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An American National Standard

Standard Practice for Thermal Qualification of Type B Packages for Radioactive Material[1]

This standard is issued under the fixed designation E2230; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice defines detailed methods for thermal qualification of "Type B" radioactive materials packages under Title 10, Code of Federal Regulations, Part 71 (10CFR71) in the United States or, under International Atomic Energy Agency Regulation TS-R-1. Under these regulations, packages transporting what are designated to be Type B quantities of radioactive material shall be demonstrated to be capable of withstanding a sequence of hypothetical accidents without significant release of contents.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.3 *This standard is used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products, or assemblies under actual fire conditions.*

1.4 *Fire testing is inherently hazardous. Adequate safeguards for personnel and property shall be employed in conducting these tests.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E176 Terminology of Fire Standards

IEEE/ASTM SI-10 International System of Units (SI) The Modernized Metric System

2.2 *Federal Standard:*

Title 10, Code of Federal Regulations, Part 71 (10CFR71), *Packaging and Transportation of Radioactive Material*, United States Government Printing Office, October 1, 2004

2.3 *Nuclear Regulatory Commission Standards:*

Standard Format and Content of Part 71 Applications for Approval of Packaging of Type B Large Quantity and Fissile Radioactive Material, Regulatory Guide 7.9, United States Nuclear Regulatory Commission, United States Government Printing Office, 1986

Standard Review Plan for Transportation of Radioactive Materials, NUREG-1609, United States Nuclear Regulatory Commission, United States Government Printing Office, May 1999

2.4 *International Atomic Energy Agency Standards:*

Regulations for the Safe Transport of Radioactive Material, No. TS-R-1, (IAEA ST-1 Revised) International Atomic Energy Agency, Vienna, Austria, 1996

Regulations for the Safe Transport of Radioactive Material, No. ST-2, (IAEA ST-2) International Atomic Energy Agency, Vienna, Austria, 1996

2.5 *American Society of Mechanical Engineers Standard:*

Quality Assurance Program Requirements for Nuclear Facilities, NQA-1, American Society of Mechanical Engineers, New York, 2001

2.6 *International Organization for Standards (ISO) Standard:*

ISO 9000:2000, Quality Management Systems—Fundamentals and Vocabulary, International Organization for Standards (ISO), Geneva, Switzerland, 2000

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method refer to the terminology contained in Terminology E176 and ISO 13943. In case of conflict, the definitions given in Terminology E176 shall prevail.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *hypothetical accident conditions, n*—a series of accident environments, defined by regulation, that a Type B package must survive without significant loss of contents.

3.2.2 *insolation, n*—solar energy incident on the surface of a package.

[1] This practice is under the jurisdiction of ASTM Committee C26 on Nuclear Fuel Cycle and is the direct responsibility of Subcommittee C26.13 on Spent Fuel and High Level Waste.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.3 *normal conditions of transport, n*—a range of conditions, defined by regulation, that a package must withstand during normal usage.

3.2.4 *regulatory hydrocarbon fire, n*—a fire environment, one of the hypothetical accident conditions, defined by regulation, that a package shall survive for 30 min without significant release of contents.

3.2.5 *thermal qualification, n*—the portion of the certification process for a radioactive materials transportation package that includes the submittal, review, and approval of a Safety Analysis Report for Packages (SARP) through an appropriate regulatory authority, and which demonstrates that the package meets the thermal requirements stated in the regulations.

3.2.6 *Type B package, n*—a transportation package that is licensed to carry what the regulations define to be a Type B quantity of a specific radioactive material or materials.

4. Summary of Practice

4.1 This document outlines four methods for meeting the thermal qualification requirements: qualification by analysis, pool fire testing, furnace testing, and radiant heat testing. The choice of the certification method for a particular package is based on discussions between the package suppliers and the appropriate regulatory authorities prior to the start of the qualification process. Factors that influence the choice of method are package size, construction and cost, as well as hazards associated with certification process. Environmental factors such as air and water pollution are increasingly a factor in choice of qualification method. Specific benefits and limitations for each method are discussed in the sections covering the particular methods.

4.2 The complete hypothetical accident condition sequence consists of a drop test, a puncture test, and a 30-min hydrocarbon fire test, commonly called a pool fire test, on the package. Submersion tests on undamaged packages are also required, and smaller packages are also required to survive crush tests that simulate handling accidents. Details of the tests and test sequences are given in the regulations cited. This document focuses on thermal qualification, which is similar in both the U.S. and IAEA regulations. A summary of important differences is included as Appendix X3 to this document. The overall thermal test requirements are described generally in Part 71.73 of 10CFR71 and in Section VII of TS-R-1. Additional guidance on thermal tests is also included in IAEA ST-2.

4.3 The regulatory thermal test is intended to simulate a 30-min exposure to a fully engulfing pool fire that occurs if a transportation accident involves the spill of large quantities of hydrocarbon fuels from a tank truck or similar vehicle. The regulations are "mode independent" meaning that they are intended to cover packages for a wide range of transportation modes such as truck and rail.

5. Significance and Use

5.1 The major objective of this practice is to provide a common reference document for both applicants and certification authorities on the accepted practices for accomplishing package thermal qualification. Details and methods for accomplishing qualification are described in this document in more specific detail than available in the regulations. Methods that have been shown by experience to lead to successful qualification are emphasized. Possible problems and pitfalls that lead to unsatisfactory results are also described.

5.2 The work described in this standard practice shall be done under a quality assurance program that is accepted by the regulatory authority that certifies the package for use. For packages certified in the United States, 10 CFR 71 Subpart H shall be used as the basis for the quality assurance (QA) program, while for international certification, ISO 9000 usually defines the appropriate program. The quality assurance program shall be in place and functioning prior to the initiation of any physical or analytical testing activities and prior to submittal of any information to the certifying authority.

5.3 The unit system (SI metric or English) used for thermal qualification shall be agreed upon prior to submission of information to the certification authority. If SI units are to be standard, then use IEEE/ASTM SI-10. Additional units given in parentheses are for information purposes only.

TEST METHODS

6. General Information

6.1 In preparing a Safety Analysis Report for Packaging (SARP), the normal transport and accident thermal conditions specified in 10CFR71 or IAEA TS-R-1 shall be addressed. For approval in the United States, reports addressing the thermal issues shall be included in a SARP prepared according to the format described in Nuclear Regulatory Commission (NRC) Regulatory Guide 7.9. Upon review, a package is considered qualified if material temperatures are within 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 vary with regulation, but are intended to give 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. Depending on the regulation used, the ambient air temperature is in the -29°C (-20°F) to 38°C (100°F) range. Normal transport requirements include a maximum air temperature of 38°C (100°F), insolation, and a cold temperature of -40°C (-40°F). Regulations also include a maximum package surface temperatures for personnel protection of 50°C (122°F). See Appendix X3 for clarification of differences between U.S. and international regulations.

6.2 Hypothetical accident thermal requirements stated in Part 71.73 or IAEA TS-R-1, Section VII call for a 30 min exposure of the entire container to a radiation environment of 800°C (1475°F) with a flame emissivity of 0.9. The surface emissivity of the package shall 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 package surface. 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. Testing shall be conducted with this point in mind.

6.3 Two definitions of flame emissivity exist, and this causes confusion during the qualification process. Siegel and Howell, 2001, provide the textbook definition for a cloud of hot soot particles representing a typical flame zone in open pool fires. In this definition the black body emissive power of the flame, σT^4, is multiplied by the flame emissivity, ε, in order to account for the fact that soot clouds in flames behave as if they were weak black body emitters. A second definition of flame emissivity, often used for package analysis, assumes that the flame emissivity, ε, is the surface emissivity of a large, high-temperature, gray-body surface that both emits and reflects energy and completely surrounds the package under analysis. The second definition leads to slightly higher (conservative) heat fluxes to the package surface, and also leads to a zero heat flux as the package surface reaches the fire temperature. For the first definition, the heat flux falls to zero while the package surface is somewhat below the fire temperature. For package qualification, use of the second definition is often more convenient, especially with computer codes that model surface-to-surface thermal radiation, and is usually permitted by regulatory authorities.

6.4 Convective heat transfer from moving air at 800°C shall also be included in the analysis of the hypothetical accident condition. Convection correlations shall be chosen to conform to the configuration (vertical or horizontal, flat or curved surface) that is used for package transport. Typical flow velocities for combustion gases measured in large fires range are in the 1 to 10 m/s range with mean velocities near the middle of that range (see Schneider and Kent, 1989, Gregory, et al, 1987, and Koski, et al, 1996). No external non-natural cooling of the package after heat input is permitted after the fire event,, and combustion shall proceed until it stops naturally. During the fire, effects of solar radiation are often neglected for analysis and test purposes.

6.5 For purposes of analysis, the hypothetical accident thermal conditions are specified by the surface heat flux values. Peak regulatory heat fluxes for low surface temperatures typically range from 55 to 65 kW/m^2. Convective heat transfer from air is estimated from convective heat transfer correlations, and contributes of 15 to 20 % of the total heat flux. The value of 15 to 20 % value is consistent with experimental estimates. Recent versions of the regulations specify moving, hot air for convection calculations, and an appropriate forced convection correlation shall be used in place of the older practice that assumed still air convection. A further discussion of heat flux values is provided in 7.2.

6.6 While 10CFR71 or TS-R-1 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. Local heat fluxes as high as 150 kW/m^2 under low wind conditions are routinely observed for low package surface temperatures. For high winds, heat fluxes as high as 400 kW/m^2 are observed locally. Local flux values are a function of several parameters, including height above the pool. Thus the size, shape, and construction of the package affects local heat flux conditions. Designers shall keep the possible differences between the hypothetical accident and actual test conditions in mind during the design and testing process. These differences explain some unpleasant surprises such as localized high seal or cargo temperatures that have occurred during the testing process.

6.7 For proper testing, good simulations of both the regulatory hydrocarbon fire heat flux transient and resulting material temperatures shall 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 are reported to be erroneously high or low. Some test methods are better suited to meeting these required transient conditions for a particular package than others. The relative benefits and limitations of the various methods in simulating the pool fire environment are discussed in the following sections.

7. Procedure

7.1 *Qualification by Analysis*

7.1.1 *Benefits, Limitations:*

7.1.1.1 The objective of thermal qualification of radioactive material transportation packages by analysis is to ensure that containment of the contents, shielding of radiation from the contents, and the sub-criticality of the contents is maintained per the regulations. The analysis determines the thermal behavior in response to the thermal conditions specified in the regulations for normal conditions of transport and for hypothetical accident conditions by calculating the maximum temperatures and temperature gradients for the various components of the package being qualified. Refer to Appendix X3 for specific requirements of the regulations.

7.1.1.2 Temperatures that are typically determined by analysis are package surface temperatures and the temperature distribution throughout the package during normal conditions of transport and during thermal accident conditions. In addition, maximum pressure inside the package is determined for both normal and accident conditions.

7.1.1.3 While an analysis cannot fully take place of an actual test, performing the thermal analysis on a radioactive material transportation package allows the applicant to estimate, with relatively high accuracy, the anticipated thermal behavior of the package during both normal and accident conditions without actually exposing a package to the extreme conditions of the thermal qualification tests described in Section 6. Qualification by analysis is also a necessity in those cases where only a design is being qualified and an actual specimen for a radioactive materials package does not exist.

