Contract No:

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Calculation Cover Sheet

Project/Task	Calculation Number	Project /Task Number
N/A	S-CLC-G-00395	N/A

Title:	Functional Classification
Pool Fire Analysis Methodology for Assessing Damage to Waste Containers	SS/SC for E7 review purposes
	Discipline: Safety

Calculation Type	Calculation Status
☒ Type 1 ☐ Type 2	☐ Preliminary ☒ Confirmed

Computer Program Number	Version/Release Number
MS Excel used as a tool; MS Visio used as a tool	N/A

Purpose and Objective

The purpose of this document is to outline an acceptable methodology for evaluating pool fires and assessing the resulting damage to standard waste containers. The methods described here may be used for assessing damage to other than waste containers and other analysis methods may be used with appropriate justification.

Summary of Conclusion

The objectives of this calculation have been met. This document presents a methodology for determining physical parameters associated with postulated flammable/combustible liquid pool fires resulting from unconfined crash/instantaneous, metered leak, and confined spills and for assessing pool fire damage to standard TRU waste containers. The methodology provides an acceptable analytically based approach derived principally from various chapters of the SFPE Handbook of Fire Protection Engineering, combined with insights gained from empirical fire tests published in literature. It also includes guidance on appropriate sensitivity checks necessary to show conservative results, and suggestions on presentation of results. With adequate technical justification, it may also be judiciously used for analysis of non-pool fires or for non-waste container targets vulnerable to thermal stress. This methodology document is not meant to be prescriptive or limiting; other analysis methodologies may also be used at the discretion of, and as technically justified by, the analyst.

REVISIONS

Rev No.	Revision Description
0	See Revision Log, Page 3

SIGN OFF

Rev No.	Originator (Print / Sign / Date)	Verification/Checking Method	Verifier/Checker (Print / Sign / Date)	Manager (Print / Sign / Date)
0	V. M. Schluszas *Signature on file* R. A. Sprankle *Signature on file*	☐ Design Check (GS/PS only) ☒ Document Review ☐ Qualification Testing ☐ Alternate Calculation ☐ Operational Testing	J. E. McAllister, Jr. *Signature on file*	S. A. Yano *Signature on file*

	Signature	Date
Additional Reviewer (Print Name): N/A	N/A	N/A
Design Authority – (Print Name): N/A	N/A	N/A
Release to Outside Agency – (Print Name): N/A	N/A	N/A

Security Classification of the Calculation

ACCIDENT ANALYSIS TECHNICAL REVIEWER CHECKLIST

Scope of Review:

Complete review for this Revision 0 document.

Yes	No*	N/A	Review Criteria
☒	☐	☐	Revision scope and strategy have been discussed verbally and are understood.
☒	☐	☐	Purpose of document is clearly stated in document and understood.
☒	☐	☐	Format of document is consistent with applicable guidance from N&CSE Analytical Support Manager. (Deviations allowed with manager concurrence.)
☐	☐	☒	Content changes made as part of this revision are identified by rev bars in right margin. (Only needed after table of contents, and not needed for format changes or in headers.)
☒	☐	☐	Revision log clearly indicates what has changed and if the results have NOT changed.
☒	☐	☐	Header consistently shows document number together with revision number in left corner and page number in right corner. Header along the long side of landscape pages has been adjusted as necessary so that header information extends from corner to corner.
☒	☐	☐	Information captured at the back of the document is organized in appendices identified alphabetically. (Appendices are not to be numbered.)
☐	☐	☒	Open items are clearly identified.
☒	☐	☐	Documents listed in the reference section are the latest versions of the documents. If a referenced document is not the latest version, a justification is provided.
☒	☐	☐	Adequate background information is provided.
☒	☐	☐	Inputs are listed in input section with unique identifier and reference.
☒	☐	☐	Inputs have been checked against source references.
☒	☐	☐	Assumptions are listed in assumption section with unique identifier, assumption, basis for why this assumption is valid, sensitivity to this assumption, and additional text.
☒	☐	☐	Assumptions have adequate justifications.
☒	☐	☐	Inputs and assumptions are called out by their unique identifiers when first used, which may simply be mention of the I&A in the methods section.
☒	☐	☐	Analytical methods are clearly spelled out, are appropriate for the intended use, and can be understood without assistance from the author. Any mathematical derivations have been checked including dimensional consistency. Any software has adequate SQA.
☐	☐	☒	Accident scenarios are clear and logical with sufficiently detailed progressions and are aligned with corresponding CHA events, DSA HA events, or DBAs, as appropriate.
☒	☐	☐	Calculations have been checked for errors including incorrect inputs. Summary tables contain latest results and have been checked for errors including transposition errors.
☒	☐	☐	Limits, criteria, and guidelines applied to results are appropriate as applied and are listed as inputs in input section.
☒	☐	☐	Conclusions are consistent with purpose, results, and limits/criteria/guidelines.

J. E. McAllister, Jr. *Signature on File*

Reviewer (print / sign / date)

* “No” responses must be explained on additional sheet placed behind checklist or at end of document.

REVISION LOG	
REV.	DESCRIPTION
0	Initial issue

DISCLAIMER

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Figure **Page**

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1.0 OPEN ITEMS

None.

2.0 REFERENCES

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3.0 INTRODUCTION

This document provides guidelines, whereby the physical parameters associated with postulated flammable/combustible liquid pool fires are determined (thermal analysis) in order to estimate the number of waste containers impacted. Pool fire damage to waste containers may occur due to a container being fully engulfed (within the periphery of the pool), partially engulfed, or within the critical heat flux distance. The methodology described here for estimating the size of the pool fire is developed using spill characteristics outlined in Chapter 65 of the SFPE Handbook (Ref. 7) and testing done by Hansen (Ref. 25). For exposures, the critical flux height is determined using the detailed method of Shokri and Beyler (Ref. 8) from the flame height, calculated as described by Heskestad (Ref. 7) and the average black body emissive power, determined using the method of Shokri and Beyler (Ref. 8).

Three types of liquid pool fires should be considered; unconfined crash/instantaneous spill fires, unconfined continuously flowing (also called metered leak) spill fires, and confined spill fires. All fuel sources should be considered consistent with the facility Fire Hazard Analysis (FHA). However, the most likely liquid fuel sources present in TRU waste facilities are those present on TRU waste handling vehicles (forklifts, pallet movers, transport trucks, etc.).

This method can also be used for assessing damage to items other than waste containers or other methods of analysis may be used with appropriate justification.

Note: The term “fuel” as used in this analysis refers to any flammable/combustible material that may be involved in a postulated liquid pool fire (mineral oil, hydraulic fluid, benzene, isopar, diesel fuel, gasoline, kerosene, alcohol, heptane, lube oil, etc.).

4.0 INPUTS

Input values associated with this calculation are provided below. It is noted that there is little to no data available for many of the thermophysical properties of the combustible materials (liquid and solid) evaluated here because many of the materials are composites or blended formulations of various constituents (e.g., diesel fuel, hydraulic fuel, polyurethane, rubber, etc.). Specifically, most of the material property data provided in Table 4-1 are developed from comparison with known data of other similar materials. Or, the properties are developed within a range of input data available. Specific input values presented here are therefore, somewhat dependent on engineering judgement, and are typically selected to be midrange within the available material parameter data set. Note also that other specific values presented in results tables, or calculation steps may be truncated or rounded for display purposes.

4.1 FACILITY INPUTS

None.

4.2 Analytical Inputs

Analytical inputs are provided in Table 4-1.

Table 4-1, Analytical Input Table continued

Parameter	Value	Reference
4.2-1. Heat of combustion (H_c) of diesel fuel	42.6 MJ/kg	Ref. 28, Table 1; Deg. API range for DFO is 30 - 39. Based on Table 4-2, net* H_c range is 42.4 - 43.0 MJ/kg (with conversion), used approximately midrange
4.2-2. H_c of hydraulic fluid	45.0 MJ/kg	Refs. 13 – 17, Average of 5 fluids. Net H_c determined from hydraulic fluid density, Input 4.2-6, using Table 4-2)
4.2-3. H_c of polyurethane (PU)	25.3 MJ/kg	Ref. 10, Table A.38 (page 3465), average of 4 PU materials
4.2-4. H_c of rubber	32.6 MJ/kg	Ref. 10, Table A.32 auto tire (page 3449)
4.2-5. Density of diesel fuel	850 kg/m^3	Ref. 28, Table 1; Deg. API range for DFO is 30 - 39. Based on Table 4-2, density range is 875.3 - 829.2 kg/m^3 (with conversion), used approximately midrange
4.2-6. Density of hydraulic fluid	880 kg/m^3	Refs. 13 – 17, Average of 5 hydraulic fluids (Chevron hydraulic fluid, Ref. 14, density converted from Deg. API using Table 4-2)
4.2-7. Density of PU	1.1 g/cm^3	Ref. 2, page 874; average of 7 PU materials
4.2-8. Density of rubber	1.13 g/cm^3	Ref. 22, midrange
4.2-9. Diesel fuel mass loss rate	0.039 kg/m^2-sec	Ref. 6, Table 26.21, use kerosene Ref. 33, page 4-11
4.2-10. Hydraulic fluid mass loss rate	0.039 kg/m^2-sec	Ref. 6, Table 26.21, use transformer oil
4.2-11. Acceleration due to gravity	9.81 m/s^2	Ref. 1
4.2-12. Standard TRU Waste Drums (55 gallon) outer diameter	23” rounded to include hoop ring closure	Ref. 27, page 16
4.2-13. Standard Waste Boxes (SWBs) dimensions	Nominally 177 cm long; 124 cm wide; 88 cm tall (69.75” x 48.8” x 34.75”).	Ref. 27, page 17
4.2-14. Shallow Pool Spill Depth	0.7 mm	Ref. 7, Equation 65.2a
4.2-15. Deep Pool Spill Depth	2.9 mm	Ref. 7, Equation 65.2b
4.2-16. HRR curve for fire involving dual** truck tires mounted on axle with fender tested by Hansen	See Figure 1	25, Test B, Appendix B.2

* Total or gross H_c is measured in a combustion bomb calorimeter in which a precise amount of fuel is burned in pure oxygen inside a pressure vessel. The Net H_c values are more appropriately used for fire calculations as described by Drysdale (Ref. 3, page 142).

** A dual tire set involves tires aligned side by side, on the same axle. A tandem tire set involves tires aligned front to back, each on a different axle. A dual-tandem tire set (typically seen on each side of the rear axles of a semi-trailer) would therefore involve four tires on each side two axles.

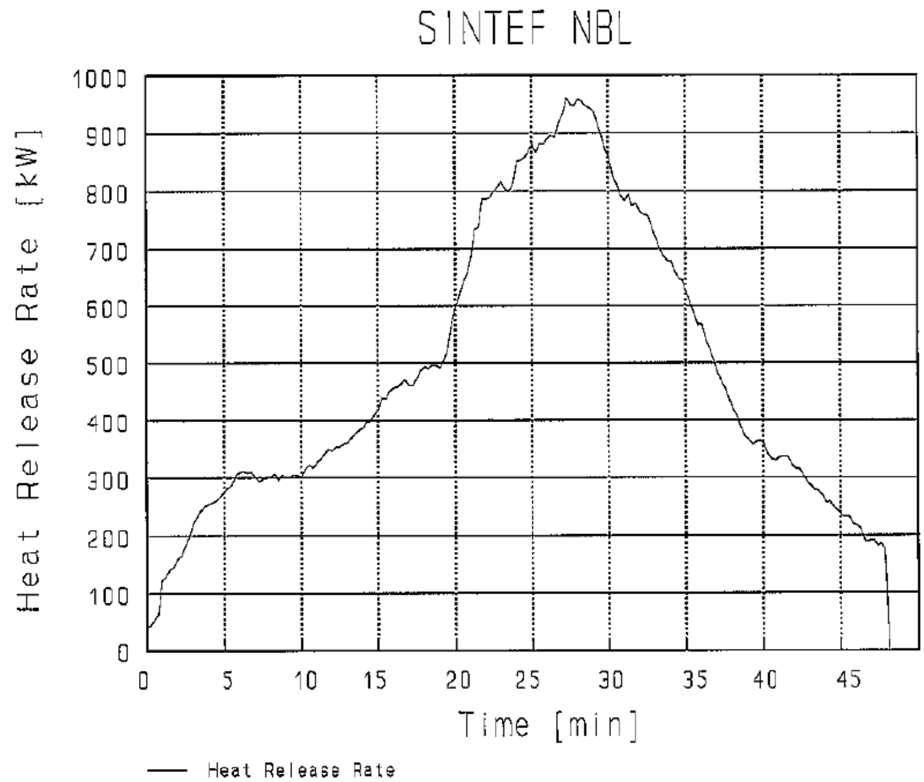
Table 4-2, National Bureau of Standards Heats of Combustion of Fuel Oils

GRAVITIES, DENSITIES AND HEATS OF COMBUSTION OF FUEL OILS

VALUES FOR 10 TO 49 DEG. API, INCLUSIVE, REPRINTED FROM BUREAU OF STANDARDS MISCELLANEOUS PUBLICATION NO. 97, "THERMAL PROPERTIES OF PETROLEUM PRODUCTS".

GRAVITY AT 60/60 F		DENSITY. AT 60°F	TOTAL HEAT OF COMBUSTION (At Constant Volume)			NET HEAT OF COMBUSTION (At constant pressure)		
DEG. API	SPECIFIC GRAVITY	LB. PER GAL.	BTU PER LB.	BTU PER GAL. AT 60°F.	CAL PER G	BTU PER LB.	BTU PER GAL. AT 60°F	CAL PER G
5	1.0366	8.643	18,250	157,700	10,140	17,290	149,400	9,610
6	1.0291	8.580	18,330	157,300	10,180	17,340	148,800	9,650
7	1.0217	8.518	18,390	156,600	10,210	17,390	148,100	9,670
8	1.0143	8.457	18,440	155,900	10,240	17,440	147,500	9,700
9	1.0071	8.397	18,490	155,300	10,270	17,490	146,900	9,720
10	1.0000	8.337	18,540	154,600	10,300	17,540	146,200	9,740
11	0.9930	8.279	18,590	153,900	10,330	17,580	145,600	9,770
12	0.9861	8.221	18,640	153,300	10,360	17,620	144,900	9,790
13	0.9792	8.164	18,690	152,600	10,390	17,670	144,200	9,810
14	0.9725	8.108	18,740	152,000	10,410	17,710	143,600	9,840
15	0.9659	8.053	18,790	151,300	10,440	17,750	142,900	9,860
16	0.9593	7.998	18,840	150,700	10,470	17,790	142,300	9,880
17	0.9529	7.944	18,890	150,000	10,490	17,820	141,600	9,900
18	0.9465	7.891	18,930	149,400	10,520	17,860	140,900	9,920
19	0.9402	7.839	18,980	148,800	10,540	17,900	140,300	9,940
20	0.9340	7.787	19,020	148,100	10,570	17,930	139,600	9,960
21	0.9279	7.736	19,060	147,500	10,590	17,960	139,000	9,980
22	0.9218	7.686	19,110	146,800	10,620	18,000	138,300	10,000
23	0.9159	7.636	19,150	146,200	10,640	18,030	137,700	10,020
24	0.9100	7.587	19,190	145,600	10,660	18,070	137,100	10,040
25	0.9042	7.538	19,230	145,000	10,680	18,100	136,400	10,050
26	0.8984	7.490	19,270	144,300	10,710	18,130	135,800	10,070
27	0.8927	7.443	19,310	143,700	10,730	18,160	135,200	10,090
28	0.8871	7.396	19,350	143,100	10,750	18,190	134,600	10,110
29	0.8816	7.350	19,380	142,500	10,770	18,220	133,900	10,120
30	0.8762	7.305	19,420	141,800	10,790	18,250	133,300	10,140
31	0.8708	7.260	19,450	141,200	10,810	18,280	132,700	10,150
32	0.8654	7.215	19,490	140,600	10,830	18,310	132,100	10,170
33	0.8602	7.171	19,520	140,000	10,850	18,330	131,500	10,180
34	0.8550	7.128	19,560	139,400	10,860	18,360	130,900	10,200
35	0.8498	7.085	19,590	138,800	10,880	18,390	130,300	10,210
36	0.8448	7.043	19,620	138,200	10,900	18,410	129,700	10,230
37	0.8398	7.001	19,650	137,600	10,920	18,430	129,100	10,240
38	0.8348	6.960	19,680	137,000	10,940	18,460	128,500	10,260
39	0.8299	6.920	19,720	136,400	10,950	18,480	127,900	10,270
40	0.8251	6.879	19,750	135,800	10,970	18,510	127,300	10,280
41	0.8203	6.839	19,780	135,200	10,990	18,530	126,700	10,300
42	0.8155	6.799	19,810	134,700	11,000	18,560	126,200	10,310
43	0.8109	6.760	19,830	134,100	11,020	18,580	125,600	10,320
44	0.8063	6.722	19,860	133,500	11,030	18,600	125,000	10,330
45	0.8017	6.684	19,890	132,900	11,050	18,620	124,400	10,340
46	0.7972	6.646	19,920	132,400	11,070	18,640	123,900	10,360
47	0.7927	6.609	19,940	131,900	11,080	18,660	123,300	10,370
48	0.7883	6.572	19,970	131,200	11,100	18,680	122,800	10,380
49	0.7839	6.536	20,000	130,700	11,110	18,700	122,200	10,390

Values for 10 to 49 deg. API, inclusive, reprinted with permission from Miscellaneous Publication of the Bureau of Standards No. 97, "Thermal Properties of Petroleum Products".



Test B. Heat release rate [kW] during combustion of the tyres. Maximum heat release was 964 kW. Time in minutes from pilot ignition.

Figure 1, Dual Tire Fire Heat Release Rate Curve from Hansen (Ref. 25) (Input 4.2-16)

5.0 ASSUMPTIONS

5.1 FACILITY ASSUMPTIONS

None.

5.2 ANALYTICAL ASSUMPTIONS

Assumption 5.2.1
Assumption: It is appropriate to model an ordinary combustible fire as a right circular cylinder fire with a footprint equivalent to the footprint of the package and centered on the package.

Basis for why this assumption is valid: This approach is standard industry practice (Ref. 8).

Sensitivity to this assumption: The analysis is somewhat sensitive to this assumption. The size and shape of the fire are used to determine levels of heat flux to nearby waste containers and thereby whether damage occurs.

Additional text: None.

Assumption 5.2.2
Assumption: The postulated fuel spill, or pool fire diameter is based on release of 75% of the combustible liquid available in a metal tank or reservoir. That is, 25% of the combustible liquids in a metal tank or reservoir is considered unavailable for contributing to the size of the postulated pool fire diameter.

Basis for why this assumption is valid: This analysis evaluates a postulated breach in a metal combustible liquid storage tank causing either a quickly forming large pool (spill) of short duration or a slowly developing small pool (leak) of long duration. A portion of the combustible liquid is expected to either remain unburned in the tank or burn within the tank, thereby not contributing to the pool size or leak duration. For industrial vehicle liquid fuel storage tanks, a breach in the container such as from a collision puncture, fire-induced structural compromise, or hose failure, could spill the liquid resulting in a free burning fire. It is not considered credible that all the liquid could spill out in any type of breach. A puncture caused by collision with another vehicle is unlikely given the heavy metal outer construction of the typical industrial material handling vehicle. If something were to puncture one of the tanks, it is further unlikely that the puncture would be at the lowest point of the tank. Similarly, a fire-induced rupture or structural failure of the tank, though possible, is unlikely to result in all the liquid contents being spilled. The tank is more likely to remain intact and burn through a cap or opening near the top of the tank where it could also receive air for continued combustion. Ruptured (or melted) hoses or feed lines to the tank typically draw from the top of the tank (minimizes sediment in system) and siphoning all the contents is unlikely as the fire would consume the hose up to the top of the tank thereby stopping the siphoning action. It is also further unlikely that the breach would occur when the tank has been recently filled. Considering these data, the combustible fuel available for contributing to a fuel spill pool fire diameter or a fuel leak pool fire duration has been subjectively reduced by 25 %.

