MEASUREMENT OF TEMPERATURE DISTRIBUTIONS IN LARGE POOL FIRES WITH THE USE OF DIRECTIONAL FLAME THERMOMETERS

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ABSTRACT
Temperatures inside the flame zone of large regulatory pool fires measured during tests of radioactive materials packages vary widely with both time and position. Measurements made with several Directional Flame Thermometers, in which a thermocouple is attached to a thin metal sheet that quickly approaches flame temperatures, have been used to construct fire temperature distributions and cumulative probability distributions. As an aid to computer simulations of these large fires, these distributions are presented. The distributions are constructed by sorting fire temperature data into "bins" 10°C wide. A typical fire temperature distribution curve has a gradual increase starting at about 600°C, with the number of observations increasing to a peak near 100°C, followed by an abrupt decrease in frequency, with no temperatures observed above 1200°C.

INTRODUCTION
Temperatures vary widely in large, engulfing pool fires of the type that can be used to qualify Type B radioactive material packages under Title 10, Code of Federal Regulations, Part 71 (10CFR71) in the United States or under the ST-1 standard set by the International Atomic Energy Agency. The turbulent mixing of fuel and air in the flame zone leads to both time and spatial temperature variations at all locations within the fire. When temperature measurement data are examined, some temperatures occur more frequently than others. The purpose of this paper is to examine some data collected from the central core of large pool fires, and sort the data to obtain an approximation of the temperature distribution functions and cumulative distribution functions that could be useful for regulatory and risk analyses.

At any location in the flame zone of a large pool fire, the local conditions and resulting temperatures vary significantly with time. Because fuel and oxygen are not premixed in a pool fire, combustion is supported through a turbulent mixing process of air and fuel vapors. Where mixtures of fuel vapor and oxygen are within the limits for flammability, and the temperature is sufficiently high, combustion occurs. As the oxygen becomes depleted locally, the flames extinguish until sufficient fuel and oxygen are again present. Through the turbulent mixing process, flames continue periodically as long as fuel and oxygen are available. At any location, the temperatures swing between those recorded within a flame and temperatures representing hot combustion products, but without combustion.

Because the fuel-oxygen mixtures are far from the stoichiometric limit, combustion is often incomplete, leading to the formation of soot particles, which aggregate and form the large smoke clouds associated with inefficient combustion. The soot particles also play a large role in the radiant heat transfer process within the flame zone since they absorb and emit radiant energy. The density of the soot particles is such that the absorption length for radiant energy in the flames is on the scale of centimeters (see Grill, et al, 1998). All of these effects combine so that temperatures in the flame zone of a fire should vary greatly both in time and space.

The measurements in this paper are intended to give typical statistics for temperatures occurring in the flame zone of large pool fires. Through inspection of the results, analysts can determine typical temperatures to use when modeling packages exposed to the pool fire environment.

DIRECTIONAL FLAME THERMOMETERS
Burgess and Fry, 1990, describe the basic concept for a Directional Flame Thermometer (DFT), which is also called a Heat Flux Gauge (HFG). As shown in Figure 1, the DFT is a cylindrical, can shaped device with flat, thin, sheet-metal ends that are backed with insulating materials. Each end of the DFT views a hemisphere of the fire, and, as the thin metal ends absorb radiant and convective energy, they quickly come into thermal equilibrium with fire temperatures. From the package designers viewpoint, the thin metal ends could be considered to

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RSi(OMe)₃ based polysilsesquioxane xerogels. (a) Gels were obtained at 1.0 M concentration generally possessed lower surface areas or were non-porous. Exceptions to this were the xerogels prepared under acidic conditions, which were non-porous regardless of the experimental conditions used in their preparation. (b) Monomer reacts violently, boiling the solution. Solutions of the materials in hot benzene (80 °C) were cooled and converted into gels at neat monomer concentration, but the gels (before drying) of these monomers were thermoreversible. Gelation was attributed to self-organization of the long chain alkyl groups.

Scanning and transmission electron micrographs of these materials were consistent with non-porous materials, but revealed no ordered supramolecular architectures. Interestingly, we found that the gels display no ordered supramolecular architectures. Solutions of the materials in hot benzene (80 °C) were cooled and converted into gels at neat monomer concentration, but the gels (before drying) of these monomers were thermoreversible. Gelation was attributed to self-organization of the long chain alkyl groups.