7.1.1.4 While today's thermal codes provide a useful tool to perform the thermal qualification by analysis producing reliable results, the limitation of any method lies in the experience of the user, the completeness of the model and accuracy of the input data. Since in these analyses the heat transfer is the main phenomenon being modeled and since it is mostly nonlinear, the thermal code used shall be verified against available data or benchmarked against other codes that have been verified. In addition, limitations of analyses for determining the thermal behavior of a package include as-built package geometry, real material properties including phase changes and destruction of insulation, and real fire characteristics, including actual convection. Code software used shall be managed in a manner consistent with the appropriate QA methodology outlined in NQA-1 or ISO 9000 as appropriate.

7.1.2 *Model Preparation*—This section describes the various aspects a thermal model shall include and the methodology of preparing a representative model.

7.1.2.1 A common approach to analyzing a package is to model the package as a drum or in a cylindrical configuration. This approach considers the package as an axisymmetric circular cylinder (outer shell) with a constant internal heat source. Another common approach is to model the packages as a finite length right circular cylinder with an impact limiter (which also acts as a thermal insulator to the package). The outer shell will surround a lead shield that contains the content heat source.

7.1.2.2 Thermal protection of a typical radioactive materials package includes the impact limiters placed at the ends of the package and the thermal shield surrounding the cylindrical section of the package. The impact limiters consist of a low-density material, such as polyurethane foam, wood, or other organic material enclosed in a steel shell, hollow steel structures or aluminum honeycomb design structure. The low-density configuration impact limiter usually has a low effective thermal conductivity.

7.1.2.3 The low thermal conductivity impact limiter reduces the heat transfer from the ends of the cask during normal conditions of transport, and into the ends of the cask during hypothetical accident conditions. Analysis often shows that for polyurethane foam impact limiters, the foam burns during a hypothetical accident and off-gases creating pressure within the impact limiter structure. This, along with the thermal expansion of the materials is to be considered in order to provide for the worst case conduction/insulating properties. Credit for the insulating properties of the impact limiters shall be taken only when structural analyses can demonstrate that the limiter remains in place under hypothetical accident conditions.

7.1.2.4 The thermal shield of radioactive waste and spent fuel packages typically is a stainless steel shell surrounding the cylindrical structural shell of the package. A gap is created between the thermal shield and the structural shell of the package. Because of the low conductivity of air contained in the gap, the heat resistance of the gap greatly reduces the heat transfer rate during both normal conditions of transport and hypothetical accident conditions. Heat transfer across the gap between the thermal shield and structural shell is modeled with conduction and radiation. Natural convection in the gap is usually neglected. Drum type packages usually have an integral thermal shield.

7.1.2.5 The package contents and their heat generation shall be considered in the model preparation. The impact limiter and the thermal shield insulation properties will result in slightly elevated temperatures during normal conditions of transport due to the resistance to heat flow from the package. Thus the package interior has higher temperatures than the surrounding ambient temperature.

7.1.2.6 When creating the model and selecting the nodes, it is important to represent all materials of construction and components essential to containment in the model. Fig. 1 shows a typical nodal network/finite difference model with node selection for temperature information on a package with an impact limiter. Additional nodes will need to be created and utilized for an accurate Finite Element Analysis or Finite Difference Analysis model.

7.1.2.7 The mesh selected in the model for temperature profile analysis in the thermal portion of the hypothetical accident analysis shall be varied depending on the temperature gradients. The finest mesh is located near the outer surface of the package where the steepest temperature gradients occur. The mesh size is increased as temperature gradients decrease, which usually occurs as the distance from the surface increases. A test for proper mesh size is to refine the mesh further and demonstrate that no significant change in calculated temperatures results from the refinement.

7.1.2.8 *Thermo-physical Properties of Typical Materials:*

(1) The thermal properties of the materials of construction need to be defined and documented as they are critical to achieving meaningful results from the analysis. Properties of the various components involved are often obtained from reference materials but all sources are to be verified for reliability by determining that the properties were measured in accordance with accepted standards (that is, ASTM) and under an accepted quality assurance program (that is, NQA-1 or ISO 9000).

(2) The material properties used need to cover the temperature range of the conditions being analyzed. If materials have properties that change with temperature, they shall be modeled with the appropriate variable properties. Note that uncertainties in the temperature dependence of material property data increase with the variation of temperature from "room temperature." Additional testing is necessary for any material that does not have well defined material properties.

(3) Parts that are small or thin, or both, and do not have a measurable affect on the overall heat transfer rates are often omitted from the model. Typical examples for this are thin parts that have high thermal conductivity and are not separated by air gaps from other components of the package being analyzed. Thin parts separated by gaps, however, act as thermal radiation shields that greatly affect the overall heat transfer rate and shall be considered.

(4) When a material phase change or decomposition is expected to occur, the analysis shall consider replacing the material properties with conservative values. For example, polyurethane begins to decompose at 200°C (400°F), and the analyst often considers replacing the polyurethane properties with those of air at the same temperature. Note that the thermal properties of polyurethane are similar to those of air and actually the polyurethane properties are not critical since the

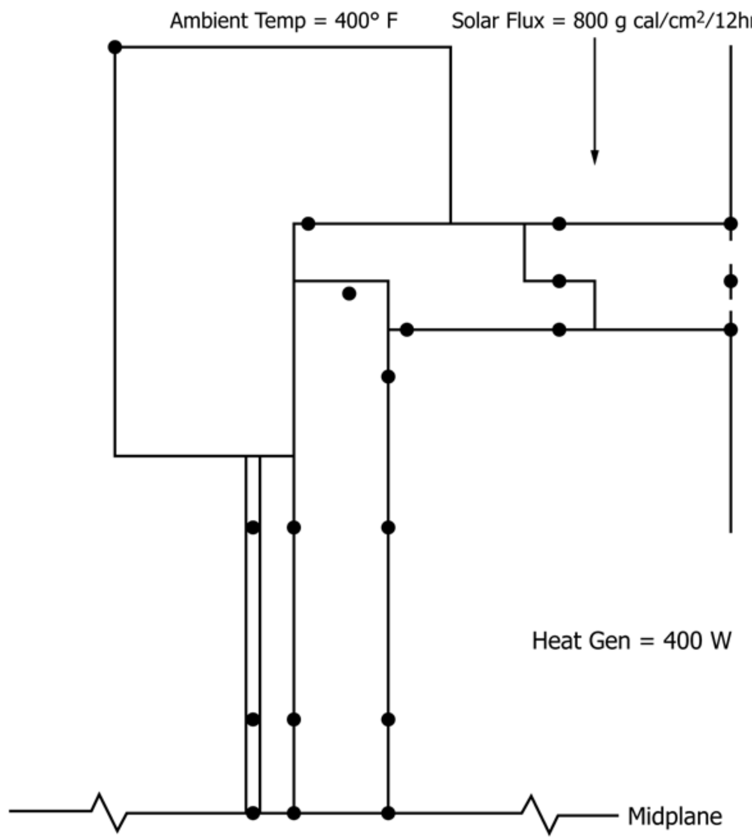


FIG. 1 Example of Node Selection When Modeling a Package

use of polyurethane results in a nearly adiabatic, that is, well insulated, surface during hypothetical accident conditions.

(5) Radiation heat transfer occurs at the outer surfaces of a package and also in the gap between the thermal shield and the structural shell. Therefore, the consideration of the surface emittance of these surfaces is critical to the model. Emittance values of the package exterior surface for the fire are specified in the regulations.

(6) The analyst shall be familiar with the how the code models radiation and, in specific, surface emissivity or absorptivity (also treated by some codes as reflectivity or albedo). In general, conservative surface emittance values are to be used in the analysis, that is, emittance value of 0.9 or unity (black body) for fire conditions, and an emittance of 0.8 shall be assumed for the outer surfaces in accordance with regulations. Package interior gap surfaces might be assumed machined for pre-fire conditions. Use of other than conservative values shall be justified.

7.1.2.9 *Model Preparation for Normal Conditions of Transport Thermal Evaluation:*

(1) A steady-state analysis for normal conditions of transport that follows 10CFR71.71 shall assume constant insolation of 387.67 W/m^2 on horizontal flat surfaces exposed to the sun (which is equivalent to the total insolation specified in 10CFR71.71(c)(1) of 800 g-cal/cm^2 for a 12-h period), 96.92 W/m^2(200 g-cal/cm^2 for a 12-h period) for non-horizontal flat surfaces, and 193.83 W/m^2 (400 g-cal/cm^2 for a 12-h period) for curved surfaces. Ambient temperature shall be 38°C (100°F). Note that insolation depends on the shape and orientation of the package surface. A transient analysis of the normal conditions of transport can be performed instead of a steady-state analysis. Thermal loads for a transient analysis are different from those discussed in this paragraph.

(2) In addition, representative internal heat generation shall be considered when preparing the model to determine the temperature distribution of the package.

(3) The model shall address external natural convection and radiation boundary conditions and temperature property variations.

(4) The temperature distribution of the package is assumed symmetric about the vertical axis and its horizontal mid-plane. The heat transfer model needs to be defined, for example, two-dimensional axisymmetric heat transfer (radial and axial). The model shall address insolation on the package surfaces. Radiation heat exchange at the package interior surfaces shall be addressed.

(5) Heat transfer within the contents of the package is often omitted in the special case where the heat generated in the contents is uniformly applied to the interior surfaces of the package. It is possible to use the package symmetry in the model to facilitate even heat transfer considerations. Spent fuel packages require special consideration as the bulk of the heat generated by the contents is transferred radially to the packaging due to the large aspect ratio and the impact limiters on the ends of the package.

(6) The inside containment vessel temperature causes the internal pressure to be elevated above atmospheric pressure. The internal pressure at steady state are estimated by assuming

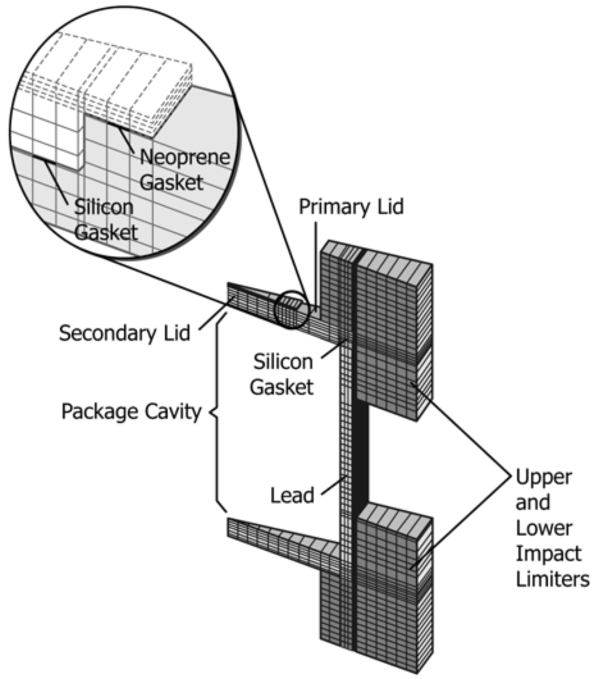


FIG. 2 Typical Package With Impact Limiters at Steady State (Using TAS)

the atmosphere contains dry air at an appropriate pressure and temperature when the package is closed. If the package contains water, assume that at steady-state transport conditions the air is saturated with water vapor. The internal pressure is equal to the sum of the dry air and the vapor pressure of water at the temperature of the environment within the containment vessel for normal conditions of transport. The stresses due to pressurization of the package need to be addressed as part of the structural analysis.

7.1.2.10 *Model Preparation for Hypothetical Accident Thermal Qualification:*

(1) The effects of the hypothetical accident thermal conditions on the package need to be evaluated. The hypothetical accident thermal conditions are defined in the regulations. The various test conditions shall be applied sequentially, which means that the thermal test follows the drop and the puncture tests. The reduction of the insulating capabilities of the impact limiter caused by the free drop and puncture test shall be considered in the analysis of packages. In cases where drop and puncture damage to the impact limiters cannot be modeled in sufficient detail, two cases are analyzed to envelope the performance of the impact limiters during a fire.