Sensitivity to this Assumption: The analysis is sensitive to this assumption. The number of waste containers affected is proportional to the diameter of the postulated liquid pool fire. The fire diameter is proportional to the quantity of liquid spilled. Increasing the pool fire diameter increases the estimated damage to waste containers.

Additional text: Though substantially unrelated to the above discussion the concept of "derating", as described in the NFPA handbook (Ref. 1), is based on this same model whereby combustible concentrations (the handbook is based on combustibles in a typical office occupancy) may be excluded from contributing to the fire due to obstructing influences or enclosures. Office combustibles may be derated by 60-90% when fully enclosed in a thin metal structure (file cabinet) or by 25% when partially enclosed (bookcase). Fire testing of closed TRU waste drums (Ref. 33, page 6-7) measured only 0.06 mass loss from drums with seal failures and also demonstrates the effect of a metal enclosure with restricted airflow. This discussion is not to determine combustible liquid fuel behavior in a fire based on office furniture or TRU waste drum testing. But, the thermophysical phenomena associated with metal enclosure of solid combustible materials is well-established in literature. And, it is reasonable to consider application of similar physical relationships for evaluating liquid combustibles in metal enclosures in this analysis.

This assumption is not applicable for tanks/reservoirs constructed of combustible material.

Assumption 5.2.3

Assumption: Unless otherwise known to be sloped, the surfaces on which pool fires are formed is relatively flat and level (not sloped).

Basis for why this assumption is valid: Considering areas evaluated in these calculations as non-sloped surfaces is conservative. Areas that are sloped are set up such that the slope leads to a drain located in, or near, the center of the access aisle at one end of the building or away from the waste containers. Storage areas within a building are assumed to be flat because there is no reason to slope a building foundation.

Sensitivity to this assumption: The analysis is relatively insensitive to this assumption relative to the number of containers involved. If the floor were sloped to flow toward the waste containers, additional containers could be involved in (impacted by) the postulated fire. But, because the spill depth would remain relatively constant the fire footprint (area) would not change. In addition, the slope could also be away from the containers. If the pad were sloped to permit collection at a low point, the pool would be deeper there and fewer containers would be involved. The worst-case pool shape would be rectangular, positioned along and underneath one side of a waste array. Representing fires in this manner would not be realistic. Fire flowing from the vehicle across the pad to the external wall would not involve as many containers as considered here.

Additional text: Where the spill surface is known to be sloped or inclined, this assumption should not be used. Section 6.1 provided guidance on evaluating spills on inclined surfaces.

Assumption 5.2.4
Assumption: Other combustibles on a vehicle are not considered to influence the size of the pool.

Basis for why this assumption in valid: The battery is typically contained within a six-sided metal compartment on the vehicle. As such, it could only possibly influence the pool size if some of the battery's plastic case melted and flowed through some compartment openings onto the floor before the fuel spill reaches its maximum size. Combustible knobs, seat cushions, hoses, wires, etc. would similarly burn in place and would not be likely to melt and flow within the time required for the fuel spill to form and burn to completion.

Sensitivity to this assumption: The analysis is relatively insensitive to this assumption. These combustibles typically represent a negligible contribution to overall vehicle heat content.

Additional text: The presence of large combustible accumulations on a waste handling vehicle such as rubber bumpers or a fiberglass body construction are not considered in this analysis. If present, the analysis should consider their potential to influence the pool fire size and heat release rate.

Assumption 5.2.5
Assumption: Only the largest single combustible liquid storage tank/reservoir needs to be considered as contributing to the size of a liquid spill pool fire.

Basis for why this assumption in valid: It is common for an industrial material handling vehicle to have multiple volumes of combustible liquid present, such as diesel fuel, engine oil, hydraulic fluid, and/or brake fluid. Breach of a tank/reservoir on the vehicle is not likely, even in a vehicle crash scenario. A breach is modeled in this analysis to spill to its maximum diameter at a bounding spill depth in a very conservative, even more unlikely scenario, and be ignited in a pool fire. There is an even lower likelihood of more than one container breaching, and an even lower likelihood that two volumes would breach at or near the same time to both contribute to the size of the postulated spill. There is a remote possibility that a second combustible liquid tank/reservoir could be damaged and breached by the fire involving the first tank spilled or involving the remaining portions of the vehicle, particularly if the tires are involved. But it is not considered credible for the subsequent tank/reservoir breach, of less volume, to occur in the same manner within the 1-2 minutes it takes for the initial tank/reservoir spill fire to be fully consumed and self-extinguish. Therefore, although all the combustibles on the vehicle can, and probably will burn, they will not contribute to increasing the footprint of the fuel spill pool fire modeled here.

The metered leak spill fire scenario, as presented in Section 6.3, is modeled in a very bounding manner, to include the involvement of one or more tires in determining the size or duration of the postulated spill which requires that the pool fire and the tire fire start at essentially the same time. While there is no physical mechanisms to achieve simultaneous ignition, the approach does eliminate the need to evaluate a wide range of uncertainties as discussed in Section 6.3 and presents an easily defensible bounding pool fire scenario. To go further yet and consider multiple tanks/reservoirs experiencing a metered leak breach is not considered credible.

Sensitivity to this assumption: The analysis is sensitive to this assumption. The amount of liquid spilled, and its spill depth or spill rate are proportional to the size of the pool spill fire and thus the number of containers affected by the postulated fire.

Additional text: None

Assumption 5.2.6

Assumption: Objects on the floor, drums, containers, pallets, etc. directly in the pool are not considered to affect the footprint of the pool.

Basis for why this assumption in valid: The spacing between the bottom of these items and the floor cannot be liquid-tight. Neglecting the containers' possible effect on pool fire footprint greatly simplifies the required modeling effort and is compensated by also neglecting their effect on the fire heat release rate and flame height.

Sensitivity to this assumption: Pool diameter has a large effect on analysis but the difference in including volume displacement is small when considered with other conservatisms that the analysis is relatively insensitive to this assumption.

Additional text: None

Assumption 5.2.7

Assumption: A burning tire, or tire set, requires approximately 10 minutes to melt in such a manner that it forms a pool sufficient to influence (increase) the pool diameter beyond the tire's original footprint.

Basis for why this assumption is valid: Conservative interpretation of empirical test data from Hansen (Ref. 25). See additional text.

Sensitivity to this Assumption: The analysis is sensitive to this assumption as it forms the basis for estimating the flow rate at which the maximum pool size is developed in the fire scenario. The scenario combines a burning tire, or tire set with the non-instantaneous breach (metered leak) of a combustible liquids tank. However, it is only sensitive where the combustible tire mass is large relative to the combustible liquid fuel mass. Otherwise, it is insensitive. Increasing the time needed to achieve molten rubber pooling decreases the pool size (by establishing a slower leak rate) and hence decreases fire damage to containers and decreases postulated radiological release.

Additional text: This analysis defines a conservative case for a leak rate driven, or metered leak, fire whereby the available fuel pours out of a breached enclosure at a rate slower than instantaneous and faster than a trickle. Because the flow rate is indeterminate and could be variable over time, the flowrate is based on tire set involvement. That is, based on a model whereby the fuel leak is slow enough to allow ignition, melting, and pooling of the rubber or polyurethane tires on a vehicle. The pool fire diameter is then based on the leak rate-driven pool fire diameter *as increased* by the maximally developed molten tire fire (Assumption 5.2.8). An estimate of the time required for the burning tire to develop its own pool fire is derived from empirical testing by Hansen. Hansen conducted four tests (labeled A-D) of dual truck tires, each test lasting about 1 hour. In tests A and B the tire is noted to begin dropping the upper parts of the tire (phenomena not noted in tests C and D) between 11 (Test B) and 15 (Test A) minutes after tire ignition. The tires in all four tests had fallen from the rims (fellies) in about 30 to 35 minutes, indicating that pooling begins at about 10 minutes (the basis for this analysis) and is completed at about 35 minutes after ignition. The conservative selection of 10 minutes accommodates uncertainties associated with timing of the scenario (tire ignites then fuel leaks; fuel leaks, is ignited, then ignites tire; or fuel and tire ignite nearly at the same time). When combined with the sensitivities described above, this is considered a conservative approach.

Note that the empirical testing described here used deflated pressurizable rubber truck tires. The analyst should consider modifying this assumption if a tire is of solid rubber or of a thermoset (non-pooling) material. Also consider, as noted above, that increasing the time needed to develop a tire pool decreases the combined liquid plus tire pool size by establishing a lower leak rate.

Assumption 5.2.8

Assumption: Hansen (Ref. 25) used a variety of tires for testing. They are taken as having an average mass of 110 lbs and an average tire size of 11.4 in. by 38 in. Spacing between dual tires and multiple axle tandem tires is assumed to be uniformly 4 in., see Figure 2.

Basis for why this assumption is valid: Interpretation of empirical test data from Hansen (Ref. 25).

Sensitivity to this assumption: The results of this evaluation are somewhat sensitive to these dimensions as they provide input to determine the solids tire fire diameter. The diameter is based on a ratio of the facility vehicle tires to the tires used by Hansen. This diameter is then combined with the metered liquid fuel leak sized to produce a combustible liquids pool fire that could burn for 30 minutes. A single burning tire pool set typically represents about 25-40% of the combined pool footprint unless there are a large number of tires in a single tire set, multiple tire sets involved, or a very small quantity of combustible liquids. In these cases, the analysis sensitivity to this assumption increases.

Additional text: None

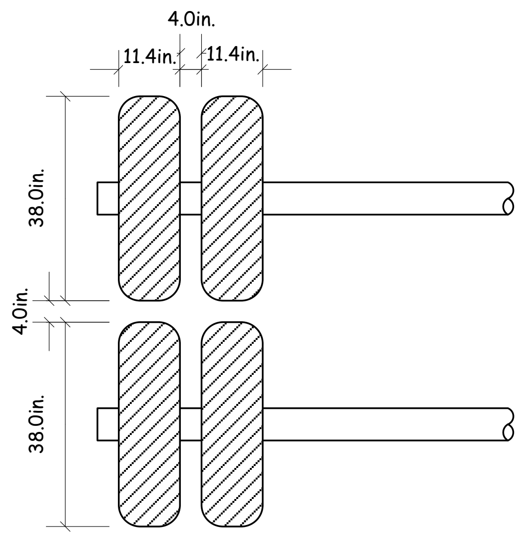


Figure 2, Typical Two-Axle, Dual Tandem Tire Arrangement

Assumption 5.2.9

Assumption: Tire groups that are closer than approximately 2 tire widths or 2 tire lengths are assumed to melt together and burn as a single pool in a manner similar to that observed in the empirical fire testing (Ref. 25) and are considered a single tire set.

Basis for why this assumption is valid: Interpretation of empirical test data from Hansen (Ref. 25).

Sensitivity to this assumption: The analysis is relatively insensitive as tire sets are typically either much further apart or much closer together than 2 tire widths, or 2 tire lengths.

Additional text: None

Assumption 5.2.10

Assumption: Pipe Overpack Containers (POCs) and Criticality Control Overpacks (CCOs) are not damaged in engulfing pool fire or room fire scenarios.

Basis for why this assumption is valid: Recent fire testing of POCs at Sandia National Laboratory (SNL) (Ref. 34 - Ref. 37) was conducted to evaluate their performance under various conditions, including when filled with combustible material. The testing determined that POCs with the UltraTech 9424S filter installed per manufacturer's specifications can be assigned a DR of zero, irrespective of whether they contain residues, particulates, combustibles, or any other waste form in an authorized configuration for scenarios bounded by the evaluated test conditions. This is documented in Operating Experience – 3 (OE-3) Report 2018-04, (Ref. 23).

Additional SNL testing of the CCO (Ref. 38) was conducted in 2020 with a payload in the inner Criticality Control Container (CCC) designed to simulate the can-bag-can K-Area downblend oxide configuration. The testing determined that although the inner pipe component was heated significantly and the packaging (bag) and tape on the innermost convenience can were consumed, there was no release of the surrogate oxide inside the convenience can.

Sensitivity to this assumption: The analysis is relatively insensitive to this analysis because POCs and CCOs are not used to store combustible materials at SRS and the release from thermal stress to oxides is relatively low.

Additional text: None

Assumption 5.2.11
Assumption: TRU waste drums engulfed in a hydraulic fluid pool fire only experience seal failure damage and do not experience lid ejection damage.

Basis for why this assumption is valid: Based on test data in Westinghouse Hanford reports (Ref. 31, Ref. 32, and Ref. 33), as well as data from more recent POC testing at Sandia National Laboratories (Ref. 34, Ref. 35, Ref. 36, and Ref. 37), lid loss can occur only if specific conditions associated with an engulfing deep pool fire are met; e.g., a "fast" fire growth rate, "rapid" flame spread rate, direct flame impingement, sufficient duration, etc. is required. Engulfing deep pool fires which can cause lid ejection are those in which burning liquid fuel surrounds the container and is capable of rapid flame spread. They must also, based on the cited test data, be capable of sustaining engulfing fire conditions in excess of 70 seconds, the time necessary to achieve lid ejection in deep engulfing pool fires. The Hanford and Sandia test data also show that seal failure requires significant incident heat flux for longer than about 90 seconds. The data indicates that if a drum has not suffered lid ejection within about 70 – 90 seconds, it will only receive seal failure.

Gottuk and White (Ref. 7) starting on page 2559 provide a description of the basic theory of flame spread on liquids. They characterize flame spread across a liquid fuel pool as being principally driven by the liquid temperature relative to its flashpoint. From page 2560:

> *Semilog plots of flame spread as a function of liquid temperature have a characteristic shape with three regions: the liquid-controlled region, the gas phase–controlled region, and the asymptotic gas phase-controlled region.*

There is little to no information on ignitability and burning rates of hydraulic fluids which, typical of most hydrocarbon fuels, have a range of thermophysical properties. Atomized spray of hydraulic fluid under pressure is a well-known fire hazard and is easily ignitable, but data on hydraulic fluid pool fires is not available. Gottuk and White describe (page 2553) testing conducted by Mealy, Benfer, and Gottuk, (Ref. 30) which evaluated a range of liquids and substrates. Pool fire testing on substrates such as plywood showed that a kerosene pool fire tended to develop slower "due to the fact that for ambient temperatures of approximately 20°C, kerosene is below its flashpoint temperature" (Ref. 30, Section 4.6.6). In their testing on coated concrete substrates, kerosene and diesel fuel were excluded "due to their inability to propagate flame under test conditions" (Ref. 30, Section 4.6.3). Table 18.2 of Ref. 5 provides the flashpoint of various liquid fuels, some of which are listed here for comparison:

Kerosene	~49°C	Benzene	-11°C
Methanol	12°C	Acetone	-18°C
Gasoline	~45°C	Diesel Fuel	52°C (min, from Ref. 28, Table 1)

The Factory Mutual Datasheet on hydraulic fluids (Ref. 39) specifies a flashpoint in the range of 150-315°C which is consistent with data in Refs 13 – 17.

The testing performed by Mealy et al., indicates that flame spread beyond the point of ignition is very unlikely with high flashpoint liquids such as kerosene or diesel fuel. Hydraulic fluid with a much higher flashpoint than those would be even more unlikely to cause flame spread beyond the point of ignition. However, in the presence of a significant long duration ignition source (such as a burning TRU waste handling vehicle) heating of the liquid above its flash point must be considered possible. In this case, liquid-phase flame spread is the only mechanism plausible to permit the greater part of the hydraulic fluid spill to become involved in the fire. Flame spread would be expected to be slow, not approaching the bounding liquid-phase flame spread rate (10 cm/s) presented in Ref. 5 (page 2567) for jet fuel pool fires.

Based on this review, unconfined hydraulic fluid spill fires are not considered capable of creating rapid heating conditions necessary to cause lid ejection in exposed standard TRU waste drums. Although, the slow propagation could enhance the possibility of seal failure damage, the depth of the unconfined pool will limit the fire duration to less than about 70 - 90 seconds. Given that engulfing pool fire conditions expose most of a container's surface to high incident flux, it is not conservative to conclude there is no seal failure damage. Therefore, it is appropriate and conservative to assess TRU waste drums as receiving only seal failure damage and no lid ejection damage in an engulfing hydraulic fluid pool fire.

Sensitivity to this assumption: The analysis methodologies described in this analysis are sensitive to this assumption as it serves to exclude hydraulic fluid pool fires from causing lid ejection on containers engulfed in the pool.

Additional text: This assumption is provided to enable the analyst to exclude considering hydraulic fluid pool fires where other hydrocarbon liquid pool fires (i.e., diesel fuel) are also available and of a similar volume.

Assumption 5.2.12
Assumption: Pool fire engulfment is taken to require a flame thickness of 0.5 m.

Basis: Heating of an object immersed in flame is maximized by limiting the potential for radiative losses from the object being heated. This is recognized in test standards for structural members exposed to hydrocarbon pool fires (ASTM E1529, Section X1.5.2.2, Ref. 40) which requires a flame thickness of 3 - 6 ft (0.9 - 1.8 m) and for shipping packages exposed to hypothetical accident conditions (10 CFR 71.73(c)(4), Ref. 41) which requires a flame thickness of 1.0 - 3.0 m. For the metered leak scenario, heating of the target is directly proportional to the amount of the target's surface involved and the fire's duration. However, the affected target surface area and the fire duration are competing parameters that are both determined from the fire's diameter. Beyler and Gottuk (Ref. 33, Section 4.3.1, page 4-11) specify a 0.5 m flame thickness as a "rule of thumb" for modeling fire damage to TRU waste containers, and it was used in Rocky Flats fire analyses (Ref. 26, page 9). That value is adopted here. It presents a certainty regarding the presence of flames beyond the target periphery to ensure a bounding 100% affected surface area, while at the same time being very conservative, ensuring a bounding fire duration.

Sensitivity: The analysis is somewhat sensitive to this assumption. The extent of engulfment most directly affects the duration of the engulfing pool fire in the metered leak scenario but only as long as the affected surface area of the exposed target is maximized at 100%. Reducing flame thickness would increase duration but if reduced enough would also decrease the affected surface area. Increasing flame thickness would decrease the duration of the fire but would not increase the affected surface area of the exposed target.

Additional Text: While modeling an engulfing flame thickness of 0.5 m may not actually achieve the incident heating specified by regulatory standards it does increase the conservativism of the modelling approach without being unrealistic. Increased flame thickness is conservative for the regulatory standards where the fire duration is fixed by criteria not related to the fuel burning rate. The regulatory standards are taken as containing a significant safety margin for the purpose of intended use. However, increased flame thickness is non-conservative for application of this analysis methodology as it results in decreased fire duration due to the higher leak rate required to achieve the larger pool. Thus the 0.5 m flame thickness is determined to be an appropriate analysis value[1].

6.0 ANALYTICAL METHODS

6.1 OVERVIEW

Three types of liquid pool fires are considered; unconfined crash/instantaneous spill fires, unconfined continuously flowing (also called metered leak) spill fires, and confined spill fires. All fuel sources should be considered consistent with the facility FHA. However, the most likely liquid fuel sources present in TRU waste facilities (hydraulic fluid, diesel fuel, and gasoline) are those present on TRU waste handling vehicles (forklifts, pallet movers, transport trucks, etc.).

