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Thermal Testing of Waste Packages for a Storage Environment

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Abstract
The Pipe Overpack Container (POC) was developed at Rocky Flats to transport plutonium residues (waste containing higher levels of plutonium than standard TRU waste) to WIPP for disposal. The POC consists of an inner containment vessel (pipe) surrounded by organic fiber dunnage inside of a 200-liter (55 gal.) 7A drum. This inner container, called a Pipe Container (PC), was designed to maintain separation of fissile material (which allowed the total fissile material loading of the TRUPACT-II container to go from 325 grams to 2.8 kg) and to provide shielding from radiation. The POC is also used for on-site storage of this type of material.

In 1997 Sandia National Laboratories (SNL) conducted a series of tests and analyses on POCs to determine the degree of protection they provide 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 drums generating sufficient internal pressure to pop off its lid and expose the top of the PC to the fire environment. The O-ring seal of this PC eventually failed due to the high temperature, and this PC could have released some of its contents if the internal pressure was sufficiently high.

The residues at Rocky Flats were inert materials, which would not generate large internal pressure within the PC if heated. However, POCs are now being used to store combustible TRU waste at Los Alamos (and other DOE sites). Therefore, starting in 2015 SNL conducted a new series of fire tests, this time to examine whether the contents of the PC would reach a temperature that would result in generation of sufficient gas to cause over-pressurization of the PC, and eventual release of some of its content. This paper will describe the various test conducted thus far, present some preliminary results from these tests, and discuss their implications, both for POCs and 7A drums.

Introduction
The Pipe Overpack Container (POC) was not specifically designed to prevent release of stored material during a long-duration fire, but the level of protection for this type of event

was not known. The POC has many design features that are similar to Type B packages that do provide protection from engulfing fires. Figure 1 shows the design features of the POC.

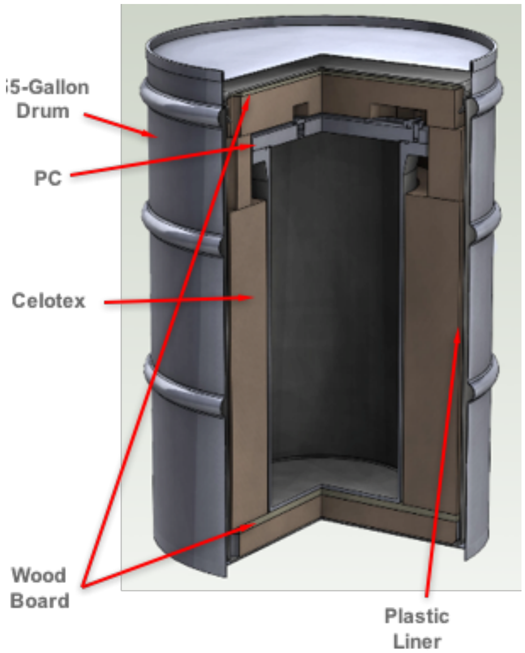


Figure 1: Components of the Pipe Overpack Container (POC). As shown, the inner metal container is called the Pipe Container (PC).

Radioactive waste storage operators would like to be able to claim some level of protection is provided by the POC for thermal assaults that could occur within storage facilities. The tests performed during the 1990s at SNL showed that it was possible for a long duration fire to cause over-pressurization of the outer 7A drum and ejection of the drum lid. Figure 2(a) shows the engulfing pool fire that contained 4 POCs and Figure 3(b) shows the damaged state of these POCs after the fire. Note that one POC lid is rotated off the top of the drum and that the two other lids are severely bowed outward.

In these tests the POC contents were inert materials that would not generate significant pressures within the PC, so even if the O-rings and filter failed, only a small fraction of the radioactive material contained within the pipe could have been released. With the addition of combustible materials in the PC, the possibility exists for generation of much higher pressures, and therefore much higher release fractions. Therefore, a new series of tests was required to determine the amount of material that could be released.

(a)

(b)

Figure 2: (a) Engulfing pool fire and (b) damage to the POCs.

New POC Fire Test Series

During 2015 and 2016, SNL conducted a series of POC fire tests to examine whether the contents of the Pipe Container (PC) inside the POC would reach a temperature that would result in the generation of gas and, subsequent over-pressurization and possibly rupturing of the PC, and to try to determine whether aerosols from materials of interest are released from the PC. These tests were performed in two phases.

