a drum without the drum lid and other components on top of the PC, as previously mentioned. More importantly, posttest examination of the PC showed significant degradation of combustibles inside the PC. From visual inspection, it is estimated that about 80 to 90% of the combustible material was affected by the high temperatures inside the PC (i.e., DR~1 conservatively). Moreover, chemical analysis of samples taken from coupons and the HEPA filter in the aerosol collection system showed traces of CeO_2 surrogate aerosol, indicating the release of aerosol (i.e., ARF ≠ 0). Because the aerosol collection system was only designed to sample material released from the PC, it was not possible to determine the approximate ARF. Before this test, it was not known if the PC would over-pressurize due to condensed material clogging the PC filter and rupture. Estimates of pressures inside the PC based on the expected high temperatures (from Phase I tests) showed the latter possibility could not be discounted. For this reason, it was deemed risky and expensive to deploy an expensive aerosol system to capture all of the aerosol released given that there was no guarantee the aerosol collection system would survive.

Additional results will be described in the following sections using posttest observations, and recorded temperature and pressure data. Temperature data is limited to measurements obtained from Phase I and Phase III tests, and the pressure data to measurements obtained in Phase III. Data will be presented separately for each test. Discussion of results and other relevant data (e.g., heat flux measurements, mass loss as a function of temperature for combustibles inside the PC, etc.) 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 22 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. Radial distances from the center of the fire to each POC outside of the fire were given in Figure 7.

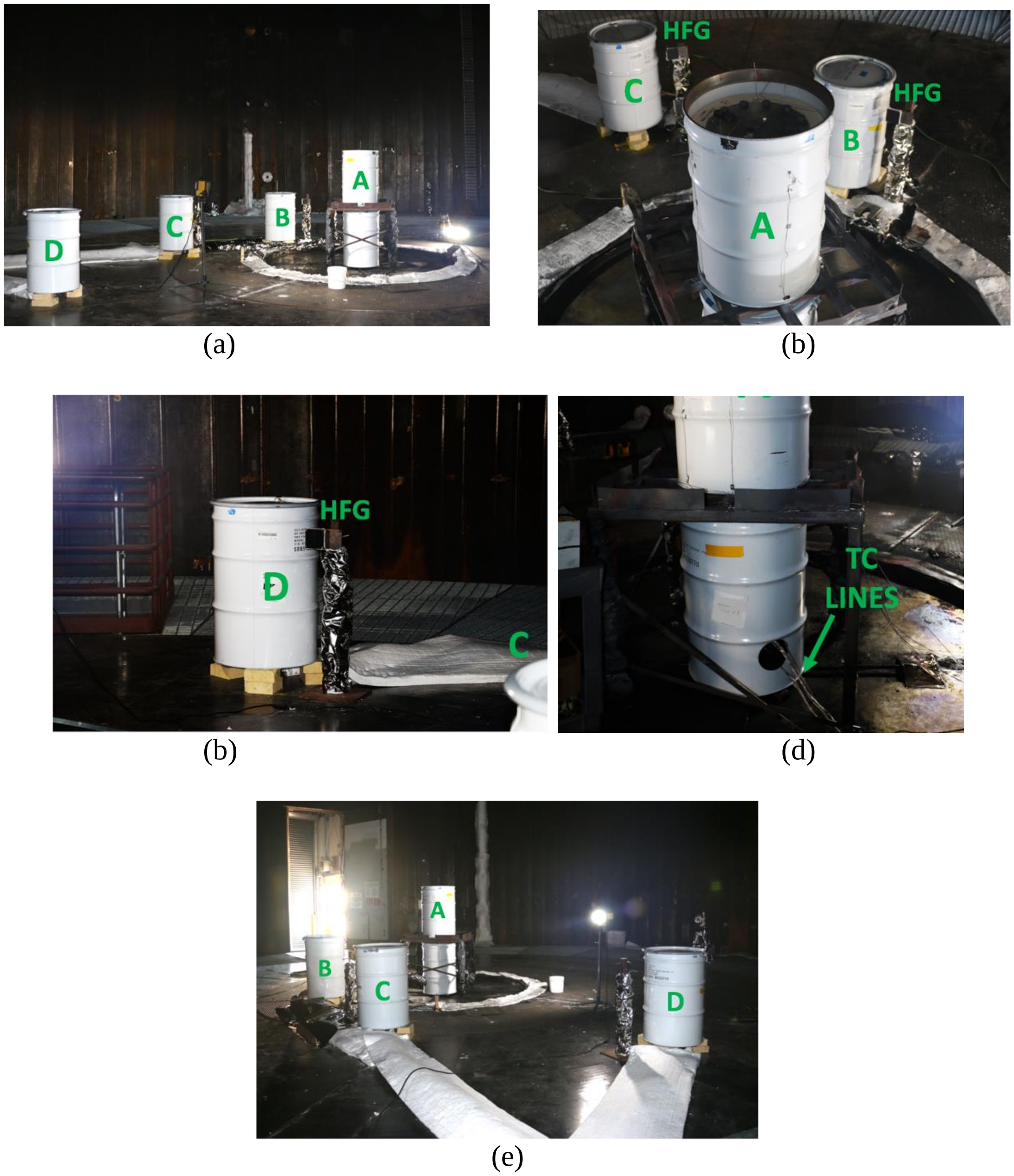


Figure 22. Images of drums before Test #1 in Phase I: (a) view from southeast side of the test cell, (b) view from above the center drum looking southwest, (c) HFG adjacent to drum D, and (d) image showing instrumentation cables from inside the center drum routed through the bottom drum, (e) view from the southwest side of

The image in Figure 22(a) was taken from the southeast quadrant of the test facility looking towards the west. As noted in Figure 22(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 22(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 22(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 22(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 23 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 23. The heavy smoke observed in Figure 23 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 23.

Figure 24 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.

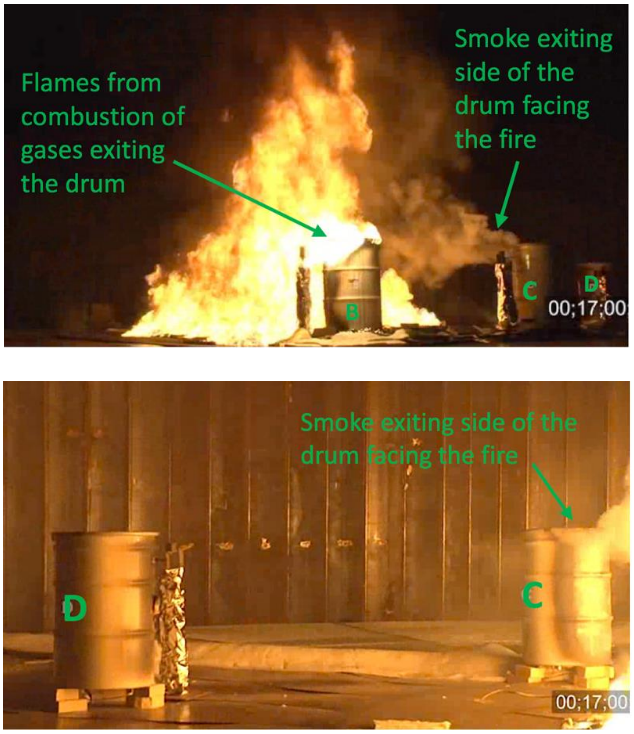


Figure 23. Screen capture of videos 17 minutes into the test showing flames around the lid of drum B and smoke on the lid of drum C.

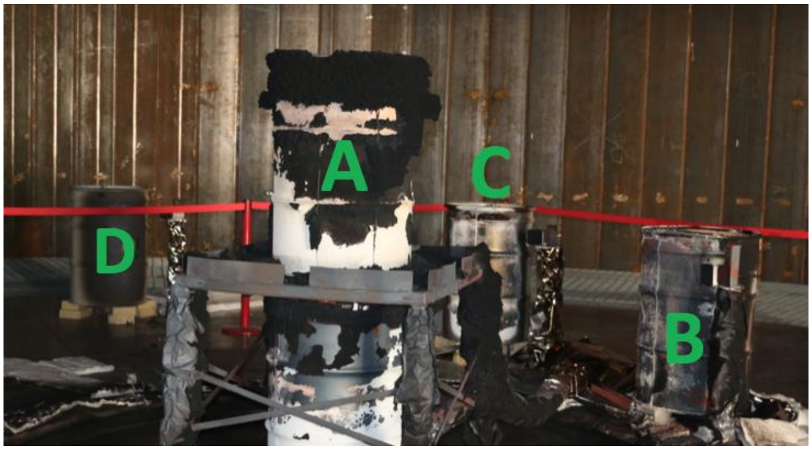
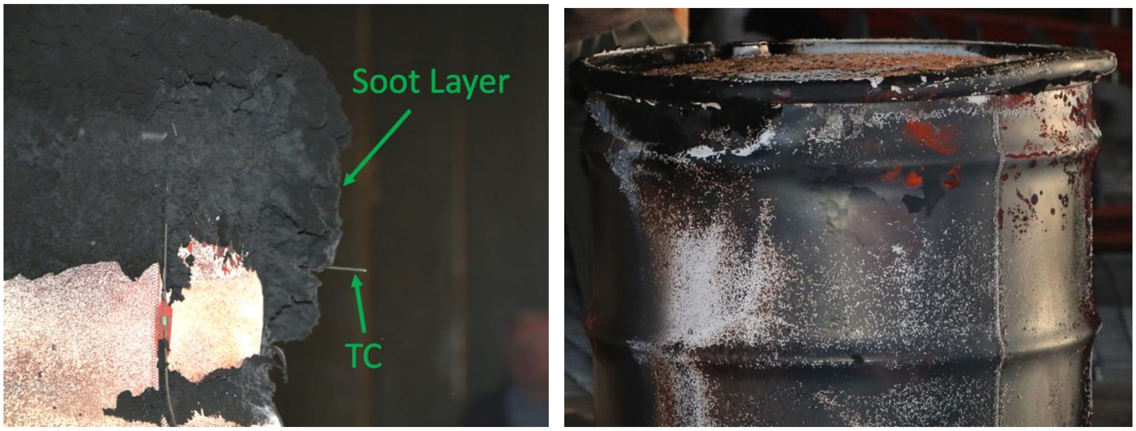


Figure 24. Post-test view of drums in Test #1.

Figure 25(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 25. (a) Soot layer on top of the drum A, (b) bulging on drum B.

Figure 26 and Figure 27 show the interior of each POC after Test #1 of Phase I. In Figure 26(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 26(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.

Figure 27(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, and then slowly dripped down as it cooled until frozen in place, forming the mushroom shape.

Figure 28 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 28(a). When the PC filter housing was removed, additional charred remains were observed inside the threaded hole (see Figure 28(b)). The source of the charred residue is unknown. Visual inspection of the filter showed the carbon media was compromised (see Figure 28(c)). The filter port was then blocked to conduct a leak test through only the PC O-ring.

(a)

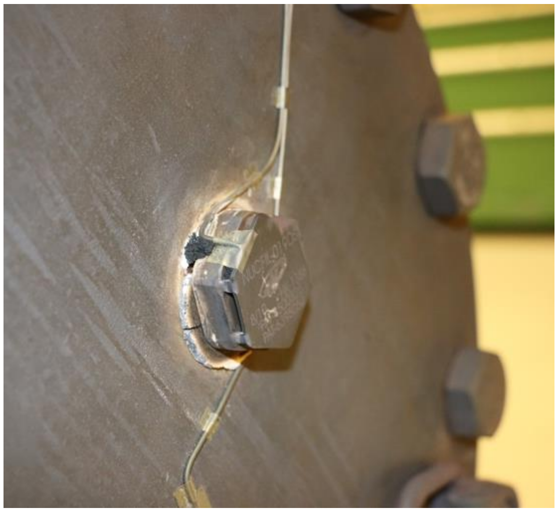
(b)

Figure 26. Internal remains of POC after Test #1: (a) drum A and (b) drum B with and without the PC.

(a)

(b)

Figure 27. Internal remains of POC after Test #1: (a) drum C and (b) drum D.



(a) (b)

(c)

Figure 28. 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 4. 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 4. 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 29 through Figure 42 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.

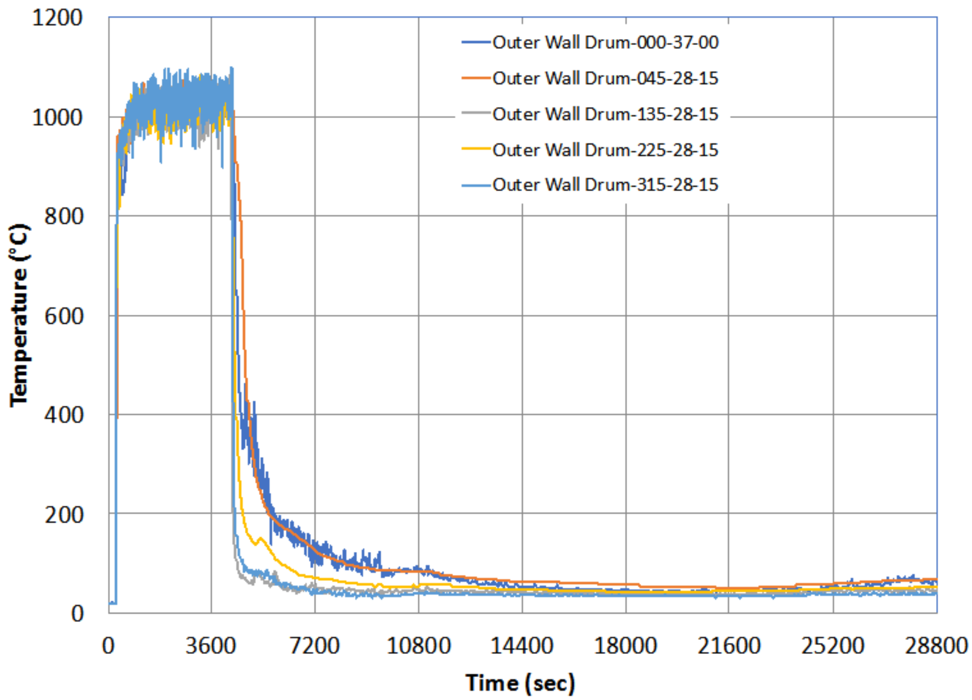


Figure 29. Temperatures on the outer wall of the drum (POC drum A).

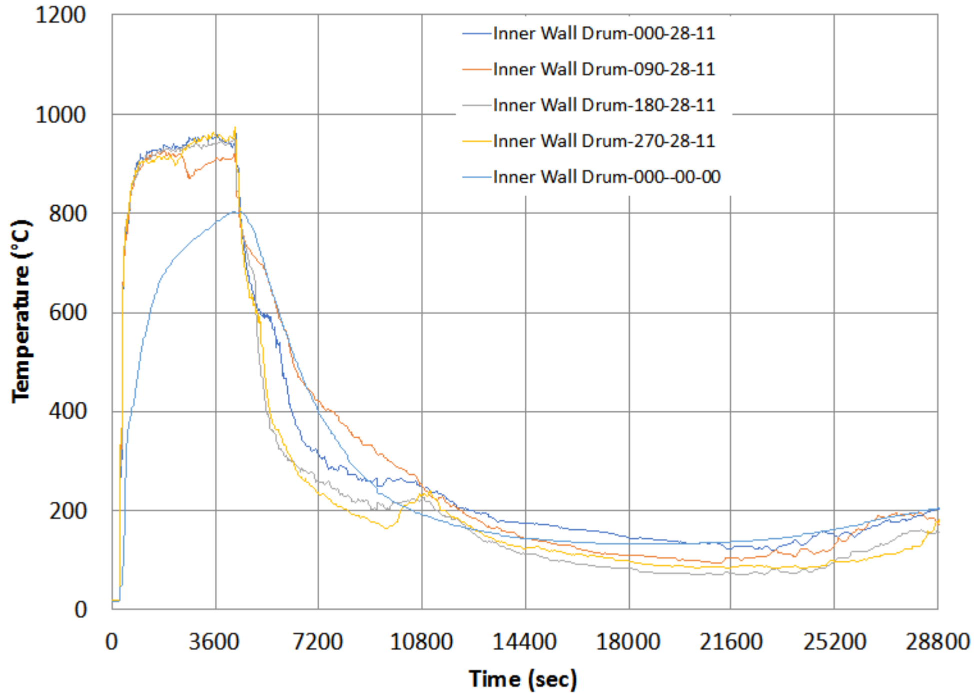


Figure 30. Temperatures on the inner wall of the drum (POC drum A).

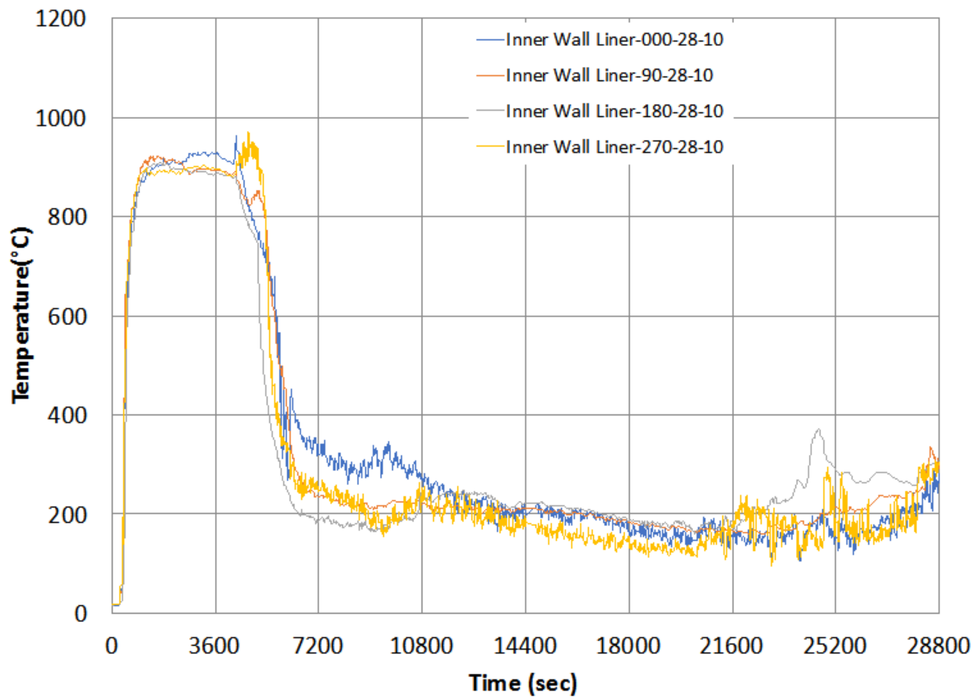


Figure 31. Temperatures on the inner wall of the plastic liner (POC drum A).

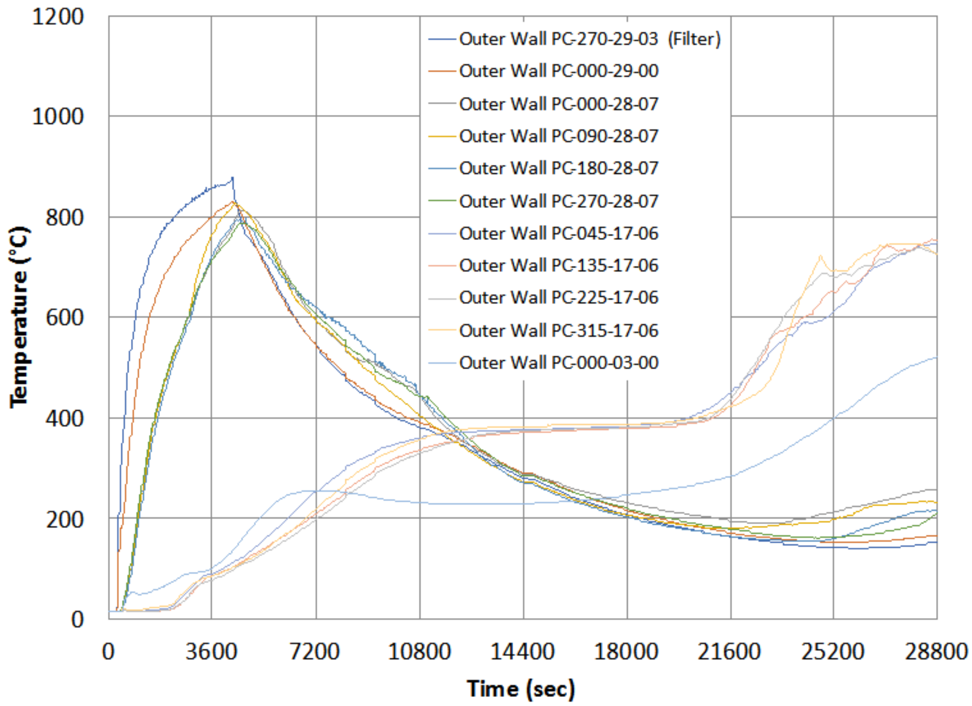


Figure 32. Temperatures on the outer wall of the PC (drum A).

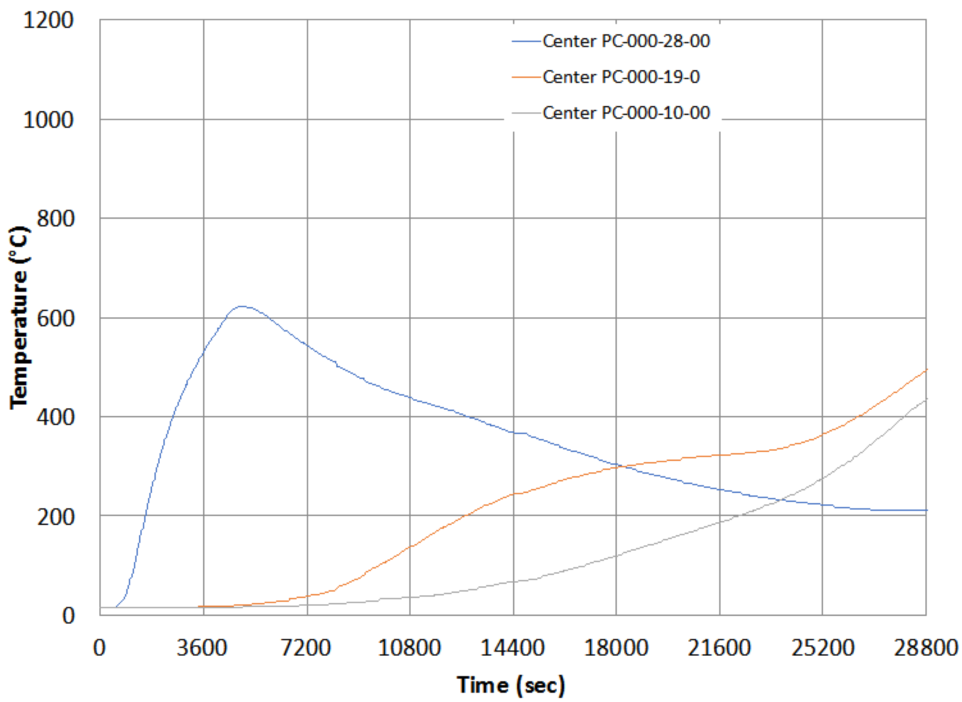


Figure 33. Temperatures in the center of the PC (POC drum A).