(2) The initial temperature distribution in the package prior to the fire shall be that determined for either the normal conditions of transport (38°C with insolation) [TS-R-1, §728] or that determined for the case of defining the type of shipment (exclusive or nonexclusive) from 10 CFR 71.43 (g) [10 CFR 71.73 (b)]. Usually, undamaged packages lead to higher pre-fire temperatures because package insulation is undamaged. However in cases where damaged conditions lead to higher pre-fire temperatures, those temperatures shall be used instead.

(3) The thermal conditions imposed on the package during hypothetical accident conditions are that the package, with the initial temperature distribution as determined above, is subjected to a fire of 800°C (1475°F) for a period of 30 min. After the 30-min period, the source fire is assumed extinguished and the ambient temperature reduced to 38°C (100°F). Any ongoing combustion that continues after the fire shall be accounted for in the analysis. Flames of the ongoing combustion are not allowed to be extinguished. In addition to the natural convection to the ambient air and radiation to the environment, the package shall be subject to insolation during the post-fire cool-down.

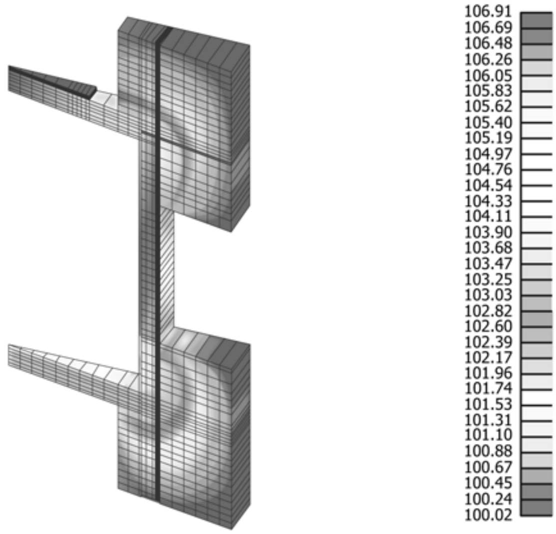
(4) To determine the effect of the reduced insulating capabilities of the impact limiter, two cases are analyzed. The first one assumes that the free drop and puncture tests had minor effects in thermal performance of the package during a hypothetical accident. The second case assumes that the insulating capabilities of the impact limiter have been completely lost. This assumption provides a conservative approach. These two cases envelop the best and worst case scenarios during the hypothetical accident thermal evaluation.

(5) Underlying assumptions shall be documented and include:

Enclosure radiation
External radiation
Natural convection
Insolation
Internal heat dissipation
Internal convection

7.1.3 *Example of Package Model:*

7.1.3.1 For demonstration purposes, consider that the typical package (see *Safety Analysis Report for the 10-135 Radwaste Shipping Cask, 1999*) is a steel encased lead shielded cask intended for solid radioactive material (see Fig. 2). Overall dimensions are 2.85 m (112 in.) diameter by 3.3 m (130 in.) height. It consists of two (2) concentric carbon steel



NOTE 1—Temperatures are in °F. Note that in the original figure, colors were used to represent temperature variations.

FIG. 3 Initial Temperatures for Transient Analysis for a Typical Package With Impact Limiters (Using TAS)

cylindrical shells surrounding a 89 mm (3.5 in.) thick lead shield. The 13 mm (0.5 in.) thick inner shell has a 1.67 m (66 in.) internal diameter and the 25 mm (1 in.) thick outer shell has a 1.93 m (76 in.) outside diameter. The base is welded to the shells. The top of the package is provided with primary and secondary lids of a stepped down design constructed of two 75 mm (3 in.) thick plates joined together to form a 150 mm (6 in.) thick lid. The lids are secured with bolts. Lid interfaces are provided with high temperature silicone gaskets.

7.1.3.2 The initial temperatures are determined from the normal conditions of transport assuming a 38°C (100°F) ambient temperature with insolation. Fig. 3 shows typical steady-state temperatures under these conditions and an assumed 400W heat generation from the contents of a typical package. For packages with large thermal mass, or fully enclosed by a thick insulating medium, such as polyurethane foam, a 24-h average insolation value is often used to determine temperatures of interior components.

7.1.3.3 Two impact limiters are located at the top and bottom of the package. The impact limiters are 10-gage stainless steel shells filled with rigid polyurethane. The inner surfaces of the body and the lid are clad with 12-gage stainless steel. The exposed portion of the cask body is provided with a 10-gage stainless steel thermal shield. A 6.4 mm (0.25 in.) gap between the cask body and the thermal shield is maintained by spacers. A potential issue during thermal qualification is the manufacturer's ability to maintain uniform gap width and potential effect of gap variation on the thermal results. The effect of gap widths in the as-manufactured package shall be considered and discussed by the analyst.

7.1.3.4 Fig. 4 shows the predicted temperatures of a typical package after 30 min following the initiation of the flame environment for the cask with the impact limiter attached. The model was created using TAS of Harvard Thermal.

7.1.3.5 After 30 min, the ambient temperature is reduced from 800°C (1475°F) to 38°C (100°F) and, consequently, the package begins to lose heat to the environment by natural convection to the still air and radiation to the environment. However, the temperature in some regions of the package continues to increase for some time due to heat conduction from surrounding regions of higher temperatures. These local temperatures will continue to increase until the content temperature exceeds the temperature of the surrounding package components. The rate at which the package cools will be reduced as insolation is applied during the cool-down time. If, as permitted in the U. S. (10 CFR 71.73(b)), pre-fire conditions are determined without the insolation specified in 10 CFR 71.71, then initial package surface and contents temperatures will often be lower than the steady state temperatures reached with insolation after the fire. If package temperatures without insolation are lower at the start of the fire, initial fire heat fluxes to the package surface will be higher, compensating, at least partially, for the lack of pre-fire insolation. For packages to be qualified under both U. S. and international regulations, this effect shall be addressed and quantified for the regulator.

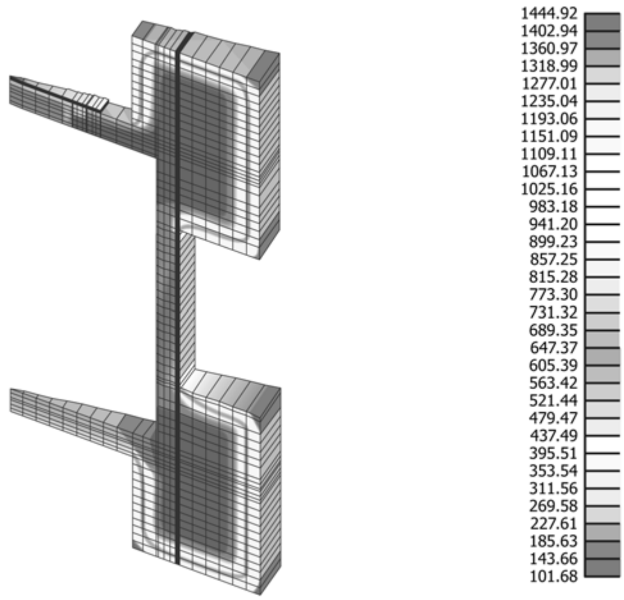
7.1.4 *Additional Information to be Reported:*

7.1.4.1 The results of the analysis shall be tabulated to summarize the maximum temperatures resulting from the hypothetical accident condition for each material of construction. In addition, graph(s) shall be included showing temperature as a function of time for representative and critical/unique locations on the container during a hypothetical accident. The interval selected shall be long enough to show all component temperatures descending with time. An example is shown below in Fig. 5.

7.1.4.2 Changes in the internal pressure shall be addressed. The internal pressure typically increases during the hypothetical accident due to heating of contents. Chemical decomposition of the packaging materials and package contents shall be considered and appropriately addressed.

7.1.4.3 Consideration of thermal stresses due to both normal conditions of transport and hypothetical accident conditions shall also be included in the analysis.

7.1.4.4 Post-fire steady state temperatures shall be analyzed. Any resultant damage (for example, smoldering or melting of a neutron or gamma shield, or both) or change in the emissivity



NOTE 1—Temperatures are in °F. Note that in the original figure, colors were used to represent temperature variations.

FIG. 4 Temperatures After the 30-Min. Fire on a Typical Package With Impact Limiters Attached (Using TAS)

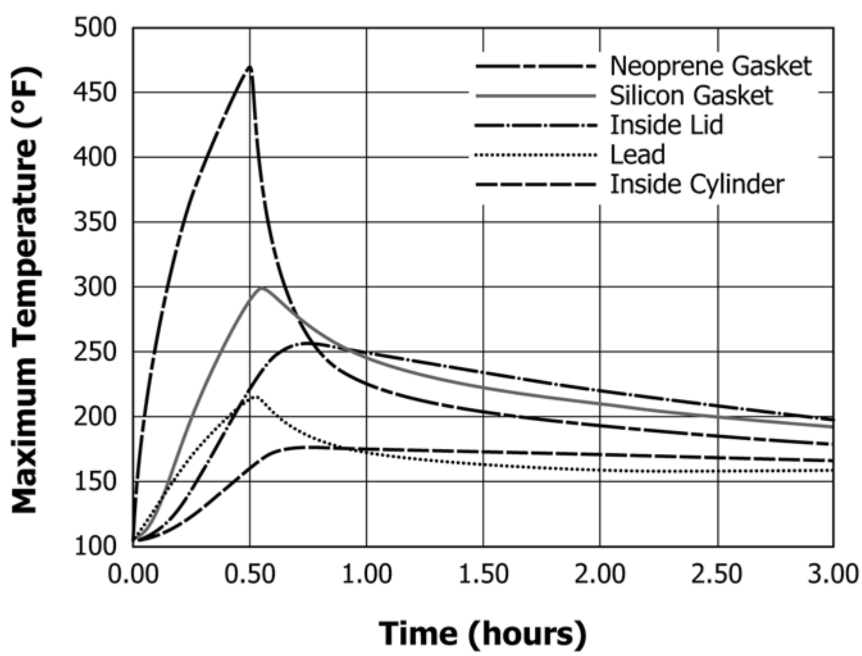


FIG. 5 Example for Temperature as a Function of Time for Selected Locations on a Sample Container During a Hypothetical Thermal Accident

of the surface of the package shall be evaluated with respect to the impact on the post-accident "normal" temperatures.

7.1.5 *Analysis Conduct:*

7.1.5.1 General-purpose heat transfer codes exist for performing the thermal analysis of packages for the transport of radioactive materials. These codes model heat transfer phenomena (conduction, convection and radiation) for multidimensional geometries with linear and non-linear steady-state or transient behavior. They model various materials with temperature dependent isotropic and orthotropic thermal and other physical properties, including phase change.

7.1.5.2 These general-purpose codes treat constant or time-dependent spatially-distributed heat-generation sources, enclosure radiation and boundary conditions including temperature and heat flux.

7.1.5.3 Most commercial FEA codes have thermal solvers and provide pre- and post-processors. The pre-processor is used to create package geometry and generate a mesh for the package, while the post-processor provides results in a graphical format. Pre- and post-processors are often in the form of a graphical user interface (GUI) which allows the user to enter data and retrieve results through a number of menu driven choices. Some older codes require entry of data in the form of an input file, without the benefit of a GUI, and rely on a third-party graphics program to plot results of an analysis. Some heat transfer codes require the use of a separate code to determine radiation form factors, which are then used by the thermal code to treat enclosure radiation. The results of the thermal analysis are often used by the structural analyst to perform thermal or pressure-induced stress analyses.

