Heat Transfer in Severe Accident Simulations*

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INTRODUCTION

Sandia National Laboratories (SNL) utilizes fire test facilities to subject military components and nuclear material shipping containers to postulated accident environments. There are two general approaches for specifying the thermal exposure. One is to specify a furnace temperature history, such as that used for building fires in the ASTM test method E-119; the other is to define the heat transfer rate to a surface in terms of the relative temperatures of the surface and the fire. The regulations concerned with the transport of radioactive materials (RAM) use the latter approach.

To begin to define the actual thermal environment, measurements of temperature and heat flux are necessary. Temperatures in the furnace/fire are important because many material limits are directly related to temperature. Test item temperatures define the response of the item to the environment. The initial response of the test item is governed by the heat flux. The heat flux levels indicate how severely an item will be thermally stressed and the integrated flux helps define the total thermal insult.

Most of the fire test work done in the United States, and indeed around the world, involves fire protection materials and/or assemblies. Standard test methods are developed by voluntary standards groups, such as the ASTM Committee E5 on Fire Standards, the National Fire Protection Association, and the International Standards Organization. Because the testing is part of the process of developing and rating the materials, large numbers of tests are conducted with relatively simple test assemblies. A number of commercial testing laboratories have a considerable amount of experience in running these types of tests. As a result, there is a large database, although much of the information is proprietary.

The analysis of heat transfer in furnaces is typically based on what is called "enclosure analysis". Because most furnaces use relatively clean burning fuels, a large fraction of the radiative heat flux comes from the walls of the furnace. The furnaces often are controlled by thermocouples that are mounted close to the test specimen. As a result, the readings are typically at an intermediate temperature between the walls and the specimen. Calculation of the heat flux from these "biased" measurements will be considered.

In the testing of fire protection materials, the test samples are generally much smaller than the test furnace, and have a relatively low thermal inertia (thermal conductivity$*$density$*$specific heat). As a result, the sample has a relatively small effect on the heat transfer in the furnace and does so for a relatively short period of time because the surface heats quickly.

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*This work performed at Sandia National Laboratories, Albuquerque, New Mexico, supported by the U. S. Department of Energy under Contract DE-AC04-76DP00789. **A United States Department of Energy Facility.

Testing of RAM shipping containers typically involves few units due to the high cost of the units. Developing any meaningful statistics is difficult, if not impossible, for any single package. As a result, SNL has made a concerted effort to develop a large database on the thermal environment in fires and the heat transfer to different types of objects in fires. In conjunction with the Department of Transportation (DOT), SNL is trying to develop a better understanding of what aspects of the package design affect the heat transfer rate.

Exposure in a fire involves combined radiative and convective heat transfer in a participating medium. The radiation heat transfer is governed by the flame temperatures, flame thickness, and the soot loading in the flame through its effect on the flame emissivity. While radiation is the dominant heat transfer mechanism, convective heat transfer can be important at early times, and increases as the size of the test unit decreases. Measurements made on test units of different sizes and shapes will be discussed. Work at SNL indicates that the heat transfer to a shipping container is affected by the physical size and shape of the container, as well as by its "thermal massiveness." As the physical size and/or the thermal massiveness increases, the peak heat flux decreases.

A "fire test" provides a "thermal insult" a package must survive to be certified. A simplified way of examining the "thermal insult" is to consider the maximum temperatures on the test unit and the rate at which these temperatures are reached. To define the thermal test environment for a shipping container, both temperature and heat flux should be obtained. In some cases, this will require separate measurements. In others, the heat flux to a package may be obtained from temperature histories of either the package or the fire. Generally, there is not a one-to-one correspondence between the average fire temperatures and the heat transfer rates.

Before trying to compare tests in a furnace and those in a fire, it should be noted that differences are expected because there are differences in the heat transfer mechanisms in the two types of tests. A number of studies of furnace tests have been made; two very useful studies are Babrauskas and Williamson (1978) and Sultan, et.al. (1986). Transportation accidents generally assume that there is a pool fire. Studies of the heat transfer in such instances have been made for RAM shipping containers and other systems; some examples are Wachtell and Langhaar (1966), Gregory, et al. (1987), Bainbridge and Keltner (1989), liquified gas tank cars (Journal of Hazardous Materials, Special Edition, January, 1989), and refineries and offshore oil platforms(Schonbucher, 1985).

