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Thermal Testing of Packages for Transport of Radioactive Wastes*

J. A. Koski
Transportation Systems Department
Sandia National Laboratories
Albuquerque, NM 87185-0717

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DISCLAIMER

INTRODUCTION

Shipping containers for radioactive materials must be shown capable of surviving tests specified by regulations such as Title 10, Code of Federal Regulations, Part 71[1](called 10CFR71 in this paper) within the United States. Equivalent regulations hold for other countries such as Safety Series 6 issued by the International Atomic Energy Agency[2]. The containers must be shown to be capable of surviving, in order, drop tests, puncture tests, and thermal tests. Immersion testing in water is also required, but must be demonstrated for undamaged packages. The thermal test is intended to simulate a 30 minute exposure to a fully engulfing pool fire that could occur if a transport accident involved the spill of large quantities of hydrocarbon fuels. Various qualification methods ranging from pure analysis to actual pool fire tests have been used to prove regulatory compliance. The purpose of this paper is to consider the alternatives for thermal testing, point out the strengths and weaknesses of each approach, and to provide the designer with the information necessary to make informed decisions on the proper test program for the particular shipping container under consideration. While thermal analysis is an alternative to physical testing, actual testing is often emphasized by regulators, and this report concentrates on these testing alternatives.

SUMMARY OF 10CFR71 THERMAL REQUIREMENTS

In preparing a Safety Analysis Report for Packaging (SARP), the normal transport and accident thermal conditions specified in 10CFR71 must be addressed. For approval in the United States, reports addressing the thermal issues must be included in a SARP prepared according to the format described in Nuclear Regulatory Commission Regulatory Guide 7.9. Upon review, a package is considered qualified if material temperatures are in acceptable limits, temperature gradients lead to acceptable thermal stresses, the cavity gas pressure is within design limits, and safety features continue to function over the entire temperature range. Test initial conditions must be at the most unfavorable normal ambient temperature for the feature under consideration, and corresponding internal pressures are usually at the maximum normal values unless a lower pressure is shown to be more unfavorable. The ambient air temperature range is taken to be -29°C (-20°F) to 38°C (100°F). Normal transport requirements of a maximum air temperature of 38°C (100°F), a solar insolation heat flux depending on surface form and location, and a cold temperature of -40°C (-40°F) are also stated in Part 71.71 of 10CFR71. Testing of full scale sections or subscale models and components is permitted if the tests can be shown to be relevant to the full scale container.

Hypothetical accident thermal requirements stated in Part 71.73 call for a 30 minute exposure of the entire container to a radiation environment of 800°C (1475°F) with a flame emissivity of 0.9. The surface absorptivity of the package must be 0.8 or the package surface value, whichever is greater. With temperatures and emissivities stated in the specification, the basic laws of radiation heat transfer permit direct calculation of the resulting radiant heat flux to a container surface temperature as shown in Figure 1. This means that what appears at first glance to be a flame or furnace temperature specification is in reality a heat flux specification for testing. Any testing must be conducted with this point in mind.

Convective heat transfer from still air at 800°C also must be included in the analysis. No artificial cooling of the container after heat input is permitted, and combustion must proceed until it stops naturally. Effects of solar radiation may be neglected for analysis and test purposes.

For purposes of analysis, the hypothetical accident thermal conditions are specified by the surface heat flux values shown in Figure 1. Note that the peak heat fluxes for low surface temperatures are between 55 to 65 kW/m^2. Convective heat transfer from still air is estimated from methods described by McAdams[3], and contributes a maximum of 15 percent of the total heat flux. The 15 percent value is consistent with experimental measurements[4].

While 10CFR71 values represent typical package average heat fluxes in pool fires, large variations in heat flux depending on both time and location have been observed in actual pool fires. Figure 2 shows results from tests with various size cylindrical objects placed in pool fires. The values in the figure have been adjusted through the use of the laws of radiant heat transfer to represent the heat flux to a cold (20°C) surface. Local heat fluxes as high as 150 kW/m^2 are routinely observed. Local flux values are a function of several parameters[5], including height above the pool. Thus the size, shape, and construction of the container can affect local heat flux conditions. As shown in Figure 2, the size of the container can also affect the average heat flux received during the fire. Designers should keep the possible differences between the hypothetical accident and actual test conditions in mind during the design and testing process.

For proper testing, good simulations of both the pool fire heat flux transient and resulting material temperatures must be achieved. Unless both the heat flux and material surface temperature transients are simultaneously reproduced, then the thermal stresses resulting from material temperature gradients and the final container temperature could be erroneously high or low. Some test methods are better suited to meeting this required transient conditions than others. The relative advantages and disadvantages of the various methods in simulating the pool fire environment are discussed in the following sections.

RADIANT HEAT TESTING

Radiant heat testing simulates the pool fire heat flux with large arrays of heat lamps. Typically 6000 W halogen filled, tubular quartz lamps with tungsten filaments are arranged around the test object. A photograph of a typical radiant heat test configuration is shown in Figure 3. Panels are typically 0.3 m (1 ft). by 1.2 m (4 ft). An intervening thin metal shroud with a high emissivity (black) surface is usually placed between the lamps and the object. By measuring the temperature of the shroud and the test object, the laws of radiation heat transfer may be used to estimate the radiant heat flux from the shroud to the test object.

Facilities Available

Within the DOE complex, the only large radiant heat facility is at Sandia National Laboratories (see Table 1 for the name of a contact). The Sandia facility can test objects up to 2 m long with a maximum diameter of 0.8 m. Input powers up to 5 MW are possible, with up to 85 per cent of the input power coupled to the test object.

Other similar facilities exist within the Department of Defense complex at Edwards Air Force Base in California and Wright-Patterson Air Force Base in Ohio. These facilities are aimed at thermal testing for aircraft purposes, and were not initially designed to emulate heat fluxes from pool fires.

Advantages

The radiant heat testing method has several advantages. Costs are lower than pool fire testing with substantially less air pollution. By placing lamps and shrouds in various arrays, control of the heat flux distribution and intensity is possible. This means that different types of fires can be simulated. For example, for shipment of nonradioactive materials, Department of Transportation regulations for pool fires and torch fires may be simulated. Also, the local heat flux variations that occur in an actual pool fire can be simulated. Results with this type of testing are also much more repeatable than with actual pool fires where wind can be an important variable.