7.1.5.4 Thermal codes shall be qualified for package evaluation by verification, benchmarking, or validation. A code is verified by comparison of the results with the results of appropriate closed form solutions.

7.1.5.5 *Sample Problem Manual for Benchmarking of Cask Analysis Codes* (Glass, et al, 1988) describes a series of problems, which have been defined to evaluate structural and thermal codes. These problems were developed to simulate the hypothetical accident conditions given in the regulations while retaining simple geometries. The intent of the manual is to provide code users with a set of structural and thermal problems and solutions which are used to evaluate individual codes.

7.1.5.6 A code is benchmarked by comparison of the results with the results of other qualified codes. An alternative code validation method is to compare the code results to results from package design-based test data or hand calculations performed under qualified QA programs.

7.1.5.7 Any code selected to perform the thermal design analysis of a radioactive material transportation package shall be subject to the QA program requirements for nuclear facilities as prescribed in ASME NQA-1 or software requirements of ISO 9000 as required by the certifying authority.

7.1.5.8 Several thermal analysis codes are available to licensees of radioactive packages to perform the qualification analyses. This document is not intended to describe the various thermal codes in detail, but a few are mentioned and briefly described in Appendix X4 for the reader's benefit. Codes not mentioned in Appendix X4 are often equally adequate to perform thermal qualification of packages to regulatory requirements. No comparison or evaluation of codes is provided in this document.

7.2 *Pool Fire Testing*

7.2.1 *Benefits, Limitations:*

7.2.1.1 Pool fire testing has been the traditional testing method by which a package is qualified to the thermal accident environment set forth in the regulations. In the test, the prototype package is placed 1 m over a pool of fuel whose lateral dimensions relative to the package meet the requirements stated in the regulation. When atmospheric conditions are quiescent, the fuel is ignited and the package is engulfed in the fire plume. After 30 min, the fuel is consumed, the fire goes out, and the prototype package is left to cool down naturally.

7.2.1.2 A convenient method for forming a pool consists of floating a layer of jet fuel (JP-8) on water in a deep steel tub (see Fig. 6). The water provides a flat surface for the fuel, which ensures the fire burns out evenly over the whole pool area when the fuel is completely consumed. A deep tub (~0.7 m) provides enough water to maintain a constant fuel substrate temperature which helps to maintain a constant fuel consumption rate during the fire. The packages are held at the required height above the pool surface with a stainless steel grill. Structures are placed throughout the pool to support fire instrumentation that might include thermocouples, calorimeters, heat flux gages, and gas velocity probes. The response of this instrumentation is used to provide evidence that the required thermal environment has been met. Sheet metal side ramps on the outside of the tub, and sheet metal skirts on the grill provide fire plume stability. These are necessary because the fuel vapor immediately above the fuel surface is heavier than air, and subject to displacement by very low velocity air currents. The effect of wind is minimized by enclosing the pool within a ring of 6 m high wind fencing.

7.2.1.3 The intention of a pool fire test is to subject the prototype package to an environment that is representative of conditions found in a transportation accident fire. Note that two different environments are under consideration here. There is a hypothetical accident condition or regulatory hydrocarbon fire environment, described in the regulations, and an actual pool fire environment, which is created at 1 m above a pool of burning liquid hydrocarbon fuel in calm wind conditions. Packages that are designed to withstand the regulatory hydrocarbon fire are considered to function safely in a transportation accident. The actual pool fire environment is a convenient means for testing packages and is usually very different from the hypothetical accident conditions as discussed below.

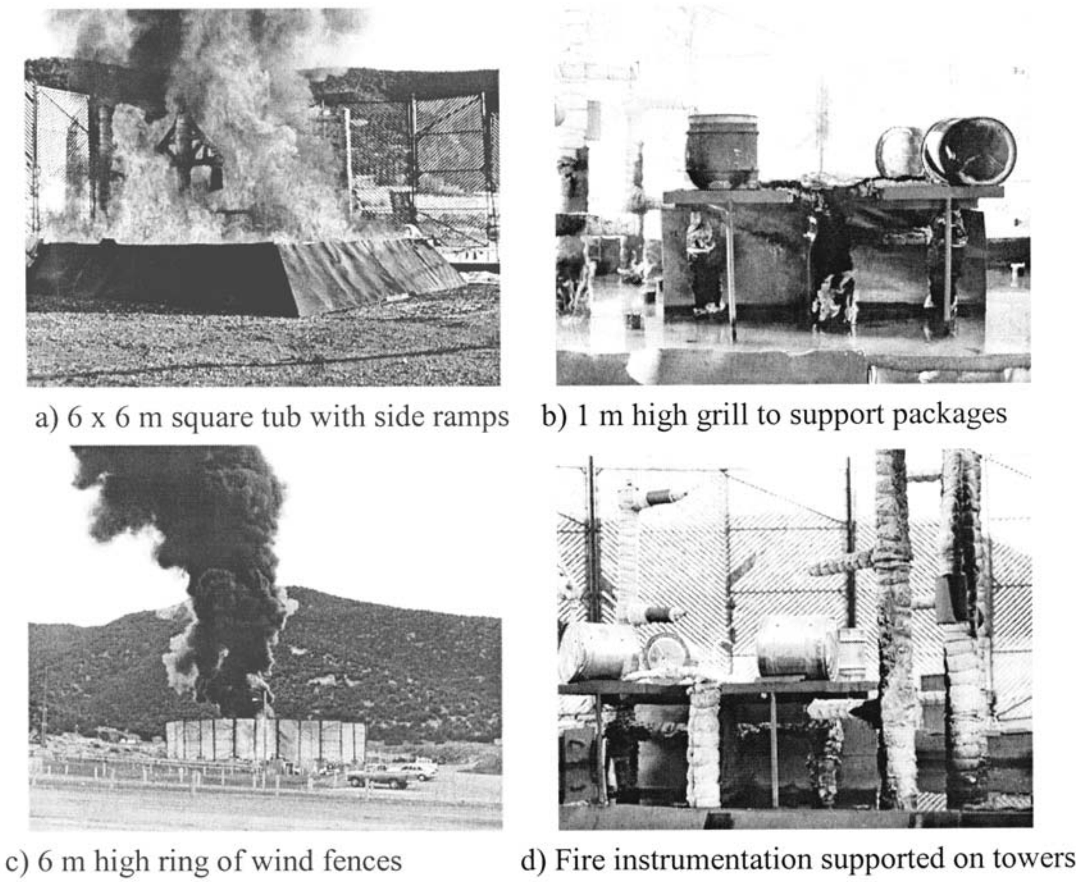
7.2.1.4 The hypothetical accident condition environment specified in the regulations is usually reduced to a schedule of heat flux absorbed through the package surface as a function of the package surface temperature. A heat balance at any instant in time on the surface of a package subjected to the regulatory hydrocarbon fire gives:

$$q_{absorbed} = 0.9 \cdot 0.8 \cdot \sigma \cdot T^4_{environment} - 0.8 \cdot \sigma \cdot T^4_{surface} \quad (1)$$

where:

$q_{absorbed}$	=	heat flux passing through the surface of the package, kW/m^2,
σ	=	Stefan-Boltzmann constant, 5.67 × 10^{-11} kW/(m^2 K^4),
$T_{environment}$	=	temperature specified in 10CFR71, 800 + 273 = 1073 K,
$T_{surface}$	=	surface temperature of the package at any instant, K,
0.9	=	specified emissivity of flames, and
0.8	=	absorptivity of package surface (minimum value).

7.2.1.5 This description of the hypothetical accident condition environment is shown in Fig. 7. Note that in the equation above, the "text book" definition of flame emissivity (see 6.3) has been used to generate the plot. The regulatory heat fluxes are compared to a description of the actual pool fire environment that has been determined from the response of thick wall passive calorimeters from which data have been gathered over the last 20 years in pool fires of sizes ranging from 1 to 20 m in diameter. The wide range is due to minor variations in wind conditions and calorimeter surface orientation with respect to the pool geometry.



NOTE 1—Some features are to meet geometrical requirements, some stabilize the plume, and others provide evidence of supplying the required environment.

FIG. 6 A Pool Fire Test and Setup That Meets the Regulatory Requirements

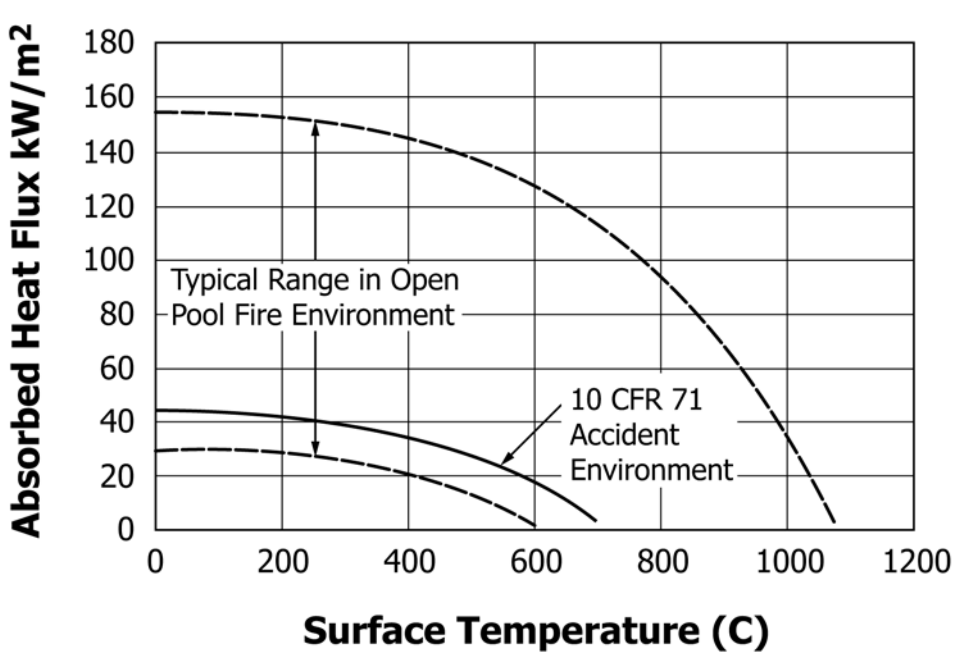


FIG. 7 Comparison of the Hypothetical Accident Fire Environment and the Actual Pool Fire Environment

TABLE 1 Four Possible Outcomes of a Pool Fire Test

Package Response to Fire	Fire Environment with Respect to 10CFR 71	
	Low Heat Flux	High Heat Flux
Pass	Inconclusive	Conclusive
Fail	Conclusive	Inconclusive

7.2.1.6 Note that in general, the pool fire provides an environment that is more intense than that of the regulatory accident environment. Because of this, there are both benefits and limitations to using pool fires for package qualification.

7.2.1.7 The main benefit of use of a pool fire is that it is a convenient means of providing an acceptable testing environment with a relatively minimal investment in equipment. The basic set up requires some source of fuel such as a rented tanker truck, a large open flat area, and some disposable metal support structures. In terms of flexibility and cost, there are obvious benefits over those associated with an oven or radiant heat facility.

7.2.1.8 A second benefit is that the pool fire environment often surpasses the requirements, providing a conservative test. Fig. 7 shows that the flux from a pool fire to an engulfed object often exceeds the criteria by a factor approaching four. Furthermore, the fact that the environment is a real fire shall not be overlooked. The so-called second order characteristics, such as fire plume chemistry or non-uniform spatial and temporal heat fluxes, affect package performance in unforeseen ways; and subjecting a prototype package to a pool fire brings out deficiencies due to features that weren't considered in the design. Examples of this that have occurred in the past with packages in pool fires include unexpected seal response due to uneven heating, and unexpected material response (outgassing, phase change, and decomposition) due to temperatures well above the 800°C (1475°F) design criteria.