TEMPERATURE AND HEAT FLUX MEASUREMENTS

One of the major difficulties associated with conducting any type of "fire test" is making accurate measurements in both the "fire" and the test unit. A variety of temperature and heat flux measurement techniques have been developed for use in fire tests. Each of these techniques presents certain advantages and disadvantages.

Measurements of temperature, in either a furnace or a real fire, present problems. As Harmathy and Sultan described it: "...the furnace temperature is a nominal value with no definite meaning, if measured with bare thermocouples, it will lie somewhere between the temperature of the furnace gases and the average surface temperature of the furnace chamber (part of which is the test specimen itself). If measured in the ASTM way (with the thermocouples enclosed in protective tubes), it may fall below any temperature prevailing in or along the boundaries of the furnace chamber, especially during the first 15 minutes of the test when the rise of temperature in the furnace is very steep."

There are two major problems involved with making temperature measurements in "fire" tests. One, as described above, is measurement errors which are related to the design of the test. Another problem may be the response time of the sensor which is based on its design.

The earliest fire tests were developed for fire safety evaluations; an example is the ASTM Test Method E119 - Standard Methods of FIRE TESTS OF BUILDING CONSTRUCTION AND MATERIALS. The test procedure involves a time-temperature curve with a slower rise than a pool fire but a higher final temperature; however, the E119 procedure does not reach temperatures comparable to a pool fire for at least an hour. In this test method, the furnace thermocouples are mounted in 1/2 inch iron, steel, or Inconel pipes. This design for the furnace thermocouples dates back over sixty years. The time constant of the thermocouple is expected to lie within the range of 5.0 to 7.2 minutes. Babrauskas and Williamson point out that the slow response can produce errors due to temperature lag of several hundred degrees centigrade during the early part of an E119 test.

Babrauskas and Williamson show that temperature measurement errors, due to radiation effects, can be 10% or more in furnaces. Both Burgess and Fry show that errors in the measured temperatures in sooty fires can reach 25%.

Measurement of heat flux in a furnace offers a number of problems; measurement in an actual fire poses additional difficulties. The most common methods of making heat flux measurements in fire tests involve the use of circular foil heat flux gages (often called Gardon gages after the developer), thermopile gages (Schmidt-Boelter gages), and variations on slug calorimeters. Each of these devices has different operating characteristics and presents certain problems. Usually, the first two types of sensors are cooled actively.

Gardon gages commonly are used for making both total and radiant heat flux measurements in fires. They were designed for making radiative flux measurements. One problem is that the absorptivity of the sensor coating is not uniform over the radiation spectrum. The manufacturers can provide adjustments to the effective absorptivity of the sensor coating to compensate for differences between the spectrums of the calibration source and the fire test. Condensation and soot deposition on these sensors, which are typically water cooled, can create additional problems.

Caution must be exercised when using Gardon gages to make measurements with a large convective fraction, resulting in changes of calibration constant. Differences of up to 25% have been reported for stagnation flow; additional changes occur when the angle of attack of the flow changes because the heat transfer to the sensor element becomes nonsymmetrical.

The thermopile types of sensors are typically used at lower flux levels, in part because of their higher sensitivity. If the temperature of the gage is not controlled, there is a potential problem with the accuracy, because the sensitivity varies as a result of temperature dependent Seebeck coefficient effects. As previously mentioned, the spectral absorptivity of the sensor coating should be obtained.

Slug calorimeters can be the small installable type of sensor, standard configurations such as plates or cylinders, or a specially designed unit that simulates the test unit. Because these devices depend on measuring a change in temperature, there is no cooling. The result is a transient, hot wall heat flux measurement. If the temperature of the device approaches the "fire temperature", the indicated heat flux goes to zero. To compare readings with other heat flux measurements, a correction is made to provide a cold wall heat flux value; this correction introduces uncertainties in the heat fluxes due to uncertainties in parameters, such as the emissivity of the calorimeter surface. As with the other two sensors, this requires a knowledge of the spectral absorptivity of the surface.