A radiant heat test can ramp from ambient to test temperatures typically in less than one minute. This heating time is much quicker than most furnaces, and eliminates the need to open the test chamber for insertion of the test unit. In addition, rapid changes in flux levels may be made during a test if test conditions are not correct. Both the temperature history and the heat flux transient simulating the pool fire can be controlled and reproduced. Shroud temperatures may be controlled at any desired level up to 1100°C (2000°F). Past simulated fire tests have been conducted at 800°C(1475°F), 870°C (1600°F), and 1100°C (2000°F). Since heat flux can be controlled and estimated, comparisons with results from analysis is easier than with other methods. To estimate the steady state heat flux, q", between two flat plates, a formula such as the following is often used:

$$q'' = \{1/[1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2-1)]\}\sigma(T_2^4-T_1^4)$$

where: ε = the surface emittance (emittance = absorptance for steady state)

σ = the Stephan-Boltzmann constant
T = the surface temperature
A = the surface area
1 refers to the test object
2 refers to the shroud

Thus, by knowing the surface emittance, relative areas, and temperatures of the test unit and the shroud, the radiative heat flux to the test object can be estimated

Diagnostics are also easily controlled. For example, unless smoke is emitted from the test piece, infrared thermography could be used to obtain detailed information on surface temperatures. If no thermal degradation occurs during testing, the test piece is reusable without the refurbishment caused by soot deposits from actual pool fire tests. Since testing is done indoors, weather is not the issue that it is in pool fire tests.

Disadvantages

Radiant heat testing is limited to small to medium containers and components. Large electrical power supplies from utilities such as power lines and transformers are required. As mentioned, the Sandia facility can require up to 5 MW of electrical power.

FURNACE TESTING

Electric and gas fired furnaces are often used for 10CFR71 thermal testing. Because the furnaces also can be used for other functions such as brazing and heat treatment of metals, they are more generally available than other types of facilities. For example, within the DOE complex, a large (2.7 m x 2.7 m x 2.7 m) electrically heated furnace exists at Oak Ridge National Laboratory[6]. Larger commercial facilities are available under contract, for example, the furnace at ABB Combustion Engineering in Chattanooga, Tennessee is large enough for a rail car.

In furnace testing, the furnace is first brought to temperature without the test piece, the furnace door is briefly opened, the test piece is inserted, and, after a furnace recovery time, the 30 minute regulatory test is started.

Facilities Available

Many furnace test facilities are available within and outside the DOE complex. Some facilities and contacts are listed in Table 1. The B-1023 furnace at Oak Ridge has been used for 10CFR71 testing and is the most carefully evaluated facility of its type within the DOE complex. The furnace is in the metal preparation area of the 9204-4 Building at the Oak Ridge Y-12 Plant. The B-1023 furnace is a Flinn and Dreffein electric car-bottom preheat furnace. The furnace is controlled by a proportional controller, and its recommended useful temperature range is from 370-1150°C (700-2100°F). The walls and ceiling of the furnace are lined with (2300°F) IFB (firebrick), and the floor is lined with 60 per cent alumina refractory. The heating elements are Driver-Harris Nichrome V in rod overbend construction. These elements are evenly distributed on the furnace walls (including the door), and elements are also hung from the ceiling in a slightly less concentrated manner. The total power rating to the coils is 450 kW.

The furnace lacks heating elements in the floor. To find a method for compensating for the lack of floor elements, several experiments were done to characterize the B-1023 furnace at temperatures at or near those used for hypothetical thermal accident physical testing[6]. These experiments ranged from a simple heatup of the furnace from ambient temperatures (to help find the length of time necessary to preheat the furnace before thermal testing) to the actual physical testing of DT-18 packages that had been accidentally damaged in previous routine use. To compensate for the lack of floor heater elements, a large steel plate was placed in the floor of the furnace. The plate and the rest of the furnace are heated to somewhat above the desired test temperature of 800°C. The plate has a large thermal capacitance so that when the door of the furnace is opened to insert the test piece, the plate maintains the 800°C temperature required by 10CFR71. Experimental curves have been developed for the furnace to assure that the minimum required plate temperature (800°C) can be maintained during the door opening and test piece insertion procedure.

The thermocouple called the control thermocouple is permanently mounted in the furnace and is the thermocouple through which the proportional controller measures furnace temperature. This thermocouple hangs 30 cm (1 ft) from the ceiling and measures the temperature of the thermocouple at that location. Other instrumentation included with the furnace are three ammeters and three voltmeters that show the quantity of power being delivered to the furnace at a given time.

The thermocouples used for the measurement of floor temperatures during tests are type K, Chromel-Alumel, with a stainless steel 316 sheath. The measurement of wall and ceiling surface temperatures is done by mounting thermocouples directly on these surfaces.

For the test series conducted on the furnace in Reference 6, fifteen surface thermocouples were mounted in the following manner: three on each of the north and south walls; one on the east wall; one on the ceiling; and seven on the door. Two 12-channel Beckman Industrial Doric Minitrend 205 digital data recorders, can log data at a maximum rate of once every minute, can be used to record temperatures.

Advantages

Furnace testing is attractive because of the wide availability of facilities and low costs. Weather, wind, air pollution and other factors that affect outdoor testing do not apply. Instrumentation of the test piece is readily accomplished. If the container does not have components that degrade during testing, then the container can be reused after testing without the cleanup required for containers subjected to pool fires. Results of tests are much more repeatable than for outdoor pool fires where wind can be an important variable.

Disadvantages

Because these furnaces were designed for other purposes, care in reproducing the correct thermal transients required by 10CFR71 is necessary. Two key issues are the surface heat flux time history and the final temperatures reached during testing. Rapid heating of a container causes stresses when materials with differing thermal expansion coefficients are in close contact, or when materials are subjected large internal temperature gradients. If the surface heat flux is lower than 10CFR71 values, then thermal stresses are also lower, though the final temperature may be the same or even higher. After inserting the test object into the furnace, recovery time for the furnace is usually allowed before the start of the 30 minute test. The combination of recovery time and test time may lead to raising the components to higher temperatures than would occur under 10CFR71 conditions. For these reasons, the thermal time history must be carefully addressed for furnace testing, and the size and weight of the test object must be considered relative to the heating rate and thermal inertia of the furnace.

