THERMAL MEASUREMENTS IN LARGE POOL FIRES

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ABSTRACT

During the summer of 1983, a series of pool fire tests was conducted in which the test item was a 1.4 m diameter, 6.4 m long, mild steel calorimeter with a mass of approximately 10,000 kg. The purpose of these tests was to study the thermal response of a large test item in a specified fire configuration, to define thermal boundary conditions, and to assess the repeatability of the fire environment. The calorimeter was used to simulate a nuclear waste transportation cask in both a geometric and thermal sense.

INTRODUCTION

There is an interest in determining the response and survivability of a variety of items when subjected to large fire which might occur in a transportation or petrochemical industry accident. Specifications for conducting simulated transportation accident tests are given by the U.S. Department of Transportation (DOT) [1] and International Atomic Energy Agency (IAEA) [2].

The thermal environment in an actual large open pool fire is not well-defined. The highly turbulent nature of a large open pool fire and its susceptibility to winds produces flow and temperature fields that are very non-uniform in both space and time. Complete and representative theoretical models that describe the environment are not available.

The tests described in this paper involved a large cylindrical test item in a hydrocarbon pool fire configured along the guidelines of [1,2]. To address the question of the repeatability of the pool fire environment and provide empirical information that could aid in modelling it, three tests were performed using identical instrumentation. A large calorimeter was used to represent a physically large, thermally massive shipping cask. Complete details of this test program are given in [3].

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TEST DESCRIPTION

The series of three half-hour tests was conducted in a 9.1 m by 18.3 m by 0.9 m deep concrete pool. The test item was a large calorimeter supported by a steel stand such that the bottom was 0.9 m above the initial level of the fuel in accordance with [1], centered within the pool boundaries with its central axis aligned with the east-west, or long side of the pool.

Each calorimeter was a 6.4 m long, 1.4 m O.D., A517 steel pipe with 3.2 cm thick walls. The calorimeters were fabricated from surplus pipe which already had 5 cm thick by 15 cm wide reinforcing ribs welded around the outside of the pipe on 61 cm centers. At the ends of the pipe, 1.3 cm thick steel plates were bolted on to seal the interior of the pipe, from here on referred to as the end caps. Three layers of 2.5 cm thick Cerablanket insulation were installed against the inner wall of the pipe and against the inside of the end caps.

The east end of the calorimeter was 5.9 m from the east edge of the pool. Instrumentation was located at three axial stations in the calorimeter. Starting from the east end of the calorimeter, Station 1 was 0.46 m away, Station 2 was 2.82 m away, and Station 3 was 5.94 m away. Each station was centered between a pair of exterior ribs. At each axial station, there were four sensing locations on the interior of the pipe. Angular location 000 was on the underside of the calorimeter, then viewing from the east and moving clockwise, angular location 090 faced south, angular location 180 was at the top, and angular location 270 faced north. There was an instrumentation station located at the center of each end cap.

At each station, a type K thermocouple was spot-welded to the inner surface of the pipe, forming an intrinsic junction. A welded bead thermocouple was placed between the first and second layers of insulation. At some stations, multiple thermocouples were used in case of failure. The use of multiple temperature measurements also increases stability and reliability for the inverse heat conduction procedure, used to estimate the heat flux, by minimizing the random error from the temperature readings.

To measure flame temperatures, 1.6 mm stainless steel sheathed, ungrounded junction, type K thermocouples were placed at various heights on water cooled towers arranged about the large calorimeter and 5 cm from the exterior surface at each measurement station on the calorimeter. Three of the towers, named A, B, and C, were 6.1 m high and had thermocouples at 142 cm and 262 cm above the initial fuel level. Five other towers, named 2, 3, 4, 6, and 7 were 12.2 m high and had thermocouples at 142 cm, 262 cm, 549 cm, and 1118 cm above the initial fuel surface. Figure 1 shows the placement of the calorimeter and the towers within the pool.

Four small calorimeters, constructed of 1018 mild steel, were installed on tower 3 which was located to the west of the large calorimeter. Two of these calorimeters were 10.2 cm diameter cylinders and the other two were 20.3 cm diameter cylinders (from this point on referred to as the 10 cm or 20 cm calorimeters). Both sizes of

Figure 1
Plan View of the Test Facility

calorimeters had 3.2 cm thick walls, were 20.3 cm long, and cut into four quadrants. The wall thickness of these calorimeters was the same as that of the large calorimeter. The mild steel was also chosen such that the thermal properties would be similar to those of the larger calorimeter. To minimize circumferential heat conduction between the calorimeter quadrants, a felt insulating strip was placed between them. The interior of each calorimeter was filled with Cerablanket insulation. The whole assembly was held together by 2.5 cm thick steel caps bolted on both ends of a calorimeter.