Slug gages can be small, fast response devices or large, slow responding units, such as the 10-ton cylindrical calorimeter used in some of the large pool fire tests conducted at SNL (for example, see Gregory, et. al or Bainbridge and Keltner). Temperature measurements from this device were analyzed with SODDIT (Blackwell, et. al), a nonlinear, inverse heat conduction code to estimate the heat fluxes.

As mentioned earlier, if any of these measurements are made in devices that are not of similar size to the test unit, then the measured heat fluxes may be higher than those experienced by the test unit.

HEAT TRANSFER IN FURNACE TESTS

The regulations do not restrict the manner in which compliance is demonstrated. Any thermal test can be considered as satisfactory, provided the heat flux incident on the package is not less than the equivalent heat flux specified by the regulations. Furnace tests have been used to demonstrate compliance with the regulations (Yusuda). At first glance, performance of a furnace test seems to be an attractive alternative to a "Pool Fire Test" (i.e., eliminating concerns with the repeatability of large-open-pool fires and environmental restrictions). However, as previously mentioned, one of the major difficulties associated with conducting any type of thermal test is obtaining accurate measurements in both the "fire" and the test unit. Accurate measurements of heat flux and temperature are necessary to assure that a furnace test provides the radiant environment specified in the regulations.

Heat Flux from a Furnace to a Test Item

The mathematical model developed by Babrauskas and Williamson will be used to determine the heat flux to a test item within a furnace . The model simulates radiative heat exchange in an enclosure containing a participating media. The model is based on the following assumptions.

(1) The temperature of the furnace gas is uniform and spectrally gray.

(2) The furnace walls are at a constant temperature.

(3) A parallel plane geometry is assumed between the furnace wall and the test item (ie., all view factors are equal to 1.0).

(4) All heat transfer within the furnace takes place by radiation.

Consequently, the net heat flux to a test item inside a furnace is:

$$q = \sigma \frac{\varepsilon_t \left[\frac{\varepsilon_g + \varepsilon_w - \varepsilon_g \varepsilon_w}{\varepsilon_g (1-\varepsilon_g) \varepsilon_w} + \left(\frac{1 - \varepsilon_w}{\varepsilon_w} \right) \right] \left(T_g^4 - T_t^4 \right) - \frac{\varepsilon_t}{\varepsilon_g} \left(T_g^4 - T_w^4 \right)}{\frac{\varepsilon_g + \varepsilon_w - \varepsilon_g \varepsilon_w}{\varepsilon_g (1-\varepsilon_g) \varepsilon_w} \left[1 + (1 - \varepsilon_g)\ (1 - \varepsilon_w) \frac{\varepsilon_g + \varepsilon_t - \varepsilon_g \varepsilon_t}{\varepsilon_g + \varepsilon_w - \varepsilon_g \varepsilon_t} \right]}$$

where

ε_g = emissivity of the furnace gas (.1, .4)

ε_t = surface emissivity of the test item (.8)

ε_w = surface emissivity of the furnace walls (.8)

T_g = furnace gas temperature (1173K)

T_t = surface temperature of the test item (K)

T_w = furnace wall temperature (1173K)

σ = Stefan-Boltzmann constant (5.66×10^{-8} W/M^2 K^4).

The absorption coefficient for the furnace gas, and consequently the gas emissivity, is very difficult to obtain. The absorption coefficient depends on the composition of the gas, including soot concentration, and, therefore, dependents strongly on furnace design. Generally, for furnaces fueled with relatively clean burning fuels (natural gas), the gas emissivity can be expected to be around 0.1. For those fueled with oil products, the emissivities can be expected to be substantially higher.

The net heat flux to a test item, as a function of the surface temperature, is given in Fig. 1. As illustrated, the integrated heat flux to the test item is strongly dependent on the emissivity of the furnace gas.