In the first phase, POCs with inert PC contents were exposed to a 30 or 60-minute fire. These inert contents had similar thermal characteristics to the typical loaded PC. In each test, one PC was fully engulfed while the others were placed at various distances outside of the fire. In some of the tests, thermocouples measured the temperature responses of the drum and the PC at different locations. In addition, heat flux gauges (HFGs) were installed adjacent to the front face (i.e., side closest to the flames) of some of the drums outside the fire with the sensing surface facing towards the center of the fuel pool to measure the incident heat flux to the hottest side of the drums.

Testing during the first phase was conducted inside SNL's Fire Laboratory for Accreditation of Models and Experiments (FLAME) facility (see Figure 4). The FLAME facility has an 18.3 m in inner diameter with a height around the perimeter of 12.2 m. Figure 4 and Figure 5 show a typical test layout. The 3-m circular pool shown at the center of these figures was initially filled with Jet-A fuel. A remote refueling system adds fuel to the pool in discrete amounts during tests to keep the POC fully engulfed (see Figure 6). To limit the fire to the desired time (i.e., to 30 min or 60 min), the pool has a drain system that dumps all remaining fuel, almost immediately terminating the fire.

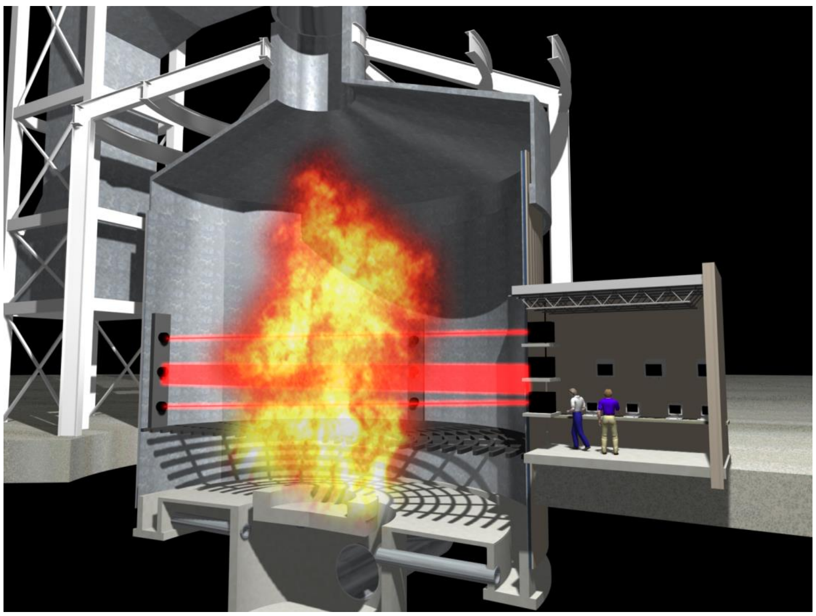


Figure 3. Conceptual drawing of the FLAME facility.

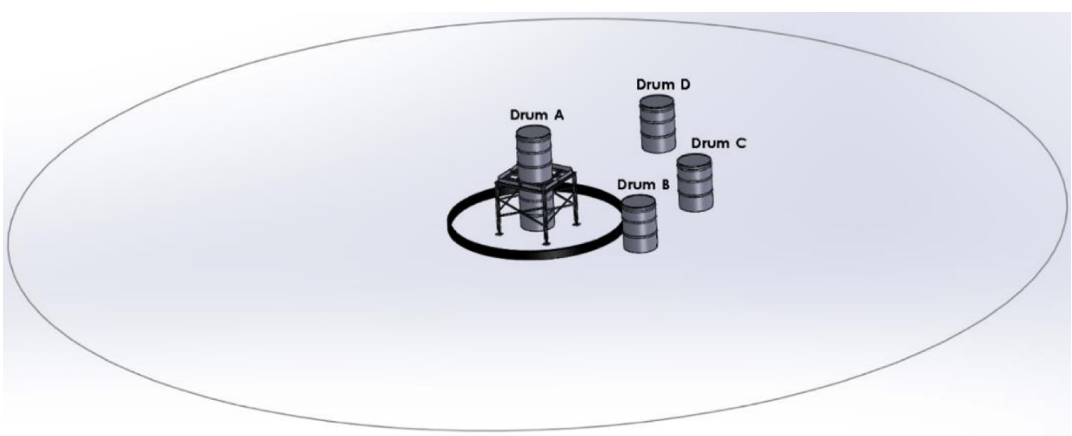


Figure 4. Layout of indoor POC tests in the FLAME facility. The inner circular wall marks the edge of the pool; the outer circular line marks the edge of the floor in the FLAME facility.