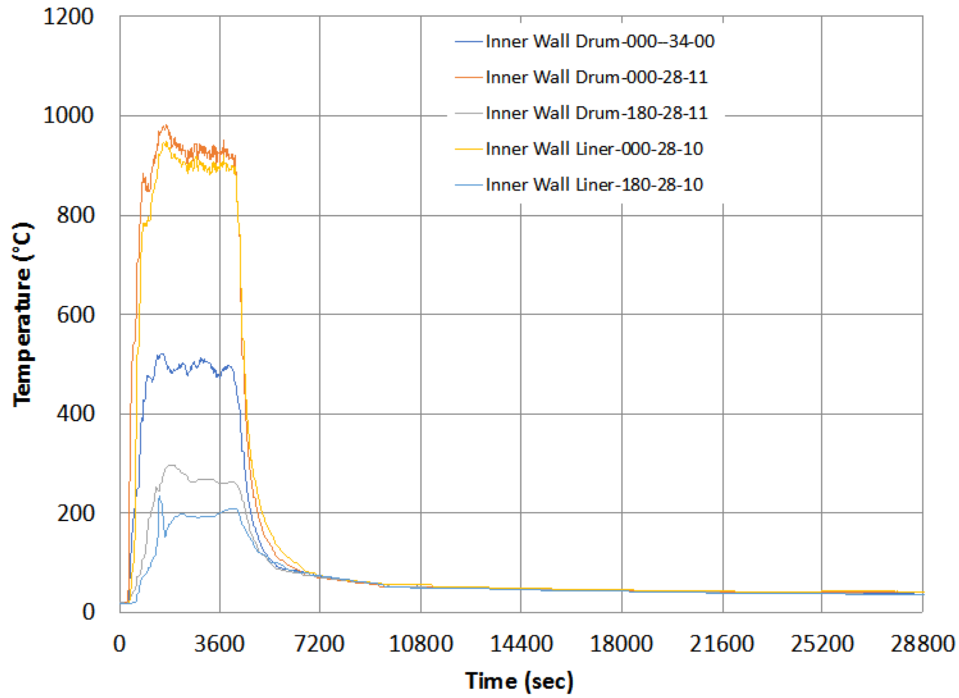


Figure 34. Temperatures on the inner wall of the drum and plastic liner (POC drum B).

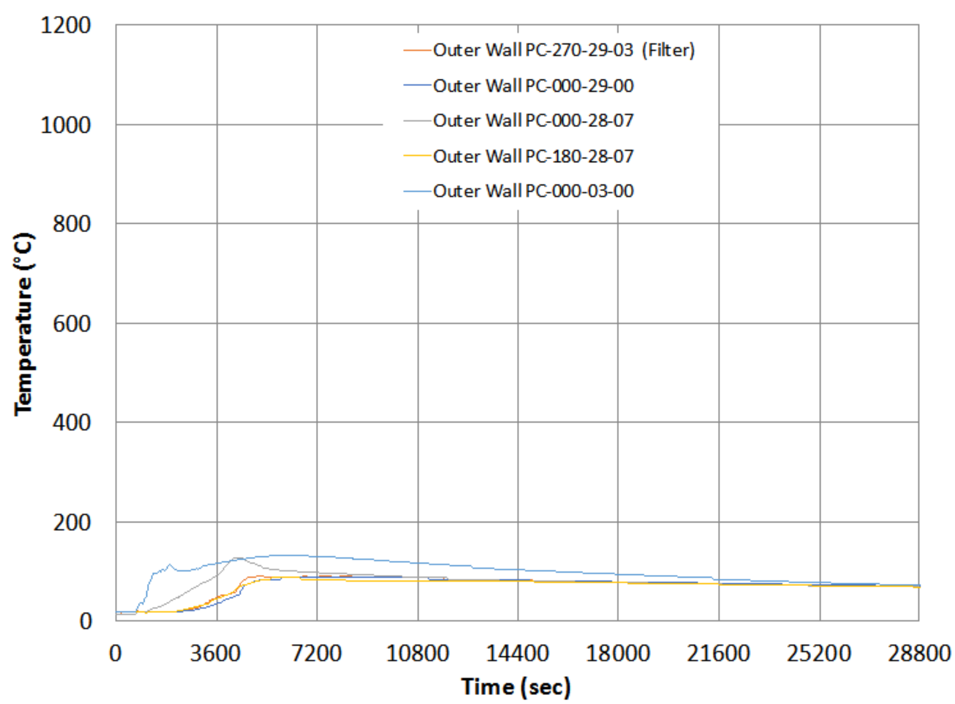


Figure 35. Temperatures on the outer wall of the PC (POC drum B).

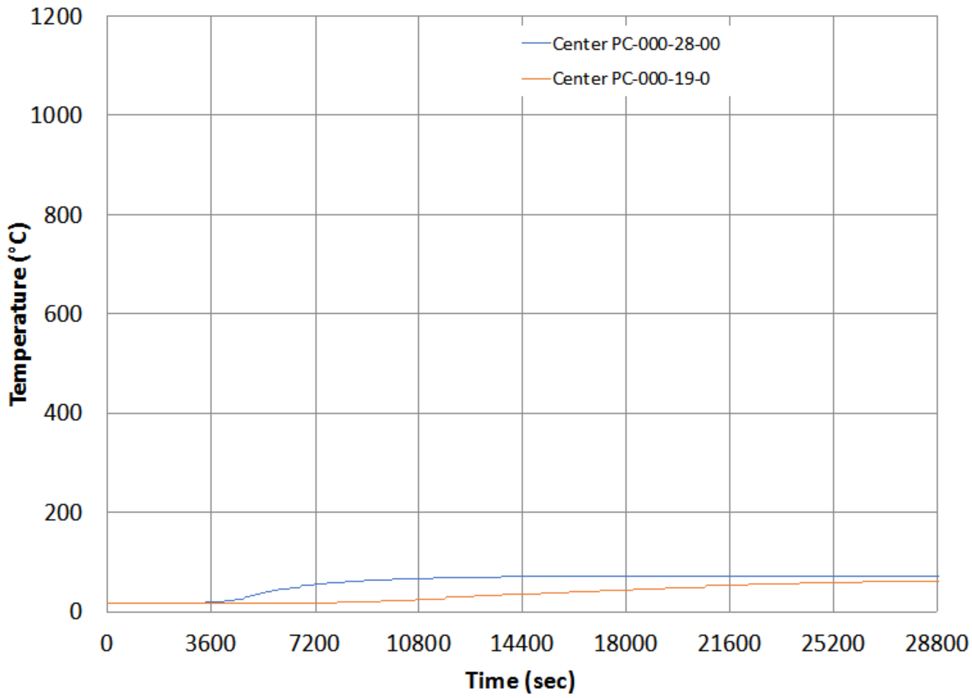


Figure 36. Temperature in the center of the PC (POC drum B).

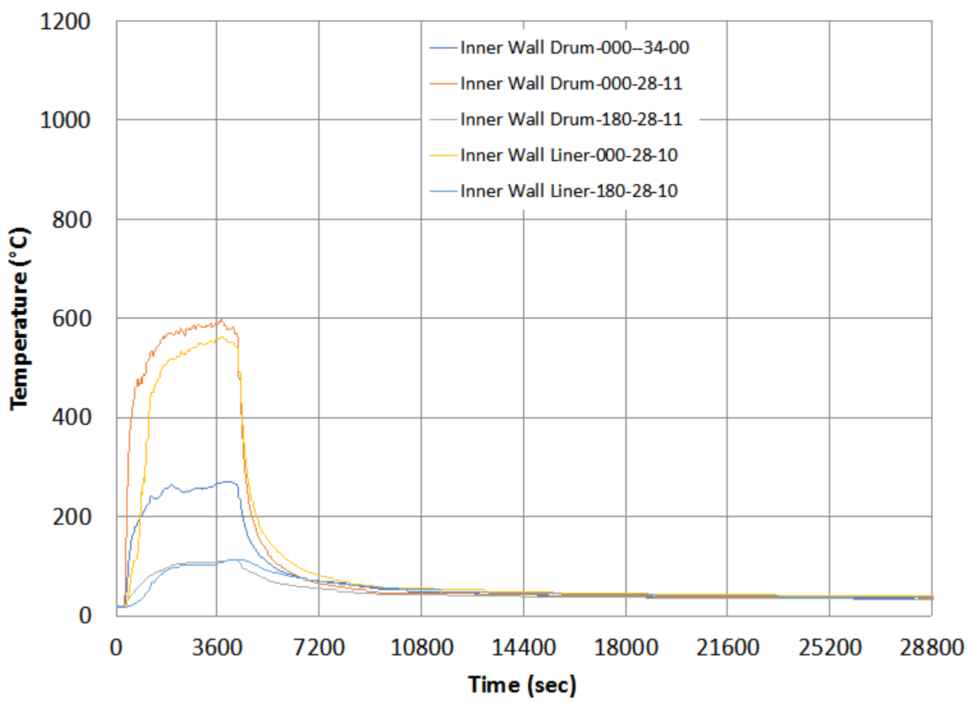


Figure 37. Temperatures on the inner wall of the drum and plastic liner (POC drum C).

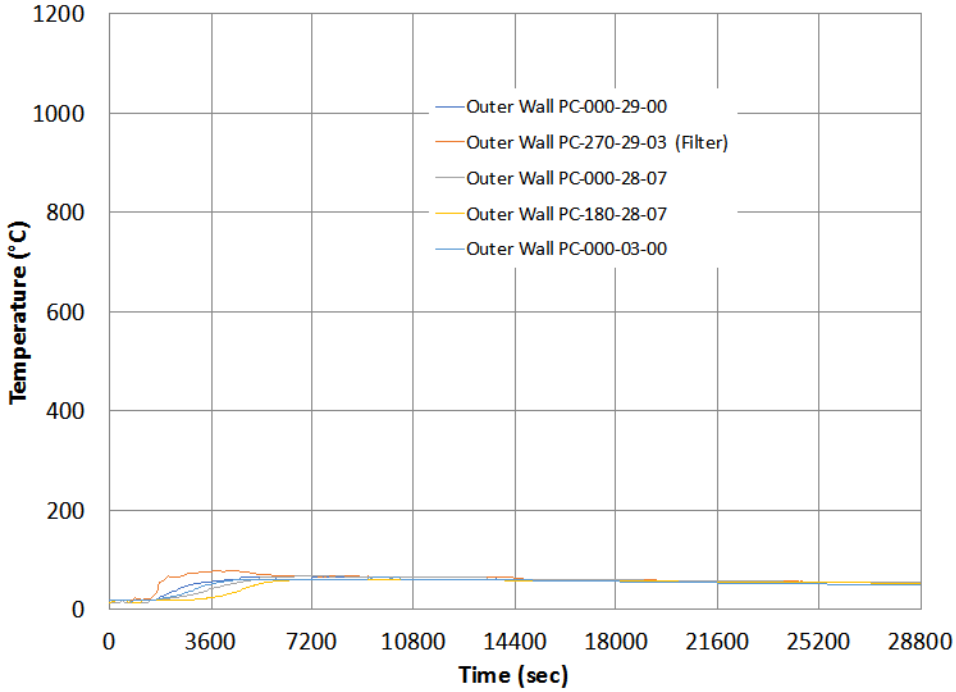


Figure 38. Temperatures on the outer wall of the PC (POC drum C).

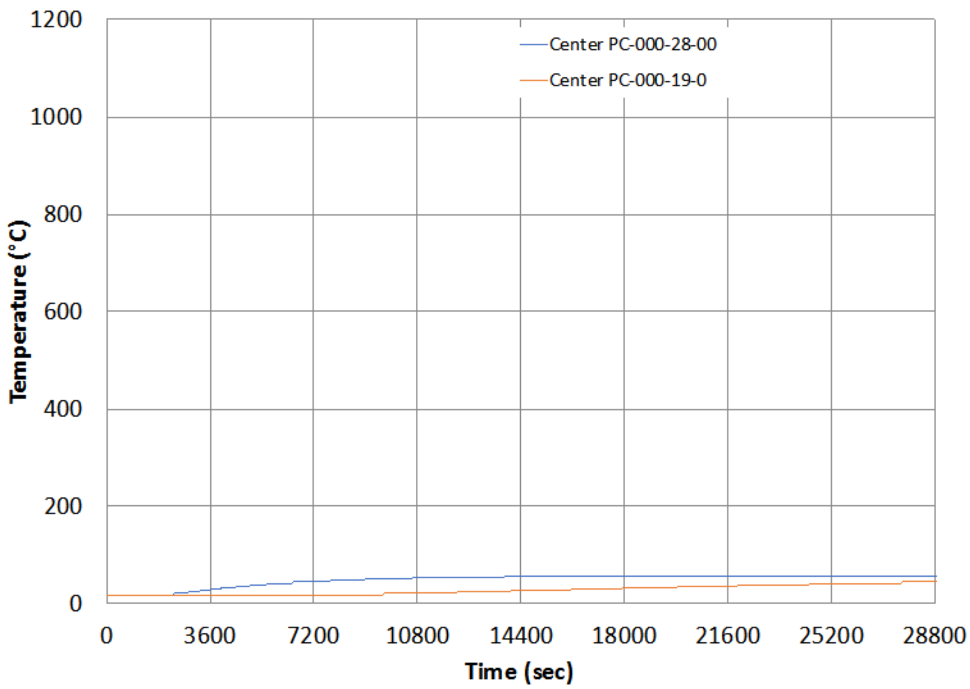


Figure 39. Temperatures in the center of the PC (POC drum C).

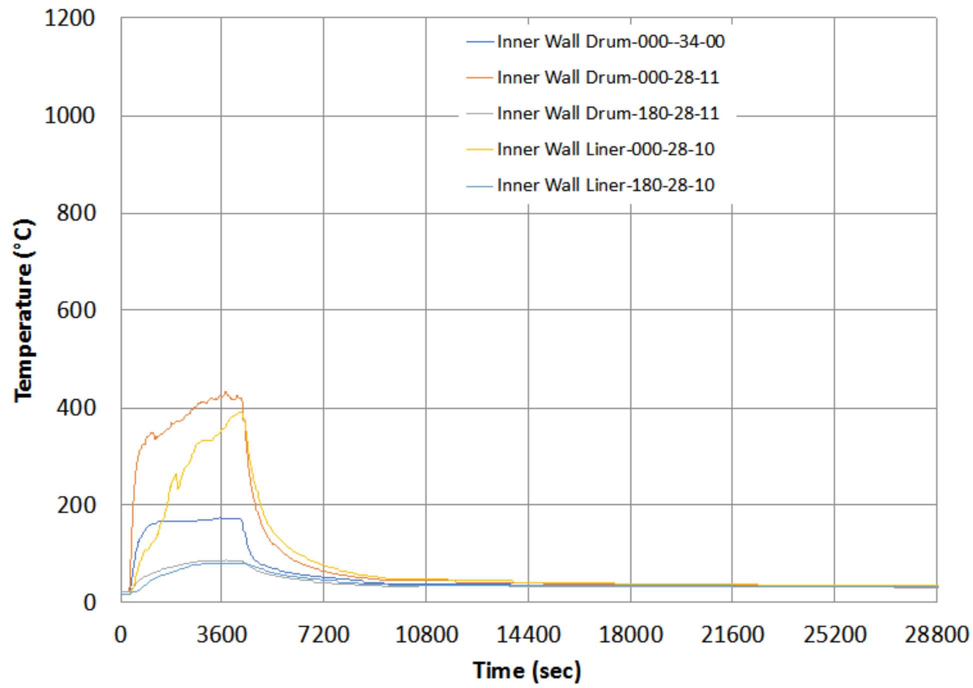


Figure 40. Temperatures on the inner wall of the drum and plastic liner (POC drum D).

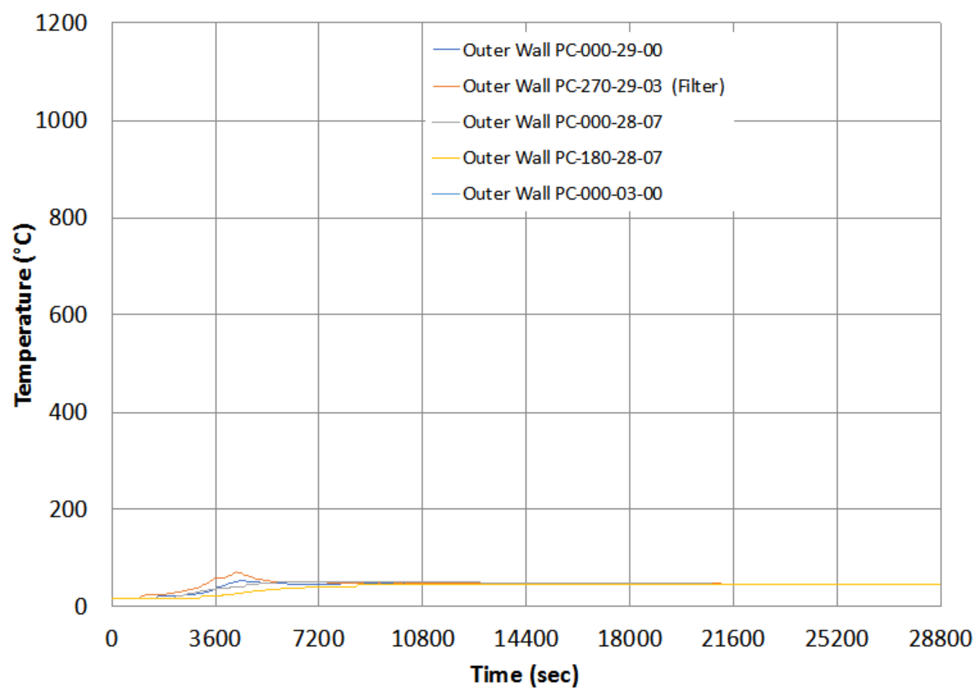


Figure 41. Temperatures on the outer wall of the PC (POC drum D).

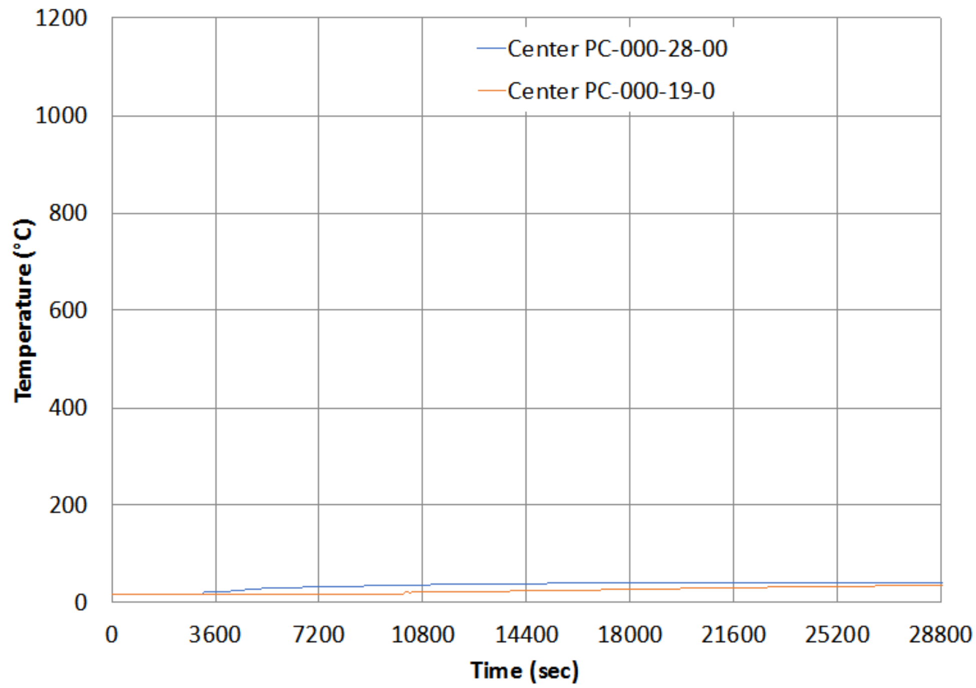


Figure 42. Temperatures in the center of the POC (POC drum D).

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 8. 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 43 shows images taken before the second test. Figure 43(a) shows drums A through D in place, while Figure 43(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 43(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 43. 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 44(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 44(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.

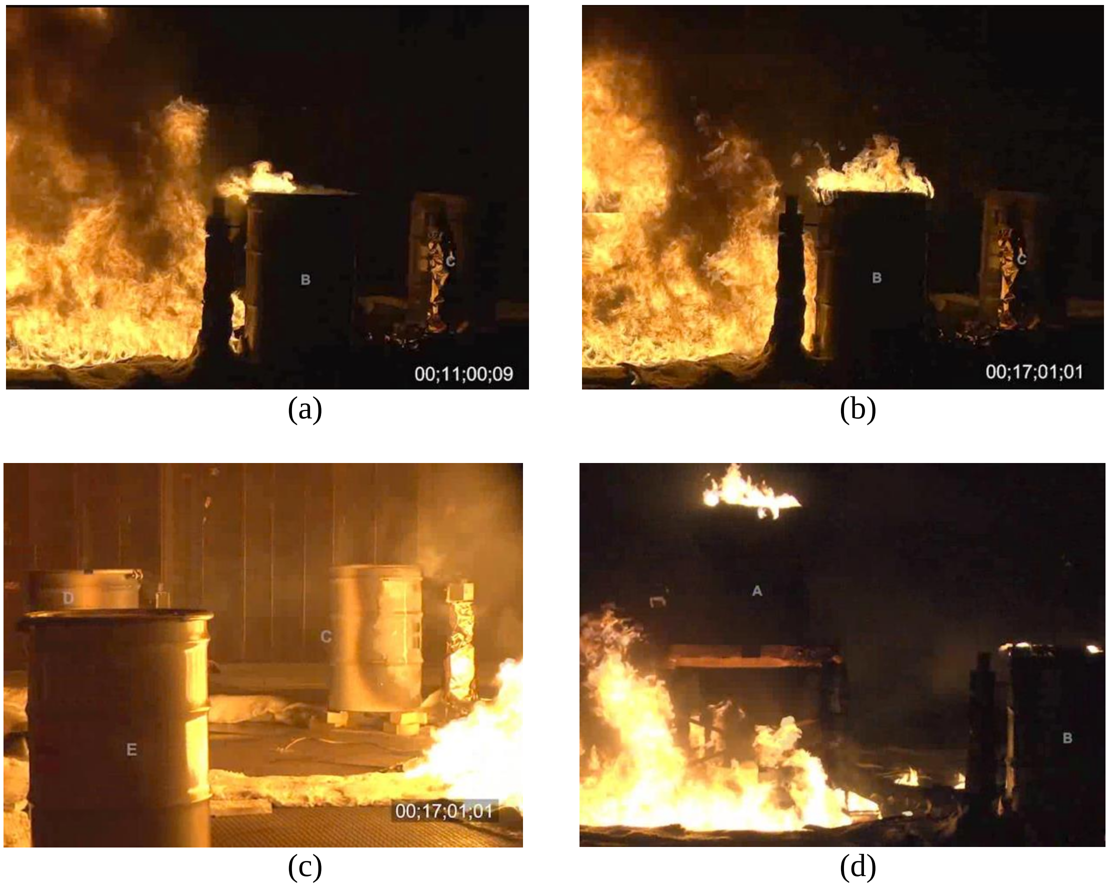


Figure 44. Screen capture showing various conditions of the drums during and immediately after Test #2: (a) drum B showing flames on the side closest to the fire, (b) drum B with flames all around the lid, (c) light smoke is observed on the hot side of drum C, and (d) flames observed around the lid of 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 44(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 23). 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 44(d)) for quite a long time. This is evidence that internal combustion continued on this drum well beyond the end of the test.