7.2.1.9 The main limitation is that the test represents a high programmatic risk because the test is destructive and only marginally under control. Once the test is initiated, there is no stopping and no readjustments are possible. One waits until the fire is over and then reconciles the available physical evidence to show that the fire environment met or surpassed the minimum requirements as set forth in the regulations. There are four possible outcomes of this post-test harmonizing activity as shown in Table 1.

7.2.1.10 The inconclusive results from the High-Fail combination in Table 1 are due to the pool fire environment being overly conservative. The inconclusive results for the Low-Pass combination are due the possibility of the fire environment not meeting the criteria. In either case, the test has to be re-done, which requires repeating the entire package testing sequence leading up to the fire as well.

7.2.2 *Test Preparation:*

7.2.2.1 Except for the basic 1 m height, every pool fire test setup is different. However, the basic simplicity of the hardware allows a great deal of flexibility. A pool, some support structure, and a supply of fuel are the basic items needed. The basic features of a pool fire test setup along with some additional comments are listed in Table 2.

7.2.2.2 Features that aid in ensuring conformance to the regulations are shown in Tables 3 and 4. Of particular note in the table is the use of wind fences to mitigate the effect of wind. Several testing organizations have successfully used this approach, however, no written documentation has been found on the design. The effect of placing a 30 m diameter ring of wind fences around a pool setup is shown in Fig. 8. The wind fences were constructed of 6 m high chain link fencing fitted with aluminum slats that provided 50 % blockage.

7.2.2.3 A fire is neutrally stable with the pool flush to the ground. The fuel vapor just above the burning fuel surface is heavier than air and has little upward momentum, and thus, is subject to lateral dislocation from minor air currents. Putting the pool surface above ground level mitigates this situation. Also, the placement of lateral dams or "flame guides" on the support stand just under the package helps to contain the vapor above the pool.

7.2.3 *Test Performance:*

7.2.3.1 The major consideration in performing the test is the effect of wind on the results. Wind, even at low speed exercises a major change in the fire environment in the lower regions of a pool fire where the test article is located. The concept of a leaning fire plume as a result of wind does not apply at 1 m above the pool surface. Instead, the fuel vapor directly above the fuel surface is pushed in the down wind direction causing the fire plume to relocate out from under the package. This phenomena occurs at very low wind speeds, therefore it is absolutely essential that the wind behavior at the test site be predictable and well understood.

7.2.3.2 An example of predictable wind behavior is shown in Fig. 9. This data (wind speed and direction) was taken at a test site located in the floor of a mountain canyon over a 5 day period. In that location, cold air drains down canyon during the night hours and heated air rises up canyon during daylight hours. The change in local direction occurs twice daily (once after sunup and once after sundown) accompanied by a lull in wind speed. Wide area weather patterns disrupt this behavior which is the cause of deviations in the Fig. 9. Note that the best time for finding low wind conditions at this site is during the early morning hours.

7.2.3.3 Once the time window is selected the concern becomes choosing the appropriate time. The wind speed and direction on a particular single day is shown in Fig. 10. The challenge is to set up the test between first light and the time the wind changes direction and perform the burn before the speed begins to rise. Accomplishing this requires a well thought out procedure and practice. For this reason, a full dress rehearsal (including lighting the fire) is highly recommended.

7.2.3.4 An example of a completed procedure where two shipping containers were subjected to a pool fire test under 10CFR71 regulations is provided in Appendix X2. The activities began several days before the actual fire, because the test units were pre-conditioned to a desired initial temperature. This was accomplished by heating the test units in place over the pool with barrel heaters.

7.2.3.5 Through reading the procedure provided as an example in Appendix X1, note that test materials were gathered, equipment checked out, and the pre-conditioning begun. On

TABLE 2 Common Features of Any Pool Fire Test Setup

Pool	Diameter limits set by 10CFR71 Depth—150 mm for fuel; 150 mm for water minimum—more is better Free Board—2 in.
Package Support Structure	Inconel material recommended—design for 10 000 psi strength Thermal expansion major consideration; use loose fitting slip joints; let gravity hold things together
Fuel Supply	On site tanks are major environmental and safety liabilities; consider truck tankers

TABLE 3 Features for Demonstrating Conformance to Regulations

Thermocouple Instrumentation	Recommend use of metal sheathed mineral filled type K thermocouples Use sufficient length to run all the way to data acquisition system; patches in mid-fire are problematical Thermal shunting is problem; avoid cold-hot-cold in routing Worst hot zone is at pool edge; use tea pot spigot for exiting pool Second worst hot zone is at exit of instrumentation access hole in packages filled with combustible shock mitigation material
Heat Flux	Recommend thick wall passive calorimeters for heat flux estimation
Wind	Propeller anemometer at 10 m height located away from the fire
Visual	Remote video cameras with at least 2 views with sound

TABLE 4 Additional Features for Ensuring Conformance to Regulations

Time	Consider adding fuel to pool during burn; sight glass and controllable fuel valve required
Calm Wind Conditions	Consider the use of wind fences; demonstrated reduction in wind by factor of 2
Package Engulfed in Flames	Fire is neutrally stable with pool flush to ground, put above the ground level Incorporate “Flame Guides” on support stand legs

the day before the test, a general announcement of the intention to test was made to interested parties. On the day of the test, the test personnel were brought in at first light and wind conditions began to be monitored. When it was apparent that the wind was going to follow the predicted pattern, preparations for conducting the test started. This involved removing the barrel heaters from the test units and fueling the pool. The pool was filled with only enough fuel to burn approximately half the required time. The fuel consumption was monitored, and a linear fuel level recession rate was established on a level versus time plot. The slope of the plot was transferred to intersect desired ending time (see Fig. 11).

7.2.3.6 The response of three thermocouples located on a tower near one of the test units is shown in Fig. 12. Two thermocouples that bracketed the test unit (in height above the pool) registered temperatures in excess of 1000°C.

7.2.3.7 The response of thermocouples attached to the surface of one of the test units is shown in Fig. 13. The surface temperatures show that the package was essentially in thermal equilibrium with the fire. The temperature levels were well above the 10CFR71 requirement of 800°C (1475°F) and is strong evidence that the fire environment surpassed the requirement.

7.2.3.8 The response of other instrumentation in the fire also confirms that the thermal environment was more intense than that required. The time-temperature history of a thick wall passive calorimeter is shown in Fig. 14. The calorimeter was constructed of thick wall SS304 pipe and was oriented horizontally in the fire at the same level as the test units. The direct observation is that the calorimeter attained temperatures higher than the required 800°C. The time-temperature curves are analyzed with the use of an inverse heat transfer technique that allows the determination of heat flux absorbed through the surface as a function of temperature. Although not shown here, the resulting curve clearly surpasses the required by more than a factor of two for all surfaces on the calorimeter.

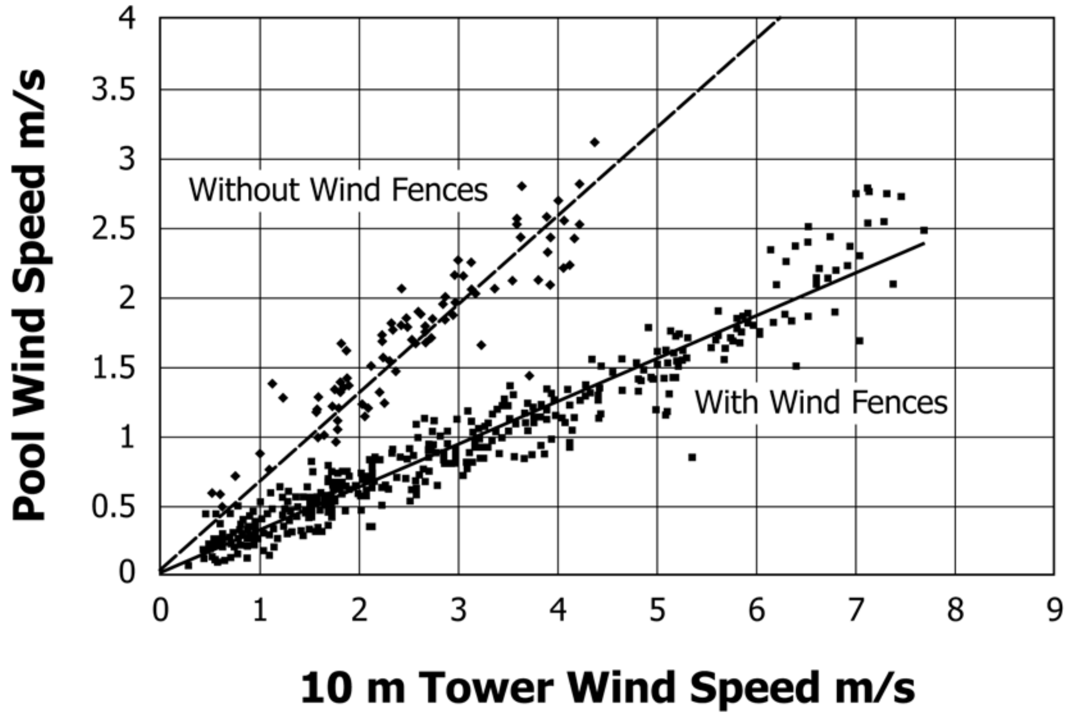
7.3 *Furnace Testing*

7.3.1 *Benefits, Limitations:*

7.3.1.1 The requirements for Hypothetical Accident Conditions (HAC) thermal testing of Type B shipping packages, as defined in the current version of 10 CFR 71.73 (c)(4), have been written specifically for the use of a pool-fire test method. However, this paragraph also allows for the use of “.... any other thermal test that provides the equivalent total heat input to the package and which provides a time averaged environmental temperature of 800°C.” Therefore, when used properly, it is possible to use a furnace to perform thermal HAC testing of Type B shipping packages. Note that "equivalent total heat input" includes both radiative and convective components.

7.3.1.2 Due to the controllable nature of furnaces, as compared to open pool-fires, there are clear benefits to use of furnace for testing. There are also practical limitations to the use of this method.

7.3.1.3 The most obvious benefit of furnace testing is the ability to control the atmosphere within the furnace, thereby making the results of testing more consistent and clearly within the requirements of 10 CFR 71.73(c)(4) or IAEA TS-R-1. With



NOTE 1—The wind speed was observed on a 10 m tower located approximately 50 m from the pool. The package level wind anemometer was located at the pool center approximately 2 m above the ground.