Thermocouples were located at the center of each quadrant; these correspond to the angular stations on the large calorimeter. Type K thermocouples were spot-welded (intrinsic junctions) to the inside surface of the cylinder at each station. A welded bead thermocouple was placed within the insulating material in the center of the calorimeter, in order to give an internal boundary condition.

The four smaller calorimeters were installed on tower 3 such that their axes were aligned in the same vertical plane as the axis of the large calorimeter. These calorimeters were placed on the tower such that the upper stations of a 10 cm and 20 cm calorimeter lined up with the upper station of the large calorimeter and the lower stations of the other two calorimeters lined up with the lower station of the large calorimeter, as shown in Figure 2.

Because the wind can drastically change the flow patterns of the fire, an average wind speed of 2 m/s is the upper limit prescribed in the IAEA test specifications [2]. An anemometer, which was located atop the bunker that housed the data logger, served as the instrument for monitoring wind speed and direction.

TEST DURATION AND FUEL CONSUMPTION

For the three tests, 66 cm of water was brought into the pool. In the pool, one centimeter depth corresponds to 1670 liters. The depth of fuel added for the first and second tests, tests A and B was 22 cm, and for the final test, test C, was 19 cm. Tests A and B were 35 minutes long, while test C was 29 minutes long. The average fuel recession rate for tests A and B was 6.3 mm/min (17.5 liters per second) while that for test C was 6.6 mm/min (18.2 liters per second).

In comparison, Babrauskas [4] reports burn rates for gasoline and liquid natural gas pool fires; the values extracted from his plots are 4.3 mm/min for gasoline and 5.8 mm/min for LNG for pools of equivalent diameter, i.e., 14.6 m. Blinov and Khudyakov [5], give experimental burning rates for gasoline and tractor kerosene; for pool diameters of 9 m and 23 m, the value as reported by Hottel [6] for both fuels and pool sizes is about 3.8 mm/min.

After the test item and instrumentation were installed and the pool filled, the fuel was ignited by a hand-held torch. The time for the flame front to travel across the surface of the pool along the long axis and fully engulf the large calorimeter was ~ 10 seconds.

Figure 2
Placement of Small Calorimeters in Relation to the Large Calorimeter

WIND EFFECTS

Large scale turbulence results in the large temporal and spatial fluctuations that characterize the test medium of a large open pool fire. The variable most affecting the conditions in an open pool fire is the ambient wind. The average values and standard deviations of wind speed for each test in this series were $2.0 \pm .9$ m/s, $1.2 \pm .8$ m/s, and $1.5 \pm .8$ m/s for tests A, B and C respectively. The prevailing wind direction for test A was from the east by southeast. For test B, the wind prevailed from the southeast. While for test C, the prevailing wind direction was from the southwest. The wind history for Test C is given in Figure 3.

Wind influences the entrainment patterns in an open pool fire, enhancing air entrainment in some areas. As a result, the temperatures are elevated or depressed depending on local air to fuel ratios and efficiency of mixing. Instabilities are enhanced and turbulent flow patterns of the flame are affected. Wake regions are formed downstream of the plume and at times, spiralling vortex flows are seen in the plume at the leeward edges of the pool. Another wind effect is the tilting of the plume such that there were times when the calorimeter, towers and other instrumentation were not fully engulfed by the flames. These wind effects are erratic in nature and result in the large spatial and temporal variations that were noted within and between tests.

FLAME TEMPERATURE DATA

A typical flame temperature history from a tower is shown in Figure 4 (tower 2, test C). The data from a single elevation possesses large fluctuations, demonstrating the effects of both the characteristic turbulence of a large open pool fire and the wind. The erratic nature of the fire plume is evident from temperature histories. There are variations from tower to tower within a test and variations from test to test.