Figure 45(a) shows the state of all the drums after Test #2. As shown in Figure 45(b), drum A was heavily coated with soot; however, the lid did not appear to bulge significantly, as seen in Figure 45(c) after the soot was removed.

(a)

(b)

(c)

(d)

Figure 45. (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 45(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 46. Not shown are the internals of drum B and E. The close-up image of drum A shown in Figure 46(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 46(b) shows the interior of drum C, the closest 7A to the fire. The thin plastic bag shown in Figure 8 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.

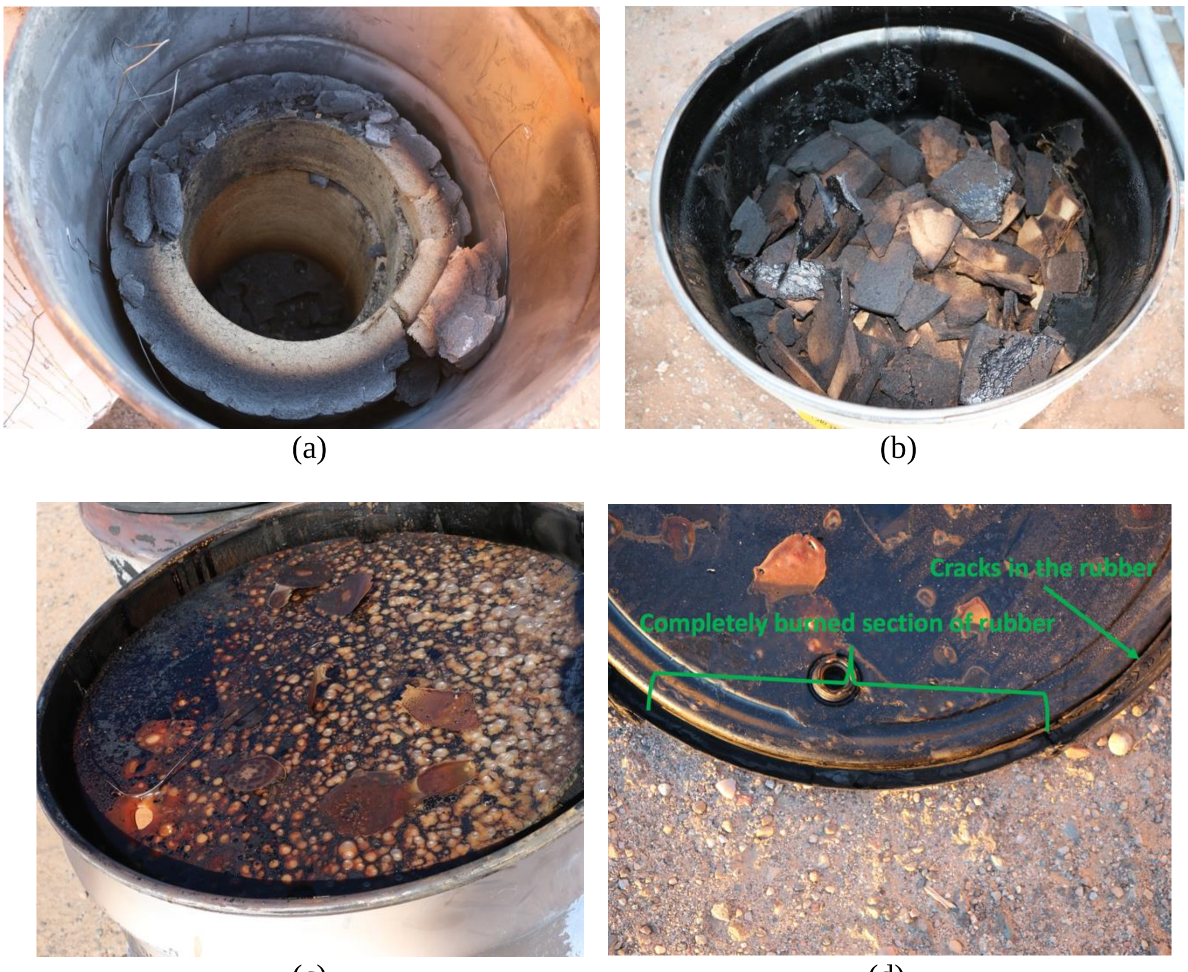


Figure 46. Internal conditions of drum A, C, and D after Test #1: (a) drum A, (b) drum C, and (c) and (d) drum D.

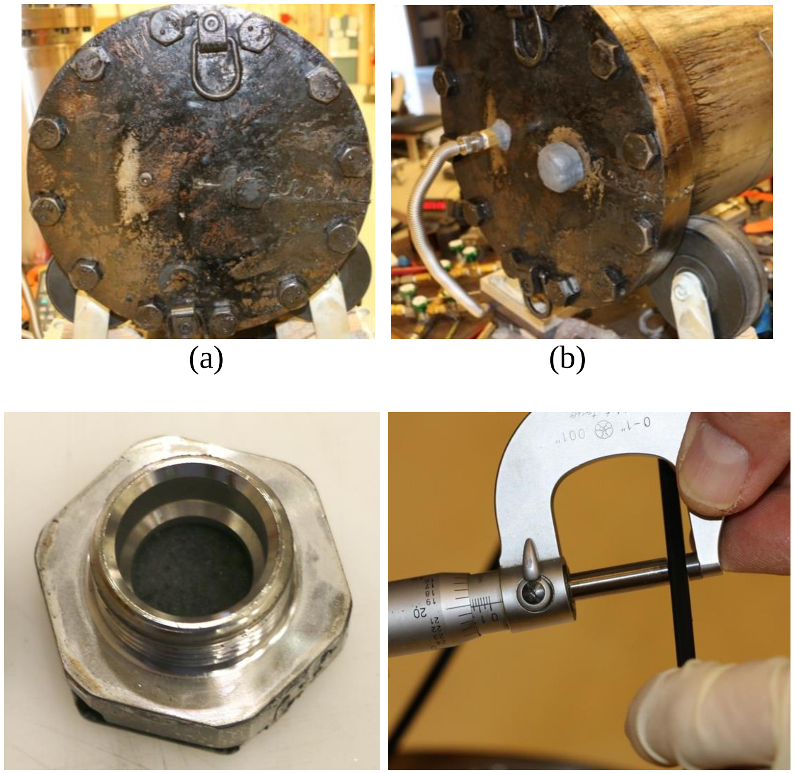
Figure 46(c) shows the inside of drum D, the only other POC outside the fire. Note that this drum was slightly further back from the fire than POC drum C in Test #1. Internally this drum showed similar damage to drum C in the first test. As shown in the figure, bubbles again appeared on top of the plastic 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 46(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 47 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 47(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 47(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 48 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 47(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 47(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 47(c) and (d).



(a) (b)

(c) (d)

Figure 47. 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.

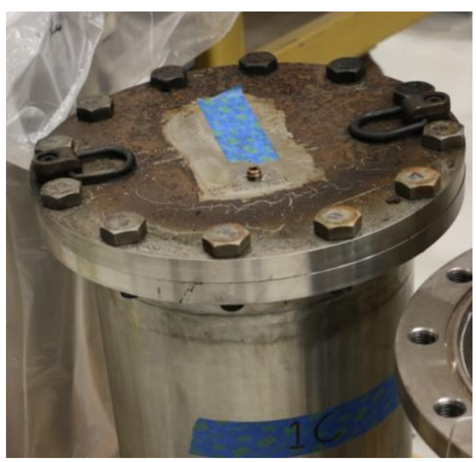


Figure 48. PC extracted from drum C.

Results of leak test on POC drums used in Test #2 are shown in Table 5. 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 5. 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 49 through Figure 62 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.

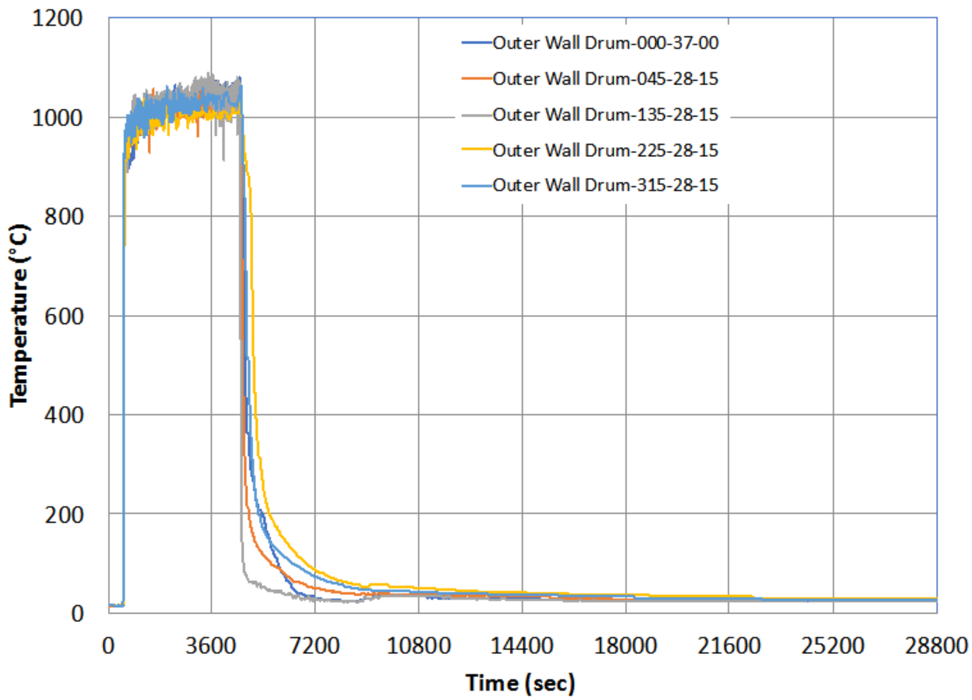


Figure 49. Temperatures on the outer wall of the drum (POC drum A, Test #2)

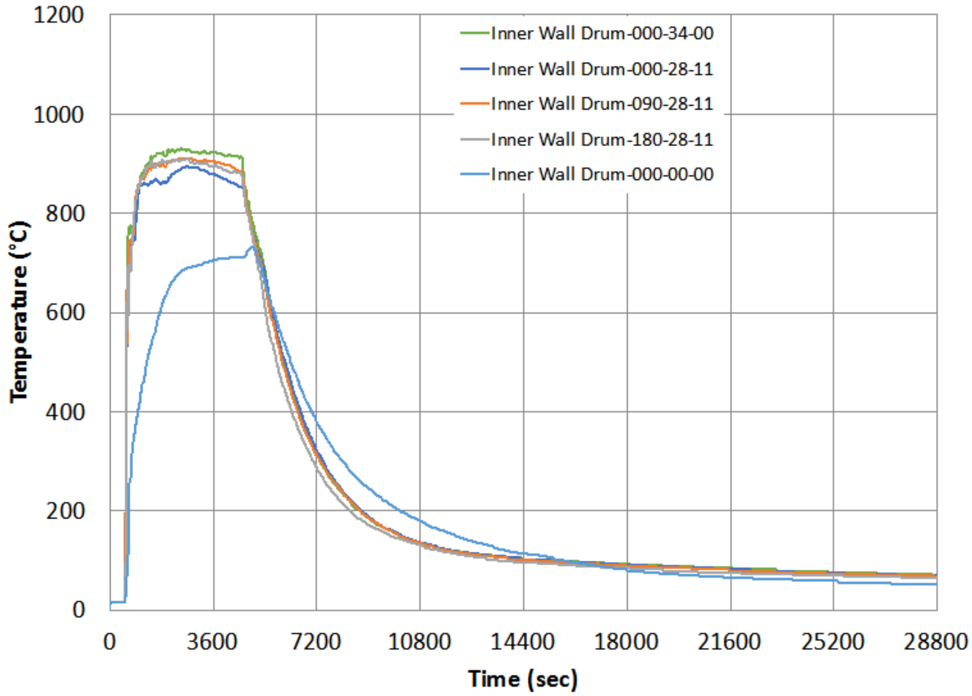


Figure 50. Temperatures on the inner wall of the drum (POC drum A, Test #2)

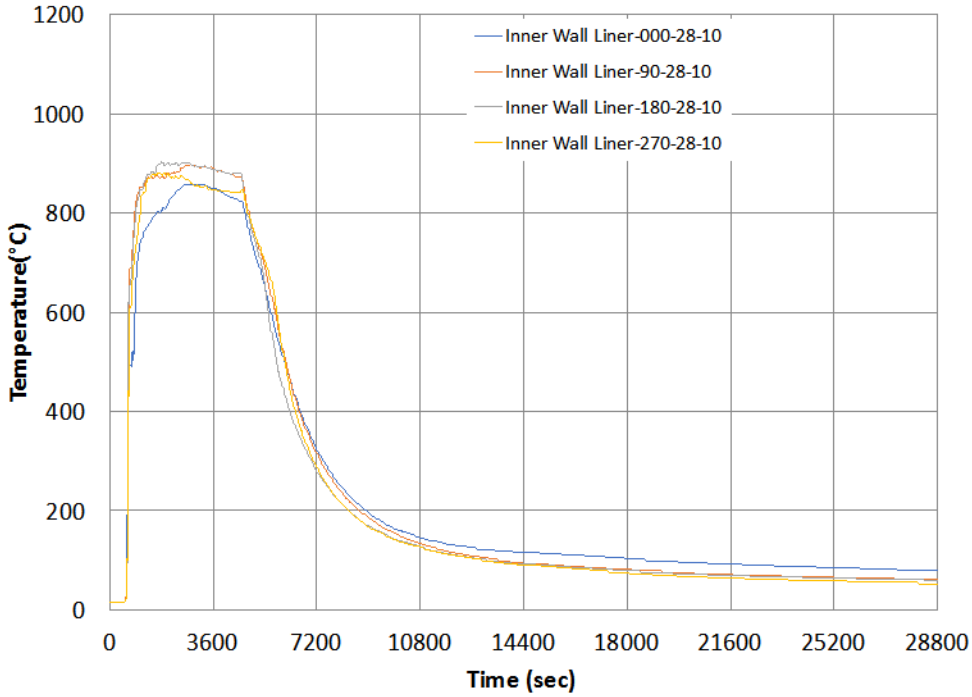


Figure 51. Temperatures on the inner wall of the plastic liner (POC drum A, Test #2)

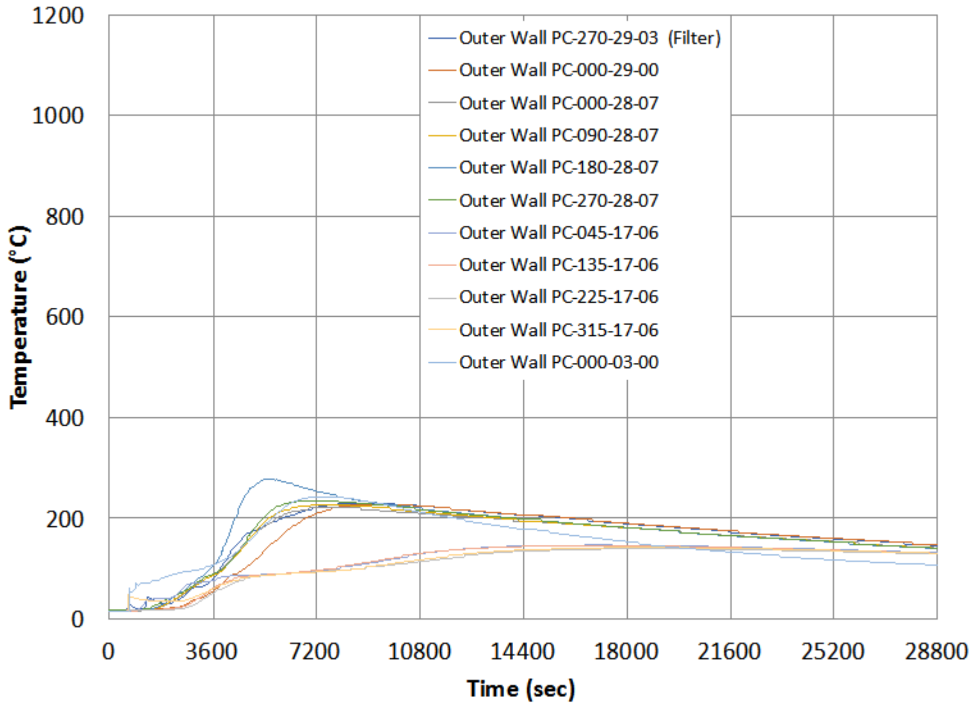


Figure 52. Temperatures on the outer wall of the PC (POC drum A, Test #2)

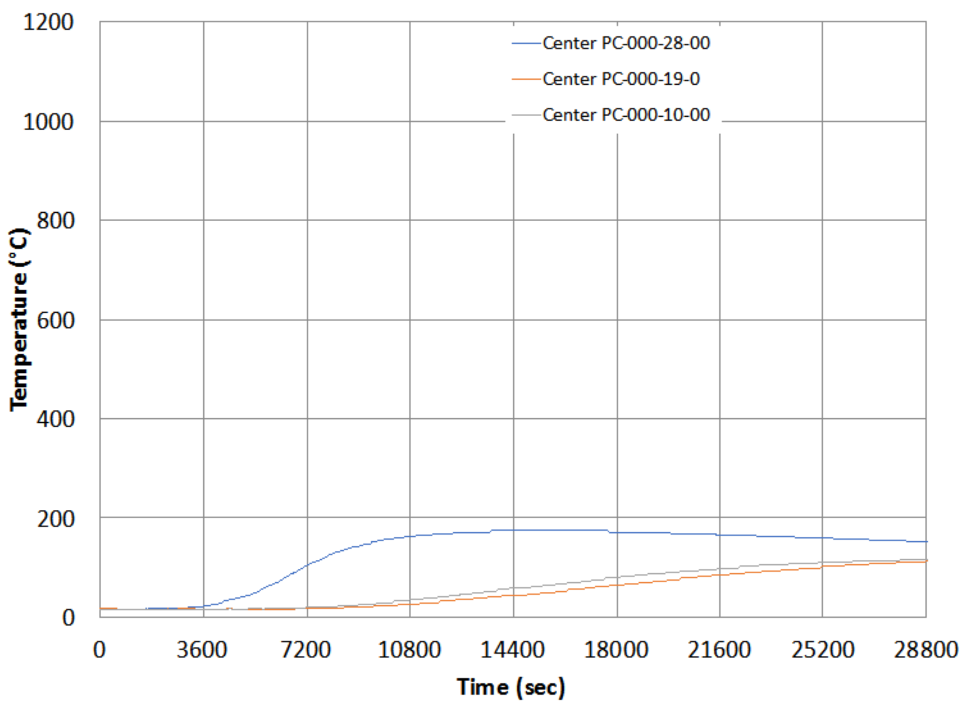


Figure 53. Temperatures in the center of the PC (POC drum A, Test #2)

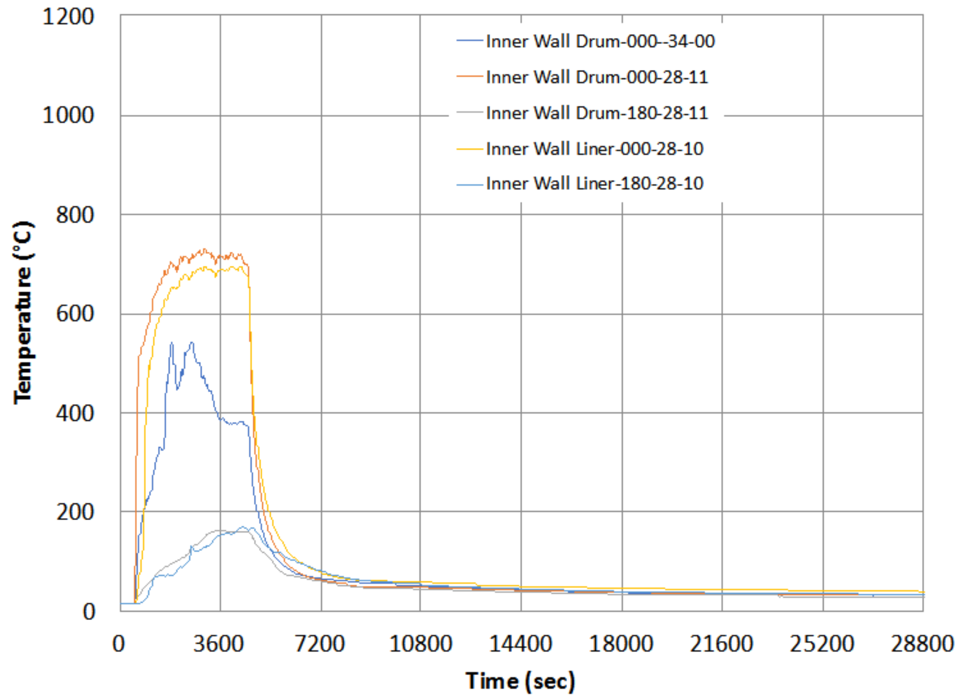


Figure 54. Temperatures on the inner wall of the drum and plastic liner (POC drum B, Test #2)