Two unconfined scenarios are considered: 1) a crash-with-rupture scenario with nearly instantaneous unconfined spill of available fuel, and 2) a metered flow/leak scenario with the unconfined spill occurring over time proportional to the spill quantity, the spill leak rate, and the fuel's burning rate. The third type, a confined liquid spill pool fire such as one occurring in a diked enclosure, is the same as the metered leak spill fire except the pool fire footprint is defined by the mechanism containing the spill (i.e., curbs, walls, ditches, etc.). Test data described in Ref. 30 (page E-3) indicates that spill depths on the order of ~ 5 mm are sufficiently deep that asymptotic (peak) burning rates are achievable. In addition, the duration of the constrained spill pool fire could be much longer. Also, the edges or sides of the pool's containment typically tend to increase burning rates, even on very shallow pool fires. Inclusion of tires should be based on the calculated duration of the postulated spill fire within the constrained area. Since the metered leak and constrained pool fire analysis methods are essentially the same, no further discussion of confined spill fires is provided in the remainder of this evaluation. With the pool fire characterized, damage to containers remote from the fire is evaluated, and a graphical solution for assessing pool fire damage to waste containers is presented.

A general overview of each of these steps: modeling the instantaneous crash spill, modeling the metered leak spill, modeling the involvement of vehicle tires in the metered leak spill, calculation of critical incident flux to containers remote from the fire, and assessing the potential for pool fire damage to standard TRU waste containers is provided in Sections 6.1.1 through 6.1.5, respectively. The technical bases and derivation of the methodologies used for each step is presented in Sections 6.2 through 6.5.

For all types of spill scenarios, the spill surface should be taken as flat and not inclined as stated in Assumption 5.2.3 unless known to be otherwise. If inclined, the analysis should consider the slope of the incline and modify the fuel pool spill area to achieve a more-likely elliptical shape. Guidance for evaluating spills on inclined surfaces may be obtained from Simmons, Keller, and Hylden (Ref. 29). Also, as described in Assumption 5.2.6, the spill area should not be adjusted for objects (pallets, drums, etc.) within the pool periphery. However, physical constraints such as curbs and room boundaries should be considered if present. Large depressions, ditches, or pits should be treated as confined pool fire with defined pool fire boundaries.

The examples in this document are based on a hypothetical material handling vehicle (forklift) using the parameters described in Table 6-1. These vehicle parameters should be provided by the facility. Results of the example pool fire analysis calculations are summarized in Table 6-4 at the end of Section 6.4.

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[1] The effect of flame temperature variations within the structure of the pool due to changes in flame thickness should be considered by the analyst but are not within the scope of this methodology document (see Ref. 42).

Table 6-1, Hypothetical Vehicle (Forklift) Analysis Parameters

Parameter	Value
Diesel Fuel Tank Capacity:	13.9 gallons (metal tank)
Hydraulic Fluid Tank Capacity:	12.1 gallons (metal tank)
Front Tire Style / Mass/Material:	Dual / 60 lbs each tire / Rubber
Rear Tire Style / Mass/Material:	Single / 60 lbs each tire / Rubber
Vehicle Dimensions:	54 in. x 78 in.

A diagram of the hypothetical forklift evaluated here is provided in Figure 3 below.

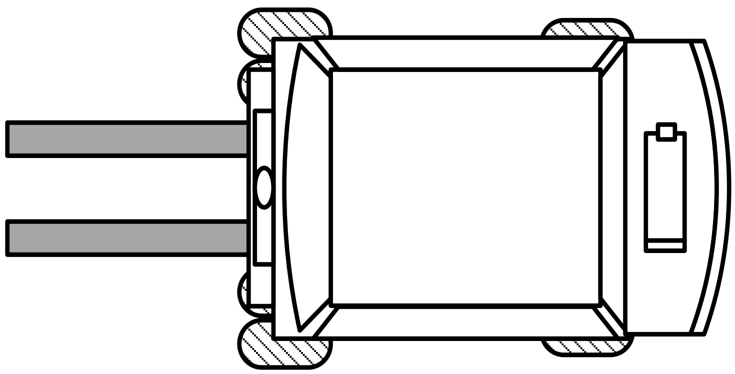


Figure 3, Diagram of Hypothetical Waste Handling Forklift Used in This Analysis

6.1.1 Unconfined Crash/Instantaneous Spill Fire Overview

This scenario models a crash or large fuel leak that spills all available liquid to a nominal depth of 2.9 mm and is then ignited; it presents the bounding diameter fuel spill, but the fuel is consumed very quickly. Although the vehicle's tires could ignite, they could not influence the spill diameter because a fire involving the tire material takes several minutes to develop and pool and the liquid spill would have been consumed by that time.

6.1.2 Unconfined Metered Leak Spill Fire Overview

This scenario model is dependent on the target's response to a pool fire and is typically evaluated as either a fixed diameter or a fixed duration fuel spill. Where the spill fire duration can burn for longer than approximately 10 minutes, involvement of the tires needs to be considered to influence the size of the pool.

6.1.3 Involvement of Tires in the Metered Leak Spill Fire Overview

Tire involvement in a vehicle pool fire is modeled as melting and flowing to a pool size that is based on empirical testing of burning tires and is related to the mass of the tire material involved. The molten tire material is assessed to displace the liquid spill thus increasing either the diameter or the duration of the metered leak spill depending on the metered leak spill analysis method used. Heating from the tire fire after the liquid fuel is consumed is appropriate if needed. It is not considered plausible for molten tire material to flow around and engulf a target as liquid fuel can do.

6.1.4 Critical Incident Flux Overview

The critical flux is that necessary to cause seal failure in a TRU waste container remote from the postulated fire. The critical incident flux is calculated using the detailed Shokri and Beyler method outlined in the SFPE Handbook (Ref. 8, page 2605).

6.1.5 Assessing the Potential For Pool Fire Damage to Waste Containers Overview

Damage to waste containers may occur due to a container being fully engulfed (within the periphery of the pool), partially engulfed, or within the critical heat flux distance. This document provides guidance for performing a scaled graphic analysis to determine, for a given scenario, the number of waste containers that are subjected to each of those three exposure conditions and therefore, potentially damaged. The graphic analysis provides a conservative technique for combining the pool fire, the vehicle, and the waste containers within the defined pool fire scenario. It also provides for tabulating the number of containers subjected to each of the specified exposure conditions. Assessing the damage to a container caused by being subjected to one of the three exposure conditions is not within the scope of this methodology document.

6.2 Unconfined Crash/Instantaneous Liquid Spills

Industrial material handling vehicles (forklifts, pallet jacks, etc.) are equipped with numerous types and quantities of combustible material. These range from minor contributors such as seat covers, knobs, hoses, and wires to major quantities in fuel tanks and tires. A significant vehicle impact is postulated to result in the rupture of the single largest tank containing combustible liquid (diesel fuel oil (DFO) or hydraulic fluid) which then spills to its maximum diameter.

The maximum spill diameter is developed in Section 6.2.2 based on a methodology described in the SFPE Handbook (Ref. 7); it results in a pool depth of either 0.7 mm (Input 4.2-14) or 2.9 mm (Input 4.2-15) and is consequently ignited. The 0.7 mm deep pool is appropriate (see Ref. 7, equation 65.2a) for most fuels and conditions. As an example, the burn duration for a 0.7 mm deep pool fire involving diesel fuel is calculated here using Equation 65.14 from reference 7, where the regression rate $\dot{y}$, the rate at which the fuel surface descends in a vertical direction as it burns, is represented in Equation 1 below as the time (t) required to burn the full fuel pool spill depth (δ) of 0.7 mm ($\dot{y} = \delta / t$):

Equation 1 $$t = (\rho \cdot \delta) / \dot{m}''$$

Where:

$t =$ duration of the fire (s)
$\rho =$ density of the liquid (kg/m^3), for diesel fuel this is 852 kg/m^3 (Input 4.2-5)
$\delta =$ depth of the pool (m), in this example the depth is 0.7 mm (Input 4.2-14)
$\dot{m}'' =$ mass burning rate (kg/m^2 s), for this example, it is 0.039 kg/m^2-s (Input 4.2-9)

Therefore:

$$t = \frac{\left(850 \frac{kg}{m^3}\right)(7 \times 10^{-4} m)}{0.039 \frac{kg}{m^2 s}} = 15.3\ s$$

Though presenting the largest pool diameter, this very shallow depth pool fire is of very short duration ~15-20 s. Based on test data in Westinghouse Hanford reports (Ref. 31, Ref. 32, and Ref. 33), as well as data from more recent POC testing at Sandia National Laboratories (Ref. 34, Ref. 36, and Ref. 37), the 15-20 second fire duration is much shorter than that required for either lid ejection (~70 seconds) or seal failure (~120 seconds). Therefore, the very shallow pool fire, though possible, is determined to result in no damage to TRU waste containers due to its short duration and does not need to be considered further in contributing to direct fire damage to containers. It may however, need to be considered for propagation to other combustible material accumulations as warranted by the fire scenario in the facility FHA.

The SFPE Handbook specifies that a spill depth of 2.9 mm "be used as a bounding value in a fuel spill fire analysis when a longer lasting but smaller fire is worth evaluating" (Ref. 7, equation 65.2b). The 2.9 mm spill depth is therefore considered conservative for use in pool spill fire analysis used in this evaluation. Other combustible concentrations on the vehicle, including the battery, are likely to burn in a severe vehicle fire and contribute to the fire's heat output. Their contribution, though not insignificant, cannot contribute to the size of the pool fire and are therefore, not germane to determining the pool size in this analysis. Pooling of molten tires, or breach of a second smaller tank would occur after the first tank volume is consumed and would also not contribute to increasing the diameter of the postulated fire.

Using Equation 1, a 2.9 mm depth (Input 4.2-15), and all the other same parameters, the fire duration is calculated to be 63 s, or approximately the time required for TRU drum lid ejection in an engulfing pool fire (Ref. 33).

If the flammable/combustible liquids are contained within a robust metal storage tank or reservoir, 25% of the liquids are considered shielded and 75% (75% derated, Assumption 5.2.2) of the liquid is considered available for the maximum credible fuel spill. The remaining 25% of the tank contents could be evaporated or burn inside/near the tank. Fuel contained in tanks not made of metal receive no derating. The size of the pool for this scenario then is based on the maximum credible spilled (derated) liquid volume of the single largest combustible liquids tank or reservoir spilled to a depth of 2.9 mm (Assumption 5.2.5).

6.2.1 Area and Diameter of Unconfined Instantaneous Crash/Spill Fire

The area of a fuel spill fire is simply taken from the volume of fuel spilled in a circular area, a cylinder (Assumption 5.2.1) at a depth of 2.9 mm. For a metal tank/reservoir, the volume is derated by 25% per Assumption 5.2.2.

As an example, consider the pool size for the crash/instantaneous spill of the hypothetical 13.9-gallon metal tank. The derated volume is 10.4 gallons (13.9*0.75 = 10.4) which converts to 0.04 m^3. The pool area is taken as the circular area (footprint) occupied by a 2.9 mm high right circular cylinder with a volume of 0.04 m^3, or 13.6 m^2. The diameter of a 13.6 m^2 circular area is, from the area of a circle, 4.16 m (13.6 ft).

6.2.2 Heat Release Rate of Unconfined Instantaneous Crash/Spill Fire

The heat release rate (HRR) of a hydrocarbon pool fire that is based on the available energy of the fuel being consumed at a constant peak mass loss rate from the surface of the pool. The pool fire analysis method for determining the HRR is taken from Equations 65.11 and 65.12 as presented in Chapter 65 of the SFPE Handbook (Ref. 5) which is reproduced here as Equation 2.

Equation 2 $$\dot{Q} = \dot{m}'' \times \Delta H_c \times A$$

Where:

$\dot{Q} =$ fire heat release rate (HRR), MW.
$\dot{m}'' =$ mass loss rate (mass burning rate) per unit area, kg/m^2-s. (0.039 kg/m^2-s for DFO, Input 4.2-9)
$\Delta H_c =$ fuel heat of combustion, MJ/kg (42.6 MJ/kg for DFO, Input 4.2-1)
$A =$ pool fire area (footprint), (13.6 m^2, determined above).

It must be noted that this approach is very conservative in that it assumes the pool fire burns at 100% efficiency so that all the available energy (albeit the derated available energy) is entirely consumed. The HRR is only used in this document to determine the pool fire flame height. The flame height is used to determine the view factor between the fire and the waste container which is in turn used to calculate the flux level to remote exposed items in Section 6.4.

In the case of the example hypothetical forklift, the HRR is calculated as:

$$\dot{Q} = \left(0.039\frac{kg}{m^2 s}\right) \times \left(42.6\frac{MJ}{kg}\right) \times 13.61 m^2 = 22.6\ MW = 22{,}600\ kW$$

6.2.3 Flame Height of Unconfined Instantaneous Crash/Spill Fire

The fire height (or flame height) of both the ordinary combustible package fire and the waste handling vehicle pool fire are determined using the Heskestad flame height correlation (Ref. 6, Equation 66.13). Note this same correlation is also cited as Ref. 7, Equation 65.29 and represents the 50-percentile intermittent flame height.

Equation 3 $$H = 0.235\dot{Q}^{2/5} - 1.02D$$

Where:
$H =$ flame height, m
$D =$ fire diameter, (4.16 m, determined above)
$\dot{Q} =$ fire heat release rate (HRR), (22,600 kW, determined above).

For this example, the diameter and HRR calculated above for the forklift can be plugged into Equation 3 to yield:

$$H = 0.235 \times (22{,}600)^{2/5} - 1.02 \times 4.16 = 8.72 \text{ m } (28.6\ ft)$$

A graphical depiction of the instantaneous crash/spill pool fire for the hypothetical forklift evaluated in this analysis is provided in Figure 4 below.

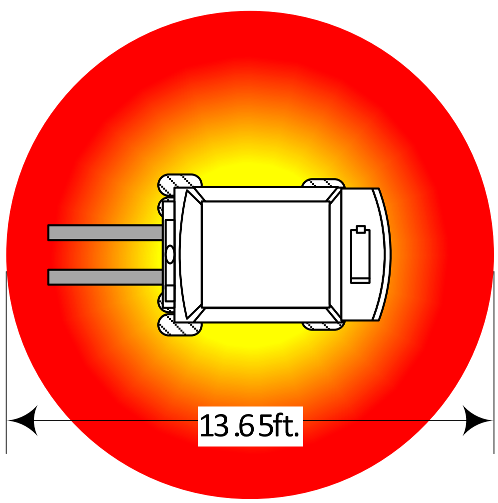


Figure 4, Hypothetical Forklift Instantaneous Crash/Spill Pool Fire

6.3 Unconfined Metered Leak Liquid Spills

6.3.1 Metered Leak Spill Fire Overview

Another type of pool fire postulated to occur at a TRU waste facility is one where the fuel spill is continuous or of long duration. The metered leak pool fire scenario involves a slow leak or release of the flammable/combustible liquid fuel volume to spill and burn over time, i.e., not instantaneous. This can occur with a small tank/reservoir puncture, loss of a hose, or other malfunction that creates a small breach in the tank or fluid delivery system.

The spill area of an unconfined, metered leak spill will continue to increase indefinitely until a physical boundary is reached or the fuel is ignited and burns. The transient nature of the metered leak spill is very dependent on the timing of the ignition and the flame spread rate relative to the fuel flow rate and the fuel's mass loss rate. With a fixed quantity of fuel, the spill area will be bounded by the unconfined crash-type spill described above where all of the volume is spilled at once. A metered leak spill fire will reach a steady-state burning size characterized by the equivalent steady-state diameter (D_{ss}) where the fire's mass loss rate is equivalent to the spill flow rate. If fire ignition occurs after the spill reaches its steady-state diameter, the spill area will decrease to the steady-state diameter. Conversely, if fire ignition occurs before the spill reaches the steady-state diameter, the spill area will increase to the steady-state diameter. These are just some of the multiple scenarios that can occur. Complicating factors to alter the steady-state fire diameter include an unknown or variable leak size (flow orifice), changes in flow rate due to head pressure, and the potential involvement of molten vehicle tire material which is described in the next subsection. If the spill rate and tire parameters are known, a steady-state spill diameter can be determined based on equations 65.26a and 65.26b for nominal spill rates (<150 gpm) or, for very large spill rates (150-600 gpm), equations 65.27a and 65.27b, from Chapter 65 of the SFPE Handbook.

TRU waste containers receive pool fire damage quickly, within the first 120-300 seconds (drums, Standard Waste Boxes (SWBs), etc.). Therefore, the unconfined metered leak spill fire need not be considered for assessing direct damage to TRU waste containers because it is always bounded by the unconfined crash/instantaneous spill fire.

Nonetheless, where the facility FHA identifies a target with a thermal stress failure threshold longer than about 120-300 seconds, the metered leak spill fire should be evaluated. For those scenarios, such as failure of a structural steel support column, the spill area should evaluate a spill rate that obtains the target failure threshold based on either specified fire duration or a specified fire diameter (typically based on target engulfment). If the metered leak spill fire results in a fire lasting about 10 minutes or longer, the vehicle tires would likely have an opportunity to influence the pool diameter and should be included as described next.

6.3.2 Involvement of Vehicle Tires in a Metered Leak Spill Fire

Empirical testing of dual truck tires (Ref. 25) indicates that although the tires burn for a significant duration, the pool size formed by the molten rubber is attained in about 10 minutes to a footprint about three times a single tire's width and length. Where multiple tires are co-located (e.g. dual or tandem tire sets) and would obviously be involved in a single fire, the spacing between tires should be included in estimating the pool size. For a metered leak pool fire lasting >~ 10 minutes, at least one tire set on a vehicle would likely contribute to increasing the size of the metered leak spill and should therefore be included in the metered leak pool fire estimates.

The metered leak fire scenario that also involves tires is considered possible, but not very likely. It could be initiated by a leak of flammable/combustible liquid from a hose or fitting that is then ignited and subsequently involves at least one tire/tire set on the vehicle. Or, the fire could initiate at the brakes (a common vehicle fire initiator), involve a tire/tire set, and then propagate to melt or damage a hose or fitting on a liquid fuel system, thereby causing a metered leak to feed the already developing tire fire. Fire development in either case is variable and difficult to quantify. An acceptable approach is to treat the liquid and solid portions of the fire as starting at or near the same time. This is a very conservative approach which encompasses any uncertainty related to the timing of the fuel leak or ignitions.

As described above, damage from a metered leak pool fire is typically evaluated by characterizing the fire according to one of two criteria. They are; 1) determine the duration of exposure that a certain size (fixed diameter) metered leak pool fire would present to a target; and 2) determine the diameter of a certain duration (fixed duration) metered leak pool fire. An example of the first, fixed diameter case, evaluating the time a structural steel column is engulfed in a pool fire, is presented in Section 6.3.4.1. An example of the second, fixed duration case, evaluating the diameter of a 10-minute metered leak pool fire, is presented in Section 6.3.4.2[2].

Tire fire involvement is treated slightly differently for each case. However, the first step in either case, is to estimate the size of the pool fire developed by molten tire material.

6.3.3 Tire Fire Analysis

This section describes the methodology for evaluating fire involving tires on a vehicle. Parameters evaluated here are used later in this calculation and are ultimately combined with the liquid pool fire in evaluation of the metered leak spill fire.

6.3.3.1 Standard Test Tire Fire Diameter

Hansen (Ref. 25) conducted fire testing of sets of dual truck tires. Some tests were conducted with just the tires, and some were conducted with a heat shield and a partial trailer body constructed above the tires. Data are extracted from these tests to develop a conservative solids pool fire size for the tires used by Hansen. Examination of the test results shows that the pool fire developed from burning the dual tires spreads laterally to a size approximately three tire widths wide and three tire lengths long (See Figure 5). Further examination indicates that the tires burn for approximately 10 minutes before they attain substantial pooling. These data are then extrapolated to other arrangements.