The mean temperatures were computed for all four measurement locations on each of the five 12.2 m high towers in each test. Table 1 presents these mean temperatures. The average values for elevation 1 range from 1065 to 1320 K, from 810 to 1270 K for elevation 2, from 610 to 1050 K for elevation 3, and from 470 to 905 K at elevation 4. The trend is for the mean temperature to be highest at the lowest elevation and to decrease as the elevation increases. Emphasizing the fact that the dominant wind direction was from the south for all the tests, the towers on the south side of the pool experienced lower mean temperatures. The north towers indicate higher mean values since they may be more centrally located in the plume as a result of the wind induced tilt.

The standard deviations from the means are also given in Table 1. The trend is for the standard deviations to be smaller at the lowest elevation and to increase as the elevation increases. This is demonstrated by the fact that standard deviations at elevation 1 average 12% of the mean temperature readings, 23% at elevation 2, 31% at elevation 3, and 38% at elevation 4. The larger spread in temperatures at the upper elevations is expected because at these heights, the wind effects are greater. The average of the mean temperature values obtained

WIND DATA, SPEED AND DIRECTION - TEST C

Figure 3

Wind History for Test C

FLAME TEMPERATURES - TOWER 2, TEST C

Figure 4
Flame Temperature
History - Tower 2
Test C

Table 1
Tower Temperatures Averages
Over Entire Test and Over "Presence" and "Absence" of Wind

Tower Temperature Averages
e1 - elevation 142 cm, e2 - elevation 262 cm, e3 - elevation 549 cm, e4 - elevation 1118 cm

		Test A				Test B				Test C			
		Test Avg (K)	Test St Dev (K)	Low Avg (K)	High Avg (K)	Test Avg (K)	Test St Dev (K)	Low Avg (K)	High Avg (K)	Test Avg (K)	Test St Dev (K)	Low Avg (K)	High Avg (K)
Twr 2													
	e1	1232	107	1212	1254	1264	93	1248	1276	1292	90	1299	1286
	e2	1110	121	1061	1163	1089	242	873	1241	1076	213	946	1206
	e3	897	215	724	1088	929	265	644	1131	960	265	455	1187
	e4	628	232	532	735	811	304	552	995	834	234	694	973
Twr 3													
	e1	1065	220	948	1222	****	****	****	****	1204	147	1186	1342
	e2	907	353	674	1220	1080	276	909	1391	1020	230	976	1355
	e3	856	413	531	1291	812	366	568	1252	611	236	540	1156
	e4	904	352	435	1160	693	283	537	974	472	155	426	828
Twr 4													
	e1	1189	220	1151	1298	1145	190	1083	1297	1093	168	1078	1159
	e2	1084	315	992	1353	997	205	905	1220	****	****	****	****
	e3	836	208	731	1147	839	223	713	1147	777	175	704	1094
	e4	584	248	470	917	623	244	508	902	569	167	515	804
Twr 6													
	e1	1205	167	1194	1257	1102	181	1062	1263	1078	116	1056	1197
	e2	1043	196	1002	1250	922	301	832	1288	825	212	758	1193
	e3	697	225	606	1162	745	243	641	1165	710	240	620	1210
	e4	550	297	439	1120	571	244	473	968	615	235	548	979
Twr 7													
	e1	1278	101	1277	1284	1320	106	1317	1323	1252	123	1208	1275
	e2	1062	227	1015	1286	1271	193	1160	1443	1269	154	1169	1320
	e3	726	248	633	1171	948	268	447	1184	1050	225	794	1181
	e4	****	****	****	****	****	****	****	****	****	****	****	****

Notes

****. No Data Available
Low Average Flame "Absent"
High Average Flame "Present"

at a single elevation from all of the towers in a test agree with the average values from the other two tests to within 8%. This agreement is very good considering the differing ambient wind conditions for each test.

In an attempt to account for wind effects, conditional sampling was used to examine the temperature data. All the data from elevation 4 on the five 12.2 m high towers for all the tests was gathered. The probability density function of these temperature measurements was found to be bimodal in shape. One mode, at low temperatures, roughly corresponds to data taken when the wind effects were strong. The other mode, at higher temperatures, corresponds to times when the flames engulfed the towers. A setpoint temperature which corresponded to the local minimum between the peaks of the probability density function was chosen. This temperature was 935 K. A signal was generated which was high when the temperature was above the setpoint and low when the temperature was below the setpoint. This corresponds to a signal representing the "presence" or "absence" of flames about the towers, as shown in the conditioning signal in Figure 4. This correspondence is not exact; however, this is a simple starting place to help in examining the fire data.