FIG. 8 The Effect of Wind Fences on Wind Speed at Package Level

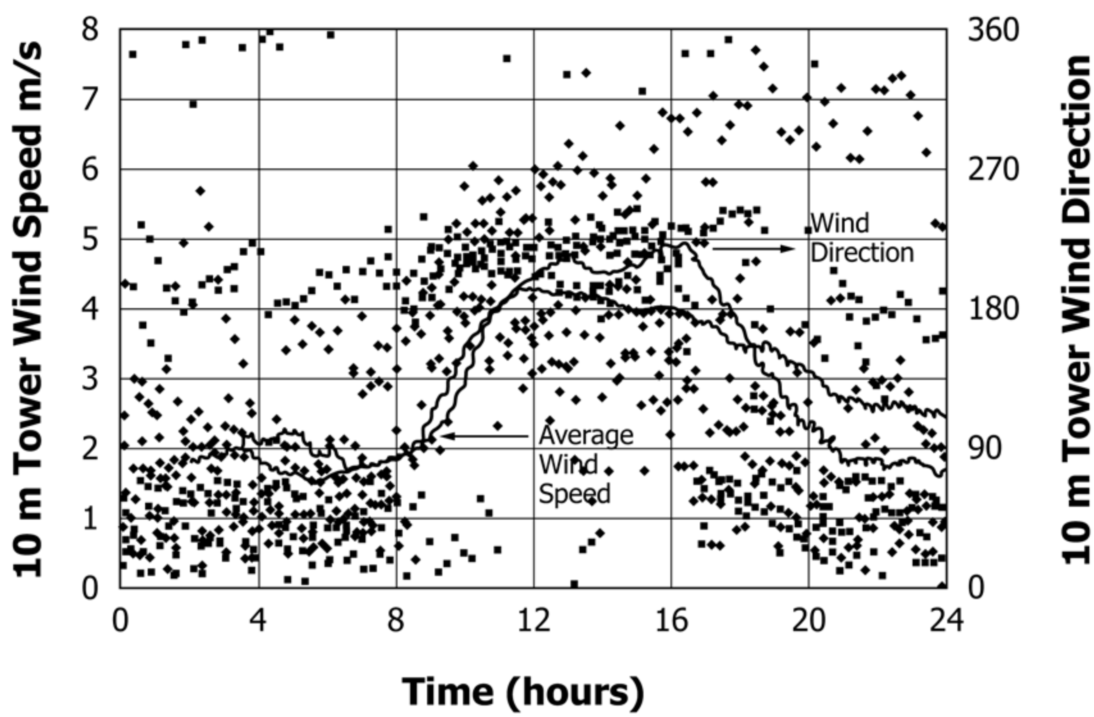


FIG. 9 Example of 5 Consecutive Days of Wind Speed and Direction at a Pool Fire Test Site

open-pool fires, ambient conditions such as wind speed have a significant impact on the temperature at which the fire burns. Because pool-fires are sensitive to ambient wind conditions, these tests are commonly performed at sunrise when quiescent conditions are found. Usually, this limits testing to one test per day. Furnace testing is typically performed with only one unit

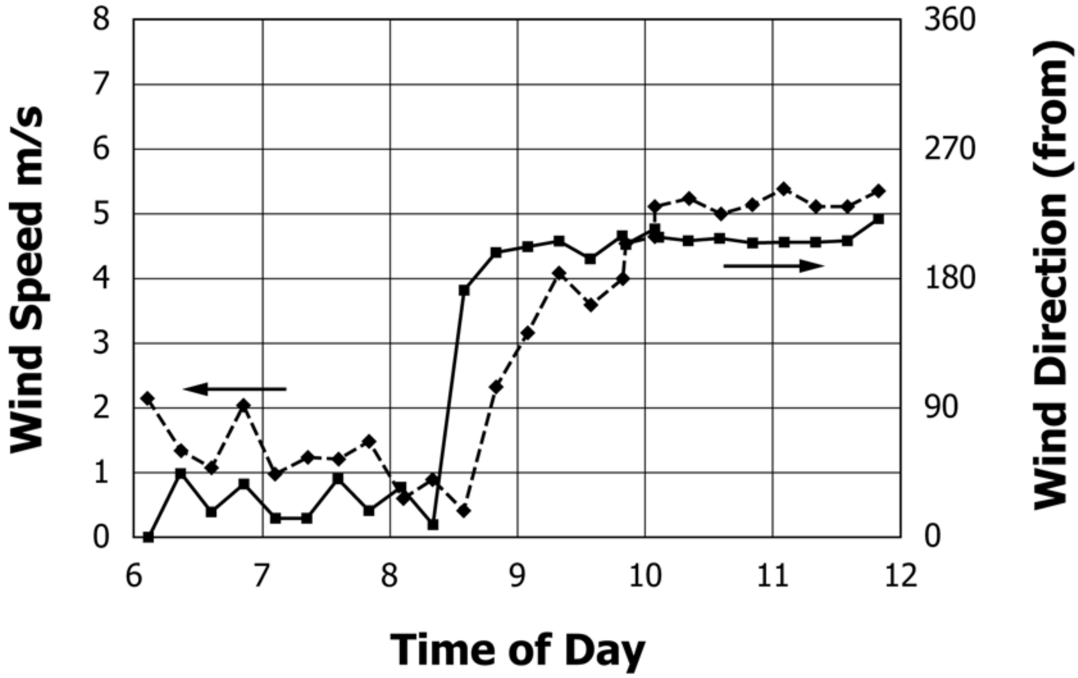


FIG. 10 Set Up Activities Start at First Light; the Fire is Ignited When the Wind Shifts in Direction

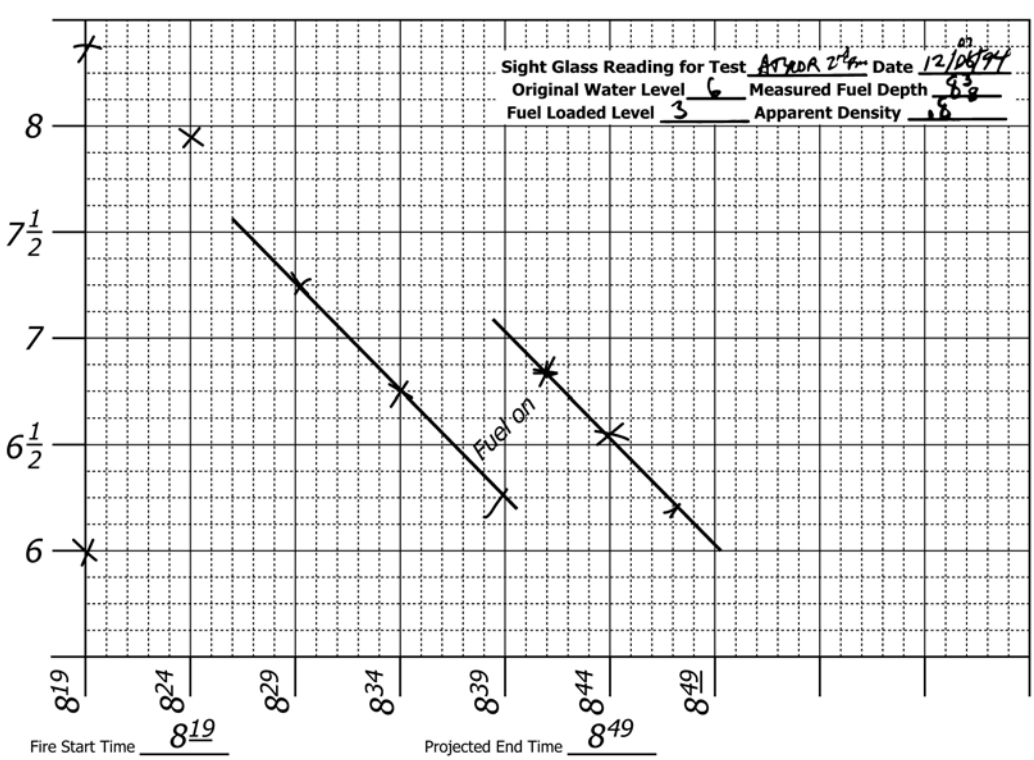
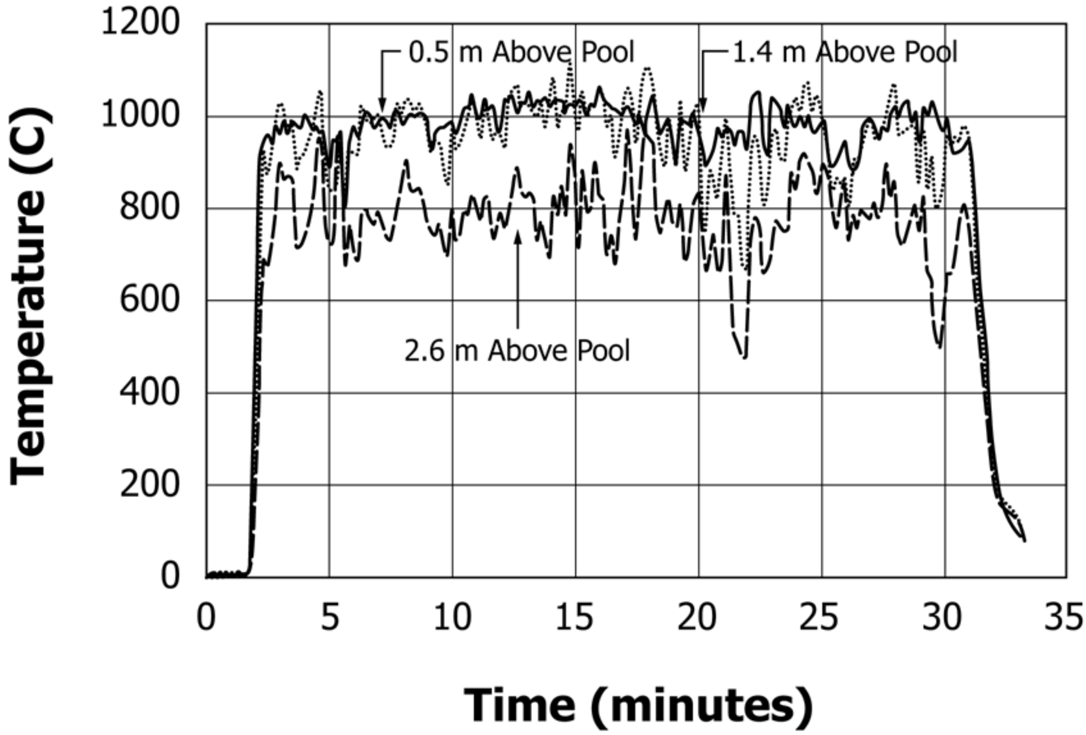


FIG. 11 Control of burn time is accomplished by adding fuel to pool during the fire. The fuel consumption rate is established during the first half of the fire, the slope is transferred to intercept the desired ending time and fuel is added until the level reaches the new line.

at a time, but since testing is not dependent on ambient conditions, tests are performed throughout the day and night as necessary.

7.3.1.4 The use of furnace testing is generally limited to smaller drum-type packages (that is, fissile material packages). Typical drum type packages consist of a thin-walled steel drum as the outer packaging with a thick layer of insulating material just beneath (foam, Celotex™, cast refractory, etc.). The containment vessel(s) with the radioactive contents is centered within the insulating material. The characteristic response of these packages to exposure to high temperatures is a quick (less than 10 min) heating of the outer layer of the package to



NOTE 1—The test item was 1 m above the pool.