Temperature Measurements in a Furnace

Realistically, the furnace thermocouples do not measure the furnace gas temperature. If measured with bare thermocouples, the thermocouple readings will lie somewhere between the temperature of the furnace gas, the average temperature of the furnace walls, and the test item surface temperature. An energy balance that neglects convection and conductive losses from the thermocouple can be used to approximate the errors in the thermocouple readings. The energy balance uses a radiation network analysis to obtain the thermocouple readings. The radiation network analysis assumes the furnace wall temperature, furnace gas temperature, and the test item surface temperature are known. Fig. 2 shows the equivalent resistor network for radiation in an enclosure consisting of three gray bodies and a participating media. The thermocouple is assumed to be a sphere, 3.2 mm in diameter, with surface emissivity of 0.8. Invoking the same assumptions as the model developed by Babrauskas and Williamson, Q/TRAN is used to solve the network, and the results are presented in Fig. 3. As illustrated, for low emissivity gases, the radiation losses from an unshielded thermocouple can have a significant impact on the thermocouple readings. Depending on the rate at which the surface temperature of the test item heats, the thermocouple readings can underpredict the furnace gas temperature by 10 to 30 percent. If the thermocouple readings are used in calculating the heat fluxes, the heat flux to the test item can be underpredicted, Fig. 4.

HEAT TRANSFER IN POOL FIRE TESTS

As noted above, heat transfer to an object engulfed in a pool fire is a very complex process. However, the primary mode of heat transfer is radiative. Convective processes are expected to be only 10-25% of the total.

A number of heat transfer measurements have been made in pool fires at SNL over the past few years. Calorimeter measurements (Gregory, et. al) made with horizontal cylinders, diameters of 10 cm., 20 cm., and 1.4 m, report the average value of the peak heat fluxes was approximately 165 kW/m^2 for the two smaller calorimeters and 130 kW/m^2 for the large one. At the lower stagnation point, convective heat transfer is estimated to be 20 to 25% of the total for the smaller calorimeters and 8% of the total for the large one. Bainbridge and Keltner provide additional analysis of this data. Conditional sampling of the large calorimeter data is used to estimate the heat flux when very low winds occur during the one-half hour fire; the average values of the cold wall flux, as defined below, range from approximately 80 to 110 kW/m^2 depending on angular location. Schneider, et. al, add measurements on a large vertical plate. All of these documents provide temperature measurements in the fires.

The heat transfer rates are obtained for the "slug" calorimeters listed above using SODDIT. Because these calorimeters are of the transient type, the temperature increases as they absorb energy and, therefore, the heat fluxes are corrected to a cold wall value using:

$$Q_{cw} = Q_{net} + \sigma\varepsilon_t (T_t^4 - T_{cw}^4)$$

where

Q_{net} = the net heat flux to a test item

T_{cw} = cold wall temperature (K)

Fig. 5 provides a compilation of calorimetry data from the large cylinder and the plate from several tests conducted at SNL (figure taken from Schneider, et al.). The average cold wall heat flux is plotted versus the average "flame temperature" at the same location. The figure shows that the cold wall heat fluxes are higher on the vertical plate than on the 1.4 m horizontal cylinder. Also shown is the blackbody radiative heat flux versus average flame temperature.

The agreement between the average values of the cold wall heat flux and the blackbody flux predicted from the average values of the flame temperature is poor. The measured fluxes are higher than the predicted ones at lower temperatures, by as much as a factor of two. Part of this difference is explained by analyses, such as those of Burgess (1986) and Fry (1985), that show the temperatures measured in the fire can be significantly lower than either the actual flame temperature or the effective radiation temperature. Another part of this difference is explained in Schneider, et al., as being due to the large fluctuations in the flame temperatures. In general, locations with lower average temperatures show higher standard deviations. Due to the fourth power relationship between the radiative flux and the temperature, use of the average temperature underpredicts the radiative flux.

Another way of looking at the problem involves comparing different measured temperatures. The "flame temperature" measurements near the plate calorimeter use 1.6 mm Inconel-sheathed thermocouples that protrude 10 cm into the flames from the surface of the plate. One part of the plate calorimeter is a 6.35 mm mild steel plate; this section is designed to heat quickly. As shown in Fig. 6, the plate temperature reaches quasi-equilibrium with the local fire conditions about six minutes after the start of the fire (about 600 seconds on the figure).

Average values of the"flame temperatures" and the plate temperatures are calculated over the time period from 250 seconds to 2180 seconds. These values are shown below. At all four locations, the average plate temperatures are well above the average "flame temperatures".