Statistics were obtained from the conditioned temperature data. The tower temperatures at each elevation were averaged during the flame present and absent periods based on the conditioning signal described above; the results are shown in Table 1. The general trends for these conditional averages are the same as the trends in the total test averages, with the mean temperatures decreasing with elevation. As can be expected, the mean flame present temperature at each elevation is higher than the mean temperature over the entire test at the corresponding elevation. The mean temperatures for the flame present condition are very consistent at the two lower elevations for all of the towers in all of the tests.

The readings obtained for the flame temperature thermocouples are lower than the true flame temperatures. The main source of error in the readings is introduced by radiative heat loss from the thermocouples. For the thermocouples mounted on the towers, the errors are believed to be small during the flame present condition and will increase during the flame absent condition. The error is probably the greatest for the flame thermocouples that are near the large calorimeter. This occurs because the extinction coefficient in the flames is on the order of $1/\text{m}$ [7] and these thermocouples are only 5 cm from a large, relatively cool surface.

For the thermocouples near the calorimeter, this error is a maximum at the early times in the test and decreases as the calorimeter heats up. The error was estimated from a simplified one parameter radiative model. The radiative view factors between the thermocouple and both the flames and the large calorimeter were found using the cross-string method with the thermocouple at the cross point. Other assumptions are a non-participating gas medium and blackbody radiative exchange between the thermocouple, calorimeter, and fire. Then, by performing a heat balance on a thermocouple assumed to be in radiative equilibrium with the fire at 1255 K and the calorimeter surface, this error is estimated to be approximately 12% of the assumed fire temperature when the calorimeter

surface is cold (365 K) and 4% when the surface is hot (1090 K). This error estimate does not encompass all factors affecting the thermocouple readings.

METHOD OF OBTAINING HEAT FLUX DATA

For these tests, the calorimeter backface temperatures were measured but it is the heat flux at the outer surface which is desired. In this case, the temperature data becomes the "boundary condition" and the problem of determining the heat flux is the inverse problem of heat conduction. This problem was solved by a numerical technique presented by Beck, Blackwell, and St. Clair [8]. The numerical technique was utilized by Blackwell and Douglass [9] to develop a computer code, known as the Sandia One Dimensional Direct and Inverse Thermal (SODDIT) Code, to generate net heat flux and surface temperature information given interior temperature data. A study was done for the large calorimeter in which it was determined that the local heat conduction was effectively one-dimensional.

A slight smoothing to the temperature data was introduced by using a smoothing spline fit and setting the standard deviation from the data to 0.5 K (actually a fairly tight fit). The reason for introducing the smoothing to the data was to insure stability in the inverse code, since noisy data can promote instabilities.

An additional smoothing feature in inverse methods is the use of what is termed "future temperature" information, a concept developed by Beck [8]. The future temperature approach allows one to use smaller computational time steps and increases stability. After an extensive review of the data from test A, four future times were used in SODDIT in the reduction of all the calorimeter data. The choice was made because it assured stability for the temperature ranges expected in the test series, without eliminating the ability to resolve specific thermal events in the tests.

The heat flux calculations exhibit higher frequency oscillations at later times in the tests. This occurs because mild steel experiences a Curie point transition centered at ~ 1035 K. From measurements made on samples taken from the calorimeter wall, this transition is characterized by a sharp spike in specific heat capacity between 975 and 1090 K. Such an abrupt change in thermal properties causes instabilities in the inverse code; the natural fluctuations in fire data compound the instability problem. For this reason, the heat flux calculations at temperatures above the transition temperature are not as reliable. Therefore, when heat flux is presented as a function of surface temperature, data is reported for values less than 1035 K. (Temperatures above 1035 K were rarely achieved by the 1.4 m diameter calorimeter.)

LARGE CALORIMETER HEAT FLUX DATA

Temperature histories for all twelve stations are presented in Figures 5, 6 and 7 for the three tests. These "temperature envelopes" can be used to examine the uniformity in a fire, the integrated heat flux which is directly related to the total temperature rise, and the repeatability from fire to fire by overlaying the

STEEL BACKFACE TEMPERATURES - TEST A

Figure 5

Steel Backface Temperature History
All Stations - Test A

STEEL BACKFACE TEMPERATURES - TEST B

Figure 6

Steel Backface Temperature History
All Stations - Test B

STEEL BACKFACE TEMPERATURES - TEST C

Figure 7
Steel Backface Temperature History
All Stations - Test C

envelopes. A narrower envelope indicates a more uniform thermal exposure over the surface of the calorimeter. This method of comparison is limited to test items with the same thermal properties, wall thickness, and geometry.