Figure 5. View of POC drums in a typical test layout.

Figure 6. Image of an indoor POC fire test showing fully engulfing conditions of the center POC drum, and showing the surrounding POC drums (bottom left).

The initial location of the fully engulfed drum was at the center of the fuel pool, and just above an empty 55-gallon drum. This vertical drum arrangement is typical of what is seen in storage facilities, where two drums are stacked on top of each other typically in a two level, four-drum- array packed arrangement. The reason for choosing the top drum as the instrumented drum is that this is likely the drum that will experience the highest temperatures in a typical storage fire should there be a fuel pool accumulated at the base of the bottom drum. The rest of the drums were located at varying distances ranging from 1.75 to 4.5 m from the center of the fuel pool, and spaced at an angular distance of approximately 45-degrees from each other. Each drum had a HFG adjacent to it. Additional standalone HFGs were placed further back from the center of the pool.

Fires typically contain a relatively cold region inside the plume and adjacent to the surface of the pool. Near the edge of the base of the fuel pool, air entrains the fire creating a hot region at the edges of the fire plume in a quiescent fire. Closer to the center of the pool at this level, there is little air entrainment, leading to less efficient combustion, which results in cooler interior zone. Further up from the fuel pool and at the edge of the fire plume, air entrains more readily further into the plume, creating hotter regions deeper into the fire plume. The extent, height wise, of the cold region from the surface of the pool varies with the diameter of the pool and the location from the center of the pool, but the shape of this cooler region resembles a dome. Objects submerge within this dome experience lower heat fluxes than outside of this region of the fire.

The second phase consisted of a single, fully engulfing POC fire test with typical combustible materials inside the PC. Due to the potential risk posed to FLAME (resulting from events following over-pressurization and subsequent rupture of the PC), this test was conducted at SNL's outdoor fuel pool burn facility.

The goal of the second phase test was to understand the structural and thermal response of the PC with typical combustibles inside, and to capture and chemically examine for materials of interest from the material escaping from the PC. To this end, (1) a pressure gauge was added to the test setup to record the internal pressure of the PC (via a small tube routed to the interior of the PC), (2) thermocouples were attached to the outer surface of the PC and to the interior of the Celotex side wall to collect temperature response of these components, and (3) an aerosol collection system was attached to the PC filter to collect any aerosol released from inside the PC. The PC was filled with typical mass quantities of the following inventory: (a) Kimwipes and plastic bags, and (b) CeO_2 powder used as a surrogate material for typical radioactive particles attached to the Kimwipes. Initial CeO_2 particles, the aerosol material of interest in this test, were between 0.6 and 1-micron in diameter. Note that prior to the test, all combustibles were tested for the presence of CeO_2 or other oxides which would bias post-test chemical analysis of the material samples collected. Other instrumentation used in this test included video cameras to record the test from various angles, and X-ray to closely monitor any significant deformation and/or rupture of the PC (if any).

Figure 7 shows an image of the drum inside the outdoor test cell, and taken at about 45-degree angle from the top surface of the pool. As in the first test phase, the instrumented drum is above an empty 7A drum. The fuel pool in this case was approximately 4m in diameter, but also filled with Jet-A fuel. The entire pool is enclosed inside an insulated fence extending about one or two inches just past the lid of the top drum.

As in the first phase, a remote refueling system was added to keep the fire going past 30-minutes. A drain system was also employed to dump the fuel and stop the fire at the desired time (30-minutes). The fence was added to shield the pool and the drums from incoming wind, guaranteeing the fire flames fully engulf the instrumented POC drum (see Figure 8).