One method for assuring that the heat flux boundary conditions in furnace testing are met has been described by Nunley[7]. Although this report was intended for use in only one segment of the DOE complex, the Nuclear Explosive Safety Division of the Albuquerque Operations Office, the methods outlined are applicable to most furnace tests, and those contemplating use of furnace testing should be aware of the approach. In this approach, the initial heat flux to the container according to 10CFR71 is first calculated with use of the regulatory temperatures and emissivities. With this heat flux known, the furnace temperature necessary to achieve this heat flux is then calculated based on actual package and furnace emissivities and the actual initial package temperature. The furnace temperature needed is not necessarily the 800°C value specified in 10CFR71, but represents the furnace temperature required to achieve initially the regulatory heat flux. This procedure is intended to assure that heat fluxes during the first few minutes of testing when the heat fluxes are the highest match the regulatory standard.

Another problem in furnace testing is accurate estimation of the furnace temperature. This problem is discussed by Keltner and Moya[8]. In that paper, a furnace calculation is presented that includes the effects of furnace gases that absorb and emit energy. Furnace thermocouples suspended within the furnace do not measure the furnace gas temperature. If measured with bare thermocouples, the thermocouple reading is determined by the temperature of the furnace gas, the average temperature of the furnace walls, and the test item surface temperature. Keltner and Moya present an energy balance that neglects convection and conductive losses from the thermocouple, but 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. 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 under predict the furnace gas temperature by 10 to 30 per cent. If the thermocouple readings are used in calculating the heat fluxes, the heat flux to the test item can be under predicted. Use of special designs, such as described by Fry[9] and Wickstrom[10] may improve the prediction because these designs more accurately measure the 'effective furnace temperature'.

POOL FIRE TESTING

For pool fire testing, the test object is supported above a pool of burning liquid, typically JP4 jet fuel. The fuel is floated on a pool of water, with the initial depth of the fuel predetermining the burn time. The pool is constructed so that it is larger than the test object by at least 1 but not more than 3 m in lateral dimensions. The burn is typically done outdoors although an indoor facility is now operational at Sandia National Laboratories.

Facilities Available

Within the DOE complex, large pool fire facilities are available at Sandia National Laboratories, Albuquerque. Within the Department of Defense, facilities are available at White Sands and China Lake. Omega Point and Southwest Research Institute are private laboratories that can provide pool fire test services (see Table 1).

The Sandia test site has several facilities including both large and small open pools that can be can be screened from wind effects as shown in Figure 4. An indoor facility, called SMERF for Smoke Emissions Reduction Facility, has a 3 m x 3 m pool in an 18 m high building with pollution control equipment (see Figure 5). Advantages of this facility include the ability to run on days when winds would be too high for outdoor fires, and a reduction in emissions, so that testing can continue at times when air pollution is a community concern.

Advantages

Pool fires provide the closest possible simulation of accidents involving flammable liquids. Large objects can be readily tested with pool fires, while radiant heat and furnace methods are limited to small to medium sized objects. Because of the close simulation of actual accidents, regulators may tend to give more credibility to pool fire tests rather than other methods. A large body of experience with pool fire testing over the years [11-17] has led to development of many useful diagnostic methods. One method, the inverse heat conduction method, has been applied most often to open pool fires, though it could be applied to other testing methods as well. With inverse heat conduction, thermocouples are at various interior positions, and by solving the heat conduction equations, surface heat fluxes and temperatures can be estimated from interior values.

Disadvantages

Because each test requires a special configuration, pool fire testing is often more expensive than other types of thermal tests. For outdoor tests, delays caused by wind and weather can further increase costs and cause scheduling problems. Use of indoor facilities such as SMERF will reduce these problems if the container size permits.

Duration of the burn is not exact as the depth of fuel required can vary depending on conditions at the time of the burn. Usually the burn time is within 2 minutes of the 30 minute requirement, and generally is on the long side to assure a full 30 minute burn.

Data such as shown in Figure 2 suggest that pool fire testing can easily result in an overtest with regard to the requirements of 10CFR71. Designs that are intended for such testing must consider this possibility.

Diagnostics are more difficult in the fire environment because instrument leads must be carefully routed away from the pool. Smoke and soot obscure direct visual measurements during the fire. As with furnace testing, measurement of local temperature within the fire is difficult, although this problem is not as significant because the pool fire already reproduces the actual accident environment. If measurement of radiant heat flux in the fire is attempted with radiometers, care must be taken. Experience shows that Schmitt-Bolter type radiometers provide more accurate results than Gardon gauges. Gardon gauges work well in a pure radiation environment and other places where convective heat transfer is not important, but tend to give erroneous reading in pool fires where the convective heat transfer can destroy the symmetry assumed for data analysis. The same problem can occur in gas fired furnaces.

Because the containers are subjected to smoke and soot, cleanup of a container for reuse may be difficult.

RESEARCH TOWARD A MORE ACCURATE FIRE MODEL

For container designs, a simple, accurate computer model of the pool fire environment can increase confidence that the design will successfully pass the thermal test. In pool fires, testing has shown that the local heat flux is a function of many variables including height above the pool, surface orientation and mass of the test object. A research program to produce a model that predicts such effects is in progress in our group at Sandia Laboratories. Experimental data from fires is being applied to calibrate a simple model of radiative heat transfer in a participating medium. Such a model has been developed[5] to explain observed fire effects. The model consists of a vertical flat plate at constant uniform temperature completely engulfed by flames of large thickness (Figure 6). Combustion gases flow upward along the plate at a specified uniform velocity. Thermal radiation exchange between the surface of the plate and the combustion products is modeled assuming 1-D gray gas radiative heat transfer normal to the plate surface. The gray gas is assumed to have a constant, uniform absorption coefficient. For fires of this type, scattering can be neglected, and the extinction coefficient is well approximated by the absorption coefficient. The combustion source term can be modeled in a variety of ways, including: 1) a uniform heat generation rate, 2) an Arrhenius-based heat generation rate, or 3) zero heat generation (representative of large quenched regions near the object).