For the four stations in the axial center of the large calorimeter, the net heat flux, the steel backface temperature, and the external flame temperature histories from Test C are given in Figures 8 through 11. Typically, the net heat flux to the calorimeter peaked at test startup, to values between 100-160 kW/sq.m, and diminished as the calorimeter surface heated up. The heat flux values naturally tracked the external flame temperature values, but there was a significant amount of filtering. Some of this filtering was due to the natural damping effects of the calorimeter; note the smooth rise of the steel backface temperature curve (thermal response time is on the order of 9 seconds). There was additional filtering due to the slight smoothing introduced in pre-processing the data and to the use of future temperature information in the actual data analysis.

The trends in the flame temperatures adjacent to the calorimeter are similar to the trends for the tower flame temperature data. For the southern or 090 station, there were periods of lower values due to wind effects. This also applies to the upper, or 180 station. Videotapes of the test show times when the southern and upper parts of the calorimeter were not fully engulfed in flame and these times correlate with times of low heat flux on the plots. Even though the winds are within the prescribed limits, changes in the winds produce fluctuating, nonuniform temperature fields in the regions around the top and windward side of the large calorimeter.

Temporal data is important in the presentation of the heat flux information, because events in the fire, such as fluctuating flame temperatures, can be correlated with heat transfer events. From the heat flux histories, total thermal input can be studied and trends within a test defined. Another useful means of data presentation is to plot heat flux as a function of surface temperature. This is the format by which test specifications are made [1,2]; thus, presenting the data in this manner facilitates a direct comparison. In this form, thermal transport mechanisms in the fire can also be studied. SODDIT provides surface temperature estimates as well as heat fluxes. These estimates are used when presenting the surface temperature data.

The heat fluxes with respect to angular station, i.e., all the heat flux values from 3 stations in each of the 3 tests, were averaged together at specific surface temperature values (note that the time at which a specific temperature is reached is different for each station in a test and from test to test). The mean values are plotted against surface temperature in Figure 12. The average of the peak fluxes for the lower stations (TX000) and the north stations (TX270) were about 130 kW/sq.m. For the southern stations (TX090), the average of the peak fluxes was 110 kW/sq.m. For the upper stations (TX180), it was 100 kW/sq.m. In general, TX000 exhibited the highest, most uniform peak heat fluxes and TX180, the lowest. Stations TX270, which were on the leeward side of the calorimeter, showed much higher peak heat fluxes than TX090 which were windward during the tests.

LARGE CALORIMETER - TEST C (T2000)

Figure 8

Net Heat Flux, Steel Backface Temperature
and External Flame Temperature Histories -
Bottom Station

LARGE CALORIMETER - TEST C (T2090)

Figure 9

Net Heat Flux, Steel Backface Temperature
and External Flame Temperature Histories -
South Station

LARGE CALORIMETER - TEST C (T2180)

Figure 10

Net Heat Flux, Steel Backface Temperature
and External Flame Temperature Histories -
Top Station

LARGE CALORIMETER - TEST C (T2270)

Figure 11

Net Heat Flux, Steel Backface Temperature
and External Flame Temperature Histories -
North Station

LARGE CALORIMETER ANGULAR AVERAGES - TESTS A, B, C

Figure 12
Average Heat Fluxes for the Test Series

Standard deviations from the mean values were computed; they are relatively large for all stations, demonstrating the random nature of the fire. Stations TX000 exhibited the smallest values, on the order of 15% of the mean. For stations TX270, the standard deviations are on the order of 25%, for stations TX090 and TX180, on the order of 35%. The stations that had greater exposure to the wind (stations TX090 and TX180) experienced larger fluctuations than the stations that were sheltered from wind effects (stations TX000 and TX270). From the visual data, the south side of the calorimeter could actually be seen at times during all three tests. Even when the plume engulfed the test item, the flame thickness was not as great on the windward and upper stations of the calorimeter; this lowers the radiative transport to these portions of the calorimeter.