Most of the polysilsesquioxanes with organic groups had lower surface areas and larger pores than the polysilsesquioxanes with R = H, or were non-porous completely. Xerogels prepared under acidic conditions, were non-porous, whereas those prepared under basic conditions were generally porous. Exceptions to this were the xerogels prepared from organotrialkoxysilanes, RSi(OR')₃, with R = Me: R = H, Me, vinyl, chloromethylphenyl, hexadecyl, and octadecyl and R' = Et: R = H, Me, Et, trimethylsilyl, chloromethyl, hexadecyl, and octadecyl. The porosity of the polysilsesquioxane xerogel prepared from HSi(OMe)₃ under acidic conditions was determined to have a surface area of 667 m²/g and a mean pore diameter of 67 nm by nitrogen sorption. The SEM of the material revealed no macroporosity. In contrast, the polysilsesquioxane xerogels prepared from organotrialkoxysilanes, RSi(OR')₃, with R = Me: R = H, Me, vinyl, chloromethylphenyl, hexadecyl, and octadecyl had the highest surface areas. Many of the remaining organotrialkoxysilanes, RSi(OR')₃, (R = H, Me, Et, chloromethyl, vinyl, dodecyl, and hexadecyl) had the highest surface areas. For instance, the polysilsesquioxane xerogel prepared from HSi(OMe)₃ under acidic conditions was determined to have a surface area of 667 m²/g and a mean pore diameter of 67 nm by nitrogen sorption. The SEM of the material revealed no macroporosity.

The majority of the gels were opaque and colloidal in appearance. The gels with R = H, Me, and chloromethyl were the most transparent. The porosity of the polysilsesquioxane xerogel prepared from HSi(OMe)₃ under acidic conditions was determined to have a surface area of 667 m²/g and a mean pore diameter of 67 nm by nitrogen sorption. The SEM of the material revealed no macroporosity. In contrast, the polysilsesquioxane xerogels prepared from organotrialkoxysilanes, RSi(OR')₃, with R = Me: R = H, Me, vinyl, chloromethylphenyl, hexadecyl, and octadecyl and R' = Et: R = H, Me, Et, trimethylsilyl, chloromethyl, hexadecyl, and octadecyl had the highest surface areas. Many of the remaining organotrialkoxysilanes, RSi(OR')₃, (R = H, Me, vinyl, dodecyl, and hexadecyl) had the highest surface areas. For instance, the polysilsesquioxane xerogel prepared from HSi(OMe)₃ under acidic conditions was determined to have a surface area of 667 m²/g and a mean pore diameter of 67 nm by nitrogen sorption. The SEM of the material revealed no macroporosity.

Scanning electron microscopy supplements porosimetry data by providing information regarding macropores (mean pore diameter >500 nm) and micropores (mean pore diameter <500 nm). For instance, the polysilsesquioxane xerogel prepared from HSi(OMe)₃ under acidic conditions was determined to have a surface area of 667 m²/g and a mean pore diameter of 67 nm by nitrogen sorption. The SEM of the material revealed no macroporosity. In contrast, the polysilsesquioxane xerogels prepared from organotrialkoxysilanes, RSi(OR')₃, with R = Me: R = H, Me, vinyl, chloromethylphenyl, hexadecyl, and octadecyl had the highest surface areas. Many of the remaining organotrialkoxysilanes, RSi(OR')₃, (R = H, Me, vinyl, dodecyl, and hexadecyl) had the highest surface areas. For instance, the polysilsesquioxane xerogel prepared from HSi(OMe)₃ under acidic conditions was determined to have a surface area of 667 m²/g and a mean pore diameter of 67 nm by nitrogen sorption. The SEM of the material revealed no macroporosity.
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represent the thin outer wall of an insulated canister-type radioactive materials package exposed to a fire.

The theory and equations governing the DFT approach are given in Fry, 1985. Heat transfer to the ends of the DFT is dominated by thermal radiation, but convection heat transfer also has some effect. Because accurate determination of the convective film coefficient in a fire is difficult, the convective effect is often ignored, leading to small errors in the temperature estimate. A discussion of this and other effects on DFT-type measurements such as the thermal response of the attached thermocouple is included in Blanchat, et al, 2000.