This simple model predicts the development of a radiation boundary layer as a result of the radiation/convection interaction between a large, cold plate and a fire. This boundary layer lowers the combustion gas temperatures near the plate, which results in a reduction in the incident radiative heat flux to the plate. Larger plates show a greater reduction in the incident radiative heat flux. For a 1 m long plate, the reduction in incident radiative heat flux is calculated to be almost 25 per cent near the end of the plate for typical pool fire conditions.

A 1 m x 1 m square water cooled plate calorimeter has been constructed to assess whether or not we are capturing the essential physics with our simple gray gas model. Since the gray gas model presently uses a constant and uniform plate temperature, the actively cooled plate calorimeter (with its relatively constant and uniform surface temperature) can provide an appropriate test for the analytical model. In particular, do the incident heat fluxes measured by the calorimeter show the same trends along its length as predicted by the simple model? If so, then we can have further confidence that our simple gray gas model does indeed capture the essential physics of the problem. Early results from the plate calorimeter experiments tend to confirm the trend of decreasing heat flux with increasing height along the cooled plate (see Figure 7).

The other important benefit of the actively cooled plate calorimeter experiments is that they will allow us to better quantify two of the important parameters in the simple model. To date, the gray gas model has been used in an interpretive rather than predictive manner because of large sensitivities in the model to the values of extinction coefficient and heat generation rate. It would be necessary to incorporate complicated soot production, combustion, and turbulence models into the gray gas model in order to accurately predict these parameters from first principles. This is not desirable for such a simple model. Instead, data from the actively cooled calorimeter experiments will allow us to estimate the magnitude of these sensitive parameters that best enable the gray gas model to match the experimental heat fluxes. Our intent is that we will then be able to couple the gray gas model to existing commercial thermal computer codes to predict with confidence the heat fluxes to objects in pool fires.

CONCLUSIONS AND RECOMMENDATIONS

The designers of shipping containers for radioactive materials have many test options available. For smaller containers, furnace and radiant heat testing offer low cost alternatives if the test can be shown to meet the heat flux and other criteria described in 10CFR71. For SARP review purposes, use of pool fire testing for final testing of small containers may speed the approval process if the reviewers perceive that the hypothetical accident environment is better simulated. For larger containers, the open pool fire offers the only testing method.

Care must be taken during container design if pool fire testing is to be done for final qualification. While the heat fluxes specified in 10CFR71 are averages for the entire package, localized heat fluxes of up to three times the regulatory value can be experienced for short periods as discussed in the introduction. If pool fire testing is the final goal, design calculations should include appropriate peaking factors for local variations in heat flux. This will assure that the thermal stresses encountered during pool fire testing are properly simulated.

For smaller assemblies and containers, furnace testing and radiant heat testing offer lower cost alternatives to pool fire testing, but at the added burden of assuring the 10CFR71 conditions have been met. One method of assuring the proper environment is to build calorimeters of the approximate size, shape, and thermal mass of the test piece and subject it to the test environment. By locating thermocouples within the calorimeter, surface heat fluxes and temperature can be estimated with inverse heat conduction methods such as those described in Reference 14. This approach would be especially applicable to furnace testing where surface heat fluxes are difficult to estimate from furnace temperature measurements. This problem is not as important with radiant heat testing if shrouds of known temperature and surface emissivity surround the test object. By knowing the shroud and test piece temperatures, the radiant heat flux to the surface may be estimated from the radiation heat transport laws.

Package designers must always consider how the testing results are to be presented in the SARP. Since the SARP reviewer does not have a separate means of access to the test data, the SARP submittal must supply the data that shows compliance to 10CFR71, and must clearly say that the regulation has been met. Instrumentation must be designed to confirm that the package meets the requirements.

Table 1 lists some of the currently available thermal test facilities along with the names of recent contacts. Many factors affect the choices of test method and location. Designers and project managers must screen the alternatives and pick the optimum for the particular container to be tested. We hope that this paper will make such choices a bit easier.

Research is in progress to complete a fire model that both accurately represents fire conditions and is fast enough to be used with standard thermal computer codes. With this model operational, predictions of container performance during testing will improve. The result will be improved container safety as well as a better first test success rate for thermal testing.

REFERENCES

1. Title 10, Code of Federal Regulations, Part 71, "Packaging and Transportation of Radioactive Material," Jan. 1, 1988, United States Government.

2. Regulations for the Safe Transport of Radioactive Waste, Safety Series No. 6, International Atomic Energy Agency, Vienna, 1990.

3. W. H. McAdams, Heat Transmission, McGraw-Hill Book Company, New York, 1954, p. 180.

4. J. T. Nakos and N. R. Keltner, "The Radiative-Convective Partitioning of Heat Transfer to Structures in Large Pool Fires," in: Heat Transfer Phenomena in Radiation, Combustion, and Fires, R. K. Shah, ed., HTD - Vol. 106, American Society of Mechanical Engineers, New York, 1989.

5. V. F. Nicolette and D. W. Larson, "The Influence of Large, Cold Objects on Engulfing Fire Environments," in Proceedings of AIAA/ASME Thermophysics and Heat Transfer Conference, Seattle, WA, June 18-20, 1990.

6. M. R. Feldman, Characterization of the B-1023 Furnace for Use in Hypothetical Testing of Shipping Containers in Accordance with 10CFR, Part 71, ORNL/ENG-10, Martin Marietta Energy Systems, January 1992.

7. S. M. Nunley, "A Combination Test/Analysis Method Used to Demonstrate Compliance to DOE Type B Container Thermal Regulations (30 Minute Fire Test)", Defense Program Guidelines for Packaging, US DOE, Field Office, Albuquerque, Nuclear Explosives Safety Division, February 10, 1992.