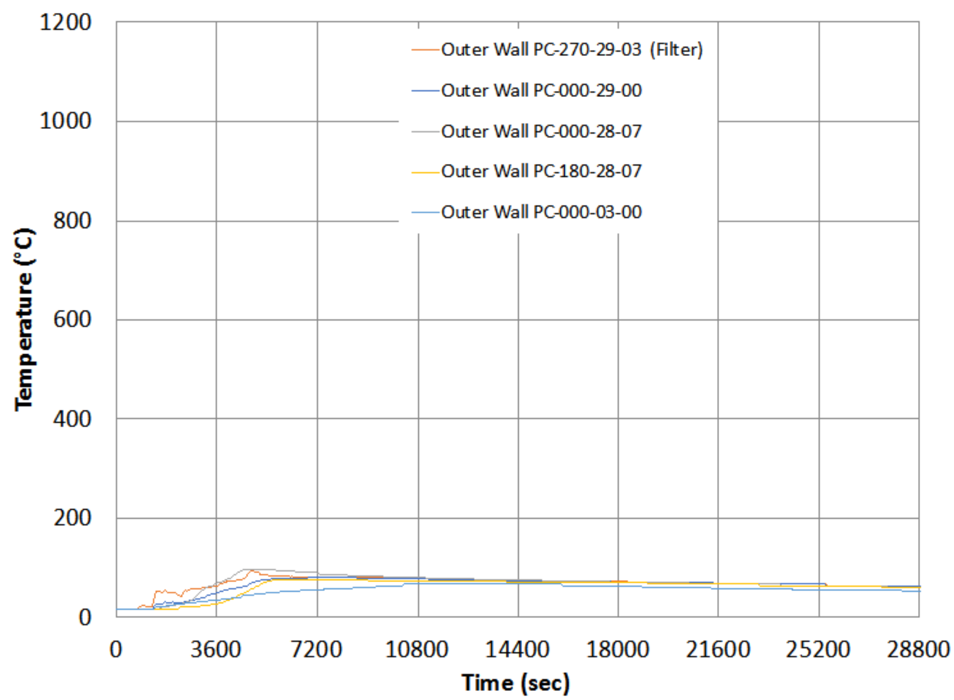


Figure 55. Temperatures on the outer wall of the PC (POC drum B, Test #2)

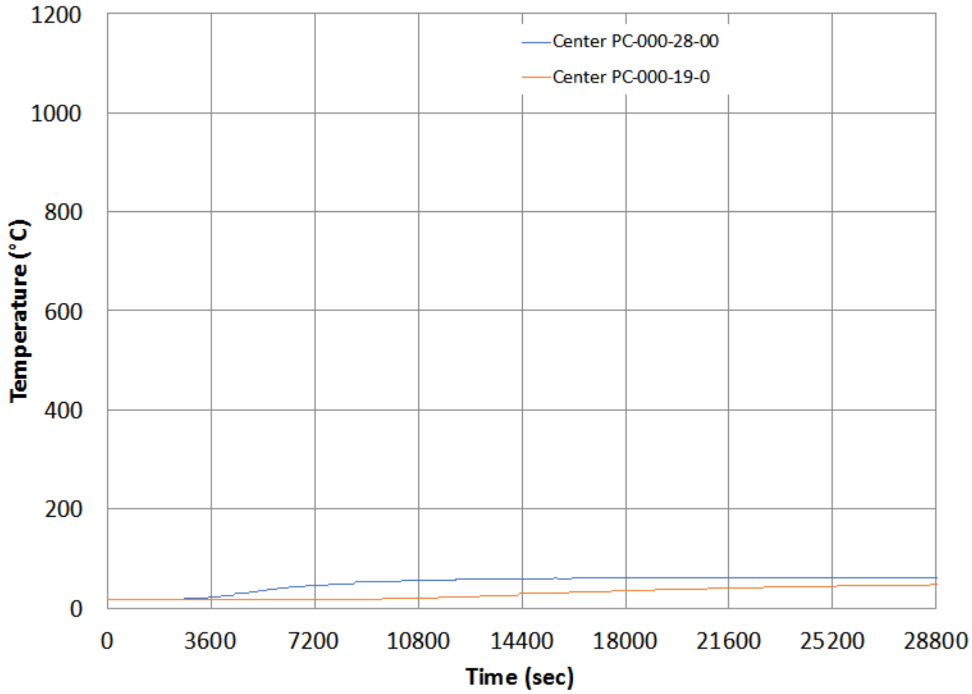


Figure 56. Temperatures in the center of the PC (POC drum B, Test #2)

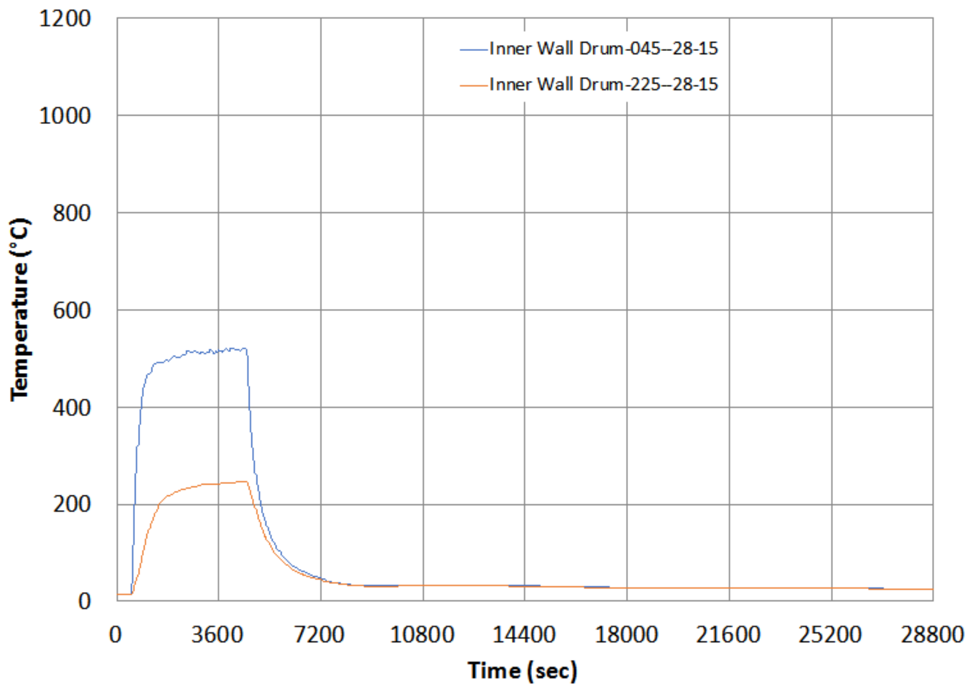


Figure 57. Temperatures on the outer wall of the drum (POC drum D, Test #2)

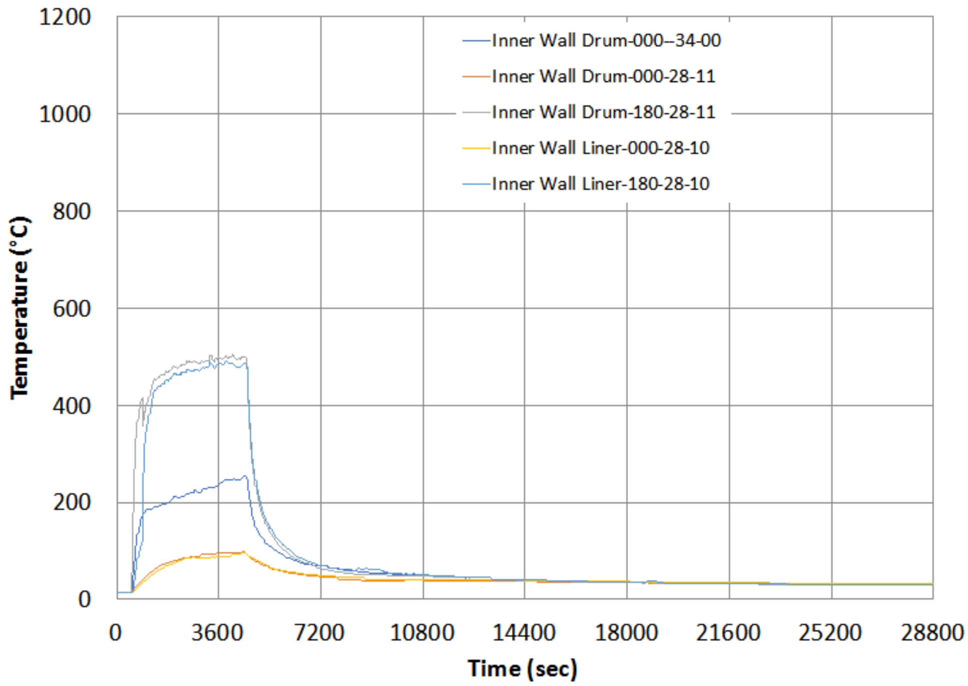


Figure 58. Temperatures on the inner wall of the drum and plastic liner (POC drum D, Test #2).

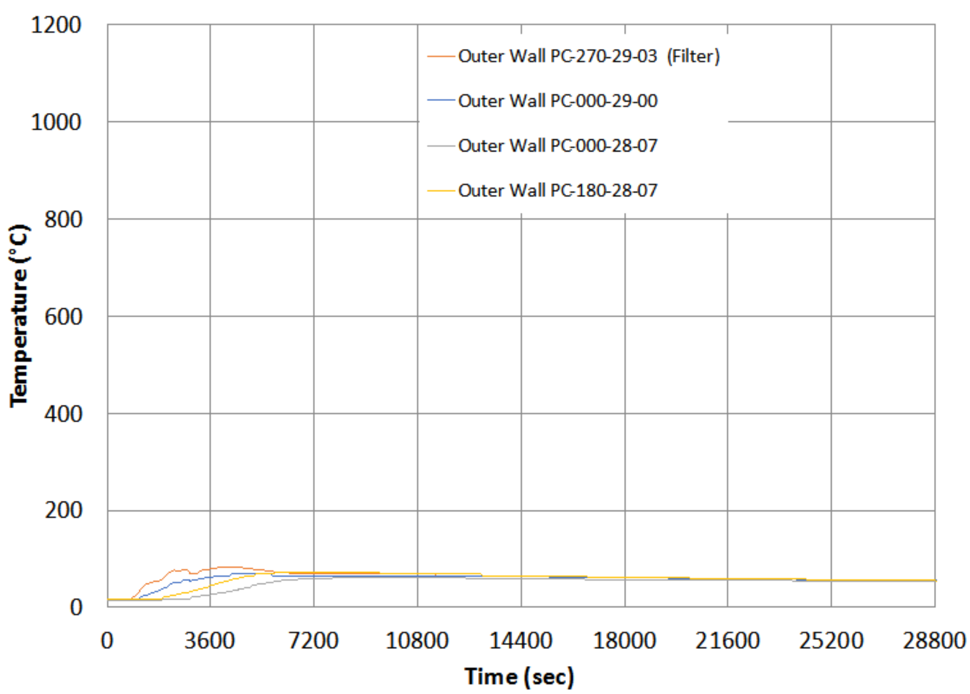


Figure 59. Temperatures on the outer wall of the PC (POC drum D, Test #2)

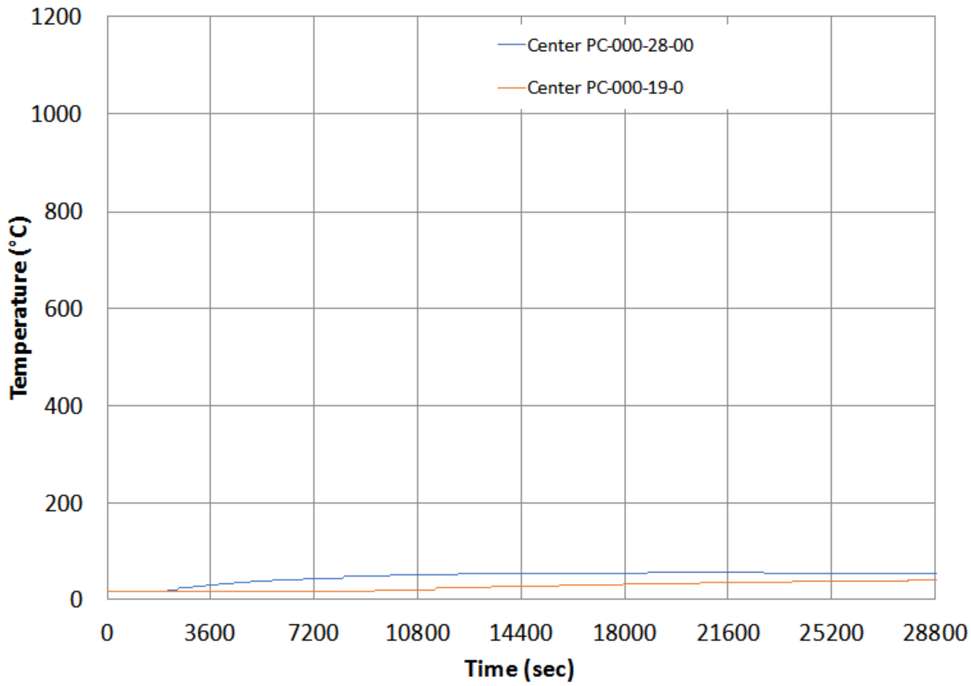


Figure 60. Temperatures in the center of the PC (POC drum D, Test #2)

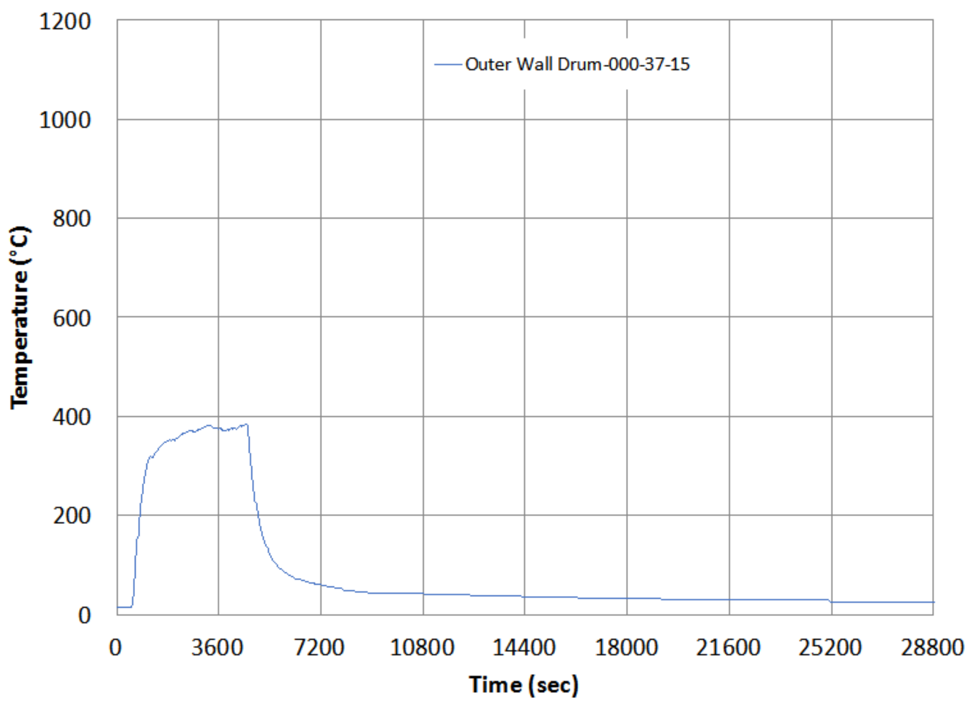


Figure 61. Temperatures on the outer wall of the drum (7A drum C, Test #2)

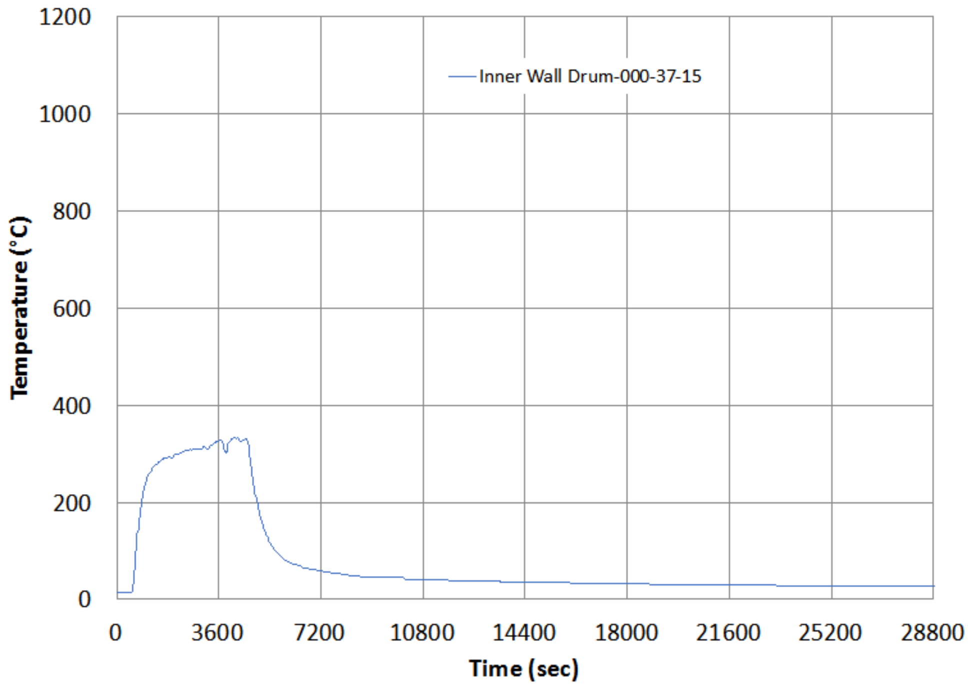


Figure 62. Temperatures on the outer wall of the drum (7A drum E, Test #2)

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 46(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 46(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 3 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 63 is an image taken prior to the test.

Figure 63. Test layout in Test #1 of Phase II.

Figure 64 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 64. Videos screen captures of Phase II Test # 1 showing ejection of lid.

Figure 65 shows the test area the day after the test. Figure 65(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.

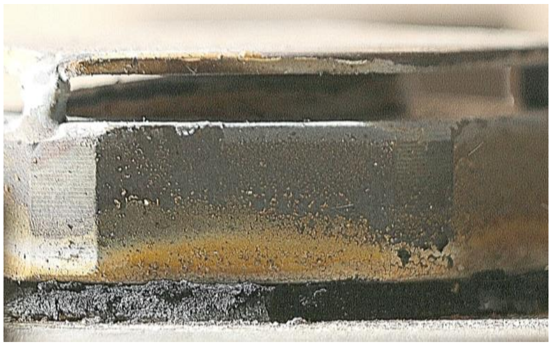
(a) (b)

Figure 65. Test remains after Test #1 in Phase II. (a) center of the pool and (b) lid by the wall of the test cell.

Figure 65(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 66(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 66(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 66. 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 67 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 13. As noted in that figure, the drum labeling scheme changed in this test but this had no special significance. In

Figure 67, the 7As are the two closest drums (E and F), while the remaining drums shown towards the back are POCs.

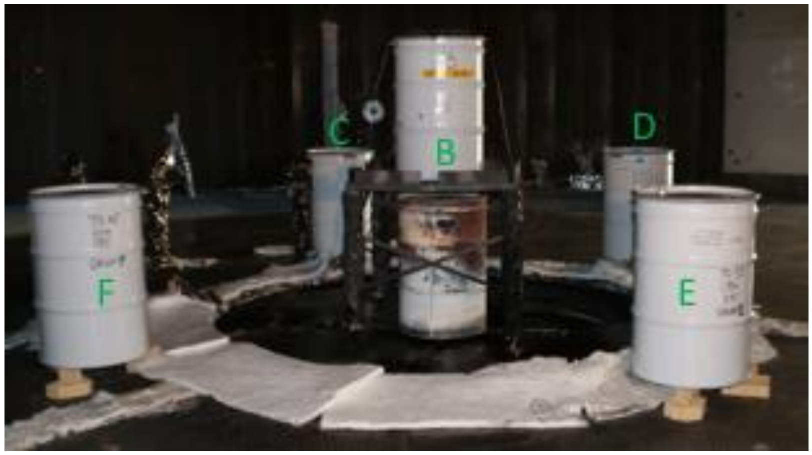
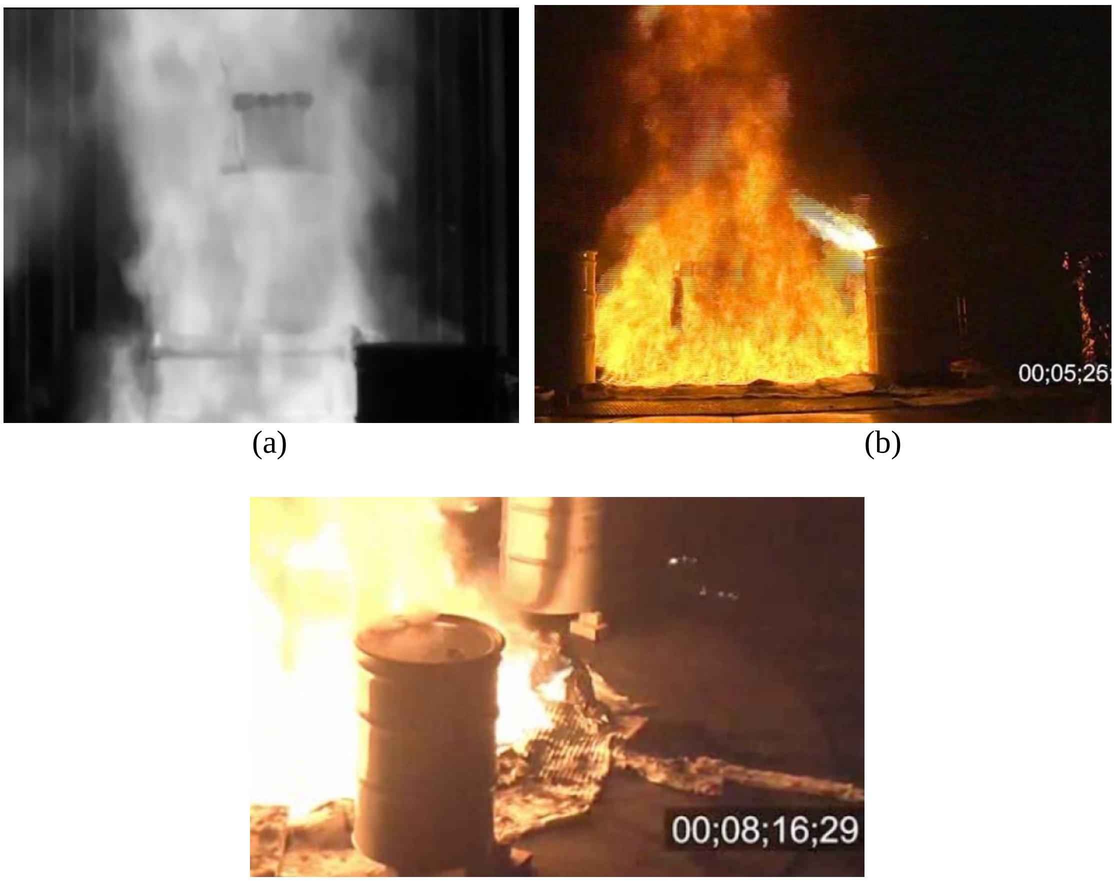


Figure 67. Image of the test layout in Test #2 of Phase II taken from the southeast corner of the facility.