Integrated heat flux values at 30 minutes are presented for the test series in Table 2. Statistics for these values are presented in Table 3. High, low, and mean values, as well as standard deviations from the mean, are provided for various groups of data. The data is grouped as follows: all cylindrical surface data with respect to test, all data for the series with respect to axial station, all data for the series with respect to angular station, and all end cap data for the test series. Note that there is approximately a two to one ratio between the high and low values for the first and second groupings and the standard deviations are about 25%. When grouped with respect to angular station, however, the spread and the standard deviations are smaller.

SMALL CALORIMETER HEAT FLUX DATA

Heat flux histories for the 10 cm and 20 cm calorimeters from Test C are presented in Figures 13 through 16 along with the closest flame temperatures located above each calorimeter. For the lower calorimeters, these flame temperatures were measured ~ 50 cm above the upper stations and for the upper calorimeters, ~ 25 cm above the upper stations. The fluctuations in heat flux for the smaller calorimeters were generally greater than for the large calorimeter. This phenomena is believed to be due to the fact that the large calorimeter damps out the local temperature variations in the flame to a greater degree. Peak fluxes for the smaller calorimeters were generally between 160-200 kW/sq.m, with the exception of the upper calorimeters in test A. These calorimeters experienced relatively low fluxes for the first half of the test.

Typically, the trends in the heat flux histories from all angular stations for a single calorimeter track each other. For the upper calorimeters, however, the heat flux values differ by as much as a factor of two from one station to the next on a single calorimeter. There are general trends for the angular variation in heat fluxes; station 270, on the leeward side, demonstrates the highest heat fluxes. The bottom station 000, follows closely, and as on the larger calorimeter, the upper and windward stations (180 and 090) demonstrate lower fluxes. The heat flux values for the small calorimeters in test A, are in general, lower than those in the other tests; a result of the generally lower local flame temperatures at the west end of the pool.

Table 2. Integrated Heat Flux at 30 Min*
(kW-hr/sq. m)

Test	Angle Degrees	Station 1 (East)	Station 2 (Middle)	Station 3 (West)
A	0	43.8	32.0	37.5
	90	38.2	28.8	26.4
	180	22.5	28.1	24.0
	270	38.5	34.5	25.0
	End Cap	18.3	*****	19.6
B	0	42.3	37.3	41.0
	90	28.2	23.6	23.6
	180	24.3	19.8	20.7
	270	38.5	37.3	33.9
	End Cap	19.6	*****	20.6
C	0	42.8	33.3	43.4
	90	25.7	21.4	33.5
	180	26.1	20.8	29.6
	270	33.7	39.1	38.3
	End Cap	21.6	*****	18.8

*Test C was only 29 min, so values were extrapolated to 30 min.

Table 3. Statistics for the Integrated Heat
Flux at 30 Min* (kw-hr/sq. m)

Cylindrical Surface	Low	Mean	Standard High Deviation (%)	
Test A-All	22.5	31.6	43.8	6.8 (21.5)
Test B-All	19.8	30.9	42.3	8.3 (26.9)
Test C-All	20.8	32.3	43.4	7.7 (23.8)
Station 1-All	22.5	33.7	43.8	7.9 (23.4)
Station 2-All	19.8	30.0	39.1	6.9 (23.0)
Station 3-All	20.7	31.4	43.4	7.6 (24.2)
0 degrees-All	32.0	39.3	43.8	4.4 (11.2)
90 degrees-All	21.4	27.7	38.2	5.3 (19.1)
180 degrees-All	19.8	24.0	29.6	3.4 (14.2)
270 degrees-All	25.0	35.4	39.1	4.5 (12.7)
End Caps-All	18.3	19.8	21.6	1.2 (6.1)

*Test C was only 29 min, so values were extrapolated to 30 min.

LOWER 10 cm CALORIMETER - TEST C

Figure 13
Heat Flux and Flame
Temperature Histories
Lower 10 cm Calorimeter

LOWER 20 cm CALORIMETER - TEST C

Figure 14
 Heat Flux and Flame
 Temperature Histories
 Lower 20 cm Calorimeter

UPPER 10 cm CALORIMETER - TEST C

Figure 15
Heat Flux and Flame
Temperature Histories
Upper 10 cm Calorimeter

UPPER 20 cm CALORIMETER - TEST C

Figure 16
Heat Flux and Flame
Temperature Histories
Upper 20 cm Calorimeter

DISCUSSION OF RESULTS

HEAT FLUX DATA

There is evidence of dome-like fuel rich vapor regions above the fuel surface in small pool fires. It has been assumed that such a region would be found in larger pool fires [10]. If the vapor dome was present in the fires in this test series, then the heat flux levels would be lowest at the 000 stations on the underside of the large calorimeters, due to a decrease in the radiant field intensity. The fact that the heat flux values are highest at the 000 stations is contrary to what would be expected. These findings indicate that no vapor dome is present; this fact is in agreement with Corlett's designation of pool fires of more than 1 m diameter as having "unstructured" flames.