Data from two different designs of DFT are used in this paper. The more recent design (see Figure 1) has an overall diameter of 102 mm and a length of 100 mm. The end plates are made from 0.25 mm thick Type 304 stainless steel shim stock, and are backed with two layers of Lytherm ceramic fiber insulation. The fire facing sides of the end plates are coated with Pyromark black paint to achieve a diffuse, gray surface. Nominal 1/16 inch (1.6 mm) diameter Type K thermocouples are attached to the rear of each end sensor plates with thin, spot welded retainer straps.

Figure 1. DFT design from Blanchat, et al, 2000.

An older, somewhat larger DFT design that was used to obtain one set of data is similar, but with 1.6 mm thick end plates, and the pipe was packed with Kaowool insulating material. The overall diameter for this DFT was 115 mm with a length of 200 mm. Thermocouples were of the same type, diameter, and attachment scheme as the DFT used for other data sets.

**FIRE DATA**

Data were collected during an experimental series involving an actively cooled calorimeter installed in the 6 m x 6 m pool fire facility at Sandia. The calorimeter experiments are described separately in Koski, et al, 1995. The locations in the pool of the calorimeter and the DFT array are shown in Figure 2. Although the temperature sampling interval, on the order of several seconds, is much slower than the frequency of temperature variations within the fire, the data can be viewed as random samples of the full range of flame temperatures that occur over several minutes, and thus represent the temperature range of the rapidly varying flames.

Figure 2. View from above of the location of DFT arrays in a 6 m x 6 m pool.

For the two tests near the center of the pool, the DFT array was arranged in to two horizontal rows as shown in Figure 3. For the test near the corner of the pool, a single row of DFTs was placed 1.5 m above the pool surface. Data from three of the pool fires conducted as part of the actively cooled calorimeter test program are presented in this paper. Tests 0262 and 0267 were conducted on September 7 and 20, 1995, and the test designated 8/93 was conducted on August 14, 1993 in conjunction with a regulatory package test. The data traces for each DFT were inspected, and only those traces that appeared to be in the hot or continuous flame...
zone of the fire were selected. This avoids data from the central vapor
dome of the fire where there is not enough oxygen to support
combustion (see Gritzo, et al., 1998), and the extreme edge of the fire
region where combustion is intermittent. Startup and final transients of
the fire have also been removed, so that the data represent only the time
during the steady burning portion of the fire. Aviation jet fuel, JP-4, was
used for the 8/93 test, while the September 1995 tests used the now more
common JP-8 aviation fuel.

Data for test 0262 are shown in Figure 4. Data from DFTs 1, 3, 8 and
9 as identified in Figure 3 have been eliminated as faulty or not showing
continuous flame response. Data from 2 to 17 minutes after ignition at a
10 second sampling interval are shown. Data for test 0267, which was a
retest of the conditions for test 0262 are shown in Figure 5. Data from
DFTs 1, 3, 4 and 8 were removed from set because the temperature-
record indicated that the DFTs were defective or not in the continuous
flame zone. Data from 2 to 28 minutes after ignition at a 10 second
sampling interval were used. Figure 6 shows the data from the test
conducted on August 14, 1993 where the older DFT design was used.
Data between 7 and 32 minutes after ignition were taken from all DFTs
at a 5 second sampling interval. Note that each of the older DFTs
contained a center thermocouple, designated DFT 2 East, Center, and
West, that measured the internal insulator temperature. Readings from
this center thermocouple are not included in Figure 6.

With the DFTs selected for data analysis, all temperatures occurred
within the 600°C to 1200°C range. No data outside of the range was
discarded during the analysis.

RESULTS

A Fortran language program was used to count the occurrences of
temperatures in DFT fire data by sorting the temperatures into 60 10°C-
wide bins in the range from 600°C to 1200°C. Through counting the
occurrences in each bin, and comparing the number in each bin to the
total count, the probability of occurrence for each temperature range was
estimated. By summing the occurrences in each bin, a cumulative
distribution of temperatures representing the probability that a
temperature will be lower than given temperature was also calculated.