8. N. R. Keltner and J. L. Moya, "Defining the Thermal Environment in Fire Tests," Fire and Materials, 14: 113 (1989).

9. C. J. Fry, "Pool Fire Testing at AEE Winfrith," in Proc. of The 9th Symposium on the Packaging and Transportation of Radioactive Materials, July 11-16, 1989, Washington, D.C., CONF-890631, prepared by Oak Ridge National Laboratory, 1989.

10. U. Wickstrom, The Plate Thermometer- A Simple Instrument for Reaching Harmonized Fire Resistance Tests, SP Report 1989:03, Swedish National Testing Institute, Fire Technology, Boras, Sweden, 1988.

11. R. S. Longenbaugh, L. C. Sanchez, and A. R. Mahoney, Thermal Response of a Small Scale Cask-Like Test Article to Three Different High Temperature Environments, DOT/FRA/ORD-90/01, U. S. Department of Transportation, Federal Railroad Administration, Washington, D.C., 1990.

12. J. M. Nelsen, Determination of Net Heat Fluxes and Assessment of Test-to-Test Thermal Input Variation for Three Large Engulfing Open Pool Fire/Calorimeter Tests, SAND 85-1821, Sandia National Laboratories, Albuquerque, NM, 1986.

13. N. R. Keltner, V. F. Nicolette, N. N. Brown, and B. L. Bainbridge, "Test Unit Effects in Large Fires," Journal of Hazardous Materials, 25: 33 (1990).

14. J. J. Gregory, Roberto Mata, Jr., and Ned R. Keltner, Thermal Measurements in a Series of Large Pool Fires, SAND85-0196, Sandia National Laboratories, Albuquerque, NM, 1987.

15. J. J. Gregory, N. R. Keltner, and R. Mata, Jr., "Thermal Measurements in Large Pool Fires," Journal of Heat Transfer, 111: 446 (1989).

16. M. E. Schneider and L. A. Kent, "Measurements of Gas Velocities and Temperatures in a Large Open Pool Fire," Fire Technology, 25 (1): 37 (1989).

17. M. E. Schneider, N. R. Keltner, and L. A. Kent, Thermal Measurements in the Nuclear Winter Fire Test, SAND 88-2839, Sandia National Laboratories, Albuquerque, NM, 1989.

Table 1. Some test facilities for thermal testing of transportation containers for radioactive material.

Facility and Contact	Types of testing done
Sandia National Laboratories PO Box 8500 Albuquerque, NM 87185 Joe Koski (505)845-9572	Pool fire, radiant heat, furnace testing
Oak Ridge National Laboratory P. O. Box 2008 Oak Ridge, TN 37831 Matt Feldman (615)576-2686	Furnace testing
NASA White Sands Test Facility PO Drawer MM Las Cruces, NM 88004 Harold Beeson (505)524-5542	Pool fire, furnace testing
Naval Weapons Center China Lake, CA 93555 Gil Cornell (619)927-2737	Pool fire
Lindberg Heat Treating PO Box 25405 Charlotte, NC 28229-5404 Skip Jones (704)536-1293	Furnace testing
Southwest Research Institute 6220 Culebra Rd. San Antonio, TX 78228-0510 Roger L. Bessey, Div. 04 (512)684-5111	Pool fires, furnace testing
Omega Point Laboratories 6868 Alamo Downs Parkway San Antonio, TX 78238 Deggary Priest (512)647-5253	Pool fires, furnace testing
Energy Analysts 2001 Priestley Norman, OK 73069 Dwight Pfenning (405)321-5778	Pool fires, torch fires

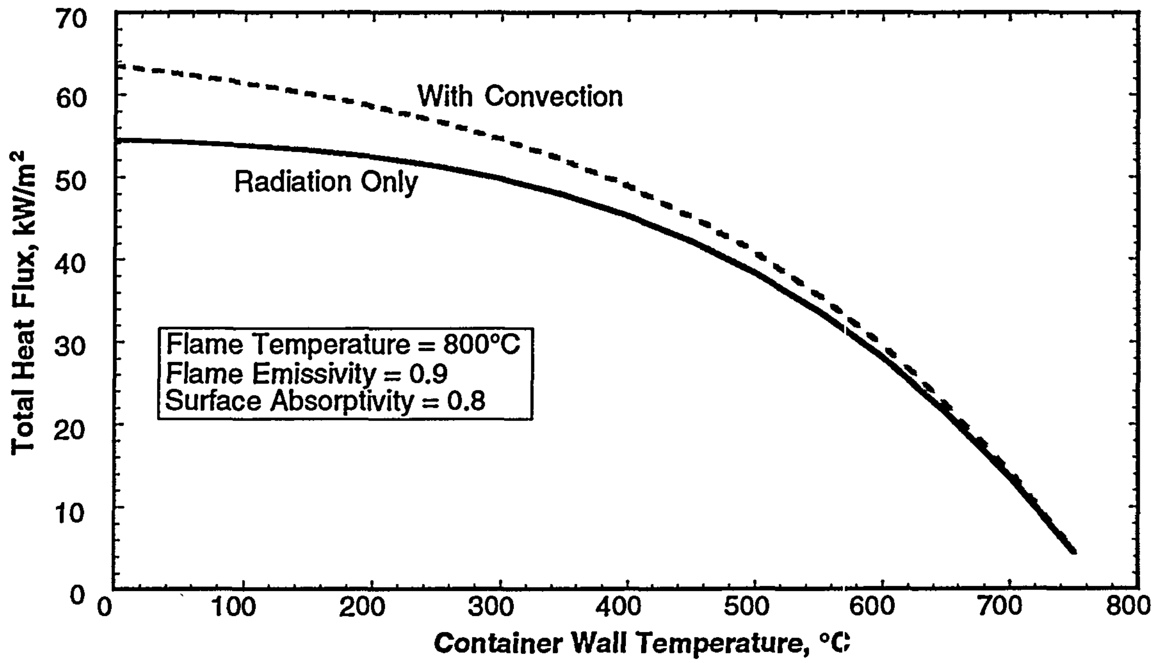

Figure 1. Heat fluxes implied by 10CFR71.