There have been studies which predict the radiant heat transfer to a horizontal cylinder engulfed in luminous flames [12,13]. In both analyses, the flame is considered as a uniform temperature, participating medium, where scattering is negligible. Formulations were done for cases in which the bottom of the cylinder was 0.3 m and 1 m above the pool and the width of the pool perpendicular to the cylinder axis was between 2.4 m and 7.6 m. The positioning of the cylinder in the fire will strongly affect the predicted heat flux distribution. The analyses predict the highest heat fluxes will be at the top and the values will decrease along the periphery to the underside of the cylinder. Again, these predictions are contrary to the findings in this test series in which the top portions of the calorimeter (stations 180) receive the lowest net fluxes and the portions on the underside of the calorimeter (stations 000) receive the highest fluxes.

On the large calorimeter, the circumferential variations in the heat flux and the integrated heat flux are probably the result of several phenomena. Fluctuating, nonuniform temperature fields have been previously noted in the vicinity of the top and windward stations due to the wind effects. Variations in the convective heat transfer are significant. For a cylinder in cross flow, the local heat transfer coefficients are highest at the lower stagnation point, decrease appreciably at the sides, and then increase up to the top of the cylinder. Because the calorimeter is a massive heat sink (the maximum absorption rate was approximately 5 MW), a cooler, soot-laden boundary layer probably exists around the calorimeter; this boundary layer is believed to act as a radiation shield. Because the boundary layer is thinner on the underside of the calorimeter, shielding would be lower than at the top, where the boundary layer in the wake region is much thicker.

An attempt was made to estimate the radiative/convective partitioning of heat transfer to the calorimeters. Using McCaffrey's velocity correlation [14] for a 544 MW fire, the velocity was estimated to be 6.8 m/s at an elevation of 1 m above the initial fuel surface. This was the location of the bottom stations on the large calorimeter and the lower 10 cm and 20 cm calorimeters. Using this velocity, the convective heat transfer coefficients at the stagnation point were calculated for the three cylinders in cross flow. The coefficients were computed for surface temperatures of 423 K and a

flame temperature of 1283 K. The convective fluxes for the 1.4 m, 20 cm, and 10 cm calorimeters respectively, were 11, 36, 42 kW/sq.m. For the test series, the average total heat fluxes estimated by SODDIT at these stations for surface temperatures of 423 K, were 130, 170, and 170 kW/sq.m. Thus, the convective flux was estimated to be 8%, 21%, and 25% of the total cold wall flux for the calorimeters.

It should be noted that the flame velocity field is directly related to the temperature field. Because the flow is bouyancy driven, when the temperature drops then the velocity will drop. However, changes in the gas properties roughly offset the effects of the lower gas velocity. As a result, the heat transfer coefficient remains approximately constant. Based on the temperature and flame velocity measurements in [15], the calculated heat transfer coefficient varied by less than 15% over a temperature range of 775 to 1275 K using the assumption of turbulent flow over a cylindrical body.

The convective heat transfer to a flat plate in parallel flow was also calculated. The analysis included the same surface and flame temperatures as above, but the velocity was estimated to be 9 m/s, using McCaffrey's correlation for an elevation of 1.6 m. This was the elevation of the instrumentation stations on the end plates of the large calorimeter. Hence, the convective flux estimate was 7 kW/sq.m. The average total heat flux estimated by SODDIT on the end plates for a surface temperature of 423 K was 108 kW/sq.m; thus, of the total cold wall heat flux to the end plates, - 6% is convective, and the balance radiative.