Figure 7 shows the probability distributions for Test 0262. Note that
the eight DFTs that produced the data were located in the flame zone of
the fire, approximately 1.5 m above the pool. Inspection of the
probability distribution shows that it is skewed toward the high
temperature end with a pronounced peak (mode) at 1000°C. Since the
distribution does not appear to be Gaussian or another commonly
recognized statistical distribution, many of the common statistical
measures such as standard deviation are not as useful as they are for
known distributions.

Statistics for Test 0267, which was intended to be a repeat of
Test 0262 provide somewhat different results as shown in Figure 8. The
useful period for collecting data in Test 0267 was longer, and nine DFTs
were observed to be in the flame zone. Although both fires were
conducted under nearly windless conditions, some variation in the peak
and distribution shape can be seen. In Test 0267, the mode of the
distribution is again near 1000°C, but a broader distribution is
observed.

The data collected from the 8/93 test shown in Figure 9 differ in that
the single-row array of DFTs is closer to the edge of the pool as shown
at the upper right of Figure 2. In addition, a thicker sensor plate, 1.6 mm
thick rather than the 0.25 mm thick for Tests 0262 and 0267, was used.
Data between 7 and 32 minutes after ignition were chosen. The results are shown in Figure 9. In this case, a broader peak of the temperature distribution is observed with a mode near 900°C. For these data not as much skew toward the high temperatures is shown.

**DISCUSSION AND CONCLUSIONS**

Measurements of fire temperature in three large pool fires show that temperatures vary greatly in the flame zone with measured temperatures falling in the range of 600 and 1200°C. The mode, or most frequently occurring temperature, in the central region of the fire was found to be near 1000°C. About 60 per cent of the temperature observations in these fires were found to lie below the mode of the curve.

Temperatures statistics gathered near the edge of the fire were found to be somewhat lower with a mode near 900°C nearly at the center of the distribution. Likely the lower temperatures are caused by temporary incursions of cold air near the edge of the fire as the turbulent convection process brings air toward the center of the fire.

Choosing a single temperature to represent the temperature distributions must be done with care because of the nonlinear nature of thermal radiation heat transfer. For transparent media, the heat transfer is governed by the difference between the fourth powers of absolute temperatures for the package and the fire. The use of the 1000°C mode temperature and a flame emissivity of 0.9 for the central region of the fire yields initial surface heat fluxes near 100 kW/m². This is somewhat less than the initial heat fluxes near 150 kW/m² observed in large pool fires (see, for example, Gregory, et al, 1989). Because of the nonlinear nature of the radiant heat transfer, increasing the effective temperature in the transparent medium heat transfer model by 100°C to 1100°C gives initial surface heat fluxes closer to the 150 kW/m² observed experimentally in Gregory, et al, 1989. This is an indication that, while transparent medium heat transfer models can provide reasonable, simple to use models for simulating package response to fires, care must be taken in their selection and use.

The data presented in Figure 7 were used to adjust the heat of combustion in a complex fire model (see Koski, et al, 2000 in these proceedings) until the fire temperature statistics from the fire model looked similar to the data presented in this paper. Initial package heat fluxes from the fire model near 150 kW/m² were then calculated. Some of the deviation from the single-temperature $T^4$ fire models can also be understood by examining the statistics. As the package surface heats, it approaches the lower temperatures in the fire temperature range. As the package surface temperature reaches the lower fire temperatures, heat transfer from those fire transients goes to zero. This means that only the transients to higher fire temperatures contribute to the heating process. As the object heats, progressively smaller fractions of the fire temperatures are above the object temperature and some cooling from the lower fire temperatures also occurs. Viewed from another perspective, the effective fire temperature that yields the correct heat transfer to the package can change as the object heats. This indicates that picking a single effective fire temperature for the entire heating process is not possible, although approximations over the full fire duration may produce useful approximations. It also indicates that any heat transfer correlations for fire conditions should include the surface temperature as a parameter.

Additional fire tests are planned as detailed by Kramer, et al, 2000, elsewhere in these proceedings. For these tests, DFTs are again planned as part of the test instrumentation. These tests should provide additional
guidance on the construction of simple fire models for risk and regulatory analyses.

REFERENCES