The PCs on the POCs were empty, but the 7As were filled with typical combustible materials (gloves, plastics, etc.) to the top (see Figure 68). 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 68. 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 69(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 69(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.

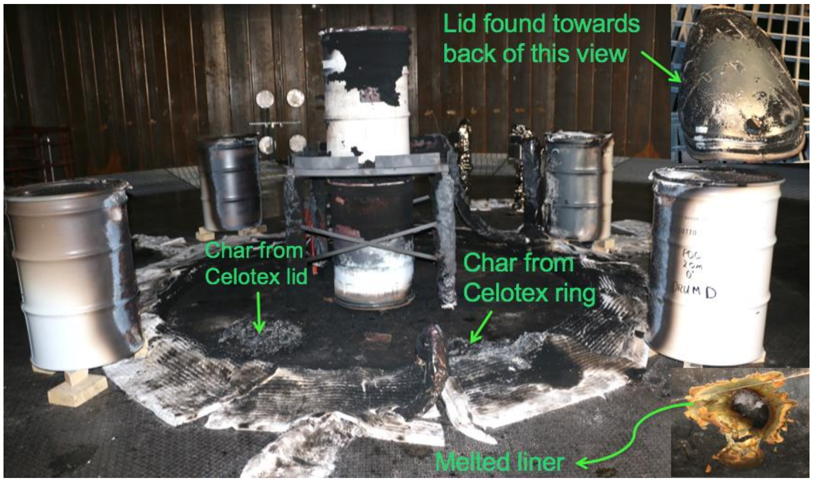


(a) (b)

(c)

Figure 69. 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 70(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 70(b) shows the PC filter recovered from the PC in drum A. Figure 70(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 70. 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 70(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 71 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 71. Left over material inside one of the 7As in Test #2 of Phase II.

Phase III

Phase II showed that for POCs fully engulfed in the fire, the POC drum lid, and the top Celotex®, and plywood components get ejected from the drum. There isn't sufficient gas released through the drum filter and/or through the edge of the drum lid once the seal is burned to allow rapid depressurization of the drum. Phase I, Test 1 and both Phase II tests demonstrated that the PC filter vent is compromised due to high temperatures and/or over pressurization of the PC. Figure 32 shows that after the fire the temperatures on the wall of the PC climb close to 400°C three hours after the fire started. The reason for this is that even if fire stops, the Celotex® continues to burn through the remainder of the test until practically all of it is consumed. Celotex® burning thus provides the additional energy to continue heating the PC. All this evidence suggests that combustibles inside the PC will decompose under this scenario. However, up to this point in the test program, it was not known when in the test the PC filter failed and the amount of combustibles that would decompose, i.e., what is the DR? More importantly, could there be a release of material from inside of the PC? To answer these questions, in Phase III, one test was conducted with typical combustibles inside the PC.

In this test, it was assumed that the drum lid and the Celotex® and plywood top had already been ejected. This allowed placement of aerosol collection system over the top of the PC filter. Because it was not known if the PC would burst during the test, the test was conducted in an outdoor burn facility.

Test 1

Figure 72 shows a long distance and close-up images of the fire taken during the test. The POC was fully engulfed for the duration of the 30-minute fire. As expected, wind fences kept the POC fully engulfed through the 30-minute test. Conditions during the test were mostly calm and with some exceptions, the plume was vertical for most of the test.

Figure 72. Phase III, Test 1 fully engulfing fire

Figure 73 through Figure 78 show temperatures measured on the outside of the POC drum, on the inner side of the Celotex® cylindrical wall (2 inches in from the inner surface), and on the surface of the PC wall. Time zero corresponds to fully engulfing conditions, which typically happened 30 seconds after ignition. In Figure 73, the TC measurement junctions were about 3 inches away from the surface of the drum, and 27 inches from the base of the drum. All TCs were spaced 90-degrees apart around the circumference of the drum. In Figure 74, the lowest TC number corresponds to the TC near the top of the Celotex® cylinder and the highest number to the TC near the bottom. The TC measuring junctions in the Celotex® were about 2-inches in from the inner wall. Starting in Figure 75, each plot shows temperatures at the same height on the PC. Except for the lid (Figure 75), TCs are spaced 90-degrees apart on the circumference of the PC flange and vessel. Measurements from TC16 (bottom of the PC) are not shown in Figure 78 because data from this TC was highly suspect, given that shunting was observed early in the test and the temperature trace was significantly different from all others at this location later in time.

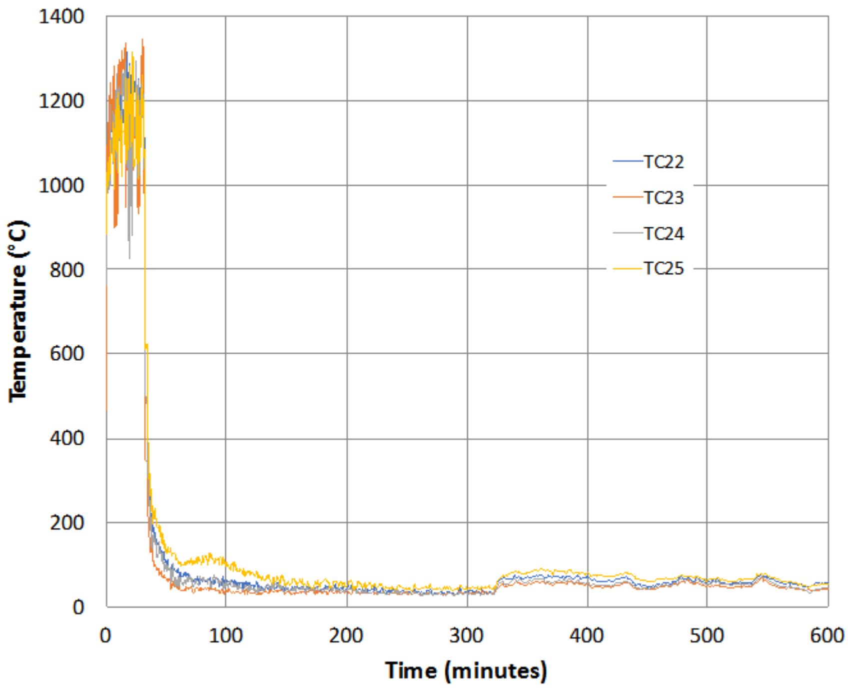


Figure 73. Temperatures measured 4-inches away from the surface of the POC drum outer wall.

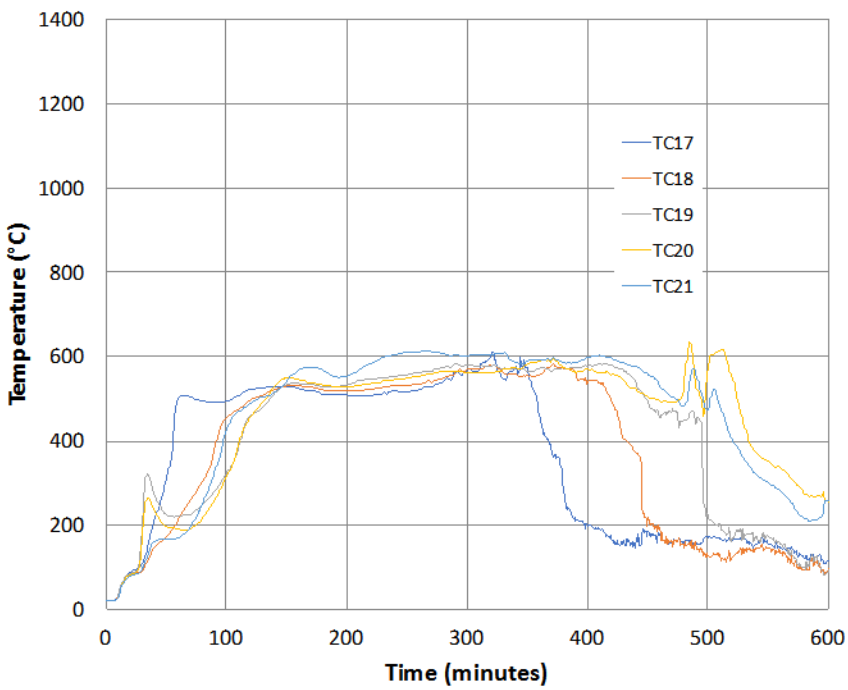


Figure 74. Temperatures measured close to the inner wall of the Celotex® side wall cylinder.

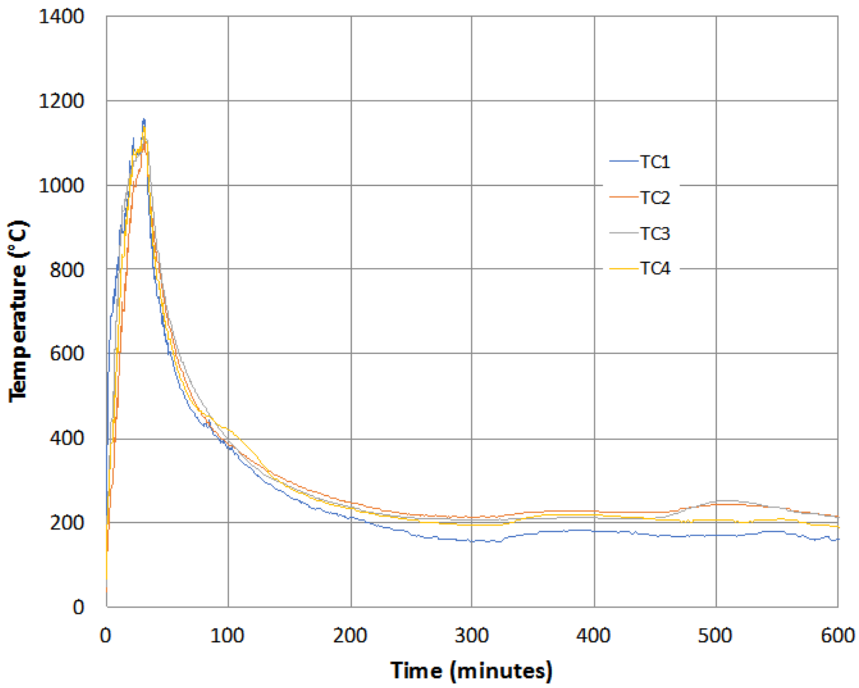


Figure 75. Temperatures measured on top of the PC lid.

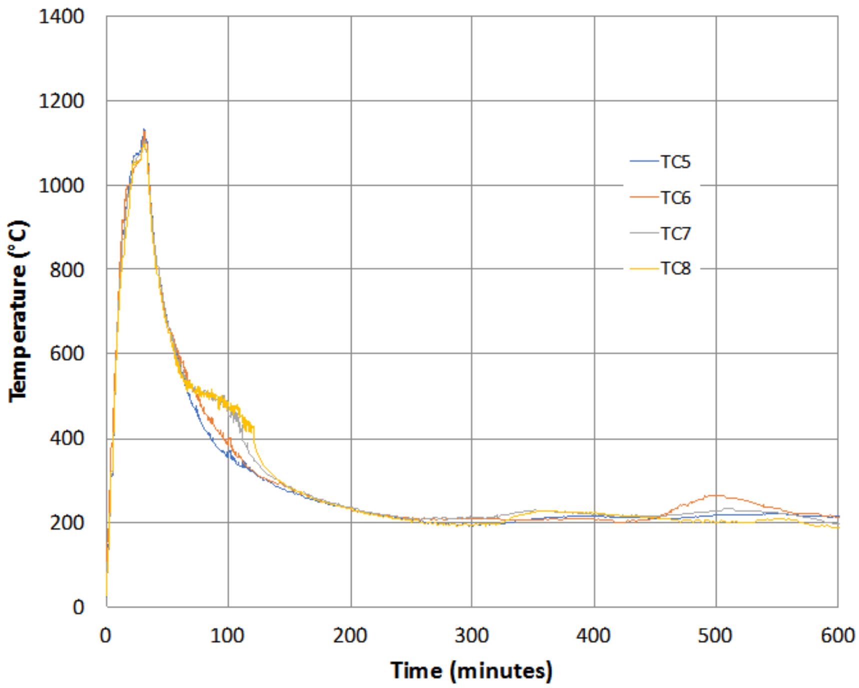


Figure 76. Temperatures measured below the PC flange.

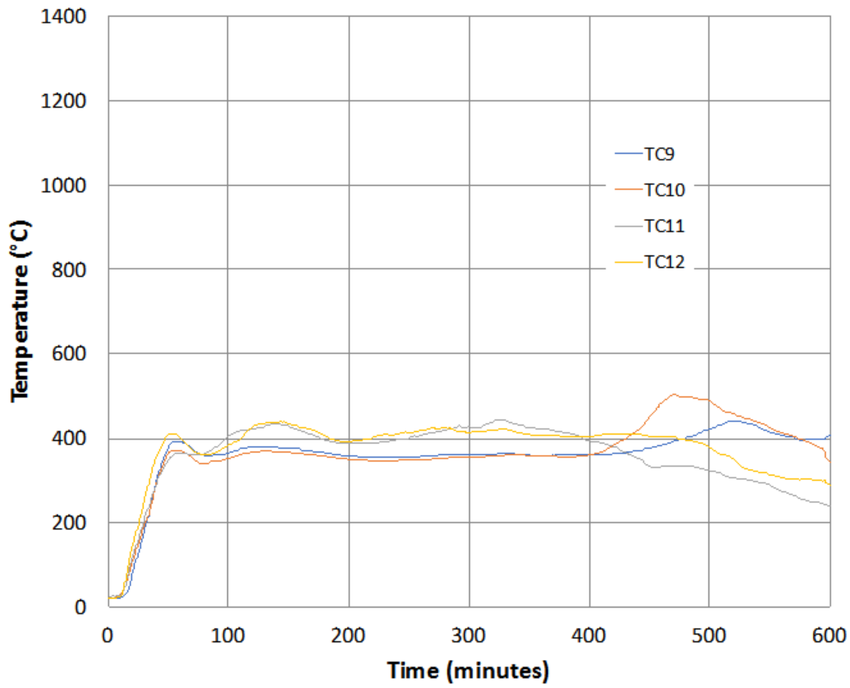


Figure 77. Temperatures measured on the middle of the PC vessel outer wall.

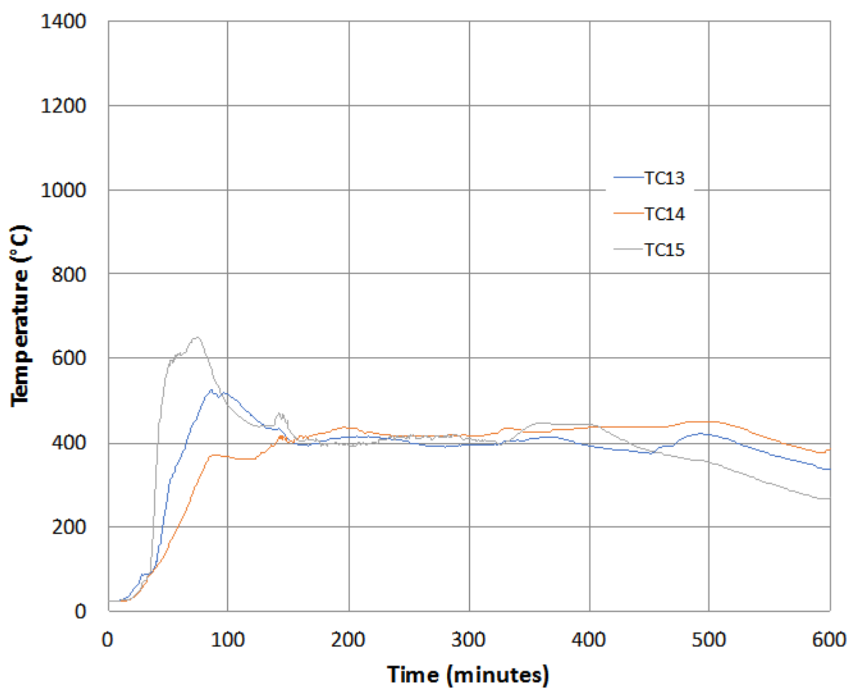


Figure 78. Temperatures measured 1-inch from the bottom of the PC vessel.

Temperatures reported on the outside of the drum in Figure 73 are not the drum wall temperatures, but flame temperatures. These TCs were installed to corroborate the drum was fully engulfed throughout the test. Peak flame temperatures were above 1200°C, and average flame temperatures were close to 1200°C, both temperatures much higher than what was measured in Phase I and II. The reason this is the case is that in Phase III the fuel pool was surrounded by an insulated fence to prevent winds from tilting the plume and exposing the drum to the environment. The fence limited energy release from the fire plume to the relatively cold environment and provided additional radiation feedback to the POC drum. This test was more severe that the tests inside FLAME.

In Figure 74, the highest temperatures are observed initially at the top of the Celotex cylinder and the lowest temperature at the bottom, as expected. After the fire is over, temperatures measured in the Celotex® continue to rise. The reason for this behavior is that at some point during the test, the Celotex® begins to burn. However, it is not clear from this plot alone why the temperatures of TC19 and TC20 rise quicker than other TCs closer to the top and bottom of the Celotex® near the end of the fire, and why shortly after the fire the temperatures of these TCs fall. Also, it is not clear why TC21 rises above all other TCs in the Celotex® after 45 minutes. Starting at 140 minutes, TCs inside the Celotex® measured about the same temperatures, as expected. This trend continues until after 350 minutes, when temperatures begin to fall in an expected manner. Beginning at 350 minutes, the Celotex® temperatures begin to drop starting from the top, suggesting this to be the time at which Celotex® or char material begins to recede, exposing the TCs. That is, thermocouples at the top of the Celotex® begin to cool first. It is believed that as the Celotex® decomposes downward inside the drum, TCs begin to be exposed to the cooler environment. Closer to the bottom, the Celotex® and plywood continue to burn; therefore, TC temperature drop is less predictable the closer the TC is to the bottom of the Celotex®. After the test, the drums were inspected and it was found that most of the TCs measurement junctions remained close to their original location, some resting on the inner wall of the drum or the PC.

During the fire test, the highest temperatures on the PC were measured at the PC lid and flange area, followed by the mid-section of the PC vessel, and then the bottom of the PC, with some exceptions. Within a given height, temperature readings were uniform around the circumference of the PC during the fire. Temperatures on the top of the PC lid and on the underside of the flange reached temperatures almost as high as the fire temperature by the end of the test because the TCs were exposed to the flame from the start of the test. Once the fire ended, temperatures at these locations drop quickly. At the end of the fire, temperatures on the mid-section of the PC were less than 260°C, and on the bottom, less than 100°C. However, temperatures measured at these locations continue to rise due to (1) heat transfer from the PC flange down to the bottom of the PC vessel, and (2) burning of the Celotex®. After 40 minutes, TC15 records higher temperatures than any other TC at the mid-section of the PC. The same is true for TC14 after 60 minutes. Note that between these times and 140 minutes, the Celotex® should still be covering the mid- and bottom section TCs. Therefore, from this plot alone it is not known why TC14 and TC15 show higher temperatures than TC9 through TC12. Between 140 minutes and 500 minutes, TCs at the mid and bottom of the PC measured about the same temperature. Thereafter, their temperatures decrease.

Beginning at 350 minutes, the Celotex® temperatures begin to drop starting from the top, suggesting this to be the time at which Celotex® or char material begins to recede, exposing the TCs. One possibility for TC14, TC15, TC19, and TC20 recording higher than expected before

350 minutes is that burning debris from the very top of the Celotex® fell in the gap between the Celotex® and the PC. It is important to note that TC15, TC19, and TC20 were bundle and routed through the same hole in the bottom of the drum, but TC14 was not. If TC shunting occurred in TC15, TC19, and TC20, it would likely affect TC15, TC19, and TC20 at around the same time, not minutes apart. Moreover, the timing at which TC19 and TC20 fall (40 minutes) also coincide with the beginning of the increase in TC15, and suggest a temperature rise evolution first in TC19 and TC20, and then TC15. TC14 is not located below TC19 and TC20; however, TC14 is only 90-degrees away from TC15 and at the same height as TC15, and follows a similar but lagging rise trend as TC15. All of the above facts suggest the possibility that the abnormal increase in temperatures observed in the plots for TC14, TC15, TC19, and TC20 could be correlated to hot debris falling through the gap between the PC and the Celotex® inner wall.

Figure 79 shows the pressure measured inside of the PC. Initially it was thought that the PC filter ruptured near the end of the test when the pressure peaks at 11psi. However, as discussed below, by this time in the test the loud sound had already been heard and observed in the test video. The rise in pressure up to the peak of 11psi observed could be due to boil off of the liquid inside the PC. More likely, the PC filter failed much earlier in the test. It is speculated that peaks in pressure observed between 5 and 10 minutes indicate the time when the PC filter ruptures. After the test, the temperature near where the pressure gauge was located begin to rise as measured by a TC placed underneath the fuel pool and close to the area. At around 35 minutes after the test starts, the temperature is above the recommended pressure gauge operating temperature, causing the pressure gauge to measure increasingly higher pressures. Therefore, pressures beyond 35 minutes should be ignored.

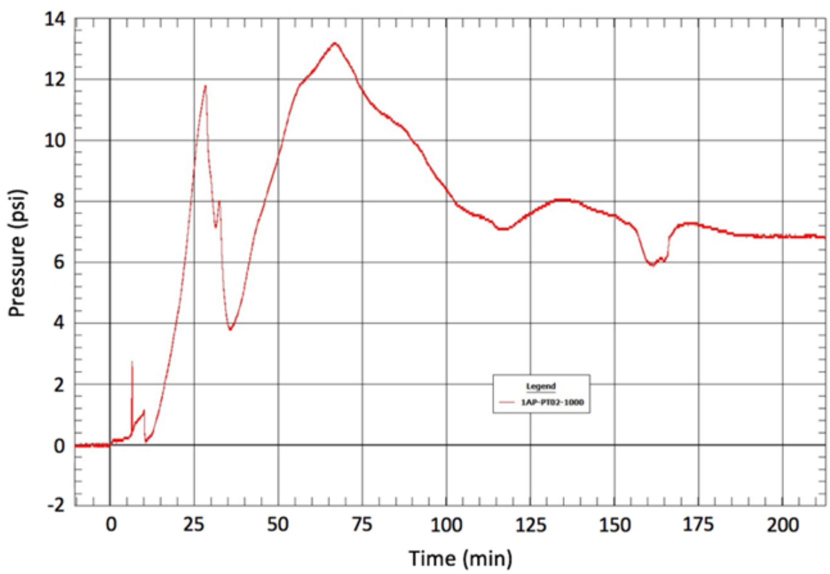


Figure 79. Pressure inside of the PC vessel.