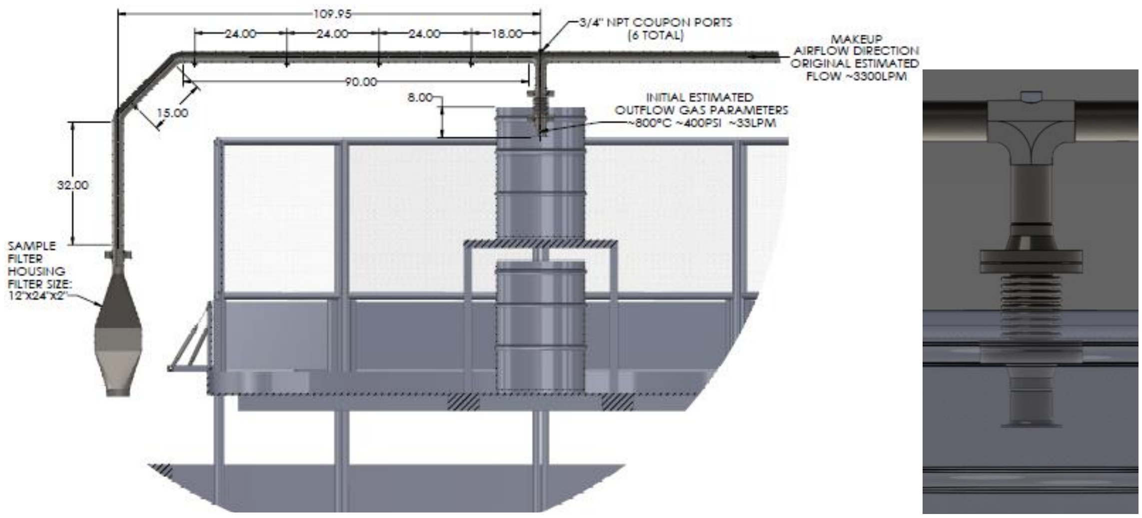
Figure 7. Image of the POC drum inside the outdoor test cell. Note that there is no drum lid, and plastic liner, Celotex, and wood board cover in the top drum.

Figure 8. Image of the fire showing fully engulfing conditions.

As shown in Figure 7, in this test phase the drum lid and the top plastic liner, wood board, and Celotex covers were missing. The reason for this change in configuration is that the first phase tests showed these components are ejected early in the test (less that 3min) in the case of the fully engulfed POC drum. Although not by intention, this change allowed for simplifications in the design/installation of the aerosol collection system.

The goal of the aerosol collection system was to collect any aerosol escaping from the PC through the filter. Chemical analysis of samples collected would give an indication if release of aerosol of interest (in this case CeO_2) occurred under the specified conditions of this test.

Prior to this test, this event had not been confirmed via previous tests in this series. A detailed diagram of the aerosol collection system is shown in Figure 9.



(a) (b)

Figure 9. (a) Schematics of the aerosol system showing the outlet HEPA filter and the location of the coupons. Not shown is the inlet end of the U-shaped pipe which mirrors the outlet end shown. (b) Close-up of the vertical section of the pipe. Contents of the POC drum are not shown. All length units are in inches.

The aerosol collection system consisted of (1) three vertical pipes: the bottom welded to the PC lid, the top welded to a horizontal section of pipe, and middle one consisting of a bellows; and (2) a long, downward-facing U-shaped pipe. The vertical pipes were concentric with the PC filter and joined to each other using bolted flanges. Due to the flow path through the PC filter, it was expected that most of the mass escaping the PC would be collected in the lower section of the vertical pipe immediately adjacent to the filter. In principle, additional aerosol released through the PC filter not trapped in this section of the pipe wall, and presumably floating in the hot gas, would eventually rise through the vertical section of the pipe with the aid of buoyancy forces.

Note that the vertical pipe was attached to the PC lid around the PC filter and only accounted for mass loss through the PC filter. A preliminary test conducted at ambient conditions using an air pressurized PC and structural computational analysis of the PC at elevated temperatures, using an internal pressure source typical of that generated by the gases from the decomposing materials inside the PC, demonstrated that most if not all the mass released from the PC would be through the filter, and not through the PC flange o-ring. (At ambient conditions the leak rate through the damage filter is about 33 standard-liters per minute. This leak rate is expected to be significantly higher at higher temperatures. The ratio of what comes out through the PC filter to what comes out of the sides of the PC flange at ambient conditions is at least 20:1 based on the PC test results.) Thus, adding aerosol collection system only around the PC filter is justified. Post-test examination of the o-ring and the flange area of the PC indicated this to be the case.