Figure 5, Hansen Fire Tests of Dual Truck Tires

The methodology used here is based on developing an expression for the relationship between combustible tire mass and tire geometry using the "standard" tire from Hansen. The fire size is calculated by adding two tire widths to the total width of the tires involved in the fire and by adding two tire lengths to the total length of the

[2] With the modeling approach described here a metered leak pool fire with tire involvement that lasts 10 minutes presents the bounding diameter pool.

tires involved in the fire, including spacing (Figure 6 and Figure 8). Tires that are closer together than about 2 tire widths, or lengths depending on the arrangement, are assumed to burn together as a single pool (Assumption 5.2.9). For simplicity, the pool area is calculated as a rectangle (slightly conservative).

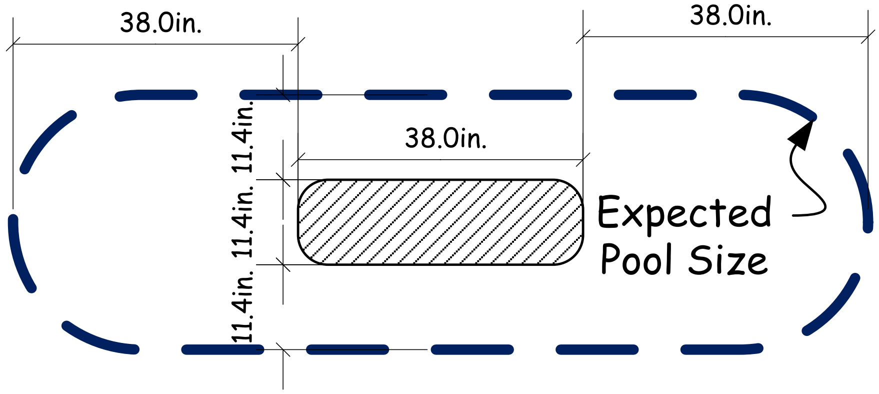


Figure 6, Graphic Representation of Expected Test Tire Fire Pool Development

The formula for the fire footprint area, with the standard tires is shown in Equation 4:

Equation 4
$$Area = \big(38(2+l) + 4(l-1)\big) \times \big(11.4(2+w) + 4(w-1)\big) \div 144$$

Where:
$Area =$ Anticipated Area (ft^2) of the fire postulated fire;
$l =$ Number of tires counted lengthwise;
$w =$ Number of tires counted widthwise (side by side).

It is noted that Equation 4, as used in this calculation is perhaps unnecessarily complex. However, the methodology accommodates different tire configurations such as dual, triple, and tandem axle arrangements. It is equally applicable to single tire, single axle arrangements. The expected pool fire size for a single standard tire on a single axle (i.e., l = 1 and w = 1) is thus calculated as:

$$Footprint\ Area = \big(38(2+1) + 4(1-1)\big) \times \big(11.4(2+1) + 4(1-1)\big) \div 144 = 27.1\ ft^2$$

A cylindrical fire of the same footprint is calculated from the area of a circle as:

$$Standard\ Tire\ fire\ diameter = \sqrt{4 \times 27.1/_{\pi}} = 5.9\ ft$$

Tires on the hypothetical forklift vehicle are either single (two per axle) or dual (four per axle with two at each end of the axle).

Tire sets are evaluated separately and for analysis purposes, they are assigned an arbitrary style designation of "T#," where the # represents the number of tires on each end of the axle. Various tire set arrangements are graphically depicted in Figure 7.

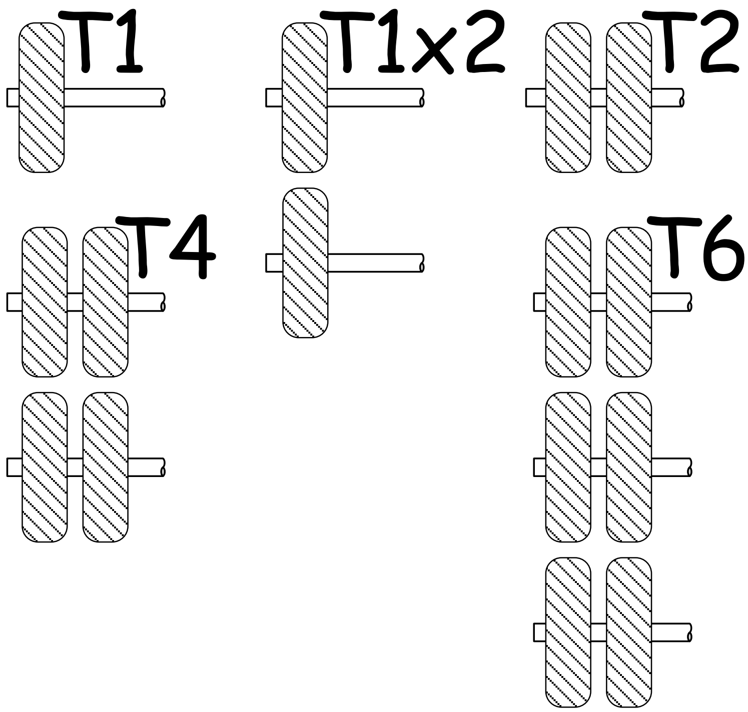


Figure 7, Various Possible Vehicle Tire Arrangement Styles

As described in Assumption 5.2.9, each of these tire styles are assumed to burn as a single, merged pool fire of cylindrical shape that has an equivalent footprint (Assumption 5.2.1) to the pool developed in a manner similar to the testing conducted by Hansen (Ref. 25). Figure 8 below provides a graphical representation of anticipated fire size and equivalent footprint cylindrical fire for the arrangements considered here, using the standard test tire dimensions from Hansen. Table 6-2 contains a summary of the associated dimensions.

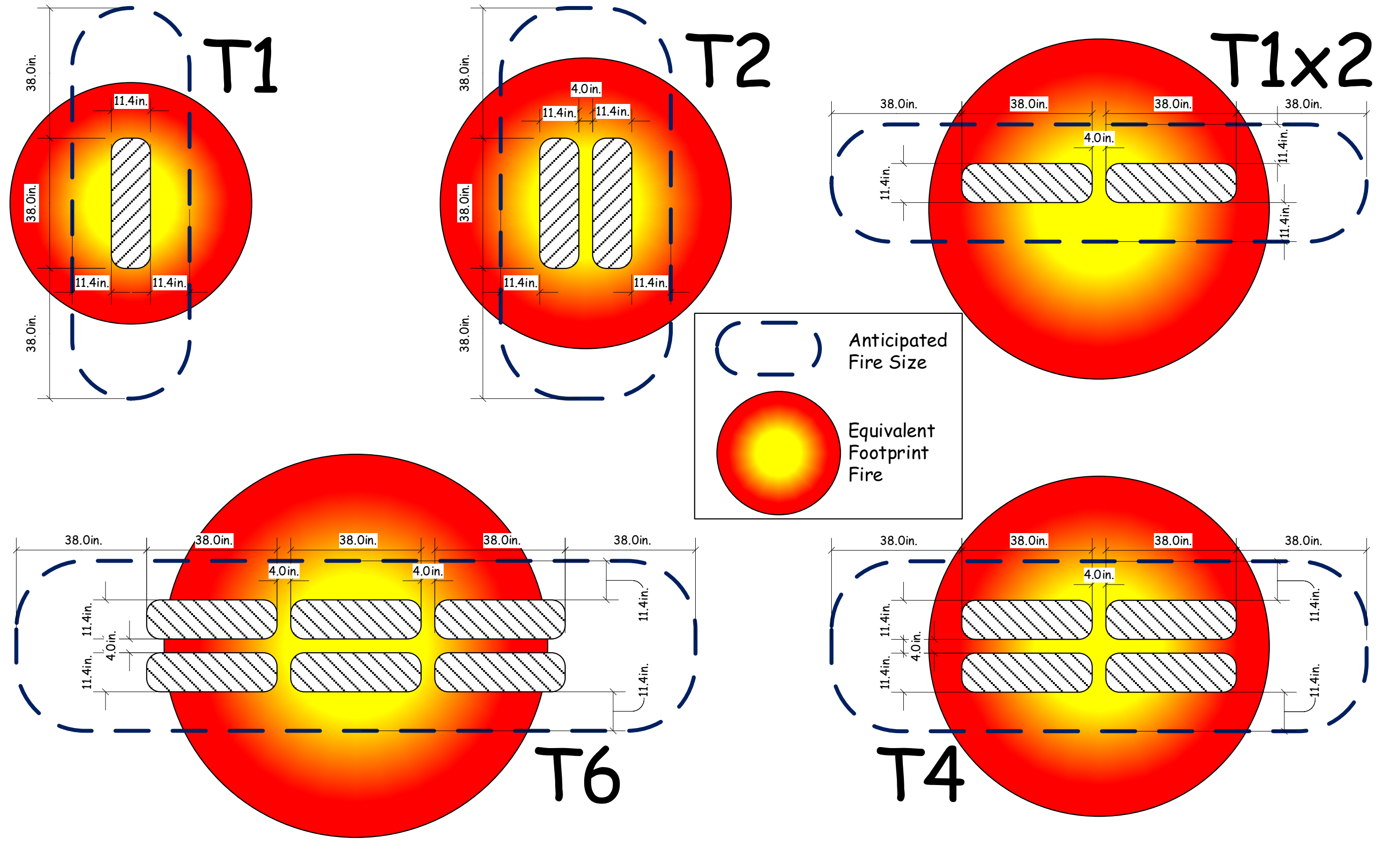


Figure 8, Various Standard Tire Arrangement Style Fire Diagrams

Table 6-2, Dimensions of Various Standard Test Tire Pool Fires

Tire Style	No. Tires lengthwise	No. Tires widthwise	Pool Area, (ft^2)	Pool Diameter(ft)
T1	1	1	27.1	5.9
T2	1	2	39.3	7.1
T4	2	2	53.7	8.3
T6	3	2	68.2	9.3
T1x2	2	1	37.1	6.9

6.3.3.2 Mass-Modified Tire Pool Fire Area

This subsection takes the standard test tire fire size calculated for each tire set, modifying it relative to the mass of combustibles specific to each individual facility vehicle evaluated. It is noted, the nomenclature notwithstanding, that the ratios are based on heat content (MJ) per tire and not mass. The tire's heat content is considered an appropriate common parameter as the heat content per unit mass of rubber or polyurethane, the heat of combustion, are of the same magnitude (Input 4.2-4, Input 4.2-3, respectively). Waste handling vehicle tires are typically either rubber or polyurethane.

As described in Assumption 5.2.8, the standard test tire is established as weighing 110 lbs (50 kg). At 32.6 MJ/kg (Input 4.2-4), a single tire contains 1,630 MJ (1630 = 50 x 32.6). The front tires associated with the hypothetical waste handling forklift (Table 6-1) are rubber and weigh 60 lbs each; the rear tires are also rubber, weighing 60 lbs (27.2 kg) each. The front tires are defined as dual tires and are represented as a T2 style on each side of the front axle. The rear tire are single tires of T1 style on each side of the rear axle. A diagram of the vehicle is depicted in Figure 3. This data should be provided by the facility. The per-tire set heat content is compared with the standard 110 lb test tire heat content of 1,630 MJ and a ratio of the "Facility-to-Test" heat content derived.

Since all the tires on the hypothetical forklift are 60 lbs (27.2 kg) of rubber, each one has a heat content of 890 MJ (890 = 27.2 x 32.6). The facility-to-test mass ratio is 0.55 (0.55 = 890 / 1630).

The ratio is then applied to the equivalent footprint fire area presented in Table 6-2 to obtain the expected molten tire area for hypothetical forklift tire fire. From there, simple geometry for the area of a circle is utilized to arrive at the "Mass-Modified Fire Diameter" for each tire set. This fire diameter is the value to be used in subsequent analyses. The application is as follows:

Equation 5 $$Area_{Facility\ Vehicle} = Ratio \times Area_{test}$$

Using dimensions from Table 6-2 above for the hypothetical forklift front tire set of Style T2, the mass modified equivalent fire area is;

$$Area_{Hypothetical\ Vehicle\ T2\ Front\ Tire\ Set} = 0.55 \times 39.3 = 21.6\ ft^2\ (2.0\ m^2)$$

The mass-modified diameter of the T2 Style front tire set fire, from the area of a circle, is 5.2 ft (1.6 m). The modified area of the T1 Style rear tire set fire is 14.9 ft^2 (1.4 m^2) (14.9 = 0.55 x 27.1). And, the mass-modified fire diameter of the T1 Style tire set is 4.36 ft (1.33 m). For this hypothetical vehicle, the front T2 style tire set presents the bounding tire pool fire diameter and is used in the beginning portion of the next analysis step.

6.3.3.3 Tire Fire Heat Release Rate

Hansen provides HRR data for each of the tire fire tests conducted at SINTEF-NBL (Ref. 25). His Test B data (Input 4.2-16) is reproduced here as Figure 9 below, superimposed with a manually drawn HRR curve to provide data points for later extrapolation. This curve is also available in the SFPE Handbook (Ref. 6, Figure 26.105). The area under the curve is calculated using triangles and rectangles as depicted in Figure 10 below to represent approximately 1468 MJ. Noting that the tires Hansen used are estimated (Section 6.3.3.2) to contain 1630 MJ each, the combined fire combustion efficiency and measurement efficiency from Hansen's testing, along with the efficiencies from the superimposing curve method used here, is determined to be approximately 45% (0.45 = 1468 MJ / (2 x 1630 MJ)). For the two 60 lb (Table 6-1) dual front tire set on the hypothetical forklift fire considered in this evaluation, an HRR curve is developed by manually adjusting both the energy output (kW) and duration (min), keeping the same basic HRR curve shape, until the area under the curve represents about 45% of the available heat content in the tires involved. For this case, the two tires contain a combined heat content of 1780 MJ (1780 = 2 tires x 890 MJ/tire). With an efficiency of 45%, the expected amount of energy released for burning the dual tire set is approximately 801 MJ (801 = 1780 x 0.45).

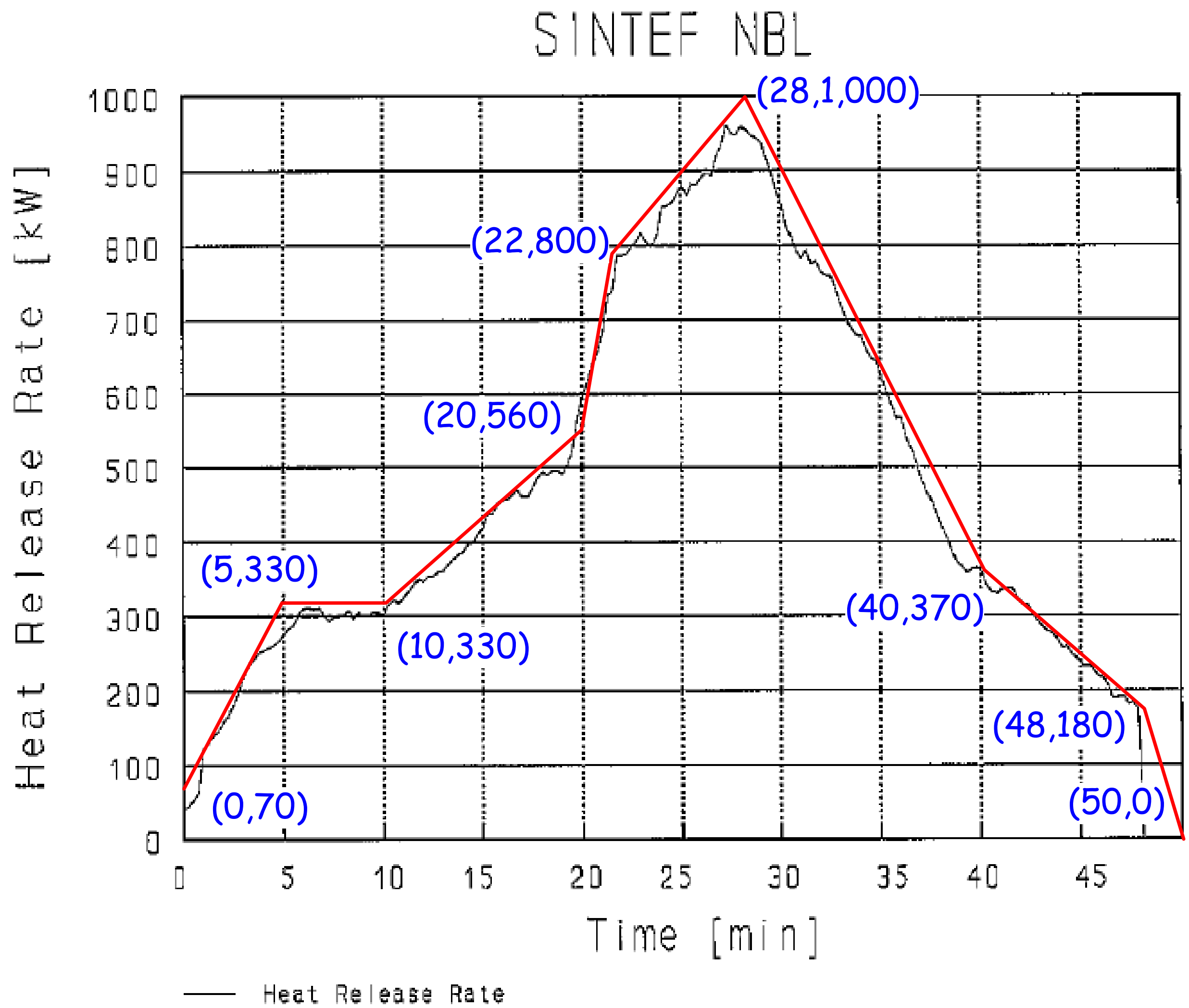
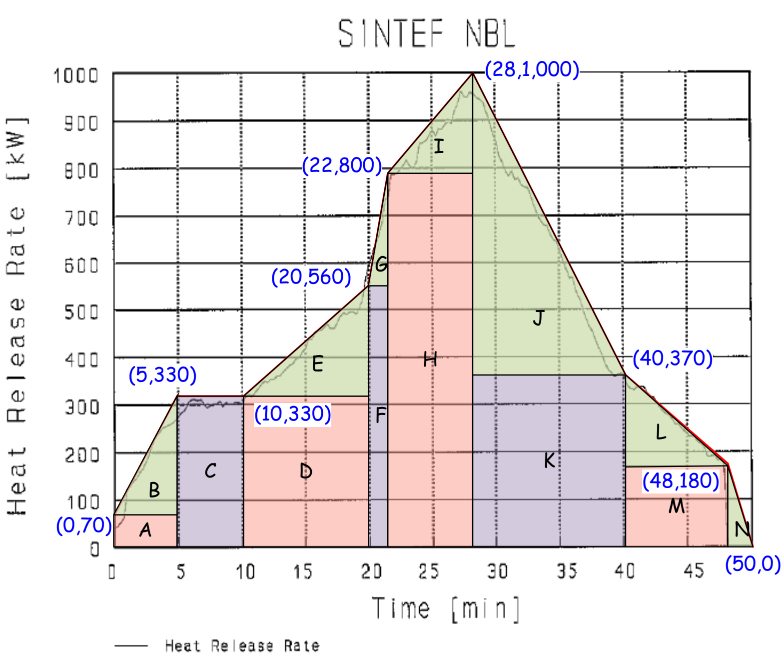


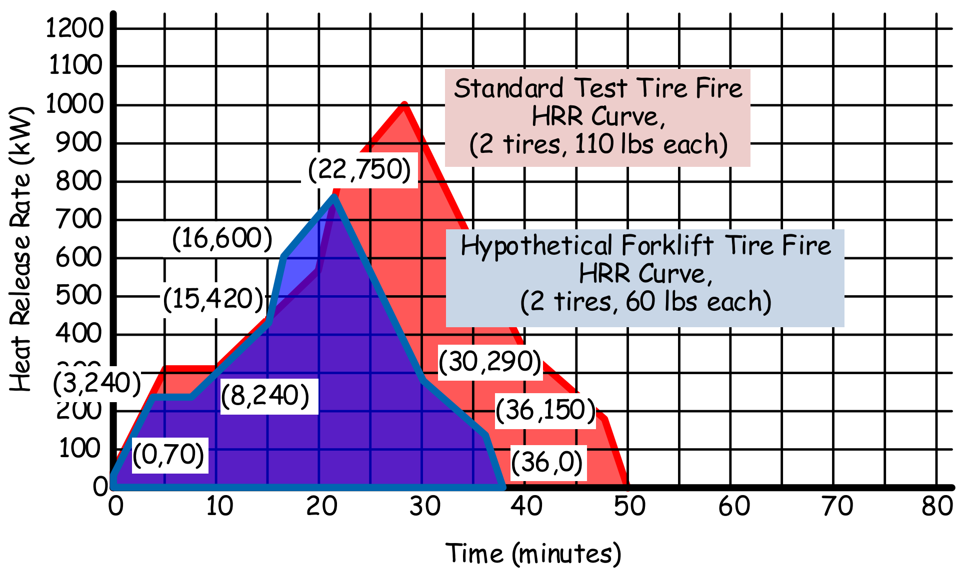
Figure 9, Dual Tire Fire HRR Curve from Hansen (Input 4.2-16) with Superimposed Analysis Curve



		Area, MJ
Rectangle	A	21
Triangle	B	39
Rectangle	C	99
Rectangle	D	198
Triangle	E	69
Rectangle	F	67.2
Triangle	G	14.4
Rectangle	H	288
Triangle	I	36
Triangle	J	226.8
Rectangle	K	266.4
Triangle	L	45.6
Rectangle	M	86.4
Triangle	N	10.8
	Total	1467.6

Figure 10, Calculation of Heat Release from SINTEF-NBL Test Data

The result of manually adjusting the standard HRR curve from Hansen to correlate it to the hypothetical forklift tire fire with the worst case tire set involved is shown in Figure 11 along with a tabulation of the area under the curve. The area, 850 MJ represents slightly more than 45% of the total heat available in the two tires (850 / 1780 = 47.8%). From this data, we can obtain the peak heat release rate (PHRR), about 0.75 MW, and the fire duration, approximately 36 minutes.