LARGE VS. SMALL CALORIMETERS

The small calorimeters were placed with either top or bottom stations at the same vertical heights as the large calorimeter, in an attempt to compare the heat transfer to objects of differing geometry and total thermal capacity. The stations of interest on the large calorimeter are the bottom west station, T3000, and also the top west station, T3180. The stations from the 10 cm and 20 cm calorimeters are the bottom stations of the lower calorimeters, stations S3000 and S4000, and the top stations of the upper calorimeters, S1180 and S2180. The heat flux was averaged for each station for all three tests with the results plotted for the lower stations in Figure 17 and for the upper stations in Figure 18.

The average heat flux curves for the lower stations in Figure 17 are relatively smooth. The cold wall flux of 130 kW/sq.m to the 1.4 m calorimeter is about 80% that of the cold wall fluxes of 165 kW/sq.m to the 10 cm and 20 cm calorimeters. The magnitudes of the fluxes to the 10 cm and 20 cm calorimeters are roughly equivalent throughout the temperature range, and above approximately 705 K, all three curves converge to the same values.

The average heat flux curves for the upper stations in Figure 18 fluctuate a great deal more than for the lower stations, and the magnitudes of the fluxes are noticeably smaller. The lower heat fluxes and larger fluctuations may be due to the amount of time these calorimeters were engulfed by flames. The cold wall flux of 90 kW/sq.m

LARGE AND SMALL CALORIMETERS - LOWER STATIONS

Figure 17
Average Heat Flux
versus Surface
Temperature - Lower
Stations, Large and Small Calorimeters

LARGE AND SMALL CALORIMETERS - UPPER STATIONS

Figure 18
Average Heat Flux
versus Surface
Temperature - Upper
Stations, Large and Small Calorimeters

to the large calorimeter is two-thirds that of the cold wall fluxes of 135 kW/sq.m to the smaller calorimeters. The fluxes to the 10 cm and 20 cm calorimeters are almost equal in magnitude but lower than the fluxes for the lower lower calorimeters reported above. The curve for the large calorimeter never approaches the curves for the smaller calorimeters.

The phenomena noted here support the postulation of an interaction between an object and the fire that surrounds it. The large calorimeter appears to alter its local environment because it is physically large and thermally massive. This indicates that the heat transfer to a test item in an engulfing fire can be highly dependent on the properties of the test item.

SUMMARY

The DOT fire test series was conducted to supply information about the thermal exposure of a large object immersed in a fire and the repeatability of the thermal environment. Thermal measurements have been presented from three large open pool fire tests run with duplicate instrumentation. Heat flux and temperature data within the lower part of the fire have been studied in a variety of ways and the strong influence of the wind has been noted. Statistics have been developed to evaluate the test to test repeatability of the fire environment. The largest factor affecting the reproducibility of the environment in a large open pool fire is the wind.

Average flame temperatures at 8 locations around the test item ranged from 1065-1320 K at a height of 104 cm and from 810-1270 K at a height of 262 cm above the initial pool surface. The spread in these values is quite large. When the temperatures are averaged for all 8 locations in each test (a larger sample size), however, the spread in values decreases. For elevation 104 cm, averages for tests A, B, and C, respectively were 1195, 1210, and 1185 K; these values are within 2% of each other. For elevation 262 cm, the average values were 1040, 1070, and 1050 K; these values are within 3% of each other.

The cold wall or peak heat fluxes to the large test item for various locations on the item ranged from 100-160 kW/sq.m. The fluxes to the underside of the calorimeter were highest, and those to the top the lowest; this distribution is counter to the heat flux distributions predicted with simplified radiation modelling. When averaged for all locations, the cold wall flux for each test was between 115-120 kW/sq.m.

The partitioning of the cold wall heat flux to the bottom location of the cylinders in cross flow was estimated to be from 8% to 25% convective and the balance radiative. The larger the radius of the cylinder, the lower the convective contribution to the total flux. For flat plates in parallel flow, the partitioning of the heat transport was estimated to be 6% convective and the balance radiative.

The total heat input or the time-integrated heat flux values for the test item were determined. The values for a single test varied with respect to location by as much as a factor of two; again, the highest

values were on the bottom and lowest on the top. When all stations were averaged for a single test, the values of 31.6, 30.9 and 32.3 kW-hr/sq.m for tests A, B and C, respectively, were within 5% of each other.

The physical size and thermal capacitance of a test item has also been shown to affect the thermal environment. The effects are demonstrated when heat fluxes to the large test item are compared to the heat fluxes to smaller items in the fire. The average cold wall peak fluxes to the large calorimeter are about 75% of those to the smaller calorimeters.

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