During the test, a loud sound was heard approximately 15 minutes into the test. It was determined after the test (and before entering the test area) from video replay that the sound came from the test cell area. Slow motion replay showed the flexible air hoses connecting the HEPA filter housings to the blowers moving at the moment when the sound is heard in the video. Posttest examination of the test cell first showed the air inlet hose disconnected and severely damaged. In addition, there were traces of green like liquid below the filter housing on the air outlet side. Initially it was speculated that the source of the liquid was condensed Fantastik®.

Figure 80 shows various images near the filter housing after insulation was removed. The left images correspond to the inlet side and the right to the outlet side.

Figure 80. HEPA filter housing and HEPA filters after the test. Images shown on the left correspond to the air inlet side and on the right to the outlet air side.

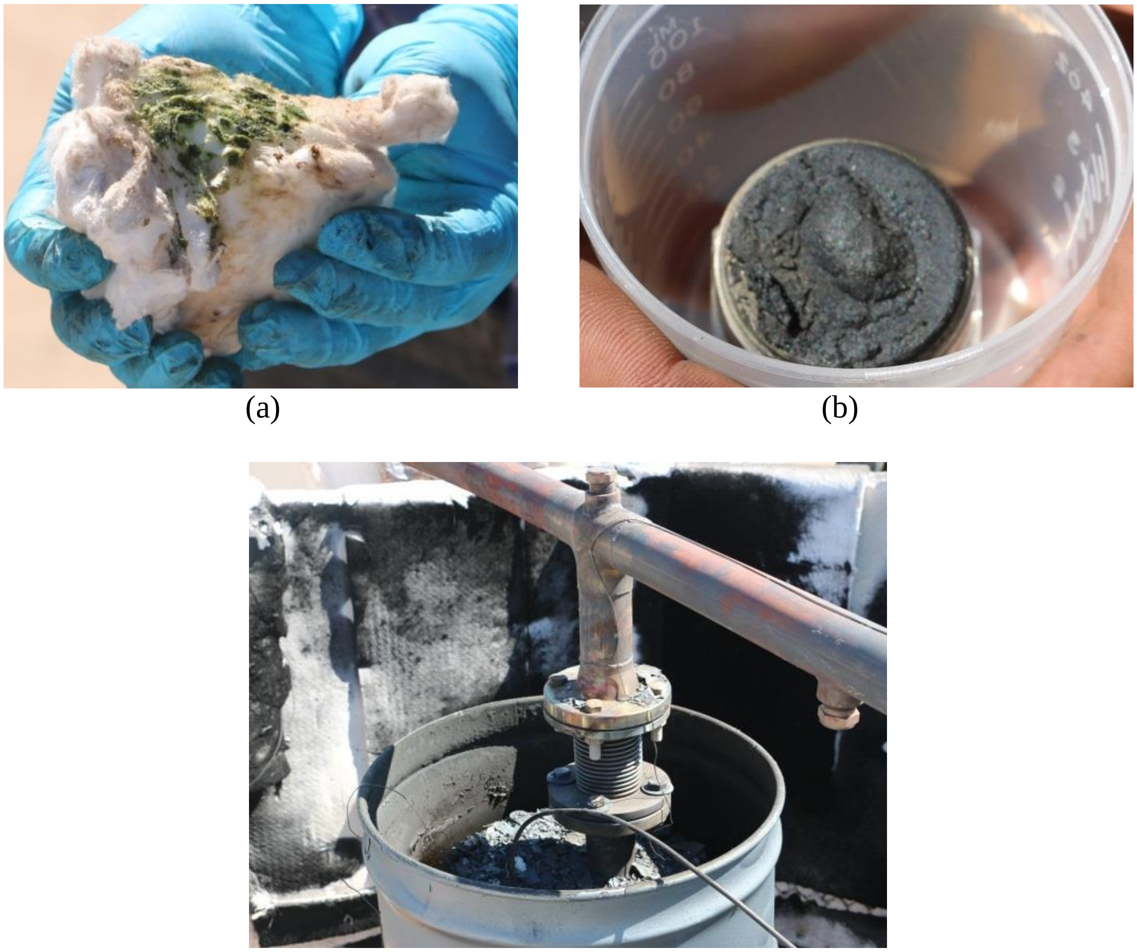
When the insulation was removed from both vertical pipe ends of the aerosol collection system and from the filter housings, evidence of liquid was found on the flanges that connected the pipes to the filter housings and on the outer surface of the filter housings. On the inlet filter side, the liquid seemed to have dripped from the flange down to the housing, and on the outlet filter side, the liquid seemed to have also come from inside the housing right where the filter was located. Once the HEPA filters were removed, it became evident that these filters had been saturated with liquid and soot-like debris during the test. On the inlet filter, the rigid carton frame was covered with soot and some amount of liquid, but the center of this filter seemed to have been mostly burned or blown away, leaving behind just the filter wiring, as shown in the lower left image of the above figure.

Consequently, the loud sound heard during the test and the recorded video is understood to be the result of first an over pressurization of the aerosol collection system initiated by clogging of the outlet filter because of condensation of Fantastik® liquid and deposition of soot. In the video, a slight delay is observed in the motion of the outlet air hose relative to when the inlet hose first jerked. The way the hoses moved in slow motion video replay suggests that once the outlet filter was clogged, a pressure wave rushed first to the inlet side, blowing that filter with a strong force, and then a weaker pressure wave bounced back to the outlet side. Thus, the outlet filter survived, but not the inlet. In addition to the outlet filter and the coupon samples, a sample of the liquid beneath the outlet filter housing was collected for later chemical analysis.

Figure 81(a) shows liquid collected in the insulation just below the inlet filter housing and Figure 81(b) shows the inner side of one of the coupon full of soot. Also shown is the top of the POC drum, after the insulation was removed. As in Phase I, Test 1, and Phase 2 tests, most of the volume between POC drum and the PC was empty; mostly small chunks of char and ash remained beneath the PC. Some debris remained on top of the lid as observed in Figure 81(c).

Figure 82 shows a series of pictures demonstrating the external state of the PC and the region around the flange vessel after the Phase III test. Starting from the top left, the PC is shown outside of the POC with the debris still on top of the lid. The flange was still wrapped with plastic to keep it sealed from the environment. Plastic was added to the flange immediately after it was unbolted from the rest of the aerosol collection system. Once the plastic was removed, samples were taken from the walls of the flange. As expected, there was significant amount of material deposited in the aerosol collection system flange. Most of the material seemed to be black tar, perhaps a mixture from condensed plastic and soot deposition. There was also significant amount of material collected on the inner side of the lid. However, material collected on the lid appeared to be mostly soot. Nevertheless, right were the vent holes were located, large amounts of tar accumulated forming a volcanic-like mass, as observed in the center right image of Figure 82.

When the lid was opened, the O-ring sheared off, half remaining on the PC O-ring groove. It appeared the O-ring had expanded to fill the groove on the top of the vessel. A few chucks were taken out and these immediately broke into small pieces, suggesting the rubber material had become very brittle, as observed in previous tests.



(a) (b)

(c)

Figure 81. (a) Sample of liquid collected on a piece of insulation laying beneath the outlet filter housing, (b) inner side of one of the coupons placed along the aerosol collection system horizontal pipe, and (c) view of the top of the POC drum after the test (Char flakes are observed on top of the PC.)

Figure 83 shows the remains of the material inside of the PC after the Phase III test. Soot was dispersed throughout the inner walls of the PC with tar accumulated heavily near the very top of the PC. As noted in this figure, a tar sample was collected from the inner wall of the PC near the top of the PC vessel for later chemical examination. Only about ¼ of the volume of the PC appeared to be filled with charred material and ashes. During inspection, a long rod was inserted into the PC to ascertain if there was any visible intact material near the bottom, but none was observed as far as could be inspected without lofting material. The material remaining inside the PC was collected inside a bag, but some soot and tar remained attached to the inner PC walls because it was difficult to extract. The contents of the bag were weighed (minus the bag) afterwards; only 1.28kg out of the original 5.92kg remained, about 20% of the original mass. After weighing the contents, the bag was shaken and the inside was inspected again after the ashes had settled. With very few exceptions, all the content appeared to be charred. Thus, it is believed that DR >> 0.8. For all practical purposes, it has been concluded that the DR was approximately1.0.

Figure 82. State of the PC after the Phase III test.

Figure 83. Inner contents of the PC after the Phase III test.

Samples from material collected on the liquid deposited beneath the outlet filter housing, the HEPA filter, the aerosol collection system coupons, the aerosol collection system flange welded to the PC, the inner top wall of the PC, and inside of the PC were examined for traces of CeO_2. Prior to sample analysis, a residual analysis of all media was conducted to measure for CeO_2. This step eliminated sampling bias. Digestion of the filter and media inside the PC was a two-step process. The first step elevated temperature immersion in nitric acid with the media in high-pressure microwave digestion vessels. After heating, in the second step, these vessels cooled and H_2O_2 solution was added to the reaction. The vessels were then sealed and heated. This step resulted in complete digestion of CeO_2 and media. The solutions were then prepared for analysis on an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS, PerkinElmer, Nexion 350D) by dilution and reduction of the nitric acid to a level of 3%. The samples were analyzed quantitatively to determine the Ce concentration in solution. The analysis was performed using NIST traceable standards, to ensure accuracy. Because only Ce concentration is measured, the CeO_2 levels in the original material were calculated with a conversion factor of 1.23. This technique has an accuracy of better than +/-10% of the measured value. Limit of detection for the solid materials and the liquid solutions on the ICP-MS were determined to be 0.5 μg/g and 0.05 μg/g, respectively. Results of the residual analysis, prior to the Phase III test, are shown in Table 6.

Table 6. Residual analysis results of all media used in Phase III.

Media	Residual Analysis
Kim Wipes (Kimberly-Clark Wypall, Model L40)	No Cerium Detected
LANL Bag-14-PVC	No Cerium Detected
LANL Bag-3-SPVC	No Cerium Detected
Fantastik ® Cleaner	No Cerium Detected
Koch Filter Media (Model 102-700-009 MERV 13)	No Cerium Detected
PC Carbon Filter	No Cerium Detected

Samples from the Phase III test were identified as an unknown liquid material from outlet end, six witness coupons with residue on the ends and two filters identified as outlet end and inlet end. The inlet end filter was reduced to primarily charred residues. The outlet end liquid was determined to be ~7.5g of liquid. A sample was taken of the liquid and diluted in 2.5% nitric acid and analyzed for cerium content. The residue was scraped off the witness coupons, weighed and digested and analyzed to determine cerium content. Three samples of approximately 0.1g were cut from the outlet end filter, weighed, digested and analyzed, to determine cerium content. Three pieces of residue from the inlet end filter were weighed, digested and analyzed to determine cerium content. The weight of the outlet end filter and residue was 400g. The weight of the recovered material inside the PC was approximately 1243.4g. Analysis of the PC content was primarily conducted to get an estimate of the ARF from a mass balance (what remained inside the PC versus what was originally inside the PC before the test.) The results of the analysis are shown in Table 7.

As expected, the largest concentrations were observed inside the PC vessel. However, because the uncertainties in the chemical process utilized to extract the Ce from the collected material inside of the PC after the test is high, the upper bound of the Ce recovered (141g±9.5g) can be higher than expected (144g originally in the PC), making it difficult to determine a credible ARF. A lower than expected concentration was observed in the flange. It is possible that when the PC filter ruptures, the highest aerosol concentrations get released from the PC and because the PC lid is hot, the gas rises quickly with the aerosol. Later, when the fire is consumed and the flange begins to cool, the material release from the PC condenses in the flange and is mostly tar and soot with little CeO_2 per unit mass. Thus, what is collected in the flange has low concentrations of CeO_2. A high concentration of CeO_2 was also measured in Coupon #2. As noted in Figure 19, Coupon #2 was 42 inches from the T-junction. Because of the incoming cold air is likely to mix with the hot gases somewhere between Coupon T and #1, it is possible a larger portion of the Ce aerosol condenses in Coupon #2 versus in all other coupons. Smaller amounts were found in Coupon #3, the outlet filter, and in the liquid. All other locations registered much lower mass concentrations than the uncertainty in the chemical analysis measurement.

Table 7. Phase III results from aerosol sampling system.

Location	Total Mass Collected (g)	Ce in the sample (μg/g)
Material inside PC	1243.6	114000
Wall of the PC	10.4	60
Flange welded to the PC	8.6	1.2
Coupon T	0.0010	<0.5
Coupon 1	0.0153	<0.5
Coupon 2	0.0268	12.2
Coupon 3	0.0615	0.5
Coupon 4	0.0903	<0.5
Coupon 5	0.2173	<0.5
Outlet end sample 1	400	<0.5
Outlet end sample 2		<0.5
Outlet end sample 3		3.9
Inlet end sample 1	–	<0.5
Inlet end sample 2		<0.5
Inlet end sample 3		<0.5
Outlet end liquid	7.5g	0.97

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. Phase I, II, 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 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 because of internal pressurization of the POC.

Inside the fuel pool, results of this test series 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 the current POC drum lid design, there isn't sufficient release of gas from inside the POC drum to prevent over pressurization even after the drum ring seal has burned off and the POC filter drum vents. Because the drum lid gets ejected early in the test (3 minutes), a significant amount of Celotex® is expected to burn during the fire. Moreover, even if some of the Celotex® remains after the fire, it is expected to burn completely after the fire without external intervention. As shown in Figure 32 and Figure 33, temperatures near the bottom of the PC continue to rise well beyond the end of the fire because of the continued combustion of the Celotex®.

Table 8 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.

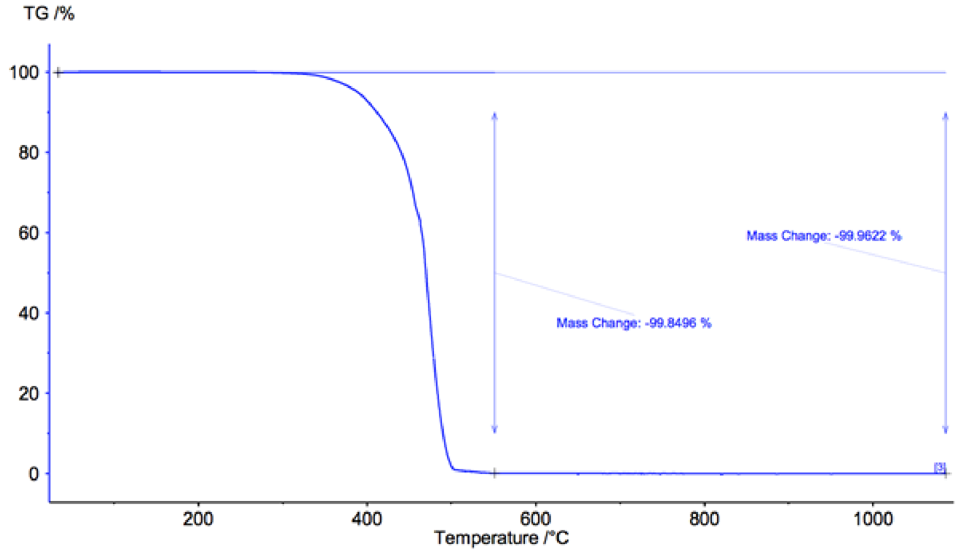
Table 8. Maximum PC temperatures observed in drum A in Phase I tests.

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

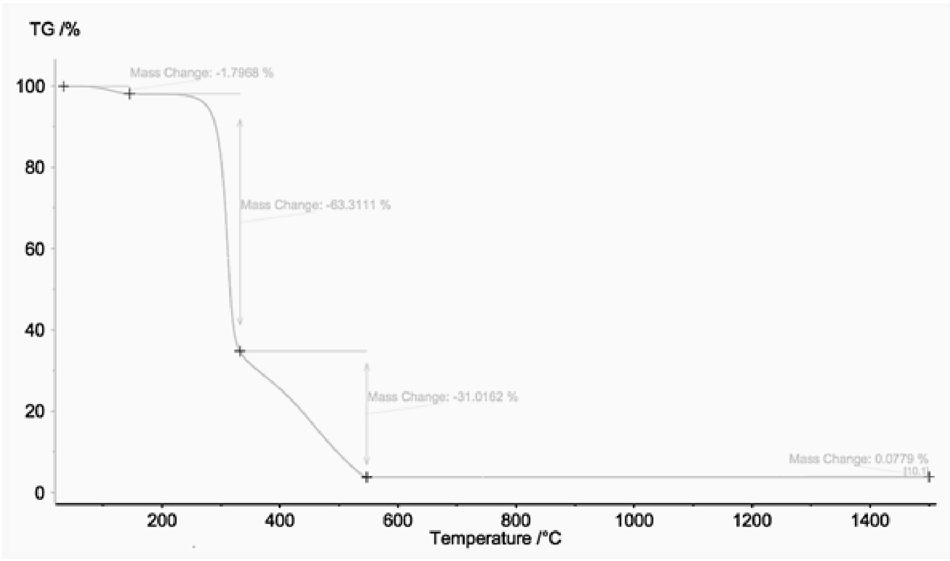
Lewallen (1972) studied thermal response of Celotex® in military standard drums and concluded that Celotex® begins to mechanically degrade at temperatures close to 140°C. More recently, Anderson (1992) suggested decomposition begins somewhere between 149 and 177°C through testing of DT-18 shipping packages. Since the PC outer wall reaches this temperature towards the end of fire in Phase I, Test 2 (see Figure 52), it appears the Celotex® is still intact on the interior (and next to the PC vessel) for most of the 60-minute fire when the lid remains. However, post-fire temperatures will lead to a significant amount of damage to remaining intact Celotex® in the case of a 60-minute fire with no post-fire external intervention. For a 30-minute fire, the Celotex® is expected to survive throughout the fire test, with some damage after the test, but not enough to compromise the interior of the Celotex® per the findings of Lewallan and Anderson.

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 8. 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, suggesting the Celotex® will remain mostly intact outside of the fire. Post-test analysis confirms the interior of the Celotex® remains in good conditions for the 60-minute case; therefore, for a 30-minute fire, little damage is expected from results of Phase I alone. Indeed, results of Phase II 30-minute fire tests corroborate this conclusion. Note however that a larger diameter fire may result in more damage to POCs adjacent to the fuel pool. Typically, with a larger diameter fuel pool there is not enough fuel in a nuclear waste storage facility to extend the fire this long. A larger diameter fire will result in a shorter duration fire given the faster recession rate associated with a larger fuel pool. A 4x4m fuel pan with 90 gallons of a mixture of diesel and gasoline will burn for less than 10 minutes, much shorter than the current fire.

Figure 84 shows results of Thermogravimetric Analysis (TGA) done on the plastic and cellulose materials obtained from TA-55 at LANL.



(a)



(b)

Figure 84. TGA results in air from typical materials inside the PC: (a) high density polyethylene and (b) Kimwipes®.

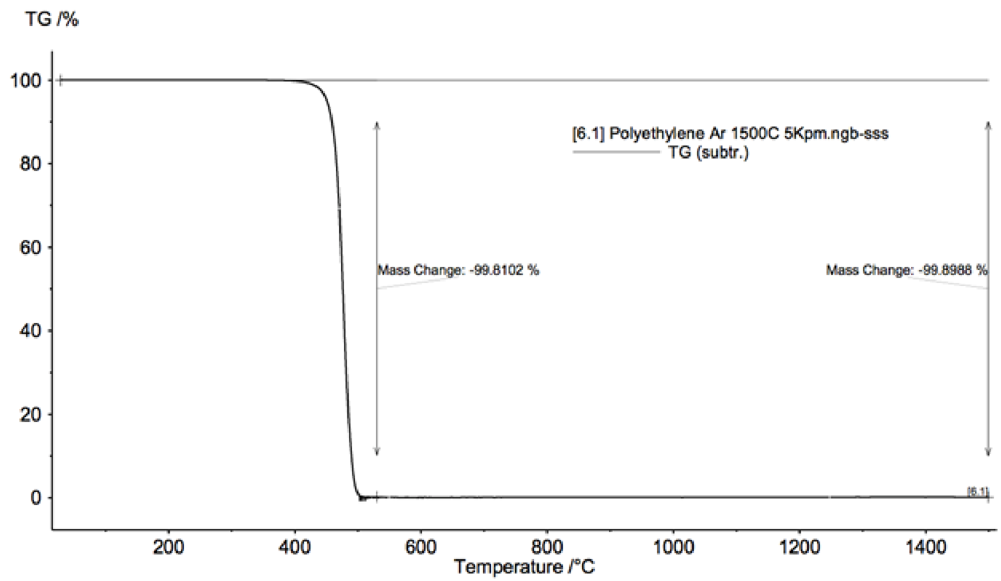
These are typical materials placed inside the PC and by far they account for the largest mass inside the PC based on the material inventories obtained from TA-55 at LANL. In the presence of air, the high-density polyethylene plastic begins to decompose around 400°C. The cellulose material analyzed, Kimwipes®, 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®.

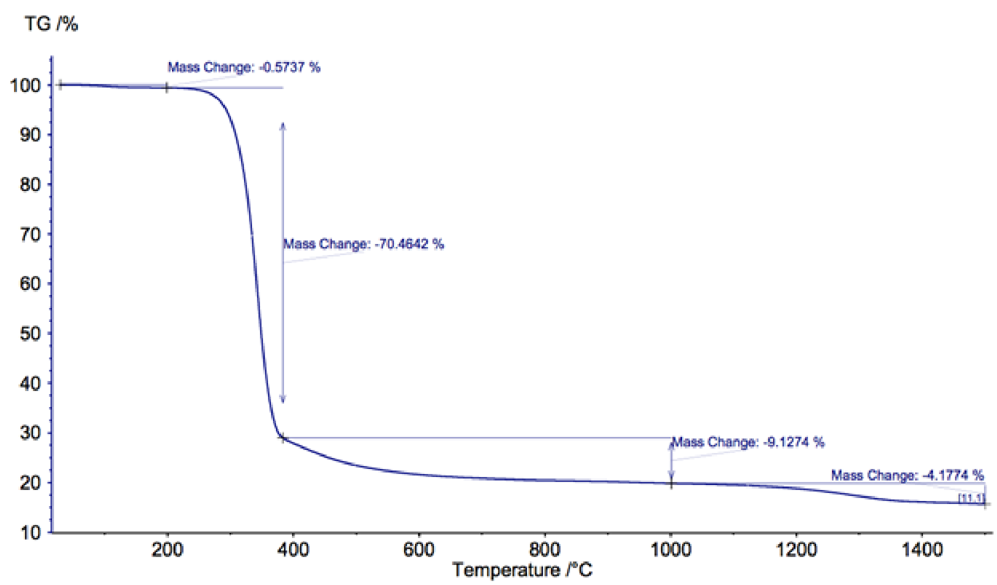
In argon, decomposition of these materials starts at lower temperatures, as shown in Figure 85. Even using the more conservative temperatures shown in this figure, these materials never reach the point where they start to decompose if the drum lid is not ejected.