Height from Pool Floor (m)	Average Flame Temperature (°C)	Standard Deviation (°C)	Average Plate Temperature (°C)
4.11	679	286	829
3.30	737	249	841
2.49	810	219	898
1.68	892	131	952

SUMMARY

For cask designers to improve analytical thermal modeling capabilities, it is important to define the "thermal insult" a fire test provides to a package. In order to define the thermal environment, temperature and heat flux measurements must be obtained. This paper discusses a range of experimental measurement techniques. Since temperature and heat flux measurements can present a large source of error, the uncertainty in experimental measurements is emphasized. Uncertainties in heat flux for furnace and fire tests can range from 10 to 50 percent. For example, the heat flux to the test item (in a fire or furnace) can be underpredicted if the readings from an unshielded thermocouple are used in calculating the heat flux. If a slug calorimeter is used to measure the heat flux, the calorimeter must be of similar size as the test unit. The measured peak heat flux may be higher than that experienced by the test unit if the calorimeter and test unit are not similar. In conclusion, it is important to be able to skillfully make measurements in a fire, and equally important to know or be able to estimate the accuracy of the measurement.

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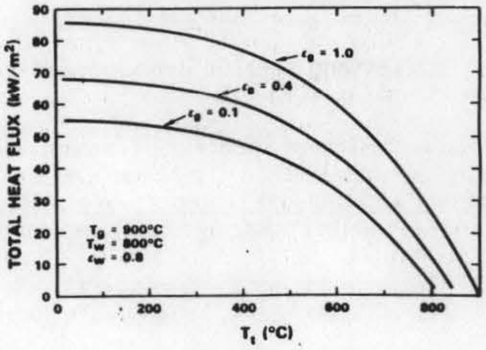

Figure 1. Calculated heat flux from a furnace to a test item

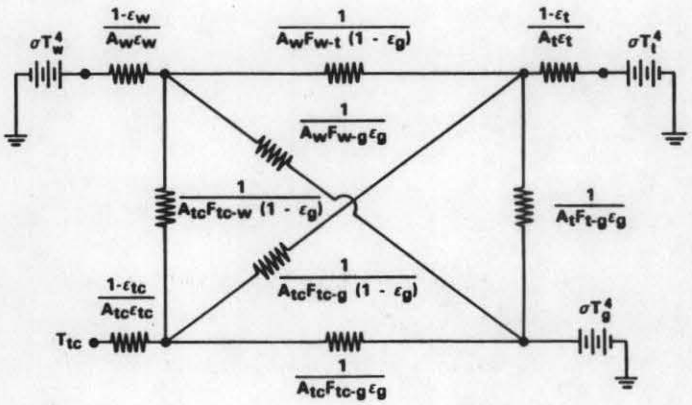

Figure 2. Equivalent resistor network for radiation in an enclosure consisting of three gray surfaces and a participating media.

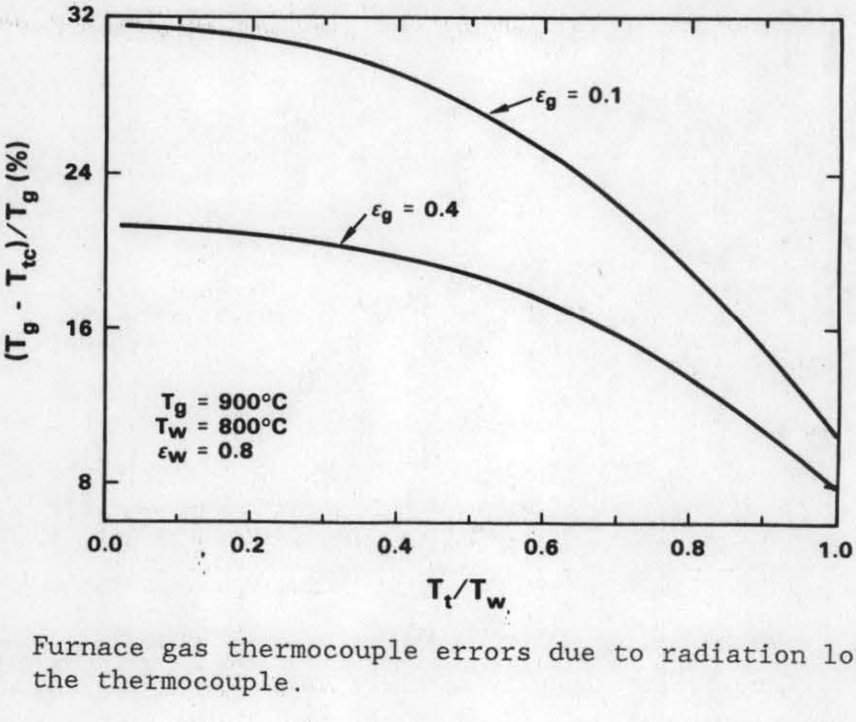

Figure 3. Furnace gas thermocouple errors due to radiation loss from the thermocouple.