		Area, MJ
Rectangle	A	12.6
Triangle	B	15.3
Rectangle	C	72
Rectangle	D	100.8
Triangle	E	37.8
Rectangle	F	25.2
Triangle	G	5.4
Rectangle	H	216
Triangle	I	27
Triangle	J	110.4
Rectangle	K	139.2
Triangle	L	25.2
Rectangle	M	54
Triangle	N	9
	Total	850

Figure 11, Hypothetical Forklift Tire Fire HRR Curve with All Tires Involved

6.3.3.4 Flame Height of Unconfined Metered Leak Spill Fire with Tire Involvement

As described in Section 6.2.3, the flame height is calculated using Heskestad's flame height correlation presented in Equation 3 above. Using the PHRR and pool diameter of the tire set only (1.6 m from Section 6.3.3.2) the flame height is calculated as follows:

$$H_{tire\ fire} = 0.235\dot{Q}^{2/5} - 1.02D = 0.235 \times (750)^{2/5} - 1.02 \times 1.6 = 1.7\text{m}\ (5.5\ ft)$$

6.3.4 Combining Liquid Spill and Molten Tire Solids in Metered Leak Spill Fire Scenarios

As previously described, the method for combining the liquid and solids portions of the metered leak pool fire are different for the two typical metered leak analysis cases; i.e., the fixed diameter case, and the fixed duration case.

6.3.4.1 Duration of a Combined Metered Leak Spill Fire of Fixed Diameter

An example calculation is provided here to assess the duration of a fixed diameter metered leak pool fire as might be considered when assessing thermal stress to a structural steel column exposed to a long duration engulfing pool fire. In this case, the pool fire is designed to be of a fixed diameter, just large enough to fully engulf the column by 0.5 m thick flames (Assumption 5.2.12). The analysis entails the following steps:

- Determine the size (footprint) of the fixed diameter pool fire based on the spatial relationships between the vehicle and column, including the 0.5 m engulfing flame thickness;
  - This step is determined graphically;
  - The pool should be centered (Assumption 5.2.1) on the tire(s) involved;

- Subtract the tire fire footprint (2.0 m^2 from Section 6.3.3.2) from the metered leak pool fire footprint to obtain the footprint of the metered leak portion (i.e., liquid portion) of the combined liquid + tire pool fire;
- From the volume of liquid fuel available, determine the leak rate then the duration of the metered leak (liquid) portion of the spill fire;
- Determine the tire fire's duration by scaling from Hansen's HRR data.

Determine the Size (Footprint) of the Fixed Diameter Pool

Using Assumption 5.2.1, with the pool fire centered on the initial tire set involved, the pool diameter which obtains a flame thickness of 0.5 m (Assumption 5.2.12) around a structural support column is depicted in Figure 12. The beam size should be based on facility conditions; a 10" column is arbitrarily selected here for illustration.

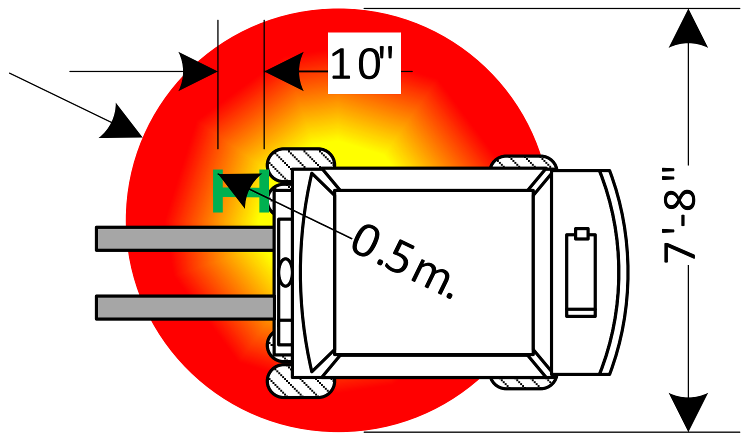


Figure 12, Hypothetical Pool Fire Engulfing Beam

The pool fire area needed to engulf the column is calculated from the area of a circle as:

$$A = \frac{\pi \times (7.67ft)^{2^2}}{4} = 46\ ft^2 = 4.3m^2$$

Obtain Footprint of Liquid Portion of Pool Fire

The methodology used here conservatively considers that the molten tire material will displace the liquid. With a fixed diameter pool, the liquid will therefore occupy a smaller portion of the pool footprint and will take longer to be consumed in metered leak fire. The liquid pool footprint portion is calculated by subtracting the tire pool footprint from the total area required for engulfment. From above, the tire pool occupies an area of 2.0 m^2, which leaves 2.3 m^2 for the liquid (2.3 = 4.3 – 2.0). This correlates to a liquid portion steady state diameter of 1.7 m.

Determine Duration of Liquid Pool Burning

The flow rate necessary to obtain the steady state diameter is calculated from Gottuk and White (Ref. 7), Equation 65.25b which is presented here as Equation 6.

Equation 6 $$\dot{V}_L = {\pi D_{ss}}^2 \dot{m}'' / 4\rho$$

Where:

$\dot{V}_L =$ Volumetric flow rate of leak, m^3/s
$D_{ss} =$ Steady-state liquid pool diameter, m (1.7 m)
$\rho =$ fuel density, kg/m^3, (850 kg/m^3 for DFO, Input 4.2-5)
$\dot{m}'' =$ mass burning rate per unit area, kg/m^2-s. (0.039 kg/m^2-s for DFO, Input 4.2-9) (peak rate used[3])

$$\dot{V}_L\, {m^3}/{s} = \frac{\pi \times (1.7)^2 m^2 \times 0.039\, {kg}/{m^2\text{-}s}}{4 \times 850\, {kg}/{m^3}} = 0.00010\, {m^3}/{s} = 1.6 gpm$$

The derated DFO fuel volume (calculated in Section 6.2.1) of 10.4 gallons would therefore burn for approximately 6.5 minutes (6.5 = 10.4 / 1.6).

The HRR for the liquid portion of the pool fire burning is determined, for later application, by using Equation 2 as follows:

$$\dot{Q} = \left(0.039 \frac{kg}{m^2 s}\right) \times \left(42.6 \frac{MJ}{kg}\right) \times 2.3 m^2 = 3.8\, MW = 3{,}800\, kW$$

6.3.4.2 Area and Diameter of a Metered Leak Spill Fire with Fixed Duration

An example calculation is provided here to assess the area of a fixed duration metered leak pool fire as might be considered when assessing thermal stress to targets with a defined time-based damage threshold. In this case, the pool fire is designed to be of a fixed duration, just long enough to burn for the duration required for the hypothetical target to reach its damage threshold. A 10-minute pool fire is arbitrarily chosen for analysis illustration. The analysis entails the following steps:

- From the volume of liquid fuel available, determine the leak rate required to obtain a total spill duration of 10 minutes;
- With the spill rate calculated, determine the steady state pool diameter and spill pool area of the metered leak pool (liquid) fire achieved.
- Add the tire fire footprint (2.0 m^2 from Section 6.3.3.2) to the metered leak pool fire footprint to obtain the total footprint of the combined liquid + tire pool fire;
- Determine the tire fire's duration by scaling from Hansen's heat release rate (HRR) data.

<u>Determine the Liquid Spill Rate Needed to Obtain a 10-minute Duration Pool Fire</u>
Using the hypothetical forklift derated volume calculated in Section 6.2.1, the flowrate required to spill the entire 10.4 gallons (0.0395 m^3) in 10 minutes is 1.04 gpm (6.6E-05 m^3/s) (1.04 gpm = 10.4 gal / 10 min).

<u>Determine the Liquid Pool Fire Steady State Diameter</u>
Gottuk and White provide a correlation (Ref. 7, Equation 65.26b) for determining the steady state diameter (D_{ss}) of a metered leak fuel spill fire, based on the volumetric spill rate as follows:

$$D_{ss} = \left({4\dot{V}_L \rho}/{\pi \dot{m}''}\right)^{1/2}$$

Where:

[3] Earlier revisions of the SFPE Handbook specified a reduced mass loss rate, 1/5th of the peak mass loss rate, for leak flowrates less than 10 L/min. The phenomenon was reported as not well understood. However, the most recent edition of the handbook (Ref. 7, page 2581) cites new data to show that "despite typical spill depths of about 1 mm, continuously flowing spill fires will reach the peak (steady-state) mass burning rates if allowed to burn long enough."

$D_{ss} =$ Steady-state pool diameter, m
$\dot{V}_L =$ Volumetric flow rate of leak, m^3/s (6.6E-05 m^3/s)
$\rho =$ fuel density, kg/m^3, (850 kg/m^3 for DFO, Input 4.2-5)
$\dot{m}'' =$ mass burning rate per unit area, kg/m^2-s. (0.039 kg/m^2-s for DFO, Input 4.2-9) (peak rate used)

For the hypothetical example forklift, the pool diameter is calculated as

$$D_{ss} = \left({4(6.6E\text{-}05)(850)} \big/ {\pi(0.039)} \right)^{1/2} = 1.35\, m\ (4.4\, ft)$$

The pool area is then taken from the area of a circle:

$$A = \frac{\pi D^2}{4} = \frac{\pi \times 1.35^2}{4} = 1.43\, m^2 (15.4\, ft^2)$$

<u>Determine the Combined Liquid + Tire Fire Steady State Area and Diameter</u>
Since the molten tire material displaces the liquid spilled, the total pool area is found by adding the liquid pool footprint (1.43 m^2) to the tire pool footprint (2.0 m^2) found previously in Section 6.3.3.2 to obtain a combined liquid + tire pool fire area of 3.43 m^2 (3.43 = 1.43 + 2.0).

The steady state diameter is then obtained from the area of a circle as 2.1 m.

6.4 Critical Incident Flux to Waste Containers Remote From Fire

Damage to waste containers remote from the fire is limited to seal failure which is defined as degradation of the container seal (gasket) or warping of the lid from its retaining ring concurrent with ignition and burning of combustible container contents. This type of container damage does not result in lid ejection and requires that the container be close enough to the fire such that it is exposed to a sufficient heat flux (critical flux).

Critical flux has been defined, based on Ref. 26, as at least one third of the container is exposed to a heat flux exceeding 15.9-kW/m^2 which is derived from interpretations of the Hanford fire tests (Refs. 31, 32, and 33). Insight from evaluation of these reports along with recent POC and CCO testing results (Refs. 34, 35, 36, and 37) suggests another seal failure criteria of 45 kW/m^2 at the point on the surface of the container that is nearest to and directly facing the fire. However, the flux gauges used in the locations remote from the fire were positioned next to and not attached to the containers used to identify the presence of seal failure. In that configuration, it is expected that they would receive additional convective and radiative losses on the back side, thereby increasing the level of radiative heat flux measured. As this evaluation presents in Sections 6.4.3 and 6.4.4, seal failure criteria of 40 kW/m^2 in lieu of the suggested 45 kW/m^2 for the point on the surface of the container nearest to and pointing directly at the fire, is determined to be more appropriate and a better analytical fit as well as being slightly more conservative.

Additional evaluation of the most recent POC and CCO test data, combined with video evidence, shows that a minimum exposure duration is also required to obtain seal failure. The test data indicates that seal failure occurs after incident radiative heating of the container surface for around 120 sec. However, the minimum incident heating duration is reduced to 60 s to address uncertainties in the data and to add conservatism in this narrow time range. Specific criteria for evaluating seal failure due to radiant heating is defined as requiring the following three elements:

Table 6-3, Critical Flux Criteria Required to Obtain Seal Failure [All Three Required]

1. At least 33% (≥ 1/3) of a container's vertical surface has direct line of sight to the center of the fire which should be graphically or visually evaluated;
2. The container is exposed to critical heat flux, defined as either:
a. 40 kW/m^2 from the fire to a differential element on the surface of the container directly facing (normal to) the fire and located mid-height of the fire; or
b. 15.9 kW/m^2 from the fire to a differential element on the surface of the container facing 60° from normal to the fire and located mid-height of the fire (may not be appropriate for non-cylindrical TRU waste containers); and
3. Incident flux exposure > 60 seconds duration; to include incident flux levels less than the critical heat flux (i.e., include time for flame spread and fire growth to steady-state conditions).

Note that criterion 3 is already obtained by evaluation of either the 2.9 mm deep instantaneous/crash spill fire or the metered leak spill fire. It is therefore not discussed further in this Subsection.

Chapter 66 of the SFPE Handbook (Ref. 8) presents several different methods for evaluating thermal radiation from hydrocarbon pool fires. These include the Point Source Screening Method, the Shokri & Beyler Screening Method, the Detailed Shokri & Beyler Method, and the Detailed Mudan Method. Beyler's summary of the methods (pages 2620-2622) includes an evaluation of their accuracy with respect to empirical data and their ranges of applicability. The following are excerpts from this summary (emphasis added):

> *All the methods used with the indicated safety factors provide conservative results. However, the variations in the predicted versus measured heat fluxes (i.e., the goodness of fit) vary considerably between methods. Methods that minimize these variations are inherently more reliable in that the method better explains the experimental data. The methods that minimize the variation are the point source model and the Shokri and Beyler method,* ***when used in their applicable ranges****. The point source model and the Shokri and Beyler model are the preferred models based on both the conservative nature of these methods and the minimization of the variations between the data and the experiments.*

Beyler's summary states that the point source model is applicable at incident flux ranges of 0-5 kW/m^2 while the Detailed Shokri & Beyler method is applicable at incident flux ranges ≥ 5 kW/m^2. Because heat fluxes below 5 kW/m^2 cannot lead to ignition of combustibles and because heat fluxes below 15.9 kW/m^2 cannot cause damage to a TRU waste container, use of the point source model in this evaluation is considered inappropriate. The Shokri & Beyler method is therefore the only heat flux method included in this analysis methodology. The analyst should ensure use of the appropriate technique for the fire scenario being evaluated. However, use of an analysis method other than the detailed Shokri & Beyler method for assessing damage to TRU waste containers should be supported by adequate technical basis.

6.4.1 Emissive Power

The Detailed Shokri & Beyler Method describes a method for predicting incident heat flux from a pool fire to a nearby target in terms of the fire's average effective emissive power where the fire is taken as a cylindrical, blackbody, homogeneous radiator. The amount of radiant heat transfer from the fire to the target is based on the spatial and geometrical relationships between the two, defined in terms of the standard radiation heat transfer view factor or configuration factor. The configuration factor is a numerical representation of the amount of the fire's entire energy-emitting surface that is received by the target. The incident flux to a target outside the fire is given as Equation 66.16 in Ref. 8 which is reproduced here as Equation 7[4].

Equation 7 $\dot{q}'' = EF_{12}$

Where:

$\dot{q}'' =$ Incident flux from the fire to the target, kW/m^2;
$E =$ Average blackbody emissive power of the pool fire, kW/m^2;
$F_{12} =$ Configuration or view factor between the fire and the target, non-dimensional.

The blackbody emissive power is provided in the SFPE Handbook as Equation 66.19 and reproduced here as Equation 8.

Equation 8 $E = 58(10^{-0.00823D})$

Where:

$E =$ Average blackbody emissive power of the pool fire, kW/m^2;
$D =$ Pool fire diameter, m.

For the instantaneous crash/spill pool fire the diameter, 4.16 m (from Section 6.2.1) is used to calculate the emissive power as:

$$E_{instantaneous\ crash/spill\ pool\ fire} = 58(10^{-0.00823\times4.16}) = 53.6\ {}^{kW}/_{m^2}$$

Table 6-4, Summary of Hypothetical Crash / Spill Pool Fire Parameters

Pool Fire Scenario	Parameter	Value		Section
Instantaneous crash/spill	Diameter	4.16 m	13.6 ft	6.2.1
	PHRR	22.6 MW		6.2.2
	Flame Height	8.7 m	28.6 ft	6.2.3
	Area	13.6 m^2	146.5 ft^2	6.2.1
	Emissive Power	53.6 kW/m^2		6.4.1

Because evaluation of metered leak fire scenarios typically considers a specific target in a specific manner, it is usually not necessary to also evaluate remote incident flux heating of other targets. Nonetheless, the same set of parameters as presented here for the instantaneous crash/spill scenario could be obtained for the metered leak fires described above. If needed, it is often useful to develop the parameters for the liquid plus tire pool fire portion and the tire pool fire portion separately, and then to assess their impact over the duration for each phase of the scenario. These types of analyses are evaluated in the same manner as the instantaneous crash/spill fire and are not presented here.

6.4.2 Configuration Factor

The configuration factor utilized for this analysis represents the geometrical relationship between the fire cylinder and a differential element perpendicular (normal) to the fire axis, and in line with the fire's base. The fire is modeled as a right circular cylinder (Assumption 5.2.1) with heat flux delivered to a waste container remote from the fire as depicted in Figure 13.

[4] Reference 8 recommends (page 2610) use of a 2.0 safety factor when the Detailed Shokri & Beyler method is used to calculate radiant heat to a target. However, the reference also recognizes that use of the 2.0 safety factor over predicts essentially all the empirical data and states (page 2611) that the safety factor should not be applied where realistic results are required. This analysis methodology derives conservative realistic results. Therefore, the safety factor should not be applied.