To collect loose aerosol at the T-junction, cold air was drawn through an upstream HEPA filter at one end of the U-shape section of the pipe (not shown in Figure 9) to clean incoming air. At the other end of the U-shape section, an additional HEPA filter was designed to collect the sizes of aerosol particles of interest. Cold air was necessary to keep the HEPA filter below its maximum operating temperature. The length of the U-shaped section of the pipe and the air flow rate were also based on this requirement. To catch any aerosol deposited on the U-shaped pipe, coupons were strategically placed at various locations along this pipe. Together, the samples collected in the section of the pipe near the filter, on the coupons, and the HEPA filter would give an indication if any aerosol of interest was released.

Phase I Test Results

Figure 10 shows an image of what the drums looked like after the 30-minute test, and some of the remains of what was ejected from the POC drum. Component ejection occurred less than 3 minutes into the test. Inside the fire, and like the 1997 SNL tests, the lid of the engulfed drum failed, and led to ejection of the top plastic liner, Celotex, and wood board covers under the increased pressure caused by expansion of hot gases inside the POC drum. Post-test visual examination of the fully engulfed drum showed no remains of the plastic liner and some ash remains of the Celotex material inside the drums. The PC was still standing at the bottom of the drum with the help of some of the intact remains of the bottom wood board.

(a) (b)

Figure 10. (a) View of center drum after the fire. Also showing are the remains of top Celotex cover ash remains inside the fuel pool. (b) Close-up view of the ejected lid (top) and the remains of the plastic liner cover (bottom) on the test cell floor.

Based on video recordings during the test, and as confirmed by post-test examination of the drums, outside the fire none of the drum lids experienced gross failure; though, adjacent to the edge of the flame (2m or less, or ~45kW/m^2 equivalent distance or higher), lid bulging occurred on the side facing the flame (see Figure 11). Internally, some degradation of the plastic liner and the Celotex was observed. Overall the bulk of the Celotex remained intact.

Figure 11. Bulging of the 7A drum lid on a POC at 2m from the center of the fire.

Figure 12 shows typical temperature response of components inside the fully engulfed POC drum, including the PC, for the 60-minute test, without and with the lid. A significantly difference temperature profile is observed in the flange area, suggesting that the effect of ejecting these components is significant.

Figure 13 shows some of the incident heat fluxes recorded with HFGs at various locations in the FLAME test cell. Data for distances less that 4.5m give an indication of the incident heat fluxes on the hot side of the drums located outside the fuel pool. The solid line drawn in the plot, which aligns well with the measured heat fluxes, represents predicted incident heat fluxes taken with a correlation obtained from [1]. As noted in this plot, the relationship between incident heat flux and distance is inversely proportional to the square of the distance from the fire, as expected.

Phase II Test Results

Figure 14 shows an image of what the drums looked like after the outdoor fire test. As expected, post-test visual examination of the drum showed no remains of the plastic liner and some ash remains of the Celotex material. The internals of the drum look very similar to those of the center drum in the first phase tests.