Given the temperatures on the outside walls of the PC and at the center of the PC, and the above TGA results, it is highly probable that there will be no melting of the high-density polyethylene and decomposition of the cellulosic material inside the PC when the POC drum lid remains in place throughout a 30-minute fire. When the drum lid and other components inside the POC get ejected, melting of the high-density polyethylene and decomposition of cellulosic material is certain in a 30-minute fire and under the conditions tested in this test series 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. This was corroborated by the Phase III test, where most of the cellulose combustibles in the PC appeared burned with no trace of the plastic inside the PC. 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 Phase III, the aerosol collection system was designed to collect samples of materials potentially released from the PC. Combustibles placed inside the PC were deemed typical based on data obtained from TA-55. However, it has since been acknowledged that the amount of Fantastik® inside the PC was higher than expected given that the combustibles are dried for a relatively long time (days or even weeks) and that the bag-out bags are checked for visible signs of moisture before they are placed inside PCs. This procedure was not followed in Phase III. Therefore, it is likely that more CeO_2 aerosol was released than expected under typical loading conditions. Higher amounts of moisture inside the PC will lead to higher pressures inside the PC at higher temperatures due to liquid boil off. However, the process leading to resuspension of particles is more complicated than simply accounting for the additional pressure that results from surplus amounts of liquid inside the PC. Pyrolysis of material can, for example, lead to suspension of micron size particles and agglomeration of CeO_2 aerosol with other particles floating inside the PC can also enhance release of CeO_2 aerosol. As such, it is difficult to predict based on data obtained from Phase III how much CeO_2 aerosol would have been released had there been less Fantastik® inside the PC. Moreover, given that the aerosol collection system was not designed to collect all material released from the PC during the test, it is difficult to give an ARF estimate here. Without further tests designed to collect all material release from the PC, this is the best that can be offered.



(a)



(b)

Figure 85. TGA results in argon from typical materials inside the PC: (a) high density polyethylene and (b) Kimwipes®.

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 8, 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 86 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 [5] compares well with the data collected, which gives confidence on the heat flux measured with the HFGs deployed in these tests. This data is only applicable when Jet-A is used as a test fuel and under the conditions of these tests in FLAME.

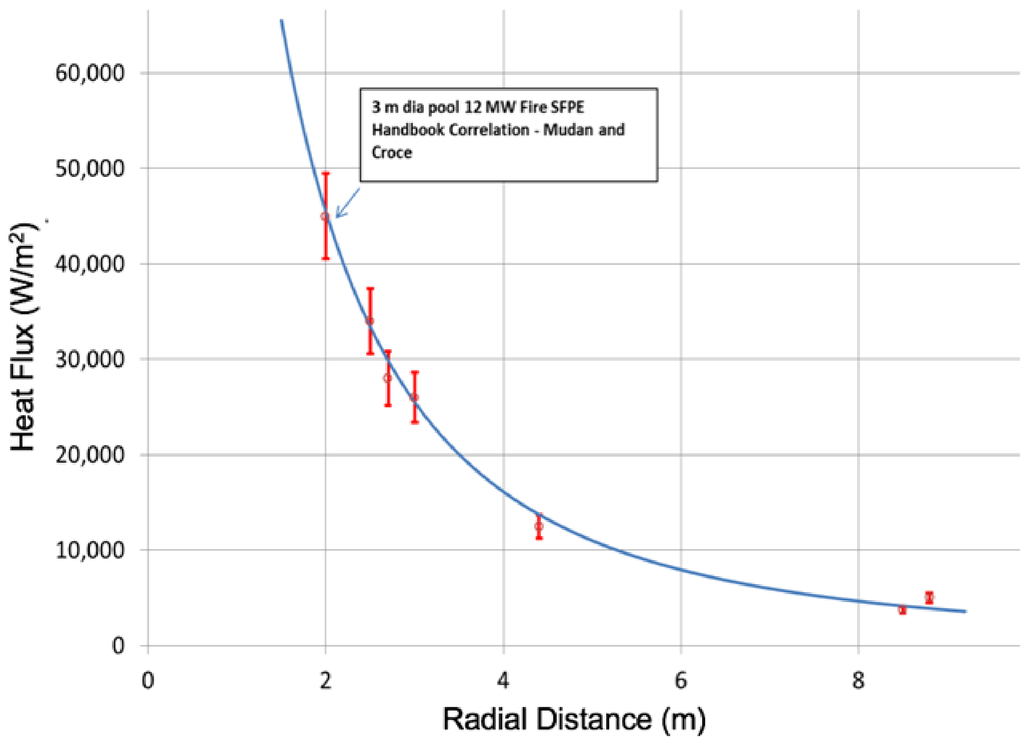


Figure 86. Heat fluxes measured inside the test cell using HFGS. The solid line represents results from the correlation given in (Drysdale, 2007).

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 [7], 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 $45kW/m^2$. However, it is recognized that a larger diameter fire could results in a different outcome. Note, however, that a larger diameter fire with the same amount of fuel will results in a shorter burning time.

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=1 for 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.

Results of Phase III show that for a POC engulfed in the fire, the DR will be one and with all likelihood the ARF will not be zero. While the PC in Phase III was loaded with typical combustibles, the amount of Fantastik® used may be higher than expected given that the wet Kimwipes® were not dried for a period of time before placing them into the bag-out bag, as typically done in TA-55 for example. Also, the amount of CeO_2 is closer to the maximum allowed inside a PC. Furthermore, the fire in Phase III was typically hotter than expected for outdoor burns; although, it is possible that such high heat flux fires can be experienced in a fire enclosure. More tests have been recommended to determine the ARF if the current POC design remains at storage sites.

Finally, predicting the exact ARF is more difficult because it requires that an attempt be made to (1) collect all the material released from the PC in a hostile thermal environment using an aerosol collection system, (2) extract as much material as possible from inside this collection system, (3) carefully process material extracted to obtain uniform representative samples, and (4) accurately analyze samples using established chemical analysis methods. All these steps incur some uncertainty, which leads to accumulated errors in the ARF estimate.

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.

In Phase I and II, the fuel consumption rate was 0.30kg/s; therefore, in 3 minutes the fire would have burned approximately 54kg (17gal) of fuel. Temperature data collected in Test #1 of Phase I showed temperatures inside the PC are sufficiently high to melt or decompose typical materials (i.e., high-density polyethylene and cellulosic material) inside a PC. For the POC 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. Based on Phase II test 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. 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. Therefore, based Phase I and II test data, for POCs inside the fire the DR should be much greater than zero. Results from Phase I and II also suggested that for POCs inside the fire the possibility exists that the ARF will be greater than zero.

Phase III was conducted to try to determine a more exact value for the DR and to ascertain the possibility of releasing aerosol material from the POC. In Phase III, combustibles were loaded into the PC and the POC was placed inside the center of a 4m diameter fuel pool. Because Phase II tests had already demonstrated that the drum lid gets ejected early in the fire (less than 3 minutes), the drum lid, and the top plastic liner and Celotex® covers were not included in the POC. This allowed an aerosol collection system to be placed over the PC filter vent to sample materials released from the PC. The fire lasted for 30-minutes. Posttest examination of the remains of the PC established that the DR is practically one under the conditions tested. Furthermore, chemical analysis of the samples collected inside the aerosol collection system showed that the ARF could be greater than zero if the drum lid is ejected. Both these results corroborated Phase I and II conclusions. Moreover, this test showed the likelihood of bursting the PC is small based on pressure measured inside the PC. Maximum pressures inside the PC were 18psi. This allows for the possibility of designing a controlled test to try to determine the ARF.

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 7As loaded with combustibles, Phase I and II tests showed that 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 IN PHASE I TESTS

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

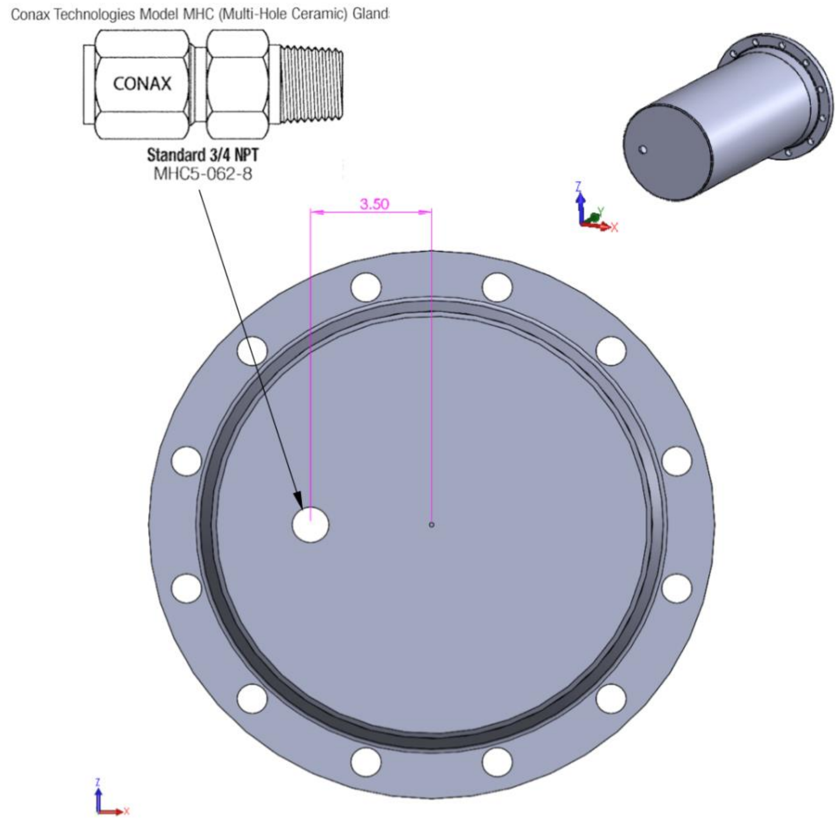
[1] Axial Location Measured from the Base of the Drum

[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

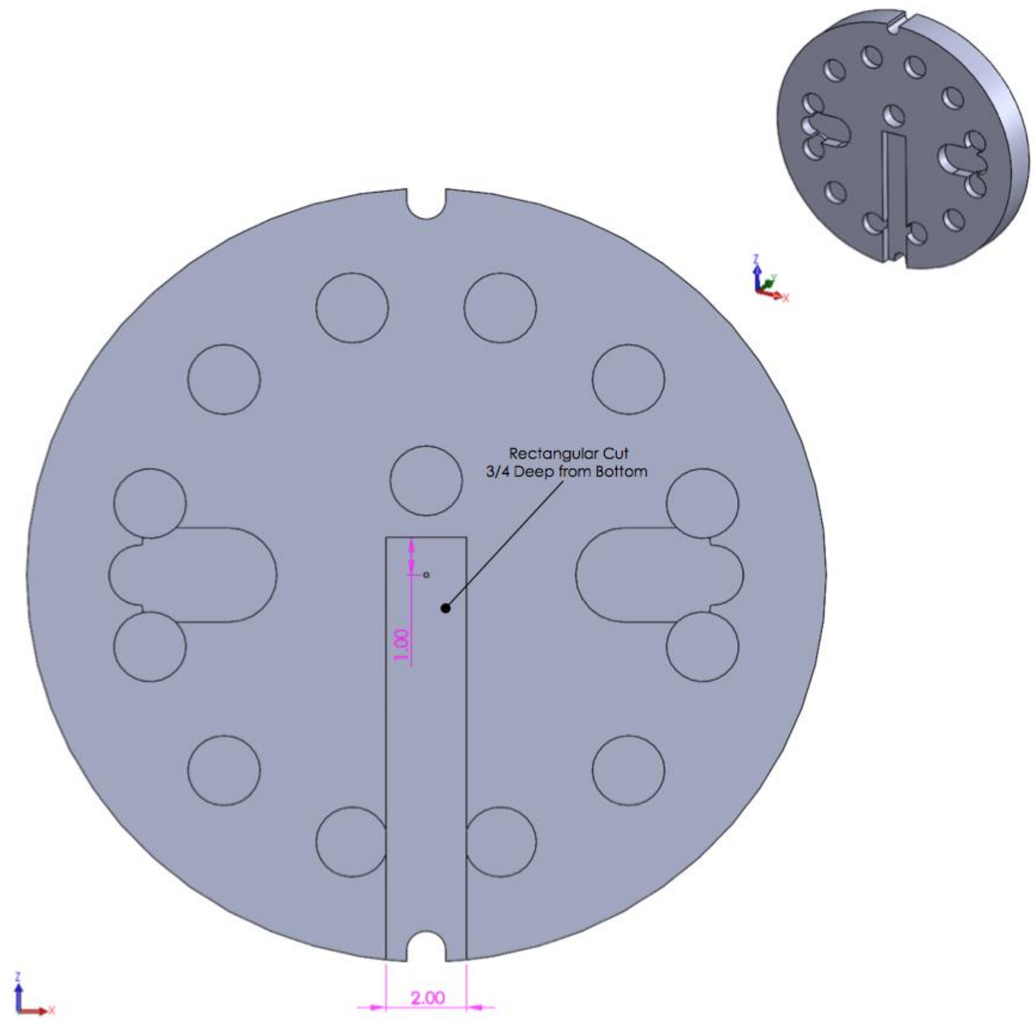


(a)

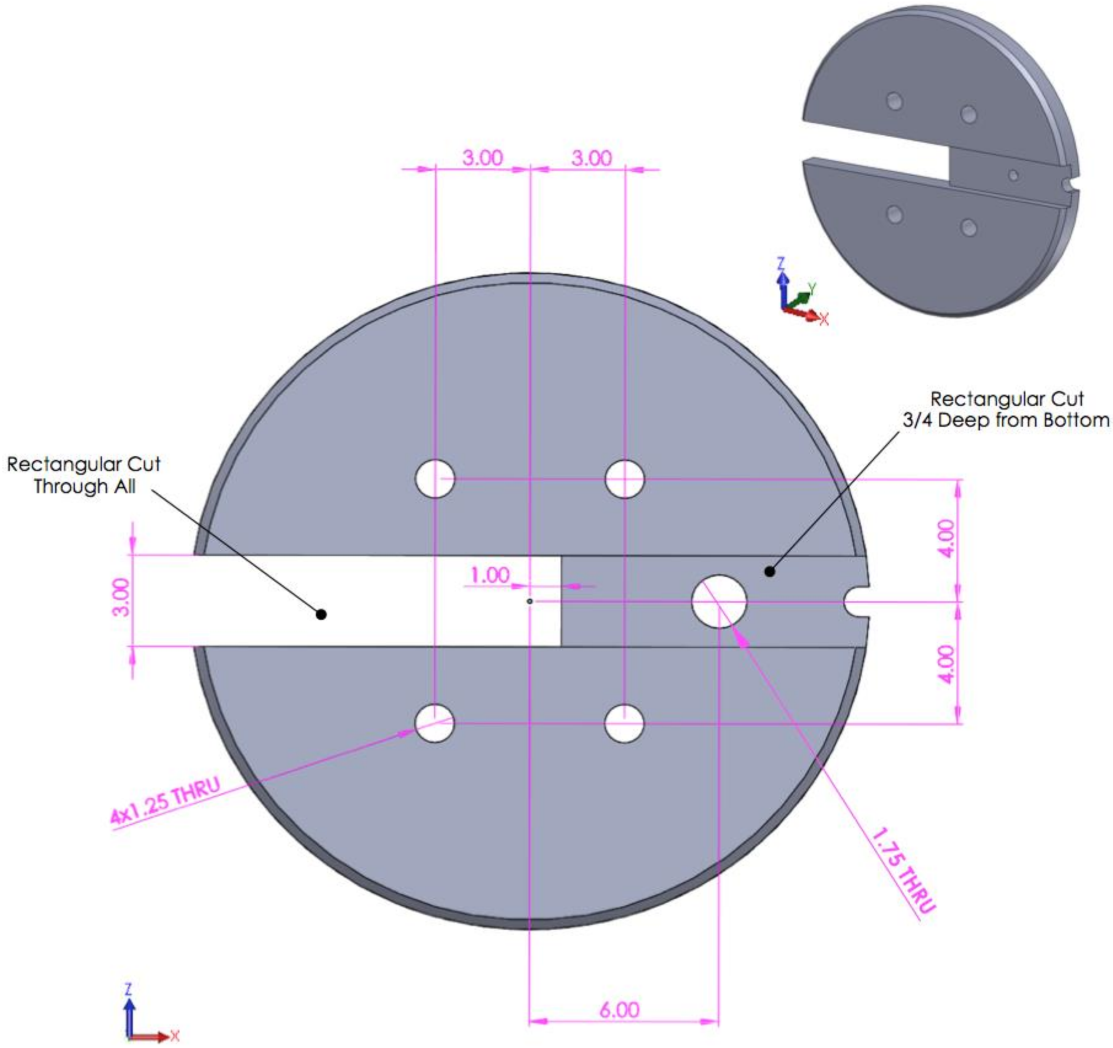
(b)

(c)

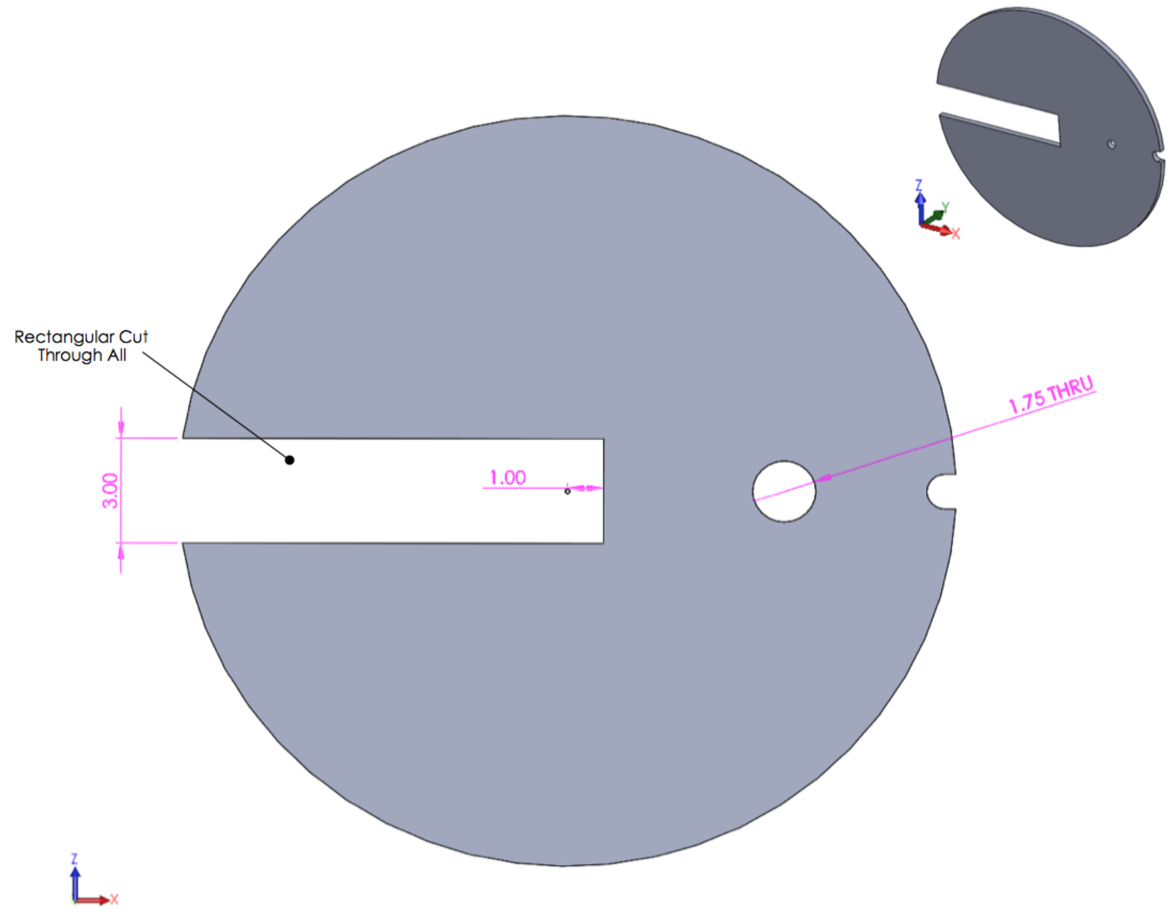
POC-DWG-0006-MOD: (a) One hole on the bottom of the PC at the locations shown. The hole is aligned with the seam on the –x axis. The hole has a Conax Multi-Hole Ceramic Gland seal as shown in the figure. The pipe thread side of the Conax feed-through goes through the hole and is welded outside of the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



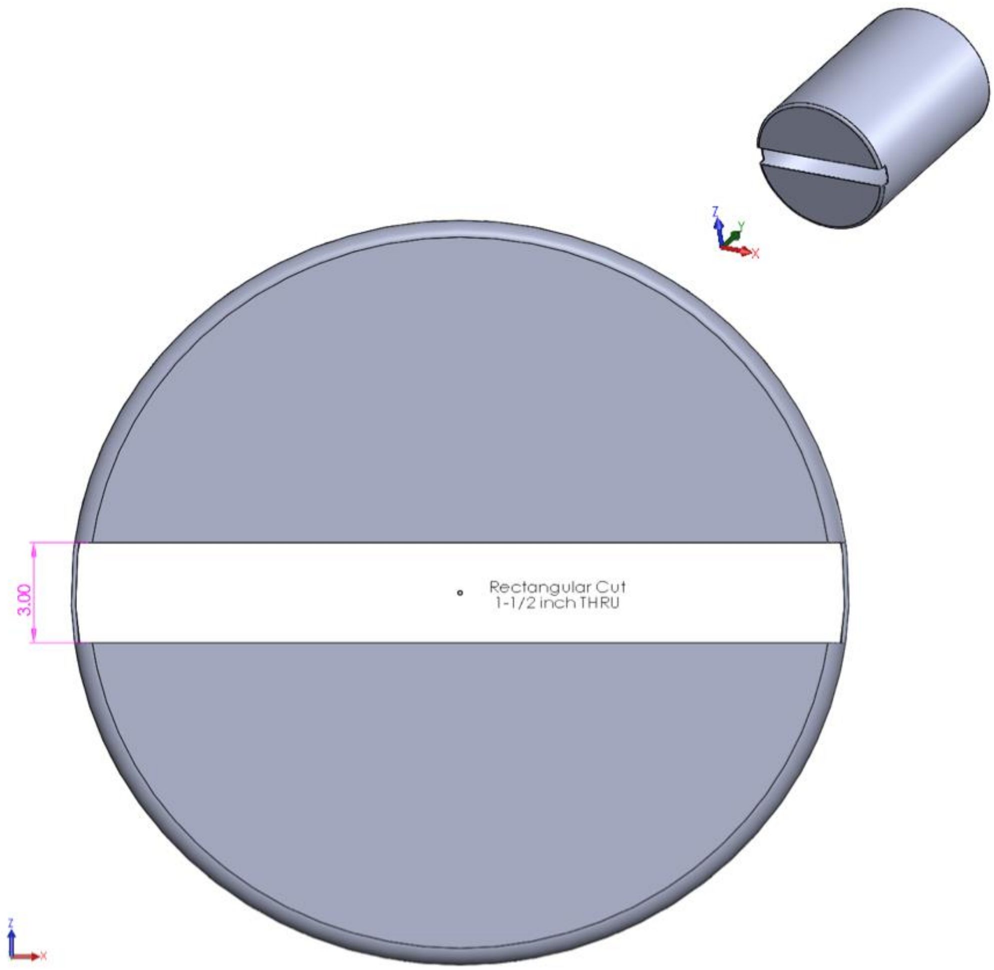
POC-DWG-0007-MOD, Part 2: One rectangular cut on the top fiberboard as shown. The cut is at the 270-degree axis with respect to the seam (0 degree or at +x axis.) The partial cut (3/4" deep) is on the bottom of the fiberboard.