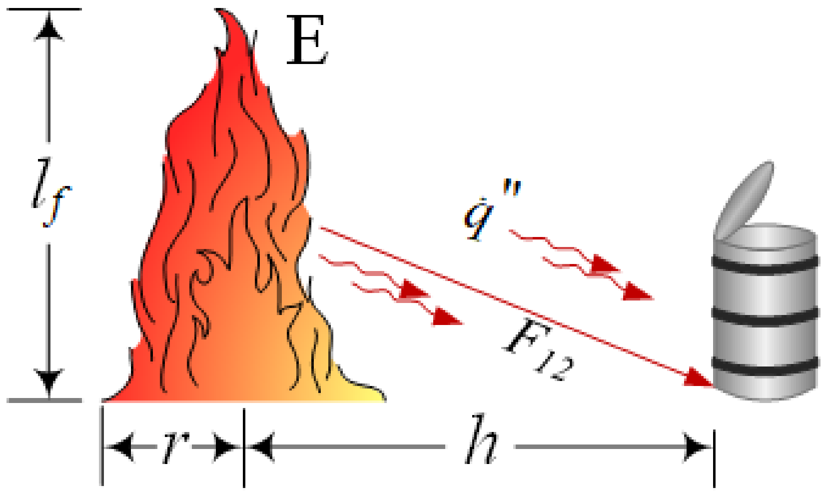


Figure 13, Configuration Factor Nomenclature for Radiant Heating of Nearby Target

The maximum configuration factor for a differential element on the vertical surface of the target waste container is obtained by determining the configuration factor for the target point positioned at mid-height of the fire and then doubling it as depicted in Figure 14.

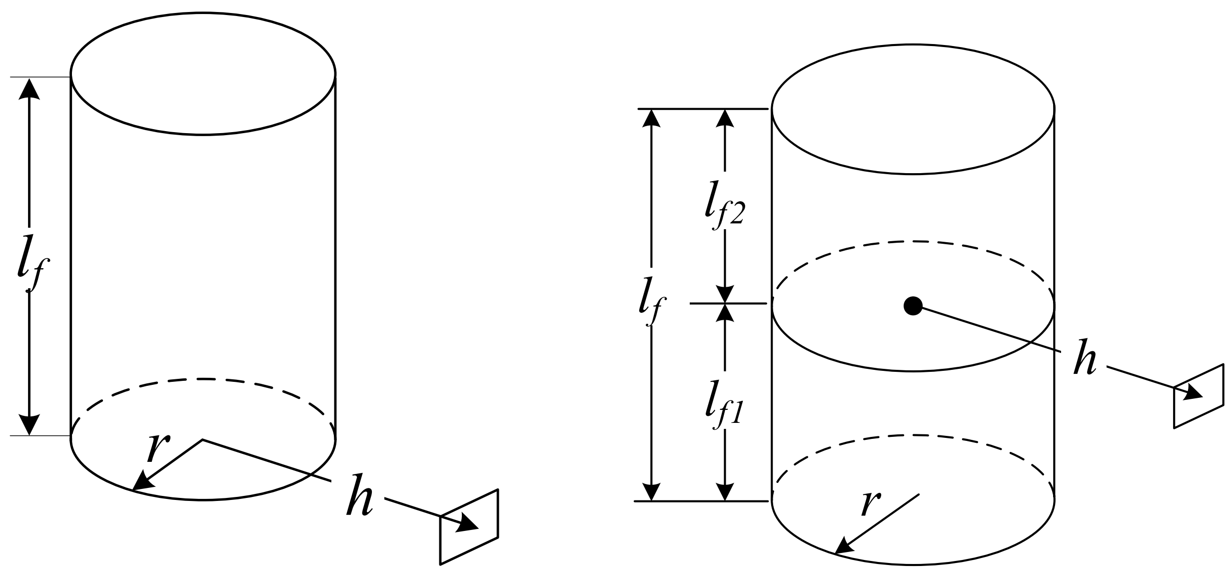


Figure 14 Maximum Configuration Factor Nomenclature

The mathematical expression for this configuration factor, as presented by Howell (Ref. 11, factor B-31) for the left hand diagram in Figure 14 is:

$$F_{1-2} = \frac{1}{\pi H}\tan^{-1}\frac{L}{\sqrt{H^2-1}} + \frac{L}{\pi}\left[\frac{X-2H}{H\sqrt{XY}}\tan^{-1}\sqrt{\frac{X(H-1)}{Y(H+1)}} - \frac{1}{H}\tan^{-1}\sqrt{\frac{H-1}{H+1}}\right]$$

This is then doubled, the flame height l_f, is reduced by half as depicted in the right hand diagram in Figure 14 and the resulting maximum configuration factor presented as Equation 9.

Equation 9 $$F_{1-2} = 2\left(\frac{1}{\pi H}tan^{-1}\frac{L}{\sqrt{H^2-1}} + \frac{L}{\pi}\left[\frac{X-2H}{H\sqrt{XY}}tan^{-1}\sqrt{\frac{X(H-1)}{Y(H+1)}} - \frac{1}{H}tan^{-1}\sqrt{\frac{H-1}{H+1}}\right]\right)$$

Where:

$F_{12} =$ Configuration or view factor between the fire and the target, non-dimensional
$l_f =$ Fire length (= ½ fire height for this calculation), m
$h =$ Distance between center of fire and target, m
$r =$ Fire radius = ½ fire diameter, m
$H =$ h/r, non-dimensional
$L =$ lf/r, non-dimensional
$X =$ $(1+H)^2+L^2$, non-dimensional
$Y =$ $(1–H)^2+L^2$, non-dimensional

For the hypothetical forklift evaluated here, the flame height and fire diameter are taken from Table 6-4. An example calculation is performed for the instantaneous crash/spill pool fire at an arbitrarily selected separation distance of 15 ft (4.57 m) from the edge of the fire to the target as follows:

l_f = fire length (= ½ fire height (8.72)for this calculation) = 4.36 m
h = distance between center of fire and target = 2.08 + 4.57 = 6.65 m
r = fire radius = 2.08 m
H = h/r = 6.65/2.08 = 3.20, non-dimensional
$L = l_f/r$ = 4.36/2.08 = 2.10, non-dimensional
$X = (1 + H)^2 + L^2 = (1 + 3.20)^2 + 2.10^2 = 22.05$, non-dimensional
$Y = (1 - H)^2 + L^2 = (1 - 3.20)^2 + 2.10^2 = 9.25$, non-dimensional

$$F_{1-2} = 2\left(\frac{1}{\pi \times 3.20}tan^{-1}\frac{2.10}{\sqrt{3.20^2-1}} + \frac{2.10}{\pi}\left[\frac{22.05 - 2\times 3.20}{3.20\sqrt{22.05\times 9.25}}tan^{-1}\sqrt{\frac{22.05(3.20-1)}{9.25(3.20+1)}} - \frac{1}{3.20}tan^{-1}\sqrt{\frac{3.20-1}{3.20+1}}\right]\right)$$

$$F_{1-2} = 0.24327$$

6.4.3 Incident Flux to Container Surface at a Point Facing Directly Toward the Fire

Continuing this example, the incident flux to a differential element on the surface of the container, at mid-height of the fire, and facing directly toward the fire centerline is calculated from Equation 7, using the emissive power (53.6 kW/m^2) calculated in Section 6.4.1 and the configuration factor, at a separation distance of 15 ft, (0.24327) as calculated in Section 6.4.2.

$$\dot{q}'' = EF_{12} = 53.6 \times 0.24327 = 13.0\ {}^{kW}/_{m^2}$$

This level of flux is below the 40 kW/m^2 threshold (Table 6-3, criteria 2a) for seal failure of a TRU waste container. Therefore, at a separation distance of 15 ft from the edge of the fire to the target, no damage or release of material will occur. The example is then extended to iteratively calculate[5] the incident flux at shorter separation distances. These iterative steps show that the critical flux failure criteria of 40 kW/m^2 (Table 6-3, criteria 2a) for a target facing directly toward the hypothetical forklift instantaneous crash/spill pool fire is not

[5] The iterative steps in this example are based on standoff distances in 3 in. increments. A more accurate result could be obtained, but 3 in. increments are well within the margins of error associated with all the other steps of this analysis approach.

obtained at a separation distance from the edge of the fire to the target greater than 0.76 m (2.5 ft). Since the fire is typically centered on the vehicle involved (Assumption 5.2.1), it is often more useful to define the separation distance to the center of the fire as that location is more easily discerned by a vehicle operator should the separation distance become a control. For this example the separation distance from the center of the fire is shown as the variable *h* in the calculation above as 2.84 m (9.31 ft).

6.4.4 Incident Flux to Container Surface at a Point Not Facing Directly Toward the Fire

Table 6-3 provides a second critical flux failure criteria of 15.9 kW/m^2 (criteria 2b) for a target facing 60 degrees from normal to the fire. This accounts for the reduction in radiant flux delivered to portions of the surface of a container that area not directly facing the container. Figure 15 below describes the geometries involved. The previous subsection calculates the maximum flux to a target by optimally placing the target facing directly at (normal to) the center of the fire, at mid-height of the fire, (point "A" in Figure 15). For a standard 55 gallon drum, the spatial distance gained between the leading edge of the drum (point "A") and the point on each side representing the extent of the critical exposure surface (point "B") is minimal, less than 6 inches. However, the effect on heat flux attenuation due to the curvature of the drum is significant. The surface of the drum at point "B" is no longer facing directly at the fire, but at an angle of θ° (60º + α) from normal to the fire and further away.

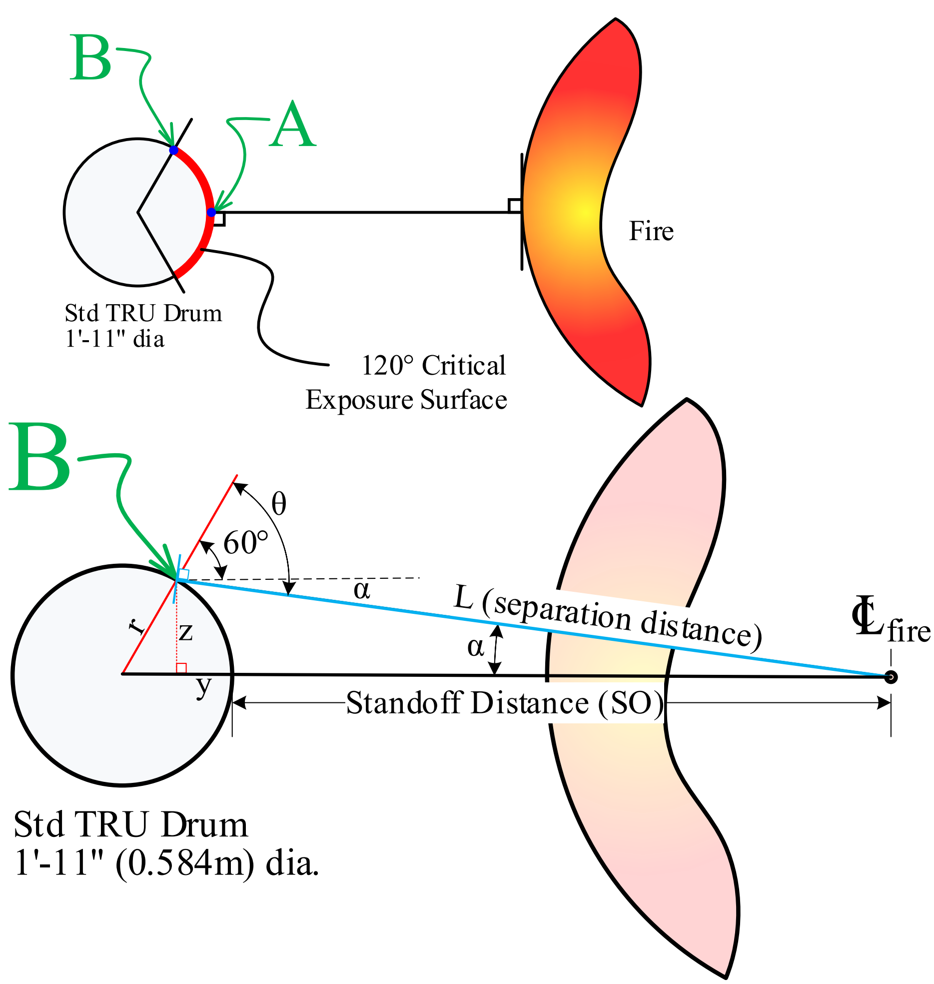


Figure 15, Drum Curvature Geometries

Howell provides the governing equation for calculating the configuration factor between two elemental areas in an arbitrary configuration (Ref. 12, factor A-1). The equation is reproduced here as Equation 10:

Equation 10 $$dF_{d1-d2} = \frac{cos\theta_1 cos\theta_2}{\pi S^2} dA_2$$

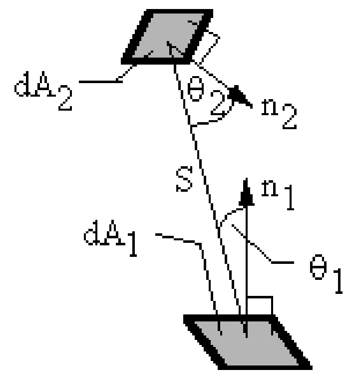


Figure 16, Configuration Factor for Two Elemental Areas in an Arbitrary Configuration

For the heat flux values calculated in the previous subsection, at point "A", both angles (θ1 and θ2) are 0º. For the heat flux at point "B", one of the angles (the fire to the target) is 0º but the other angle (the target to the fire) is 60º + α°. Comparing the form of the governing configuration factor equation for point "A" (θ1=0, θ2=0), to the form of the governing configuration factor equation for point "B," (θ1=0, θ2=60+α)), or any other point on the drum surface, we get the following relationship:

$$Configuration\ Factor_{Point\ "A"} = \frac{cos\theta_1 cos\theta_2}{\pi S^2} dA_2 = \frac{\cos 0 \times cos\ 0}{\pi S^2} dA_2 = \frac{1}{\pi S^2} dA_2$$

$$Configuration\ Factor_{Point\ "B"} = \frac{cos\theta_1 cos\theta_2}{\pi S^2} dA_2 = \frac{\cos 0 \times cos\theta_2}{\pi S^2} dA_2 = \frac{cos\theta_2}{\pi S^2} dA_2$$

It is clear then that at a point on the container surface (modeled as a differential element) that is not normal to the fire simply results in modifying the calculated configuration factor by the cosine of the included angle, in radians. This is done for the example above of the hypothetical forklift instantaneous crash/spill pool fire (pool diameter = 4.16 m from Section 6.2.1) at a standoff distance of 15 ft (4.572 m) from the edge of the fire to the target (6.652 m from the fire centerline to the nearest point on the container surface; 6.652 = 4.572 + 4.16 ÷ 2). First, it is necessary to calculate the angle θ (60° + α) which varies with container diameter (0.584 m for a standard TRU waste drum, Input 4.2-12) and standoff distance ("SO") from the fire center to the nearest point on the surface of the container, and convert it to radians. From the geometry depicted in Figure 15, above, the distance "y" is one half the drum radius $(r/2)$ and the distance "z" is $\sqrt{3/4}\,r$ for a target at 60° from normal. The angle θ is calculated as:

Equation 11 $$\theta = 60 + cos^{-1}\left(\frac{SO + r/2}{\sqrt{SO^2 + SO \times r + r^2}}\right)$$

Where:

$SO =$ Standoff distance from the fire center to the nearest point on the surface of the target, 6.652 m

$r =$ Container radius, 0.292 m (from Input 4.2-12)

$$\theta = 60 + cos^{-1}\left(\frac{6.652 + {}^{0.292}/_{2}}{\sqrt{6.652^2 + 6.652 \times 0.292 + 0.292^2}}\right) = 62.130° = 1.0844\ radians$$

The separation distance "L" is the distance from the center of the fire to the target at point "B" located on the surface of the container 60° from normal to the fire. The separation distance "L" is the denominator in the above equation calculated as:

$$L = \sqrt{6.652^2 + 6.652 \times 0.292 + 0.292^2} = 6.80 \text{ m}$$

The configuration factor to a differential element pointing directly toward the fire at a separation distance of (6.80 m) is then calculated using Equation 9 above as 0.23477.

The configuration factor at 1.0844 radians is then calculated as:

$$Configuration\ Factor_{Point\ "B"} = Config.Factor_{Point\ "A"} \times cos\theta_2 = 0.23477 \times \cos(1.0844) = 0.10974$$

The incident flux at this point is then calculated from Equation 7, using the emissive power (53.6 kW/m^2) calculated in Section 6.4.1.

$$\dot{q}'' = EF_{12} = 53.6 \times 0.10974 = 6.11 \ {}^{kW}/_{m^2}$$

This level of flux also falls below the threshold for seal failure of a TRU waste container. Therefore, at a separation distance of 15 ft from the edge of the fire to the target, no damage or release of material will occur. The example is then extended to iteratively calculate the incident flux at shorter separation distances. These iterative steps show that the critical flux failure criteria of 15.9 kW/m^2 (Table 6-3, criteria 2b) for a target turned at a 60° angle from normal to the hypothetical forklift instantaneous crash/spill pool fire is obtained at a distance from the center of the fire to the target of 2.84 m (9.3 ft) or less.

A summary of these results is provided in Table 6-5.

Table 6-5, Summary of Hypothetical Pool Fire Incident Flux Thresholds

Pool Fire Scenario	Critical Flux Criteria Applied	Standoff Distance from Center of Fire to Target		Standoff Distance from Edge of Fire to Target	
Instantaneous crash/spill	40.0 kW/m^2 at 0°	2.84 m	9.3 ft	0.76 m	2.5 ft
	15.9 kW/m^2 at 60°	2.84 m	9.3 ft	0.76 m	2.5 ft

It is noted that either of the critical flux criteria specified in Table 6-3 as criteria 2a (40 kW/m^2 incident flux to a point on the container's surface normal to the fire) and 2b (15.9 kW/m^2 incident flux to a point on the container's surface at 60° from the fire) may be used to evaluate seal failure damage to waste containers. An examination of the hypothetical example results in Table 6-5 shows that the standoff distance for instantaneous crash/spill fire scenarios is the same for either method. Part of the reasoning for this is that both criteria use the same emissive power and pool fire diameter to calculate incident flux and the emissive power as well as the configuration factor are derived primarily from the pool diameter.

A comparison of the standoff/separation distance required to avoid seal failure using each of the two criteria (Figure 17) for instantaneous crash/spill pool fires indicates they are within about 10% of each other for pool fires up to about 7.0 m (23 ft) in diameter. The two criteria obtain the same results for pool fire diameters of about 4.0 m. Above that value, the 15.9 kW/m^2 at 60° criteria (criteria 2b) provides slightly more conservative results, trending toward more conservatism as the pool fire diameter increases. For pool diameters less than 4.0 m, the 15.9 kW/m^2 at 60° criteria is slightly less conservative and indicates that at separation distances below 3.0 m the target container would only suffer seal failure if placed within the periphery of the pool.