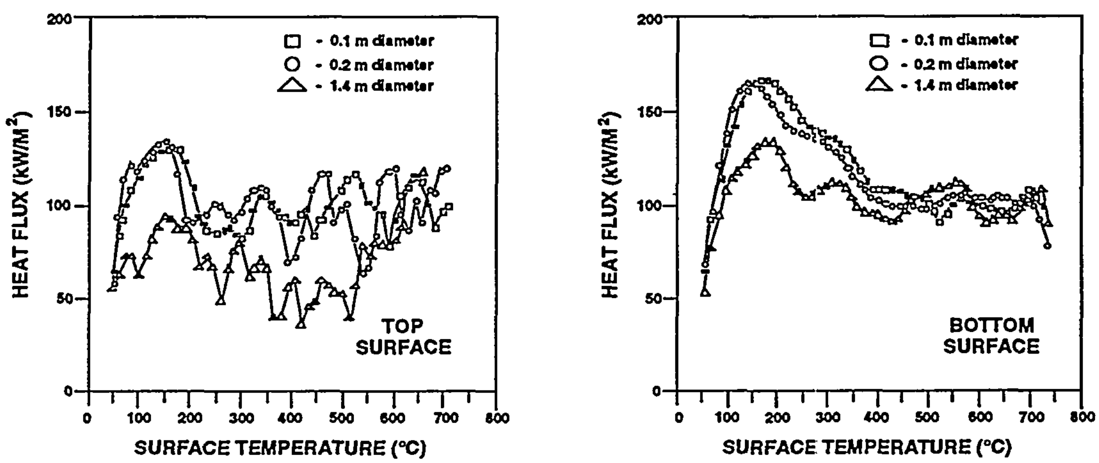

Figure 2. Cold wall heat fluxes measured in pool fire for various sized cylinders[14].

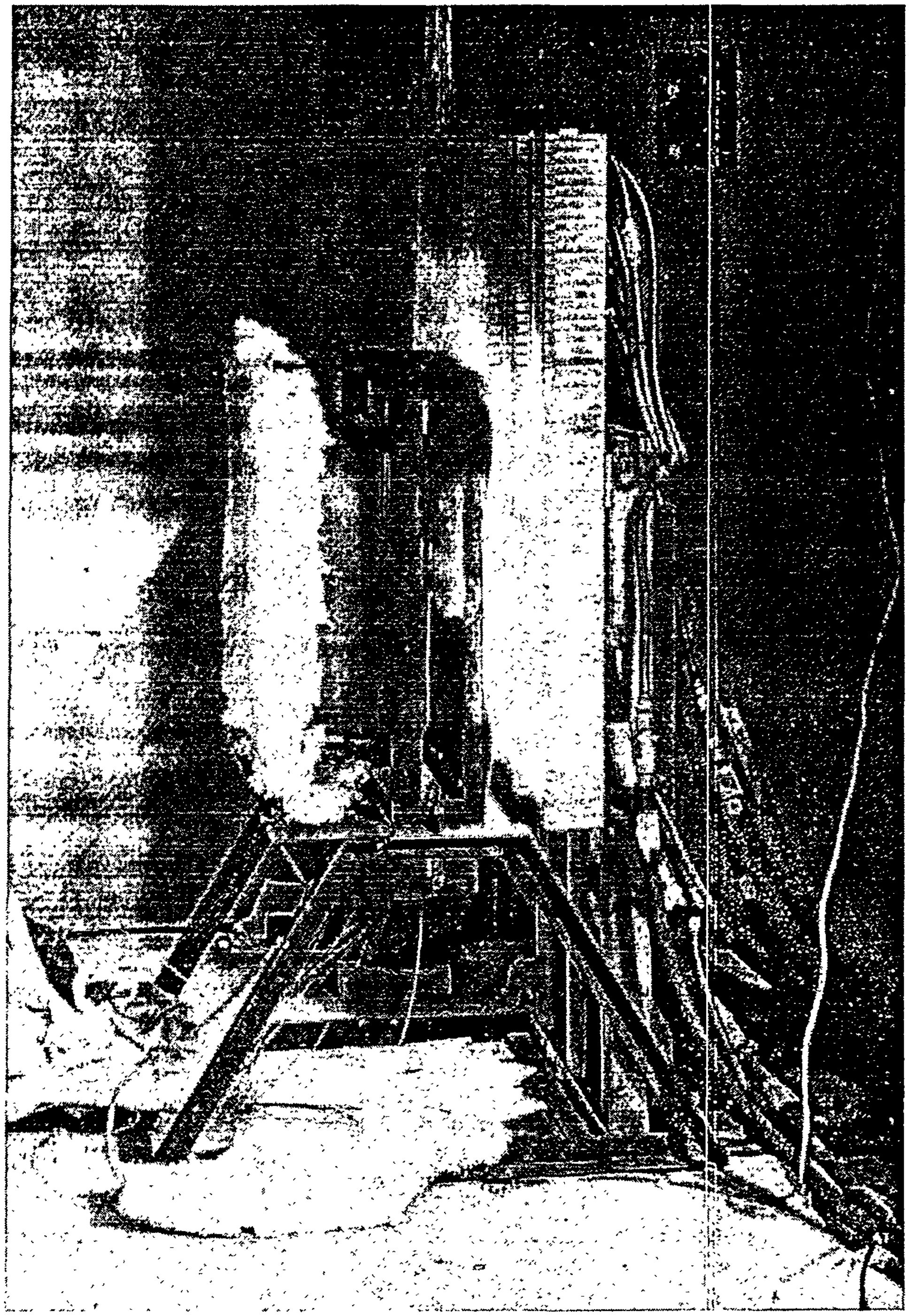

Figure 3. Typical radiant heat test arrangement.