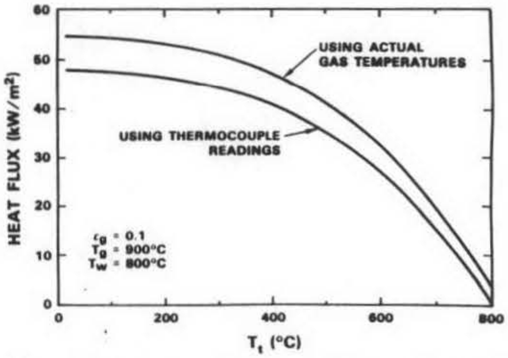

Figure 4. Using the thermocouple readings in calculating the heat flux from a furnace to a test item.

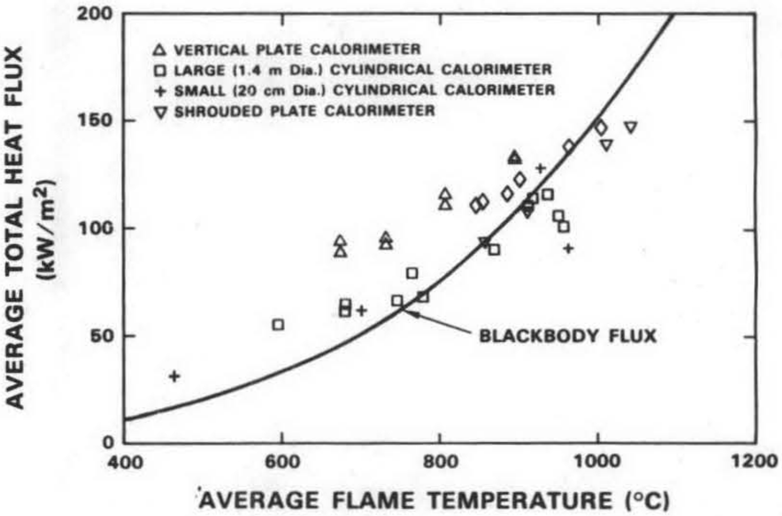

Figure 5. Cold wall heat flux as a function of average flame temperatures

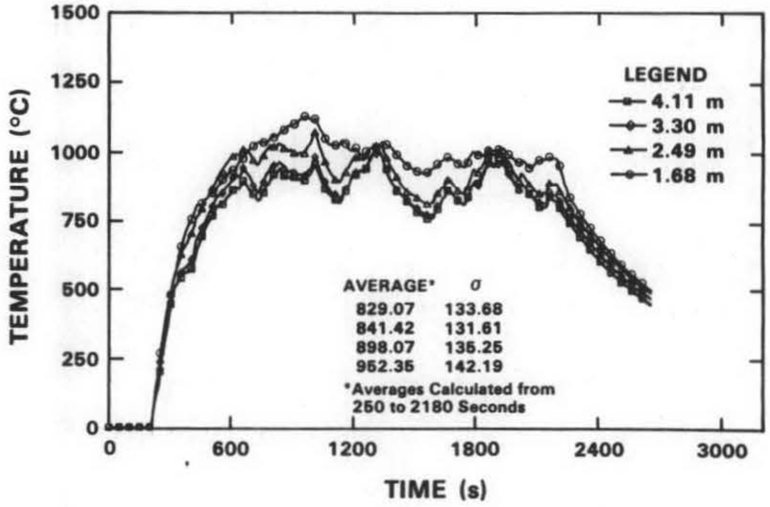

Figure 6. Backface temperature for a plate calorimeter as a function of time.

Session III-2

Packaging Subsystems