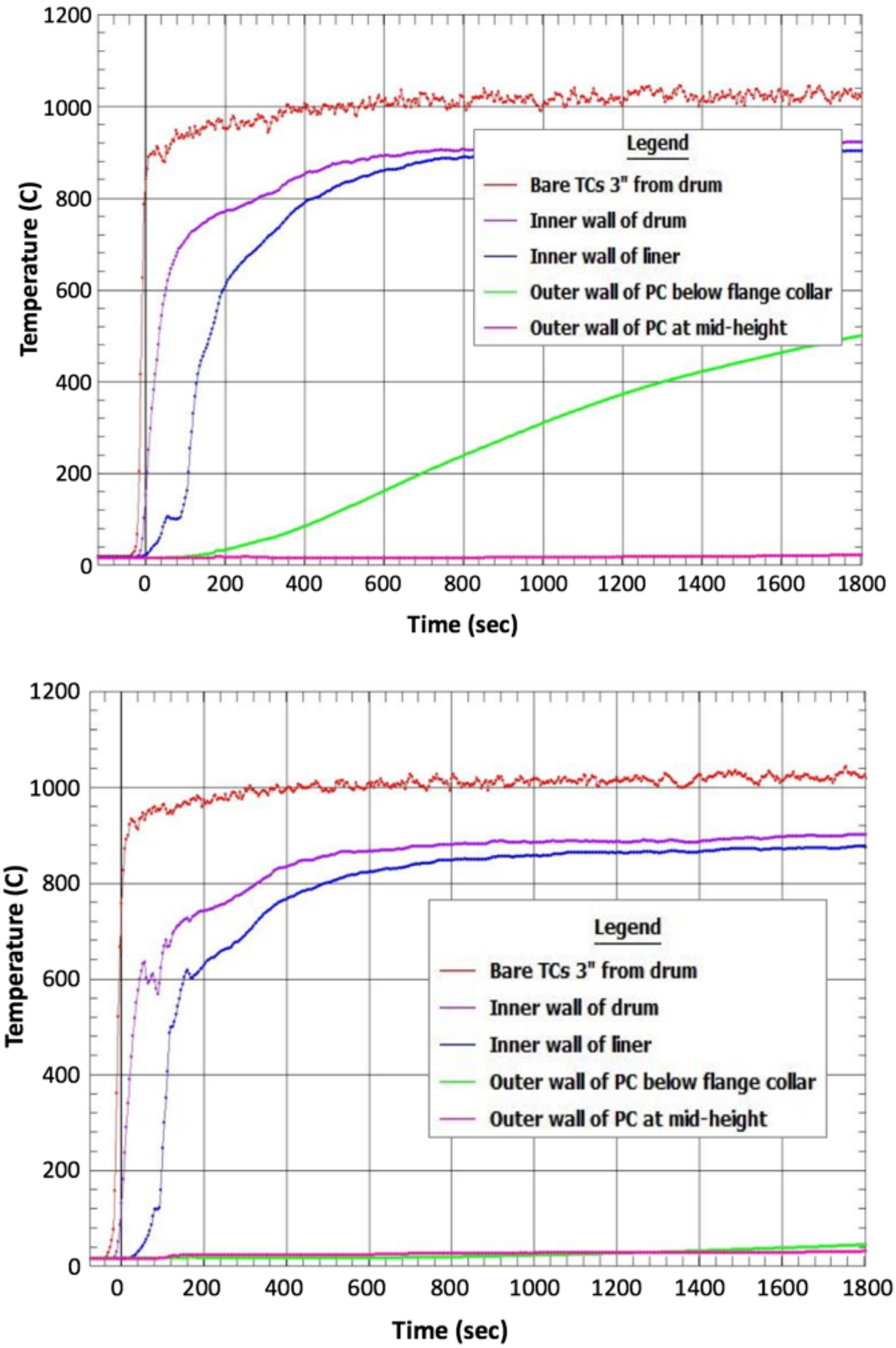


Figure 12. Temperature response at various locations in the POC: upper graph without the drum lid, and plastic liner, Celotex, and wood board covers, and lower graph with standard components.