FIG. 12 Temperature Time Histories of Thermocouples in the Fire Near a Test Item

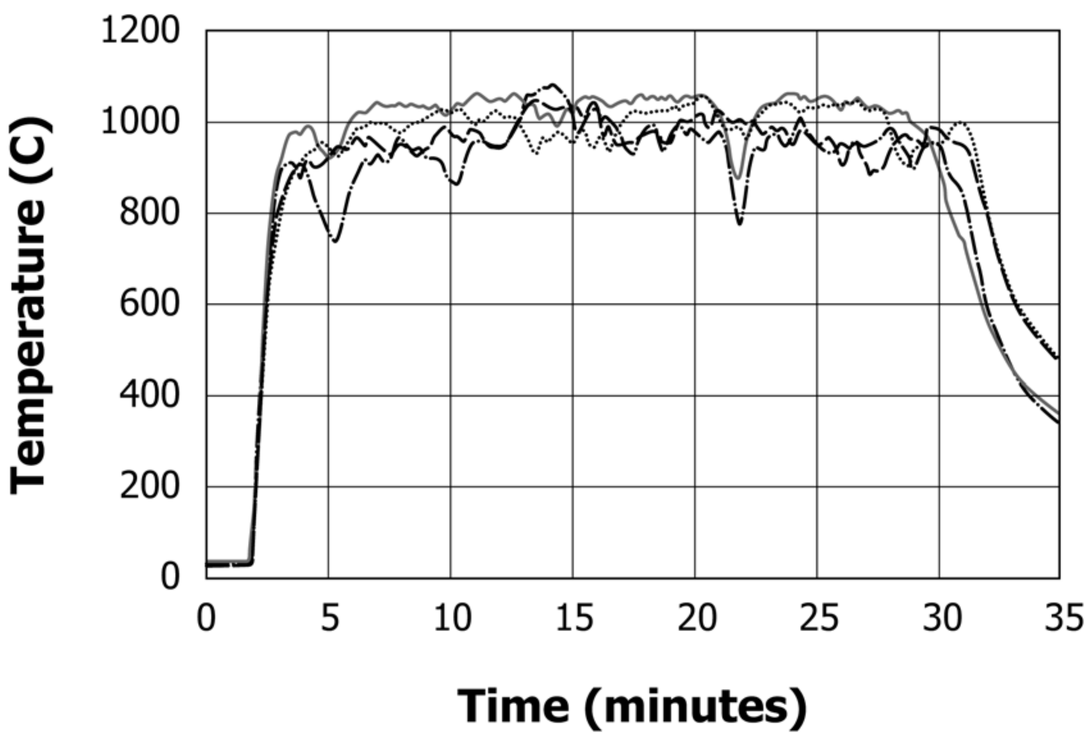


FIG. 13 Temperature of Package Surface in 4 Locations During the Fire

temperatures close to that of the test apparatus (that is, 800°C [1475°F]). As the skin (outer surface) of the package approaches the temperature of the test apparatus, the limiting heat transfer mechanism shifts from radiation to the package, to conduction within the package, resulting in a greatly decreasing flux to the package. For larger cask type packages, a typical design usually includes a massive steel outer wall resulting in a very large heat sink. Since the surface of such a heat sink is not be likely to equilibrate near the ambient test temperature during the course of a 30 min test, the heat flux to the package

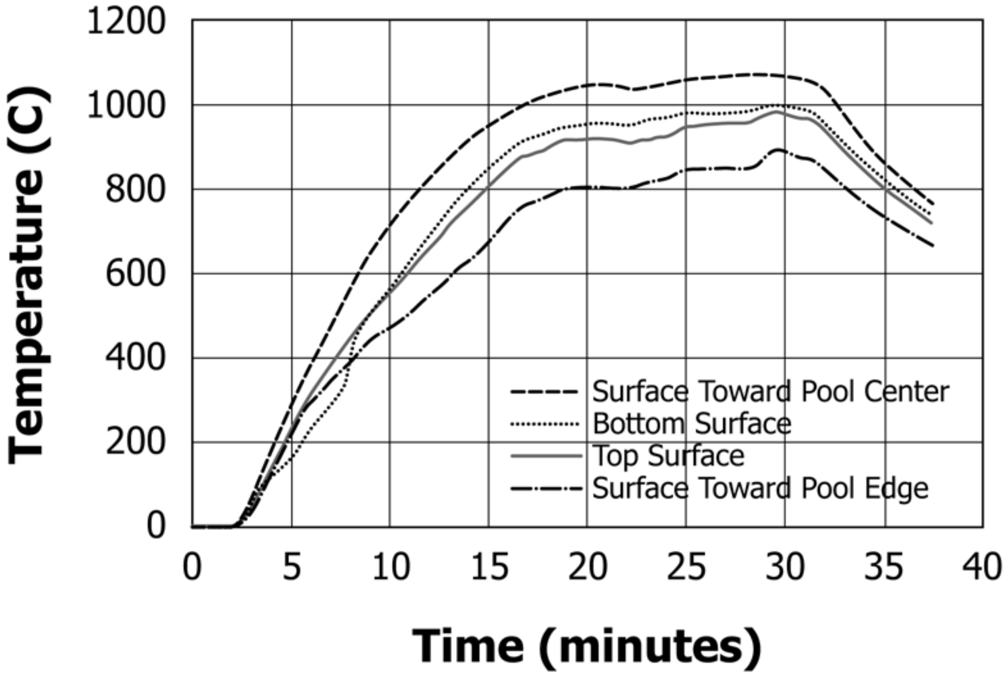


FIG. 14 Response of a Thick Wall Stainless Steel Calorimeter

over the duration of the test is much more constant than with a drum-type package. In such a case, stored heat within the walls of the furnace is dissipated during the test and the task of keeping temperatures of the various furnace surfaces at or above the required regulatory temperature is incumbent on the heating system of the furnace (that is, gas or electricity). It is unlikely that any electric furnaces have the ability to provide the heat input required for large, cask type packages.

7.3.2 *Test Preparation and Configuration:*

7.3.2.1 Initial test preparation begins with the selection of the furnace to be used. It is strongly recommended that a gas-fired furnace rather than an electric furnace be used for this type of testing for two reasons. First, general experience has shown that heat input (that is, heat flux) into a gas-fired furnace is much greater than for an electric furnace (oven). Thus, getting the furnace back to 800°C (1475°F), after loading of the test specimen, and maintaining the required temperature throughout the duration of the test is much easier. Second, 10 CFR 71.73 currently requires "......any combustion of materials of construction, shall be allowed to proceed until it terminates naturally." It is likely that the atmosphere within an electric furnace will become oxygen deprived if any combustion of materials of construction takes place; thereby possibly limiting further combustion of these materials. While it is also possible for a gas-fired furnace to become oxygen deprived, steps taken, as outlined below, ensure this does not take place.

7.3.2.2 The furnace shall have an interior surface area that is much larger than the surface area of the test specimen. This large furnace surface area to package surface area ratio relieves the tester of the need to determine the emissivity of the furnace surface(s). The regulations require that a pool fire "provide an average emissivity coefficient of at least 0.9...." This is necessary because a fully engulfing fire has the same surface area as the package being tested. However, when the surface area of the furnace is much greater than the surface area of the package, the emissivity of the furnace surface has no effect on the rate of heat transfer to the package, rather the rate of heat transfer to the package is controlled by the absorptivity of the package (for radiative heat transfer). A furnace surface area of at least 10 times that of the package is recommended.

7.3.2.3 The furnace used for package testing shall have a digital control system for regulation of the temperature within the furnace. Typical control systems include two thermocouples, one for the main control and one as a high-temperature limit in case the main control unit fails (usually due to thermocouple malfunction). These control thermocouples are typically mounted to monitor atmospheric temperatures within the furnace, while the temperatures of greatest interest to package testers are those of the furnace surfaces which are radiating to the package. It is also possible for flames from a package being tested to impinge directly on the control thermocouple resulting in high temperature readings and possible loss of power to the furnace. For these reasons, it is necessary to use a furnace in which the control and upper limit furnace temperatures are easily adjusted. It is also recommended that a furnace with a maximum operating temperature of at least 1000°C (1832°F) be selected (1100°C [2012°F] preferred).

7.3.2.4 Loading of the test specimen, and to a lesser extent, unloading is key to a successful completion of the tests. A furnace is typically heat soaked prior to loading of the test specimen. During loading, a significant decrease of the temperatures (both atmospheric and surfaces) within the furnace often takes place. Thus, loading the specimen both quickly and safely is important. For most furnaces a loading time of up to 90 s is acceptable; however, this is dependent on the individual furnace and it is recommended that mock trials be used prior to loading to determine the effects of loading on furnace temperatures. Loading is achieved either by an automatic loading machine that is specifically outfitted for the furnace being used or through the use of a forklift. Clearly the machine that has been outfitted for the specific purpose of loading the furnace is preferable as repeatability is assured. Loading with a forklift requires great skill on the part of the operator.

7.3.2.5 The package shall be loaded onto a stand inside the furnace. It shall not be loaded directly onto the floor of the furnace. If the package is set on the floor, the area directly below the package will most assuredly drop below the regulatory temperature of 800°C (1475°F). Thus, the package is not "fully engulfed" as is required by regulations. The stand shall be designed in a manner such that contact between the stand and the package is minimized, and the obstruction of the view of the furnace surfaces from the package shall also be minimized. When using a loading machine to load the furnace, the stand is usually a permanent part of the furnace test set-up. For forklift loading, the stand is placed in the furnace prior to the test (this is required). The package is then loaded onto the stand to initiate the test, and when the test is complete both the package and stand are removed as single piece. Removing a hot package from a stand is very difficult with a forklift and removing both the stand and the package is considerably easier and safer (the stand is designed for ease of forklift use; the package will not be designed to specifically facilitate removal of the package from the stand).

7.3.2.6 The regulations require "an average flame temperature of at least 800°C (1475°F) for a period of 30 min or any other thermal test that provides the equivalent total heat input to the package and which provides a time averaged environmental temperature of 800°C." To ensure that the time averaged environment is at least 800°C, it is necessary to monitor the temperatures of the surfaces that are radiating to the package, namely the walls, floor and ceiling of the furnace (assuming a rectangular furnace). The simple use of the control thermocouple as evidence of the time averaged temperature environment is not sufficient for several reasons. For one, combustion gases from the package's materials of construction impinges on the control thermocouple indicating a hot furnace when in fact the wall temperatures are actually decreasing, sometimes significantly. Also, some furnaces have relatively uneven heating from side to side or from front to back thereby rendering the reading of a single thermocouple useless. Finally, since most of the heat transfer to the package is through radiant transfer, it is paramount that the radiative environment within the furnace be documented.

7.3.2.7 Mounting of thermocouples within a furnace has been successfully achieved in two different manners in the past. If the owner of the furnace is amenable to structural modifications, the simplest method is to mount the thermocouple through the wall of the furnace by first drilling holes in the furnace and then pushing the thermocouples through the holes. A less invasive but also less dependable technique is to run the thermocouple leads along the walls of the furnace such that the thermocouple junctions are mounted in the respective locations. If this method is used, then typically all the leads come together at the bottom of the furnace and out the door. If an electric furnace is used, it is important to ensure that the thermocouple leads do not come in contact with the heating elements, especially if the latter method of installation is used. As the furnace heats-up, the thermocouple sheaths will grow in length. In an electric furnace, this allows the sheaths to come in contact with the heating elements resulting in shorted-out thermocouples.

7.3.2.8 Thermocouples shall be mounted in the walls of the furnace in such a manner to measure the temperature of the wall (not the temperature of the atmosphere near the wall). This requires that the junction of the thermocouple be mounted flush with the surface of the furnace. When bringing thermocouples through the wall of the furnace, the hole shall first be drilled all the way through the wall. Mounts are then attached to the outside of the furnace and the thermocouples are brought through the mounts until the end of the junction is just flush with the furnace surface. For thermocouples that are strung along the furnace surfaces, a small area of the refractory is scratched away creating an indentation for the thermocouple junction. For use of either method of mounting, the thermocouple tip shall then be covered with a very light covering of a refractory patch material. This ensures that the emissivity of the radiative surface at which the temperature is being measured is similar to that of the furnace wall and it also assures that a surface (or slightly sub-surface) temperature rather than an atmospheric temperature is being measured.

7.3.2.9 A minimum of three thermocouples shall be placed on each distinct radiative surface within a furnace. Assuming a box type furnace, this totals to 18 surface thermocouples (3 on each of 4 walls, the floor and the ceiling). The thermocouple placement shall ensure that all zones of the radiating surface are measured. By assuming that the surface area of the furnace is much larger than the surface area of the package, in effect one is assuming that all furnace radiating surfaces are supplying heat. Thus, all areas of these surfaces need to be monitored. An easy way to accomplish this is to mount the three thermocouples on a single surface in a diagonal line. Specifically, mounting the thermocouples in a horizontal or vertical line shall be avoided.