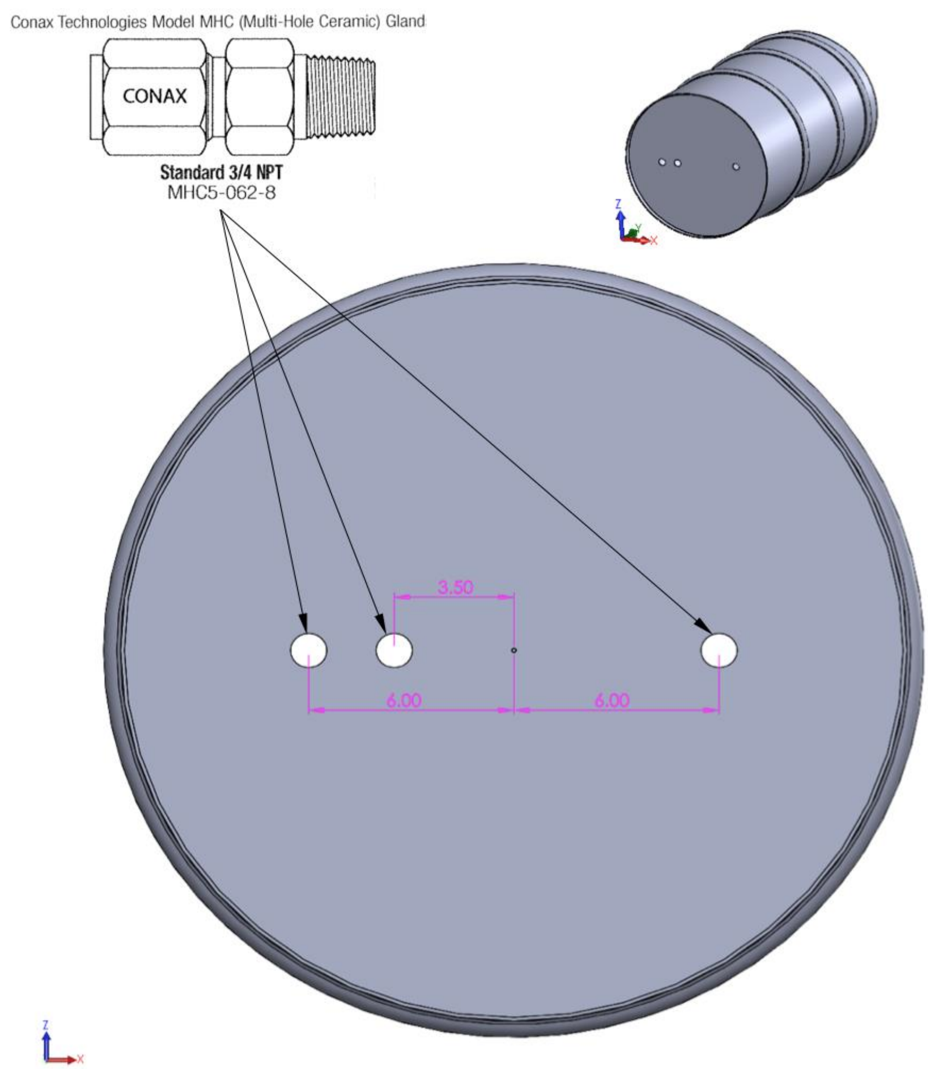
POC-DWG-0007-MOD, Part 7: Holes and rectangular cuts through bottom fiberboard. Each 1-1/4" hole is filled with a 1-1/4" DIA x 1-7/8" steel rod flush with the bottom of the fiberboard (opposite side, not shown). The 1-3/4" hole is for visual inspection of the TC cable leads. The partial rectangular cut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



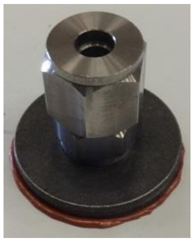
POC-DWG-0007-MOD, Part 8: Hole and rectangular cuts on the bottom plywood. The rectangular cut and the 1-3/4" hole are the same as in the fiberboard. This cut extends nominally 1" beyond the center of the fiberboard. As in the fiberboard, the hole is used for visual inspection of the TC cable leads.

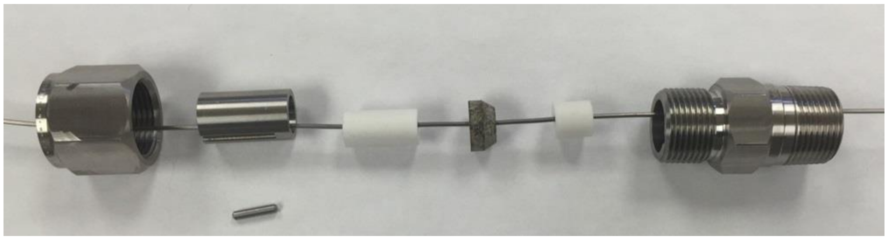


POC-DWG-0011-MOD: Rectangular cut 1-1/2” (nominal) deep through the bottom of the plastic liner.



(a)

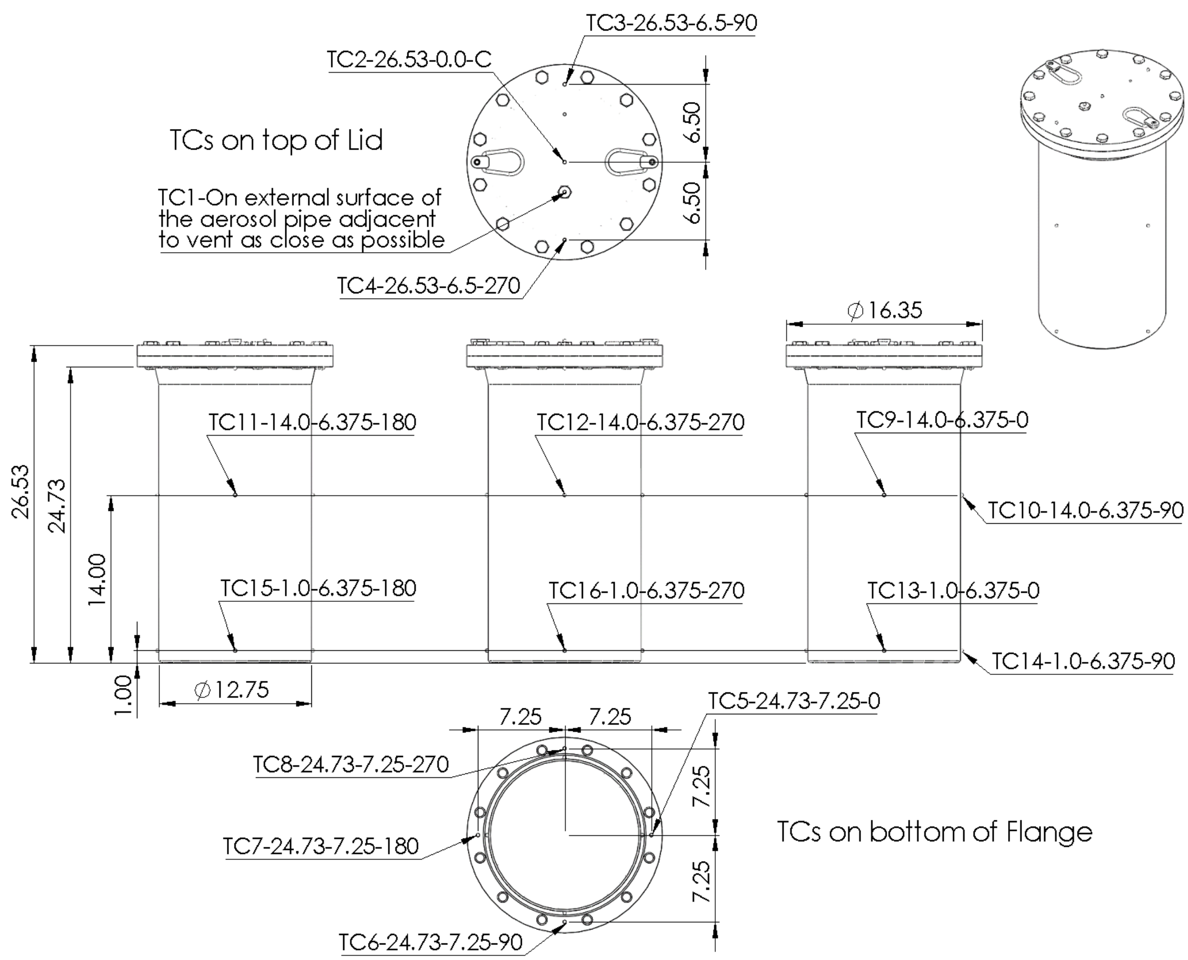




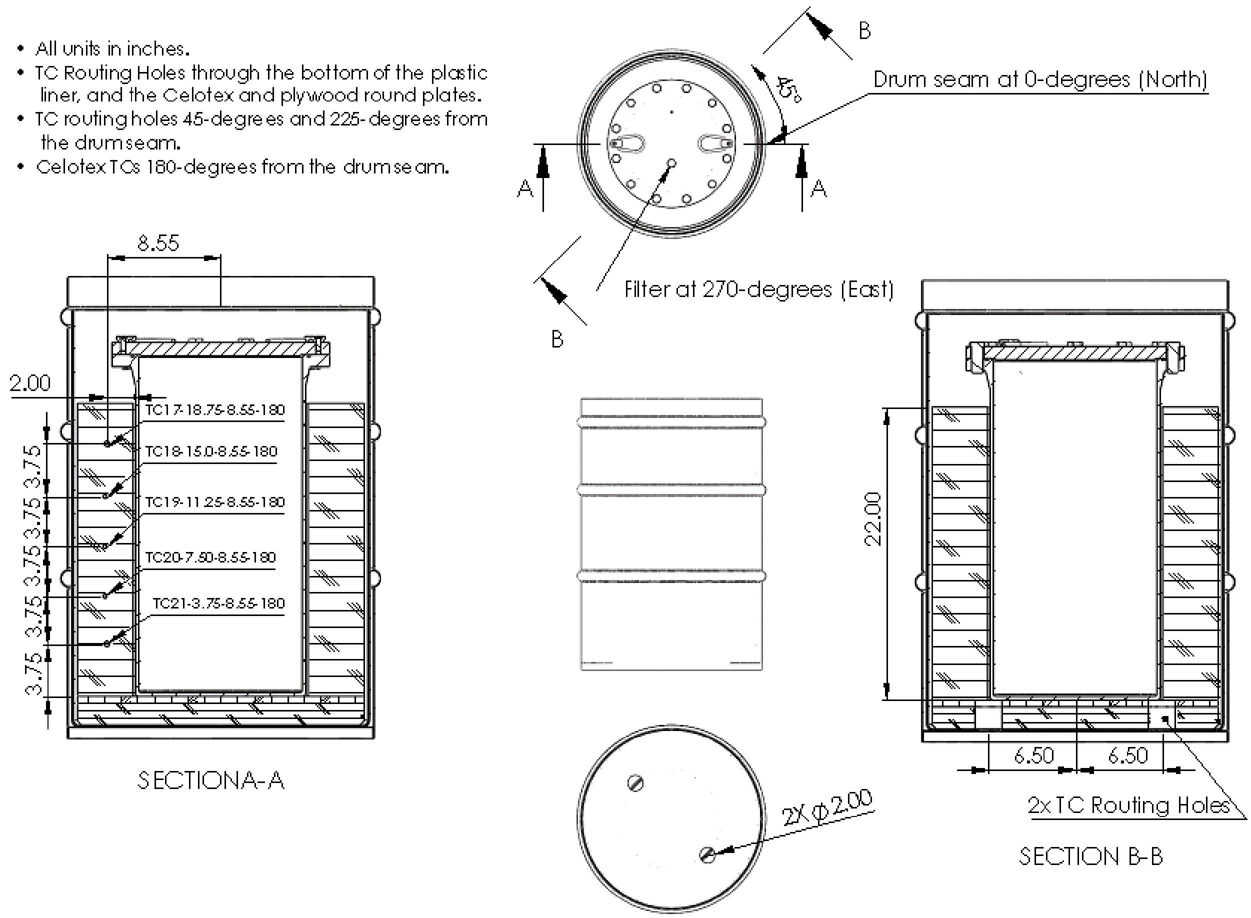
(b) (c)

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.

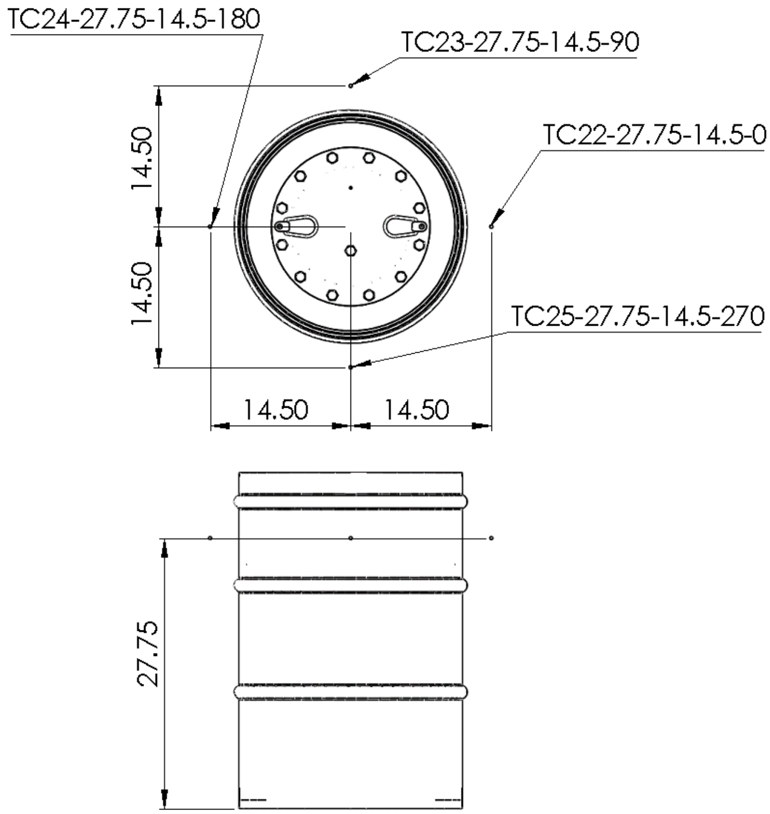
APPENDIX C: LOCATION OF TCs ON THE PC IN PHASE III TEST



TC-LOCACTIONS-PC: Location of TCs on the PC surface shown in the above drawing with views in clockwise order starting with the center view: front, right side, top, left side, and bottom. TC labels are as follow: TC<id>-<height>-<radial distance from center of the PC>-<angle>. If the radial distance is zero, a “C” is used. The PC filter was located on the east side (270-degrees) of the test cell.

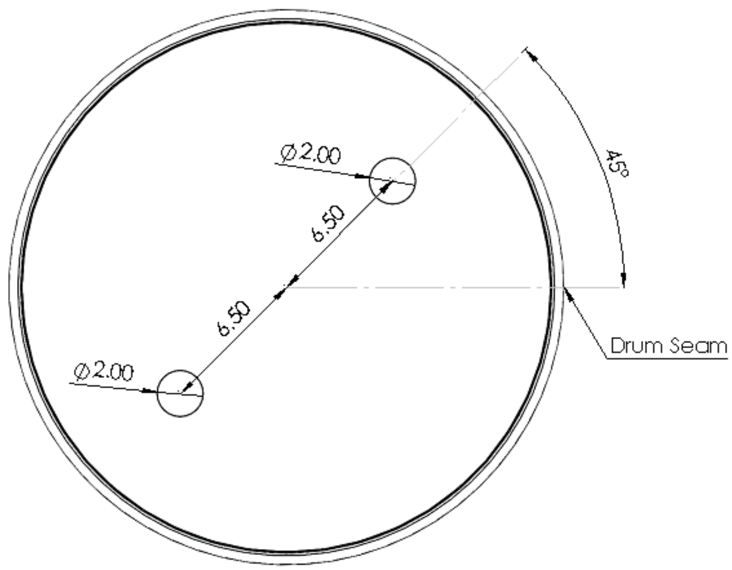


TC-LOCACTIONS-CELOTEX®: Location of TCs in the Celotex® shown in the above drawing with views in clockwise order starting with the center view: front, right side, top, left side, and bottom. TC labels are as follow: TC<id>-<height>-<radial distance from center of the PC>-<angle>. The drum seam was located on the north side (0-degrees) of the test cell.

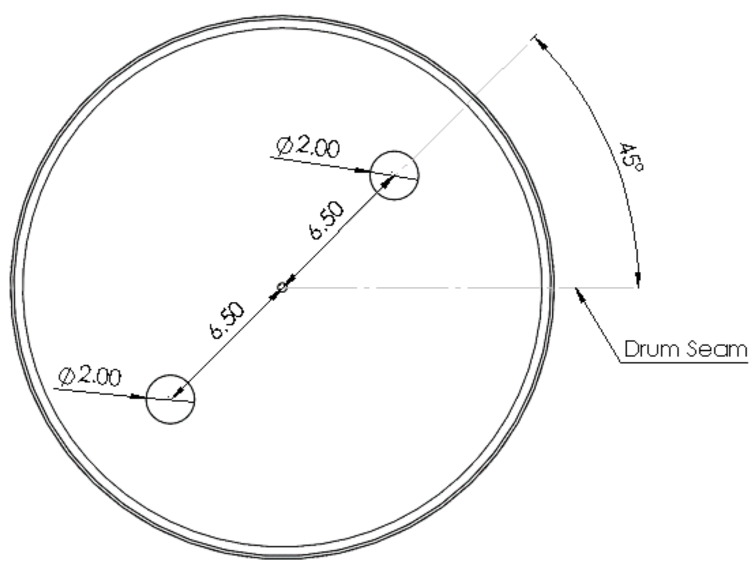


TC-LOCACTIONS-DRUM: Location of TCs on the outside the POC drum shown in the above drawing. Only front and top views are shown. TC labels are as follow: TC<id>-<height>-<radial distance from center of the PC>-<angle>. The drum seam was located on the north side (0-degrees) of the test cell.

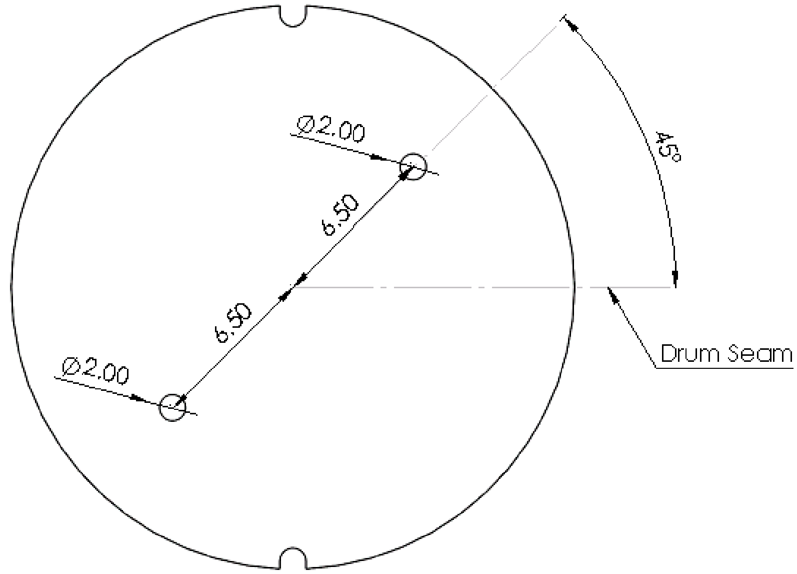
APPENDIX D: MODIFICATIONS TO THE POC FOR INSTRUMENTATION IN PHASE III



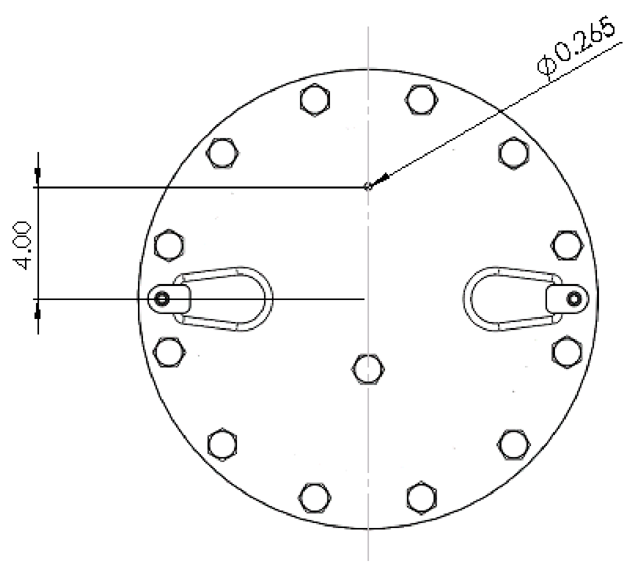
POC-DRUM-MOD: Top view of the POC 55-gallon drum showing holes to be drilled. The angular dimension is given with respect to the seam of the drum. All dimensions shown are in inches.



POC-PLASTIC-LINER-MOD: Top view of POC Rigid Plastic Liner showing holes to be drilled. The angular dimension is given with respect to the seam of the drum and shows alignment of plastic liner with respect to the drum seam. All dimensions shown are in inches.



POC-CELOTEX®-MOD: Top view of Plywood/Celotex (fiberboard) Spacer. The holes penetrate the entire thickness of the Plywood and Celotex spacer at the bottom of the POC. The angular dimension is given with respect to the seam of the drum and shows alignment of spacer with respect to the drum seam. All dimensions shown are in inches.



POC-PC-MOD: Top View of PC. One 0.265-inch thru hole on the PC lid. All dimensions shown are in inches.

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