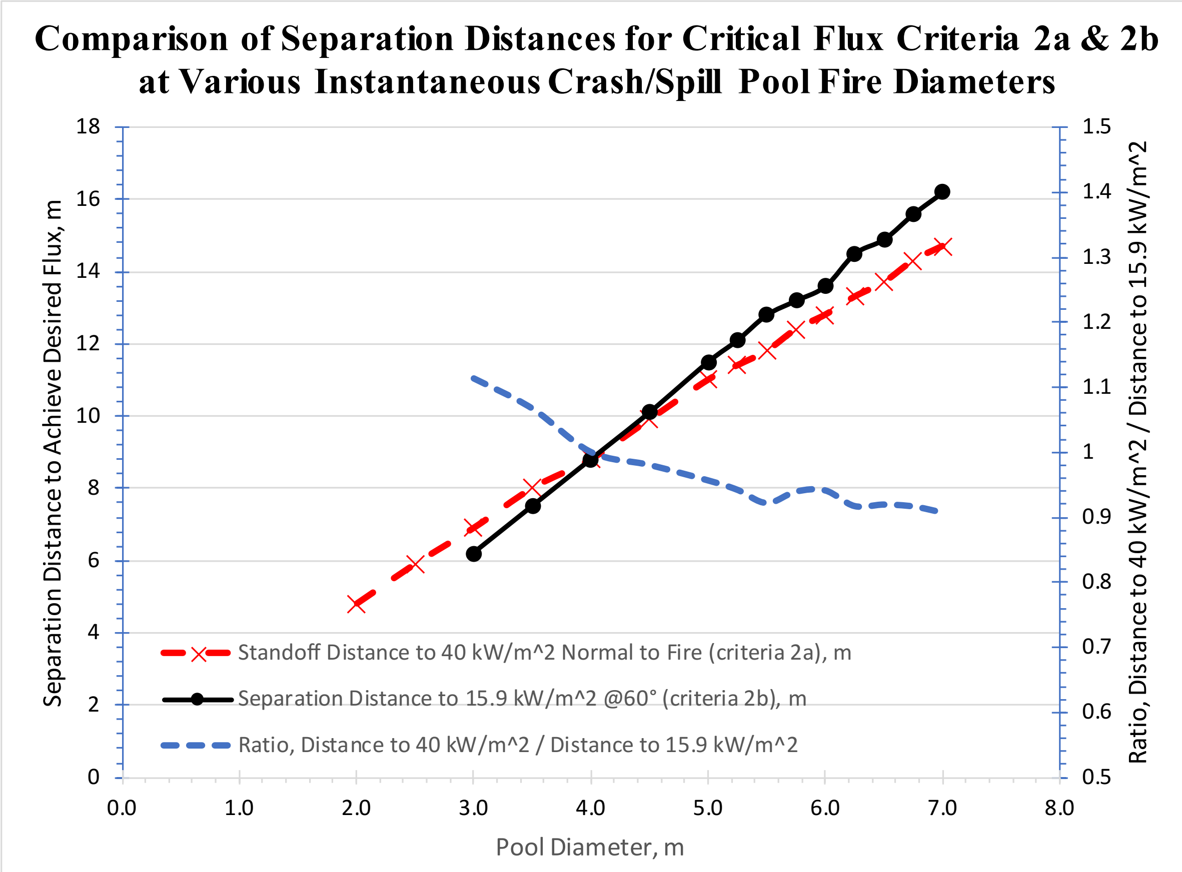


Figure 17, Comparison of Critical Flux Criteria for Seal Failure

The above comparisons are *not* directly applicable to metered leak fires because the pool diameter and flame height are derived primarily from fitting to empirical data and the fire parameters are perturbed by inclusion of the effects of molten tire material on pool diameter and heat release rate. Nonetheless, given the approximations and conservatisms used in developing these methodologies, either the 15.9 or 40 kW/m^2 criteria should be considered appropriate for use. There is no need or intent to require a large set of sensitivity tests to choose the most bounding approach for every variation to be considered, though a limited number of sensitivity checks may be needed. The analyst should select the approach most analytically appropriate to the particular set of fire scenarios being evaluated, develop a technical basis for the methodology or methodologies employed, and apply them consistently.

6.5 Assessing the Potential for Pool Fire Damage to Waste Containers

Once the size of the pool fire is obtained, it is necessary to assess the potential for pool fire damage to waste containers. Damage to waste containers may occur due to a container being fully engulfed (within the periphery of the pool), partially engulfed, or within the critical heat flux distance. However, this methodology document only addresses when a container is exposed to one of those three conditions for a given pool fire scenario; i.e., it only provides guidance for assessing the potential for damage to waste containers. Determining the level of damage a container might experience in any of these three exposure conditions is not within the scope of this methodology document.

The number of engulfed containers and the number of those in the first row out from the pool, as well as the number of containers exposed to sufficient critical flux, is best determined from a graphic analysis. The graphic analysis should consider the operational practices (vehicles used, containers involved, container spacing, etc.) of the facility. An example analysis of the hypothetical forklift instantaneous crash/spill pool fire assessed in this analysis, is provided below. Hypothetical facility conditions include palletized TRU waste drums on one side of an 7 ft – 8 in. wide access aisle with unpalletized drums on the other side. The 2.9 mm deep instantaneous crash/spill pool fire is typically the only pool fire that needs to be considered for damage that causes lid loss as it will always bound the metered leak pool fire involving the same largest flammable/combustible liquid tank.

Damage to containers near enough to the fire to receive critical flux, as assessed in Section 6.4, should be considered for all pool fires evaluated.

Potential damage estimates performed in this analysis are based on a method of scaled graphical modeling that relates the size of the postulated fire to the number of waste containers (drums, SWBs, overpacks, etc.) that would be involved. Waste containers are considered to be involved if they are located in a pool fire, in the first or second row out from a pool fire, or exposed to a damaging thermal radiative flux (critical flux) of the pool fire. Estimates are obtained for various events (fires and fire/impacts combinations). The fire size and the standoff distance from which a fire could impact a drum or SWB are as described in previous subsections of this analysis.

The modeling methodology is summarized as follows:

1) For each fire event to be analyzed, the worst-case configuration (array) of drums, SWBs, overpacks, or other containers potentially exposed to the fire is graphically depicted based on scaled objects consistent with facility operations. The building's physical layout is important and must also be graphically depicted except where the limited scope of the fire being considered is small relative to the large open area of the waste storage array as may be the case with single container events.
2) Graphically depict (to proper scale) the pool fire or exposure fire diameter and, as applicable, the standoff distance of the fire event. The fire should be positioned to maximize container damage consistent with facility operations.
3) Count and tabulate the quantities of those containers directly involved in the pool. The graphic depiction (See example in Figure 18) should differentiate at least three damaging exposure conditions which can lead to two types of direct damage, lid ejection and seal failure[6]. Each exposure condition should be highlighted with a distinct letter designation and color/shading to assist in the tabulation of those quantities. The three exposure conditions are: those fully engulfed in the pool fire (designated "A"), those containers in the first row out from the fire (designated "B"), and those in the second row out from the fire (designated "CC"). Note that the depiction of containers in the second row out (designated "CC" here) are only provided for conceptual understanding as the actual number to be assessed for damage is calculated from the number of containers in the second row out. (See example in Figure 18).
4) Count and tabulate those quantities of containers outside the pool or exposure fire area but within the standoff distance/area to indicate those containers that are within the distance that would result in seal failure only (designated "C" here). Likewise, the individual containers exposed are highlighted with a distinct letter designation and color/shading to assist in the tabulation of those quantities. It should be noted that credit is taken (where reasonable to do so) such that additional containers are not counted due to the shielding effect provided by obstructing objects (including other containers) that are physically closer even when the containers are otherwise within the standoff distance.

   Note: If the number of containers involved approaches the number associated with a reduced damage ratio, the analyst should consider estimating damage to a lesser number as a conservative application of damage ratios.

[6] Other types of damage include impact and impact plus pool fire engulfment and are based on the specific scenario being evaluated.

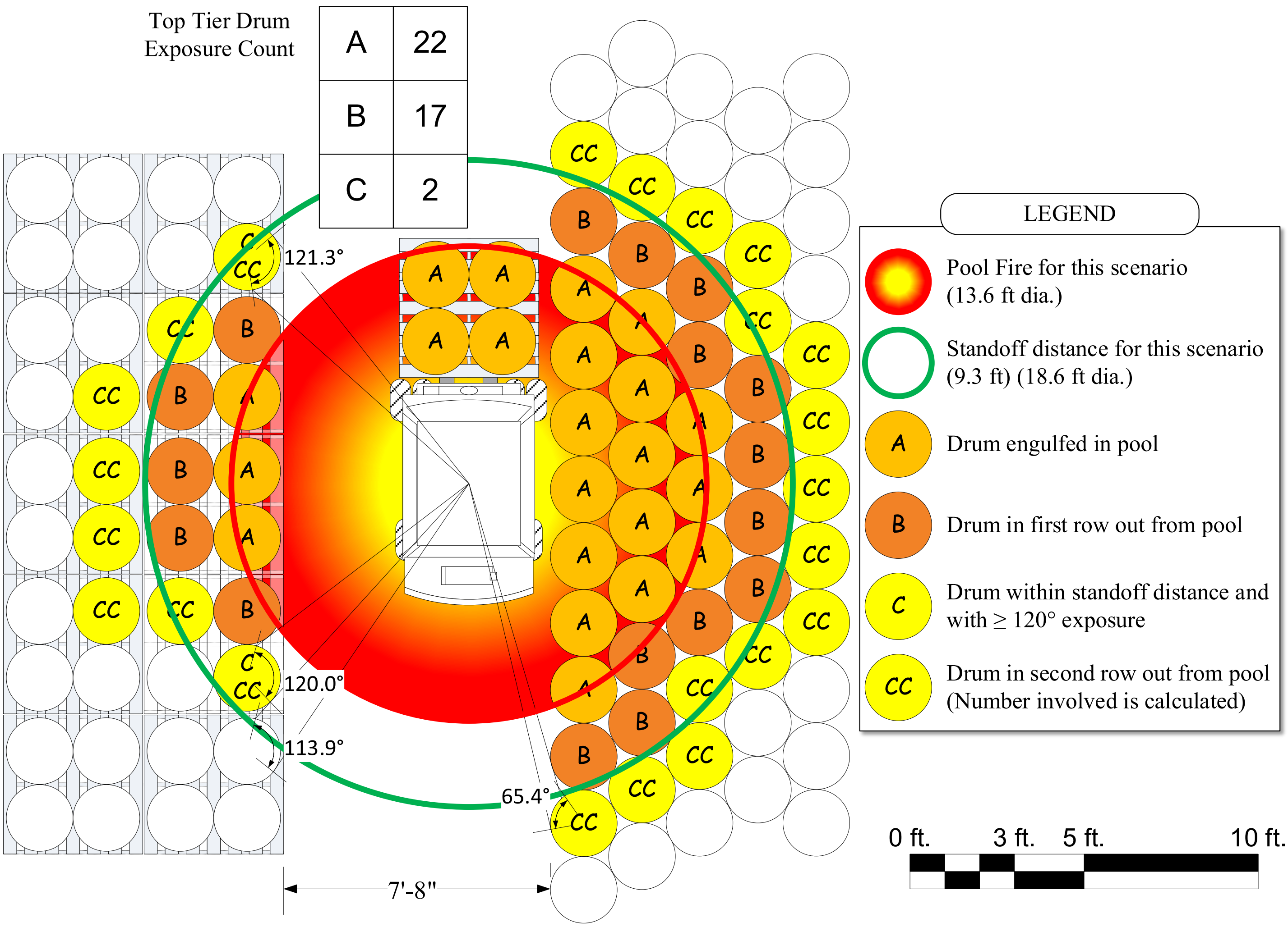


Figure 18, Graphic Analysis of Containers Exposed in Hypothetical Crash/Spill Pool Fire

A few notes about development of the scaled graphic analysis are provided as informational aides:

- The pool area and standoff distance are depicted with the pool periphery overlaid to aid in determining which containers are engulfed.
- The fire is centered on the forklift as a reasonably appropriate depiction, as discussed previously.
- The forklift is shown as in-transport with a pallet load of drums on the forklift tines. This should be conservatively based on operational practices in the facility.
- While test data indicates complete drum engulfment ("A" drums) is required to obtain engulfing drum exposure, a conservative practice, depicted here, is to qualitatively include the drum if it is more than halfway within the pool's periphery.
- The first row out "B" drums are graphically depicted based on their proximity to the fully engulfed "A" drums; some are partially inside the pool and others are entirely outside the pool.
- As noted above, the second row out "CC" drums are depicted for conceptual information, they may be omitted if desired.
- Some drums are both within the standoff distance ("C" drums) and in the second row out ("CC" drums). They are labeled with both designators.
- The 7 ft – 8 in. aisle spacing shown Figure 18 could end up being a facility control as smaller aisle spacing would increase the number of drums damaged in the pool. To address this, it is common practice to position the waste arrays to touch both sides of the forklift or the sides of the pallet to depict physical limitations of the arrangement and eliminate controls even though the forklift couldn't feasibly operate in such a configuration.

- The dimensions of the forklift itself are only relevant to the analysis if used as input for aisle spacing.
- The forklift is conservatively depicted as being adjacent to the dense packed array of drums in lieu of being adjacent to the palletized array. The scenario should be based on plausible worst case conditions. For example, the forklift would normally drive down the center of the aisle, but since it could be off center, it is depicted within the physical limitations of the facility configuration.
- A manual count of the top tier of containers involved is provided for input to the consequence calculations.
- Drums receiving critical flux are included if any portion of the drums surface touches the standoff distance line regardless of which critical flux criteria is employed. This is because the standoff distance is calculated based on nearest point on the drum surface to the fire and is part of the analysis methodology as depicted in Figure 15.
- Some drums within the standoff distance are not depicted as receiving critical flux. Heat flux to those drums is obstructed by the intervening drums.
- Based on critical flux criteria 1 (Table 6-3), a drum can receive critical flux only if it is within the standoff distance and has a direct line of sight to the center of the fire over 1/3 (120°) of its surface. Note the bottommost involved drums on both sides of the aisle are within the standoff distance, but they're partially obstructed, and therefore not designated as receiving critical flux.
- A scale is provided to enable calculation reviewer to check the accuracy of the diagram manually. This indicates the diagrams could be drawn manually and are not drawn with a validated graphic software package.

7.0 RESULTS

This document provides guidance for assessing the potential damage to waste containers caused by postulated pool fires in a defensible conservative manner and includes example calculations for each step based on the hypothetical parameters of a hypothetical waste handling vehicle (forklift) involved in a postulated pool fire. From this data, the methodology calculates, for both the instantaneous crash/spill and metered leak plus tires pool fires, the following results:

- Liquid pool fire area
- Liquid pool fire diameter
- Liquid pool fire peak heat release rate
- Liquid pool fire flame height
- Tire fire pool size
- Tire fire pool diameter
- Multiple tire set pool size and diameter
- Combined tire sets and liquid pool size and diameter
- Combined tire sets and liquid pool fire heat release rate
- Combined tire sets and liquid pool fire flame height
- Assessing incident critical flux (two methods)
- Assessing the potential for pool fire damage to waste containers

8.0 CONCLUSIONS

This document presents a methodology for determining physical parameters associated with postulated flammable/combustible liquid pool fires resulting from unconfined crash/instantaneous, metered leak, and confined spills and for assessing pool fire damage to standard TRU waste containers. The methodology provides an acceptable analytically based approach derived principally from various chapters of the *SFPE Handbook of Fire Protection Engineering* combined with insights gained from empirical fire tests published in literature. It also includes guidance on appropriate sensitivity checks necessary to ensure conservative results, and suggestions on presentation of results. With adequate technical justification, it may also be judiciously used for analysis of non-pool fires or for non-waste container targets. This methodology document is not meant to be prescriptive; other analysis methodologies may also be used at the discretion of, and as technically justified by, the analyst.

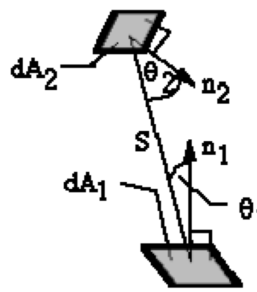
9.0 CONSERVATISMS

General conservatisms in the methodologies presented in this document are described as follows, in no particular order:

- The metered leak fire analysis methodology developed here is based on a conservative fire scenario where a liquid spill occurs, is ignited, and burn at essentially the same time that the vehicle tires ignite, burn, and flow to attain their maximum influence on the combined pool fire geometry.
- All separation distance calculations are based on maximizing incident flux by arbitrarily raising the target differential element to mid-height of the fire (See critical flux criteria 2a and 2b in Table 6-3 and Figure 14). For most fires, the mid-height of the fire is above the top of the receiving waste container. The calculated incident flux at that point is then taken as uniform over the height of all containers within that separation distance, regardless of the containers' height or vertical position.
- While test data indicates complete drum engulfment is required to obtain engulfing drum exposure ("A" drums), this analysis conservatively includes the drum if it is qualitatively assessed to be more than halfway within the pool's periphery.
- Pool fire engulfment is taken to require a flame thickness of 0.5 m. A greater flame thickness would not alter the portion of the engulfed item's surface being heated; but it would reduce the duration of the engulfing fire. Given that regulatory criteria for flame thickness as found in ASTM-1529 and 10 CFR 71.73 is more than approximately twice this value, the 0.5 m flame thickness assumed appropriate in this methodology document (see Assumption 5.2.12) is very conservative.

SECTION C
Factors Between Differential Elements

A-1: Two elemental areas in arbitrary configuration:



Governing equation:

$$dF_{d1-d2} = \frac{\cos\theta_1 \cos\theta_2}{\pi S^2} dA_2$$

To download a copy of this equation in MS Word 97 Format, click HERE.

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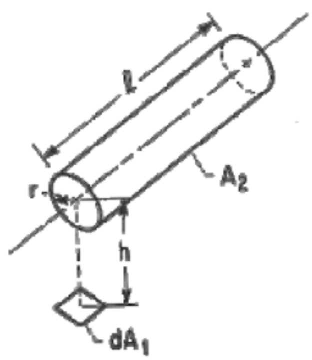
>

SECTION B
Factors From Differential Elements to Finite Areas

B-31: Plane element to right circular cylinder of finite length and radius, normal to element passes through one end of a cylinder and is perpendicular to cylinder axis.

Reference: Hamilton and Morgan, 1952



Definitions: L=l/r; H=h/r; X=$(1+H)^2+L^2$; Y=$(1-H)^2+L^2$

Governing equation:

$$F_{d1-2} = \frac{1}{\pi H}\tan^{-1}\frac{L}{\sqrt{H^2-1}} + \frac{L}{\pi}\left[\frac{X-2H}{H\sqrt{XY}}\tan^{-1}\sqrt{\frac{X(H-1)}{Y(H+1)}} - \frac{1}{H}\tan^{-1}\sqrt{\frac{H-1}{H+1}}\right]$$

To download a copy of this equation in MS Word 97 Format, click HERE.

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ConocoPhillips Hydroclear® AW 46 Hydraulic Fluid

Categories: Fluid; Lubricant

Material Notes: **Description:** Conoco Hydroclear AW Hydraulic Fluid is specifically designed for use in high-pressure systems which require greater wear protection and deposit control than that provided by standard antiwear hydraulic fluids. Hydroclear AW Hydraulic Fluid is specially formulated with proprietary additive chemistry and Conoco hydrocracked base oils. Hydroclear AW Hydraulic Fluid is recommended for use in a variety of high-pressure mobile and stationary hydraulic systems utilizing vane, piston or gear pumps. Hydroclear AW Hydraulic Fluid has been tested and approved by Denison Hydraulics in accordance with its premium HF-0 requirements. Hydroclear AW Hydraulic Fluid significantly exceeds the requirements of and has been formally approved by Cincinnati Milacron under specifications P-68 (ISO 32), P-70 (46) and P-69 (68). Hydroclear AW Hydraulic Fluid exceeds Vickers M-2950-S, Vickers I-286-S and U.S. Steel 127 and 136 requirements. Hydroclear AW Hydraulic Fluid MV is available in several grades formulated with exceptional shear stable additives. Hydroclear AW Hydraulic Fluid MV grades are high-viscosity index products with exceptionally low pour points and superior low-temperature pumpability. Hydroclear AW Hydraulic Fluid MV grades can be used year-round in hydraulic systems in virtually all climates.

Information provided by ConocoPhillips.