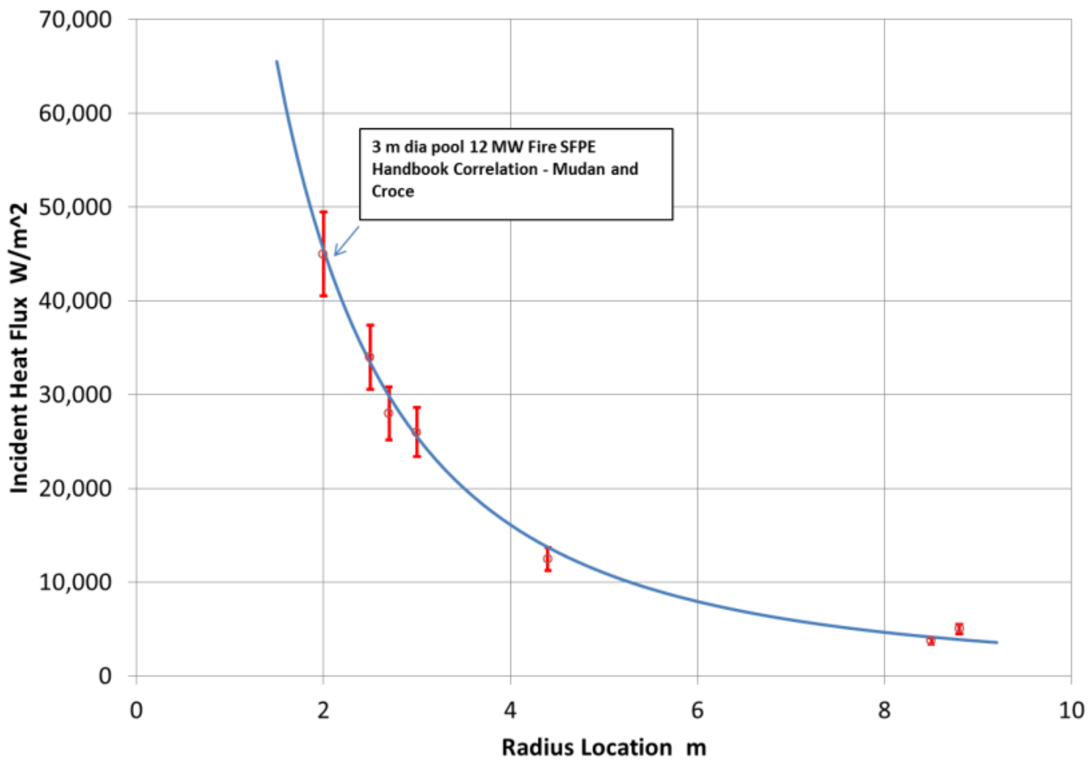


Figure 13. Incident heat fluxes (red) recorded with HFGs for various test and at various distances. Superimposed on the data are correlation results for typical incident radiation from a fire plume as a function of distance.

One significant finding from this test, as evidence by these images, is that the pressure build-up inside a PC with combustible material is not sufficient to rupture the PC. This finding allows future test to be conducted indoors under more controlled conditions.

Figure 15 shows material that escaped through the filter and condensed on the side of the lower section of the vertical pipe immediately outside the PC filter, and a coupon with soot extracted from the aerosol collection system on the horizontal section of the pipe. As expected, accumulation of material was heavy in this region. This material seemed to be a black tar-like substance likely from condensation of gases and soot from the plastic material and burned Kimwipes. Material accumulation was mesh less on the second vertical section of the pipe and was made up primarily of soot particles. A soot like material was collected from the sample coupons and from the HEPA filter.

Figure 14. POC drum without a lid after the 30-minute engulfing fire. The right image shows a close-up of the vertical section of the pipe after the test when the insulation was removed. The bellows portion of the vertical pipe was added to allow for unobstructed deformation of the PC lid due to thermal stresses.

Figure 15. Material collected on the first section of the vertical pipe (left) and on one of the sample coupons on the horizontal section of the U-shaped pipe (right).

As of this writing, no chemical analysis results have been obtained; therefore, it is hard to corroborate the origin of the material collected, or whether CeO_2 was released from the PC. Further testing is planned under more controlled conditions given that it is now known the PC will not rupture under planned testing conditions.

Overall, temperatures recorded in this test were higher than the ones recorded in indoor tests. The reason why this is the case is that in this test the proximity of the fences shielded the lower part of the fire plume from the cooler environment, preventing release of thermal radiation energy from this part of the fire plume, as compared to a fire that does not use fences. This is one drawback of using fences to guarantee fully engulfing conditions.

Summary

Overall, all evidence collected, including temperature response of the PCs, indicated that for drums outside the fire the PC filter remained intact, suggesting that if the lid stays on and all the Celotex remains intact for the most part, both these components provide enough thermal radiation shielding/insulation to prevent the PC from heating to the point where the PC filter fails. This conclusion is only valid for drums at maximum distance equivalent to a 45kW/m^2 incident heat flux and under the fire testing conditions outlined here.

Acknowledgments

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References

[1] Drysdale, Dougal. "An Introduction to Fire Dynamics". John Wiley & Sons, Chichester, UK, 2nd Edition, 2007.