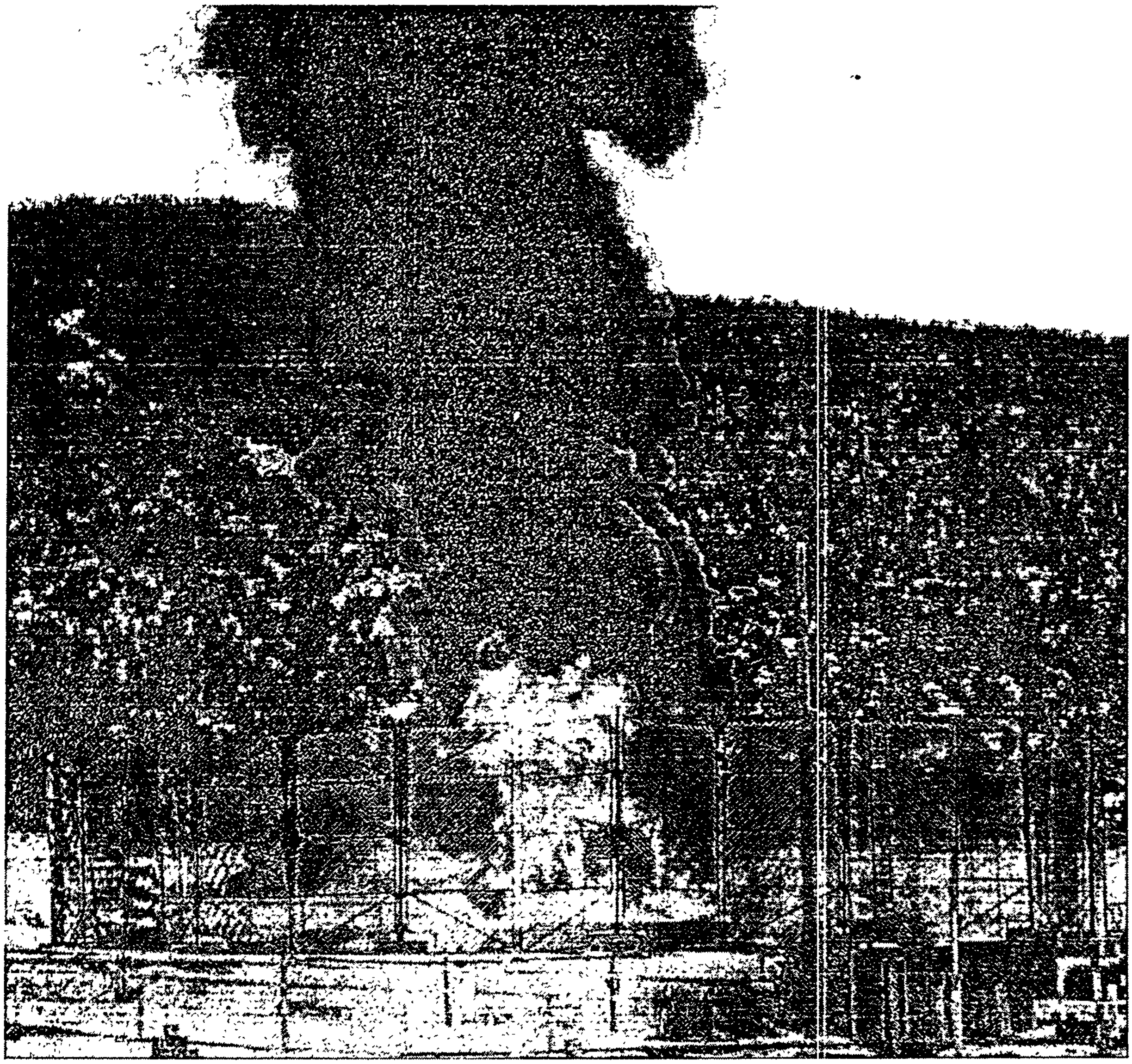

Figure 4. Open pool fire. Note wind screen surrounding fire area.