Phillips 66 Lubricants was spun-off from ConocoPhillips in 2012, and branding was further reorganized in 2016. The Hydroclear® trade name is no longer in use but products may be available under different names.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.866 g/cc	0.0313 lb/in³	
Viscosity Measurement	100	100	Viscosity Index
Saybolt Viscosity at 100°F	237 SUS	237 SUS	
Saybolt Viscosity at 210°F	49 SUS	49 SUS	
Kinematic Viscosity at 40°C (104°F)	46 cSt	46 cSt	
Kinematic Viscosity at 100°C (212°F)	6.8 cSt	6.8 cSt	
Oxidative Stability	7500 hour	7500 hour	ASTM D 943
ASTM Color	0.50	0.50	

Mechanical Properties	Metric	English	Comments
Four Ball Wear	0.400 mm	0.0157 in	

Electrical Properties	Metric	English	Comments
Dielectric Strength	40.0 kV/mm	1020 kV/in	No thickness given

Thermal Properties	Metric	English	Comments
Pour Point	-34.4 °C	-30.0 °F	
Flash Point	232 °C	450 °F	

Descriptive Properties	
Emulsion Characteristics (40-40-0)	10 minutes
FZG	Pass 12

ChevronTexaco ECO® ISO 46 Hydraulic Oil AW

Categories: Fluid; Lubricant

Material Notes:

Features

Chevron ECO Hydraulic Oils AW are environmentally responsible hydraulic oils.

They are manufactured from high viscosity index re-refined paraffinic base oils.

They provide antiwear protection, corrosion resistance, oxidation inhibition, and foam suppression for maximum protection in motors and hydraulic systems.

Applications

Chevron ECO Hydraulic Oils AW:

- are recommended for vane, gear, and piston type hydraulic pumps operating over 1000 psi.
- are recommended for all types of hydraulic pumps operating at lower than 1000 psi.
- can be widely used in machine tools, presses, die casting equipment, plastic injection molding machines, circulating systems, and hydraulic control systems.
- can be used in the lubrication of plain and antifriction bearings, air line lubricators, reciprocating air compressors, and moderately loaded gear sets.

Key Words: CPS Number: 233903; MSDS Number: 6982

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
API Gravity	31 °	31 °	
Viscosity Measurement	97	97	Viscosity Index; ASTM D2270
Saybolt Viscosity at 100°F	237 SUS	237 SUS	
Saybolt Viscosity at 210°F	48.7 SUS	48.7 SUS	
Kinematic Viscosity at 40°C (104°F)	46 cSt	46 cSt	ASTM D445
Kinematic Viscosity at 100°C (212°F)	6.7 cSt	6.7 cSt	ASTM D445

Thermal Properties	Metric	English	Comments
Pour Point	-15.0 °C	5.00 °F	ASTM D97
Flash Point	210 °C	410 °F	ASTM D92

Descriptive Properties	
Re-refined Oil Content, % of Base Oil	100

Some of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or engineering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your calculations to minimize rounding error. We also ask that you refer to MatWeb's terms of use regarding this information. Click here to view all the property values for this datasheet as they were originally entered into MatWeb.

ExxonMobil 10W Mobil Hydraulic

Categories: Fluid; Lubricant

Material Notes: Mobil Hydraulic 10W is a high performance hydraulic oil formulated from advanced base oils and a balanced additive system designed to satisfy a wide range of heavy-duty hydraulic equipment requirements. This product is specifically engineered using an effective balance of ashless dispersants and metallic detergents combined with inhibitors to control oxidation, wear, corrosion and rust. Mobil Hydraulic 10W is used in a wide range of on and off-highway hydraulic applications.

Hydraulic systems and components used in conjunction with equipment from American, European, and Japanese manufacturers; Hydraulic systems where wide ambient temperatures are encountered; Hydraulic systems containing gears and bearings where good anti-wear properties are required; On and off-highway industries including: trucking, construction, mining, quarrying, and agriculture

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.877 g/cc @Temperature 15.0 °C	0.0317 lb/in³ @Temperature 59.0 °F	ASTM D4052
Viscosity Measurement	107	107	Index; ASTM D2270
Kinematic Viscosity at 40° C (104°F)	37.7 cSt	37.7 cSt	ASTM D445
Kinematic Viscosity at 100° C (212°F)	6.1 cSt	6.1 cSt	ASTM D445
Ash	0.50 %	0.50 %	Sulfated Ash, wt%; ASTM D874

Chemical Properties	Metric	English	Comments
Total Base Number	4.0	4.0	mg KOH/g; ASTM D2896

Thermal Properties	Metric	English	Comments
Pour Point	-30.0 °C	-22.0 °F	ASTM D97
Flash Point	232 °C	450 °F	ASTM D92

Phillips 66 FR Hydraulic Fluid ISO Grade 100

Categories: Fluid; Lubricant

Material Notes: **Description:** Conoco FR Hydraulic Fluid is a fire-resistant, water-in-oil, invert-emulsion fluid for hydraulic systems, such as those found in underground mining equipment in which fire hazard and personnel safety concerns require water content for fire control. It is approved by the Mine, Safety, and Health Administration (MSHA) and the Factory Mutual Research Corporation (FMRC). FR Hydraulic Fluid is premixed and ready to use. It contains 40 vol. % water in oil. The oil provides a continuous outer layer to protect the hydraulic system from rust, corrosion and wear. The water provides excellent fire resistance in case of leakage. Thus, FR Hydraulic Fluid offers an extra margin of safety when compared to conventional petroleum hydraulic oils. FR Hydraulic Fluid is manufactured with high viscosity-index paraffinic base oils that are fortified with antiwear agents, biocides, rust and corrosion inhibitors and special emulsifiers that produce a stable, homogeneous mixture with a milky color. Proper system preparation is necessary if changing from a petroleum hydraulic oil or water-glycol fluid to FR Hydraulic Fluid. Avoid cork seals, as well as butyl seals and packing, because they tend to swell in service. Avoid filters and strainers on the pump inlet side of the system, as well as absorbent filters such as waste-packed or fuller's-earth units. Use paper filters only if the manufacturer can assure that they are compatible with water-containing fluids. To prevent excessive water loss, operate the system under 2000 psi pressure and do not allow temperatures to exceed 150°F (65°C). Most systems will run cooler with FR Hydraulic Fluid than with ordinary petroleum or synthetic fluids. The only special consideration is maintaining the proper water content, since water will be lost through evaporation. The MSHA requires a minimum of 40 vol. % water for adequate fire resistance. A stock solution is available for determining water content in the field.

Information provided by ConocoPhillips.

Phillips 66 Lubricants was spun-off from ConocoPhillips in 2012.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.930 g/cc	0.0336 lb/in³	
pH	9.4	9.4	
Viscosity Measurement	200	200	Viscosity Index
Saybolt Viscosity at 100°F	477 SUS	477 SUS	
Saybolt Viscosity at 210°F	92 SUS	92 SUS	
Kinematic Viscosity at 40°C (104°F)	103 cSt	103 cSt	
Kinematic Viscosity at 100°C (212°F)	18.5 cSt	18.5 cSt	

Mechanical Properties	Metric	English	Comments
Four Ball Wear	0.550 mm	0.0217 in	

Thermal Properties	Metric	English	Comments
Melting Point	-34.4 °C	-30.0 °F	Freezing point
Maximum Service Temperature, Air	65.6 °C	150 °F	
Pour Point	-28.9 °C	-20.0 °F	

Descriptive Properties		
ASTM Rust Test A & B	Pass	
Color	Milky White	
Slush point	-2°F	
Vickers 104°C Pump Test	250	Vane weight loss, mg.

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Phillips 66 MV22 Super Hydraulic Oil

Categories: Fluid; Lubricant

Material Notes: **Description:** Conoco Super Hydraulic Oil is a high-quality antiwear hydraulic fluid formulated from premium Conoco hydrocracked base stocks to provide superior water separation, antiwear protection, rust and corrosion inhibition, oxidation resistance and thermal stability. Super Hydraulic Oil is recommended for use in a variety of high-pressure mobile and stationary hydraulic systems utilizing vane, piston or gear pumps, especially where water contamination is a frequent occurrence. Super Hydraulic Oil has been tested and formally approved by Denison Hydraulics in accordance with its premium HF-0 requirements. Super Hydraulic Oil also has been formally approved by Cincinnati Milacron under specifications P-68 (ISO 32), P-70 (46) and P-69 (68). Super Hydraulic Oil exceeds Vickers M-2950-S, Vickers I-286-S and U.S. Steel 127 and 136 requirements. Super Hydraulic Oil is available in a variety of viscosity grades, including two multiviscosity (MV) grades for low temperature operation. Super Hydraulic Oil MV22 and MV32 are high-viscosity index products with exceptionally low pour point and superior low temperature pumpability. Super Hydraulic Oil MV22 and MV32 can be used year-round in hydraulic systems in virtually all climates.

Information provided by ConocoPhillips.

Phillips 66 Lubricants was spun-off from ConocoPhillips in 2012.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.854 g/cc	0.0309 lb/in³	
Viscosity Measurement	140	140	Viscosity Index
Saybolt Viscosity at 100°F	121 SUS	121 SUS	
Saybolt Viscosity at 210°F	43 SUS	43 SUS	
Kinematic Viscosity at 40°C (104°F)	23 cSt	23 cSt	
Kinematic Viscosity at 100°C (212°F)	4.9 cSt	4.9 cSt	
ASTM Color	0.50	0.50	

Mechanical Properties	Metric	English	Comments
Four Ball Wear	0.450 mm	0.0177 in	

Electrical Properties	Metric	English	Comments
Dielectric Strength	35.0 kV/mm	889 kV/in	No thickness given.

Thermal Properties	Metric	English	Comments
Pour Point	-44.4 °C	-48.0 °F	
Flash Point	193 °C	379 °F	

Descriptive Properties	
Emulsion Characteristics (40-40-0)	10 minutes

Unipetrol JET A-1 AFQRJOS Issue 18 Jet Kerosene

Categories: Fluid; Solvent

Material Notes: Jet Kerosene is a mixture of liquid hydrocarbons, with boiling point ranging between 135 and 280°C. It is obtained from crude oil by distillation and by other technological processes. It may contain additives to improve its usage characteristics. Jet kerosene is a flammable liquid class II of fire hazard, with flash point above 38°C.

Information provided by Unipetrol RPA

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.775 - 0.840 g/cc	0.0280 - 0.0303 lb/in³	
Viscosity Measure	<= 8.0 cSt @Temperature -20.0 °C	<= 8.0 cSt @Temperature -4.00 °F	
Evaporation Loss	10 % @Temperature 205 °C	10 % @Temperature 401 °F	

Thermal Properties	Metric	English	Comments
Crystallization Temperature	<= -47.0 °C	<= -52.6 °F	
Flash Point	>= 38.0 °C	>= 100 °F	

Component Elements Properties	Metric	English	Comments
Sulfur, S	0.0030 %	0.0030 %	Mercaptan Sulfur
	0.30 %	0.30 %	

Descriptive Properties		
Appearance	Visually pure, light, without mechanical impurities and undissolved water at ambient temperature	
Aromatics Content (%), max	25	
Doctor Test	negative	
Resinous Content, mg/100cm³, max	7	
Sootless Flame Height mm	19	with 3% naphthalenes

Some of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or engineering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your calculations to minimize rounding error. We also ask that you refer to MatWeb's terms of use regarding this information. Click here to view all the property values for this datasheet as they were originally entered into MatWeb.

Phillips 66 Transformer Oil

Categories: Fluid; Lubricant

Material Notes: **Description:** Conoco Transformer Oil, an insulating oil of very high dielectric strength, is suited for oil-filled transformers in both large substations and small pole-mounted transformers. It is also suited for use in circuit breakers, switches and any other oil-immersed electrical equipment. It meets the requirements of ANSI/ASTM D3487 Type II for inhibited oils. This specification provides uniform functional characteristics for petroleum electrical-insulating oil and is recognized by the Institute of Electrical and Electronic Engineers (IEEE) and other professional societies that deal with insulating materials. It also meets Westinghouse Specification PDS 55822AG and Federal Specification VV-L-530A.

Information provided by ConocoPhillips.

Phillips 66 Lubricants was spun-off from ConocoPhillips in 2012.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.872 g/cc @Temperature 15.6 °C	0.0315 lb/in³ @Temperature 60.0 °F	
Viscosity Measurement	72	72	Viscosity Index
Saybolt Viscosity at 100°F	56 SUS	56 SUS	
Saybolt Viscosity at 210°F	34 SUS	34 SUS	
Kinematic Viscosity at 40°C (104° F)	9.0 cSt	9.0 cSt	
Kinematic Viscosity at 100°C (212° F)	2.3 cSt	2.3 cSt	
ASTM Color	0.50	0.50	

Electrical Properties	Metric	English	Comments
Dielectric Breakdown	32000 V	32000 V	VDE Electrodes at 60 hertz (0.04 inch gap)
	47000 V	47000 V	Disc Electrodes at 60 hertz
	60000 V	60000 V	VDE Electrodes at 60 hertz (0.08 inch gap)

Thermal Properties	Metric	English	Comments
Pour Point	-55.0 °C	-67.0 °F	
Rotating Bomb Oxidation Test (RBOT)	300 min	300 min	ASTM D2272
Flash Point	157 °C	315 °F	

Descriptive Properties	Value	Comments
Acid/Sludge Test	0.01	72 Hours
	0.03	162 Hours
Aniline Point	172°F	
Approved Antioxidant Content	0.26 wt.%	
Corrosive Sulfur	Noncorrosive	
Gassing Tendency	-14.5 cc/min	80°C
Interfacial Tension	46 dynes/cm	25°C
Moisture	Max 20 ppm	
Neutralization No.	Max 0.01	
Polychlorinated Biphenyls (PCBs)	Nil	
Power Factor	0.003 %	60 hertz, 25°C
	0.087 %	60 hertz, 100°C

Some of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or engineering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your calculations to minimize rounding error. We also ask that you refer to MatWeb's terms of use regarding this information. Click here to view all the property values for this datasheet as they were originally entered into MatWeb.

Unipetrol PND 33-352-94 Extra Light Fuel Oil

Categories: Fluid; Solvent

Material Notes: Extra light fuel oil si a mix of liquid hydrocarbons obtained from crude oil through distillation and other refining processes, boiling mostly within 150 to 370 °C. It may contain additives to lower its freezing point or additives to improve other characteristics. Extra light fuel oil contains colouring agent and tracers. Extra light fuel oil is designed to be used predominantly in special environmentally sensitive and protected regions requiring low-sulphur fuel, and for household heating.

Information provided by Unipetrol RPA

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.860 g/cc @Temperature 20.0 °C	0.0311 lb/in³ @Temperature 68.0 °F	
Viscosity Measure	>= 6.0 cSt @Temperature 20.0 °C	>= 6.0 cSt @Temperature 68.0 °F	
Ash	<= 0.010 %	<= 0.010 %	
Evaporation Loss	<= 65 % @Temperature 250 °C	<= 65 % @Temperature 482 °F	
	>= 85 % @Temperature 350 °C	>= 85 % @Temperature 662 °F	

Thermal Properties	Metric	English	Comments
Melting Point	-10.0 °C	14.0 °F	
Flash Point	>= 56.0 °C	>= 133 °F	Pensky a Martens

Component Elements Properties	Metric	English	Comments
Sulfur, S	0.20 %	0.20 %	

Descriptive Properties	
Total Impurity Content %, max	0.05

Unipetrol R2 Heavy Fuel Oil

Categories: Fluid; Solvent

Material Notes: Heavy fuel oil R2 is a mixture of mostly higher hydrocarbons obtained from crude oil through distillation and other refining processes. It may contain additives to lower its freezing point, or additives to improve other characteristics. Heavy fuel oil R2 is used widely throughout industries. Application fields depend on technical as well as economic aspects, and specific operational circumstances of the consumer.

Information provided by Unipetrol RPA

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	0.990 g/cc @Temperature 20.0 °C	0.0358 lb/in^3 @Temperature 68.0 °F	
Viscosity Measure	<= 10 cSt @Temperature 150 °C	<= 10 cSt @Temperature 302 °F	
	<= 57 cSt @Temperature 100 °C	<= 57 cSt @Temperature 212 °F	
	<= 118 cSt @Temperature 80.0 °C	<= 118 cSt @Temperature 176 °F	
Ash	<= 0.14 %	<= 0.14 %	

Thermal Properties	Metric	English	Comments
Melting Point	40.0 °C	104 °F	
Flash Point	>= 110 °C	>= 230 °F	in open crucible

Component Elements Properties	Metric	English	Comments
Sulfur, S	<= 1.0 %	<= 1.0 %	Low sulfur
	<= 2.0 %	<= 2.0 %	Mid sulfur
	<= 3.0 %	<= 3.0 %	High sulfur

Descriptive Properties	
Mechanical Impurities and Water %	1

efunda

Properties of Common Solid Materials

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Introduction

Properties of common **solid** materials are divided into following categories:

Physical properties: Density, melting and boiling temperature.

Mechanical Properties: Including basic mechanical properties, such as elastic modulus, shear modulus, Poisson's ratio, and mechanical strength properties, i.e., yielding stress, ultimate stress, elongation.

Thermal Properties: Coefficient of thermal expansion, thermal conductivity.

Electric Properties: Electric resistivity.

Acoustic Properties: Compression wave velocity, shear wave velocity, bar velocity.

Note:
1. All properties are under **1 atm** (1.01325×10^5 Pa; 760 mmHg; 14.6959 psi) and at room temperature **25 ºC** (77 ºF) unless specified otherwise.
2. Further information on a specific material can be obtained by clicking the **name** of that particular material in the following table.
3. Users who prefer Standard or other unit systems rather than the SI units, click the **amount** (number) of the specific material property for unit conversion.
4. Materials in different phases at room temperature: **Liquid**, **Gas**.

Physical Properties

Material	Density ($\times$1000 kg/m^3)	Melting Point (ºC)	Boiling Point (ºC)
Aluminum [Al]	2.71	660.3	2519
Aluminum Alloy	2.64 - 2.8	565.0 - 660.0	-
Brass	8.4 - 8.75	930.0	-
Brass; Noval	8.4	-	-
Brass; Red (80% Cu, 20% Zn)	8.75	1000	-
Brick	1.8 - 2.4	-	-
Bronze; Regular	7.8 - 8.8	1050	-
Bronze; Manganese	8.3	-	-
Carbon [C]	2.25	4492	3642
Ceramic	2 - 3	3870	-
Concrete	2.3 - 2.4	-	-
Copper [Cu]	8.94	1085	2562
Copper Alloy	8.23	925.0	-

Cork	0.15 - 0.2	-	-
Glass	2.4 - 2.8	-	-
Gold [Au]	19.32	1064	2856
Iron [Fe]	7.87	1538	2861
Iron (Cast)	7 - 7.4	-	-
Iron (Wrought)	7.4 - 7.8	-	-
Lead [Pb]	11.3	327.5	1749
Magnesium [Mg]	1.74	650.0	1090
Magnesium Alloy	1.77	1246	2061
Monel (67% Ni, 30% Cu)	8.84	1330	-
Nickel [Ni]	8.89	1455	2913
Nylon; Polyamide	1.1	-	-
Platinum [Pt]	21.4	1768	3825
Rubber	0.96 - 1.3	-	-
Silicon [Si]	2.33	1382	-
Silver [Ag]	10.49	961.8	2162
Solder; Tin-Lead	8.17 - 11.34	215.0	-
Steel	7.85	1425	-
Stone; Granite	2.6	-	-
Stone; Limestone	2 - 2.9	-	-
Stone; Marble	2.6 - 2.9	-	-
Stone; Quartz	2.6	-	-
Tin [Sn]	7.3	231.9	2602
Titanium [Ti]	4.54	1668	3287
Titanium Alloy	4.51	-	-
Tungsten [W]	19.3	3422	5555
Wood; Ash	0.56 - 0.64	-	-
Wood; Douglas Fir	0.48 - 0.56	-	-
Wood; Oak	0.64 - 0.72	-	-
Wood; Southern Pine	0.55 - 0.64	-	-
Zinc [Zn]	7.14	419.5	907.0