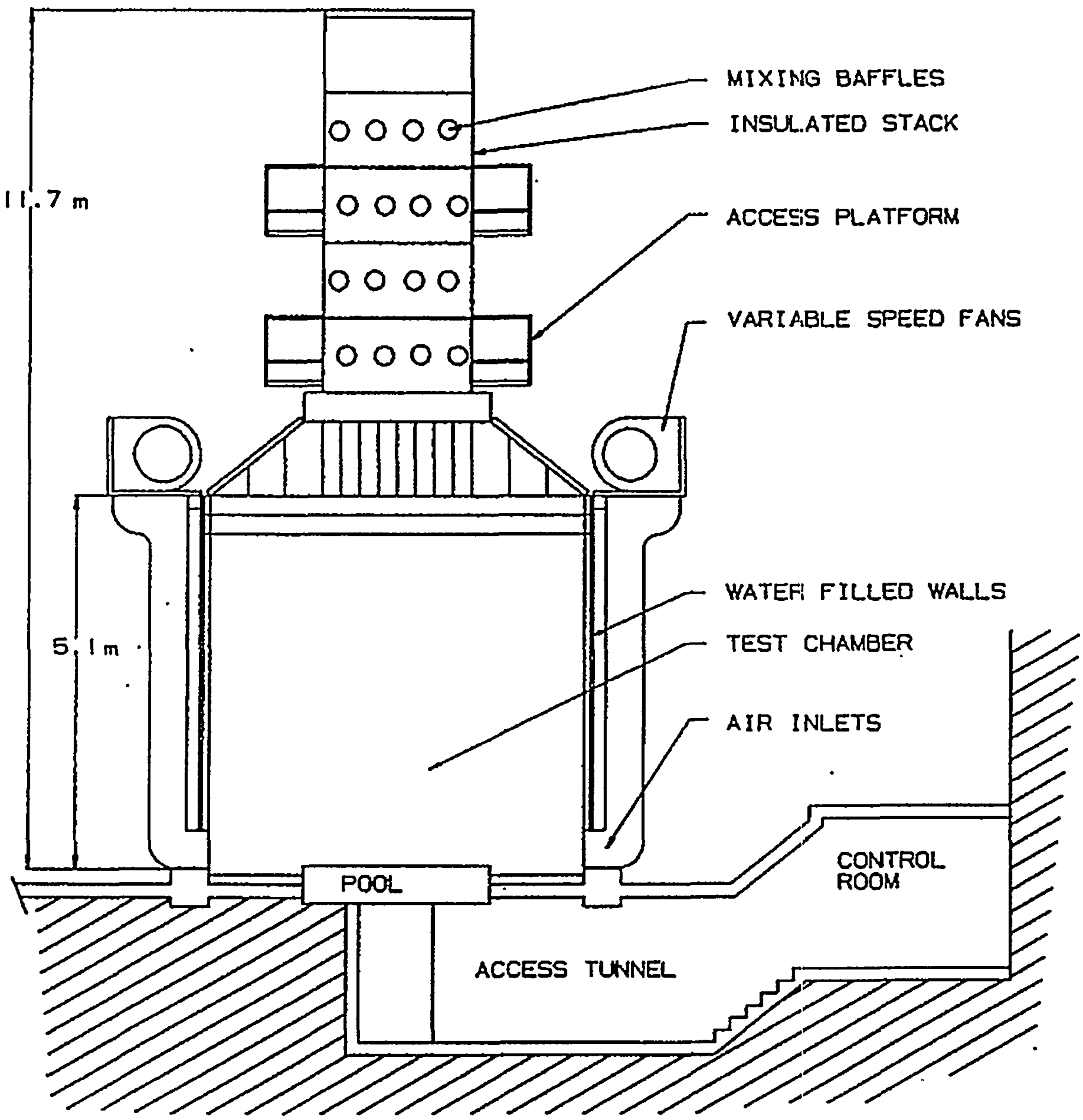

Figure 5. Arrangement of Smoke Emissions Reduction Facility (SMERF)

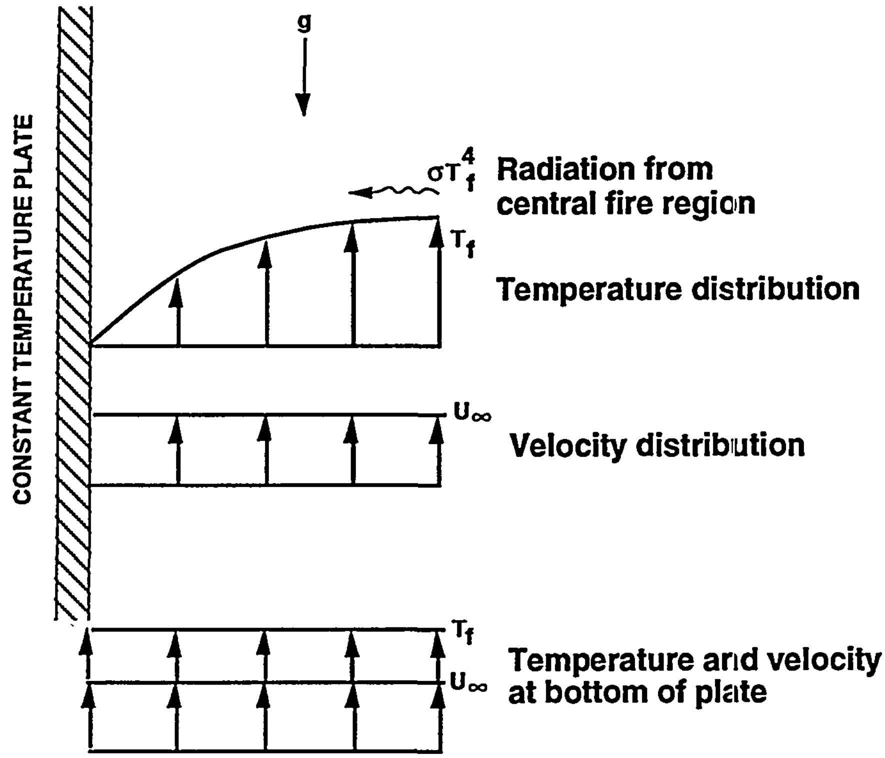

Figure 6. Gray gas radiative model.

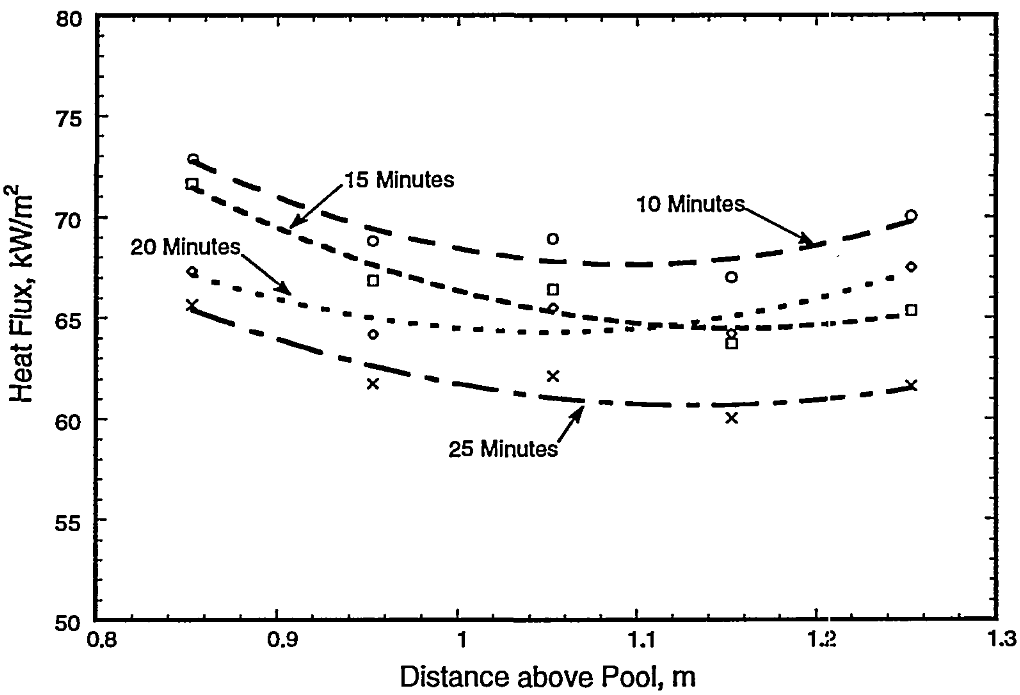

Figure 7. Heat flux data from cooled plate calorimeter in an outdoor fire.