7.3.2.10 Additional items within the furnace for testing purposes, specifically test stands, shall be instrumented with thermocouples. The stand shall be at temperature at the beginning and throughout the duration of the test, thus demonstrating that the stand is not acting as a protective heat sink for the package.

7.3.2.11 A computerized data acquisition system to gather and record data is recommended but not required. All portions of the data acquisition system shall be calibrated and certified as discussed in Appendix X5 of this document. Prior to testing, the furnace temperatures shall be recorded during the heat-soak process as well as between consecutive test runs. During these times, collecting (recording) data at 15 min intervals is recommended. During testing, temperatures shall be recorded at least every minute with 15 or 30 s intervals suggested.

7.3.2.12 As 10CFR71 requires "......any combustion of materials of construction, shall be allowed to proceed until it terminates naturally," it is necessary to ensure that the oxygen level within the furnace remains at or above the level that is found at the center of a pool fire test. This is accomplished in a gas-fired furnace by de-tuning the burners such that excess air is forced into the furnace during testing. Monitoring of the oxygen level in the flue gases leaving the furnace during testing is then used to document the availability of O_2 for materials of construction combustion during testing. Monitoring of O_2 levels within an electric furnace is more complicated as flue gases generally do not exist. In such a situation, some other technique shall be employed to ensure the oxygen level does not drop too low and is documented. Additionally, some packages are constructed of materials which will not combust at the temperatures associated with this type of testing. When it is shown that no materials of construction are combustible, then there is no need to monitor oxygen levels within the test apparatus.

7.3.2.13 To meet the requirements of 10 CFR 71, the test specimen shall be at the shaded normal conditions of transport (NCT) temperature prior to the initiation of the thermal test.

7.3.2.14 The package to be tested shall be instrumented such that the surface temperatures of the package is monitored. A typical mounting approach is described in Appendix X5. Note that the junction of the thermocouple shall not have a direct "radiative view" of the furnace heat source. Such a view skews temperature measurements. The ends of the thermocouple are typically covered with a foil piece as described in Appendix X5.

7.3.2.15 Prior to inserting the package into the furnace, the functionality of all of the thermocouples (both those measuring furnace temperatures and package temperatures) shall be checked. Once it is determined that all thermocouples are working, the package is readied for insertion (for example, picking the package up with a forklift or loading the package onto a loading machine, usually with an overhead crane). The orientation of the package is important, especially if there is significant damage to the package from previous structural testing. While this standard does not deal with package orientation, one shall be able to defend the orientation used as "worst-case."

7.3.3 *Additional Data to be Reported*—The following data shall be recorded during testing:

7.3.3.1 All thermocouple data (typically in 15 or 30 s intervals for the duration of the test),

7.3.3.2 Time at which the package is inserted into the furnace,

7.3.3.3 Time at which the test begins,

7.3.3.4 Time at which the package is removed from the furnace, and

7.3.3.5 Test apparatus gas oxygenation (every 5 min during the test when combustible materials of construction are present).

7.3.4 *Test Conduct:*

7.3.4.1 The actual testing of the package is simple and straightforward. The furnace door is opened and the package is loaded into the furnace. When the test is complete, the package is removed from the furnace. However, the determination of when the test begins, and thereby when it ends (that is, 30 min later) is less straightforward.

7.3.4.2 The regulations require a "....thermal test that provides the equivalent total heat input to the package (of an 800°C [1475°F] pool fire with an emissivity coefficient of 0.9) and which provides a time averaged environmental temperature of 800°C." There are several ways to get to this point each of which, if properly documented, is acceptable.

7.3.4.3 The method which requires the least calculational input is often referred to as the "steady-state" method (see Combination Test/Analysis Method…, 1992, and Shah, 1996). For this type of test, the package is inserted into the furnace and the surface of the package is allowed to come to temperature (800°C [1475°F]). The point at which all package surface thermocouples and the average of the furnace thermocouples read 800°C (1475°F) or greater is considered the beginning of the 30-min test. During the ensuing 30 min, the package surface temperatures as well as the average furnace temperature shall remain at or above 800°C (1475°F).

7.3.4.4 Since a perfect 800°C (1475°F) pool fire never heats a package surface above 800°C (1475°F) it is clear that this test method meets all of the requirements in 10 CFR 71.73(c)(4) and IAEA TS-R-1, Section VII. From the perspective of the applicant/tester/package manufacturer, the steady state method is an over test of the package, however from the perspective of the regulator, the benefit of this test method is that this method will adequately satisfy the regulatory requirements for the hypothetical accident conditions and provide added support to the applicant's assertion that the package met the requirements. For small drum-type packages, it often takes 8 to 12 min for the drum surface to reach 800°C (1475°F), thus the package is actually inside the furnace for 38 to 42 min. Also, to heat the package to at or above 800°C (1475°F), it is typically necessary to run the furnace at 820 to 850°C (1508 to 1562°F). Some furnaces have cold spots that require the tester to keep that average temperature of the furnace higher just to ensure that portions of the package surface, which have a strong view of a cold spot, remain at or above 800°C (1475°F). Clearly, the steady-state method cannot be used on large heat-sink packages.

7.3.4.5 Some additional guidance has been provided by the United States Department of Energy for thermal testing of packages in the form of Combination Test/Analysis Method Used to Demonstrate Compliance to DOE Type B Packaging Thermal Test Requirements, SG 140.1. The document is of limited use since the publication date of 1992 predates the inclusion of convection as a necessary component in the thermal test defined in 10 CFR 71. This document provides information for use in a non-steady-state method; however, a specific furnace temperature above 800°C is used for the duration of the test simply based on the instantaneous heat flux at the beginning of the test. The information is inconsistent with the current version of 10 CFR 71.73 as the time-averaged environmental temperature is now specified. The methods presented are acceptable, though stringent, test methods.

7.3.4.6 To perform a furnace test without utilizing the steady-state method, some knowledge or analysis of the package's response to a pool-fire test is needed. If the total heat input (that is, the integration of the heat flux from the beginning of the test to the end) a package receives if exposed to a perfect 800°C fully engulfing pool-fire including the heat transfer from radiation and convection is determined, then it can be shown that the package subjected to a furnace test received either a greater or lesser total heat input during the actual physical testing. For a test method to be acceptable, it must provide an equal or greater total heat input as well as an "averaged environmental temperature of 800°C." Some general guidelines for performing such an analysis are found in Van Sant, et al, 1993. This document also predates the current version of the regulations, but the insight necessary to make the discussed calculations is included.

7.3.4.7 The method of loading and unloading the test specimen varies from furnace to furnace. As stated earlier, if a loading machine is used, it is likely the stand will stay in the furnace after the test, but if a forklift is used, it is usually easier to remove the test specimen and the stand as a single unit. Because the furnace is typically turned off during this time and losing heat due to the door being open, it is necessary to complete the loading process as quickly as possible. This allows the furnace to stay hotter, and especially if the steady-state method is used, allows the 30-min test period to begin sooner. It is paramount that all loading and unloading activities as well as other processes associated with the test (data acquisition, etc.) be thoroughly practiced and/or tested, as appropriate, prior to test initiation.

7.3.4.8 Once the package has been unloaded from the furnace, it shall cool naturally. This means that the package must not be exposed to either significantly cold temperatures or to breezes of any sort. Ideally, the ambient temperature shall be near 38°C (100°F). Recent interpretation of the regulations has required the inclusion of the effects of insolation during the cool-down period. This is typically shown, through analysis, to be insignificant. However, the applicant often desires to simulate the insolation according to 10 CFR 71.71.

7.3.4.9 After unloading, the temperatures of the surfaces of the package typically fall quickly. This data is of no real use, so there is no need to continue monitoring these temperatures. Some test specimens are instrumented to record interior package temperatures such as containment vessel temperatures. Typically, these values will continue to rise for some time after the package is removed from the furnace. Such temperatures must continue to be monitored until well after they have peaked. Generally, the data are recorded at 5 to 15 min intervals. This information often also proves helpful in determining the relative non-effect of introducing insolation following the thermal test.

7.3.5 *Adjustment of Results for Differences from Regulatory and Initial Boundary Conditions:*

7.3.5.1 There are no specific adjustments necessary for Type B shipping packages thermally tested in a furnace. Standard methods for making adjustments for items such as reduced content weight, package temperature gradients due to decay heat of contents, etc, be made as outlined in Appendix X1 of this document.

7.3.6 *Abnormal Events, Remediation:*

7.3.6.1 There are many abnormal events that take place during furnace testing. However, remediation of such problems is often nearly impossible. It is strongly recommended that the entire test procedure be practiced using a cold furnace well in advance of the actual test to ensure that all procedures will work correctly and that unexpected difficulties are discovered prior to the actual test. It is also recommended that some practice take place with a "dummy" test unit and an "at-temperature" furnace to ensure that expectations of the test are met.

7.4 *Radiant Heat Testing*

7.4.1 *Benefits, Limitations:*

7.4.1.1 Pool fire testing (see 7.2) has been the traditional method by which one tests a package to 10CFR71. A package is exposed to an engulfing fire for the required duration of 30 min. Other methods exist by which one generates the environment specified in 10CFR71, for example furnace testing discussed in 7.3. The use of radiant heat lamps is another method for thermal testing of packages.

7.4.1.2 Radiant heat simulations of high temperature environments have been used for many years for high temperature testing (that is, up to 1200°C [2200°F]). In this method, infrared lamps are the heat source and are made of a spiral wound tungsten filament enclosed in a fused quartz envelope and powered electrically. Each lamp is about 30 cm long and 10 mm in diameter (12 in. long and ⅜ in. diameter). Typically, arrays of these lamps form lamp panels as shown in Fig. 15. The lamp panels are placed in front of a stainless steel or inconel enclosure that surrounds the package to be qualified as shown in Fig. 16. The lamps heat the steel enclosure (which is normally painted black, $\varepsilon = 0.85$), which heats the package. The enclosure is typically instrumented with a number of mineral insulated, metal sheathed thermocouples to measure the enclosure temperature. The enclosure is rapidly brought from ambient to the "flame temperature," in the case of 10CFR71 the flame temperature is 800°C (1475°F). The enclosure is then stabilized at 800°C (1475°F) for the proper duration of the experiment, namely 30 min as shown in Fig. 17.

7.4.1.3 Benefits of radiant heat testing become evident when one notices the limitations of traditional pool fire testing (see 7.2). In pool fire testing, one exposes a package to an engulfing pool fire for 30 min as specified in 10CFR71.73.

7.4.1.4 The radiant heat testing alternative bypasses some limitations of traditional pool fire testing. By use of lamps and a steel enclosure painted black, one obtains a known temperature heat source (measured with thermocouples), of high emissivity (black paint), that is not dependent on the wind speed or direction. Experience with Pyromark® black paint has been good. The emissivity stays high (about 0.85) even after the initial curing, which causes some black smoke. Measured emissivity before and after the paint was applied has been found to be stable at about 0.85. If care is taken, the enclosure is made of relative uniform temperature (for example, ±5 %) so the temperature source is uniform at whatever temperature is desired (for example, 800°C (1475°F)). The test length is controlled precisely by beginning the test when the enclosure reaches the desired temperature and simply turning off the power system when 30 min has elapsed as shown in Fig. 17. Lastly, if desired, the non-uniformity present in all pool fires is avoided by use of the uniform temperature enclosure.

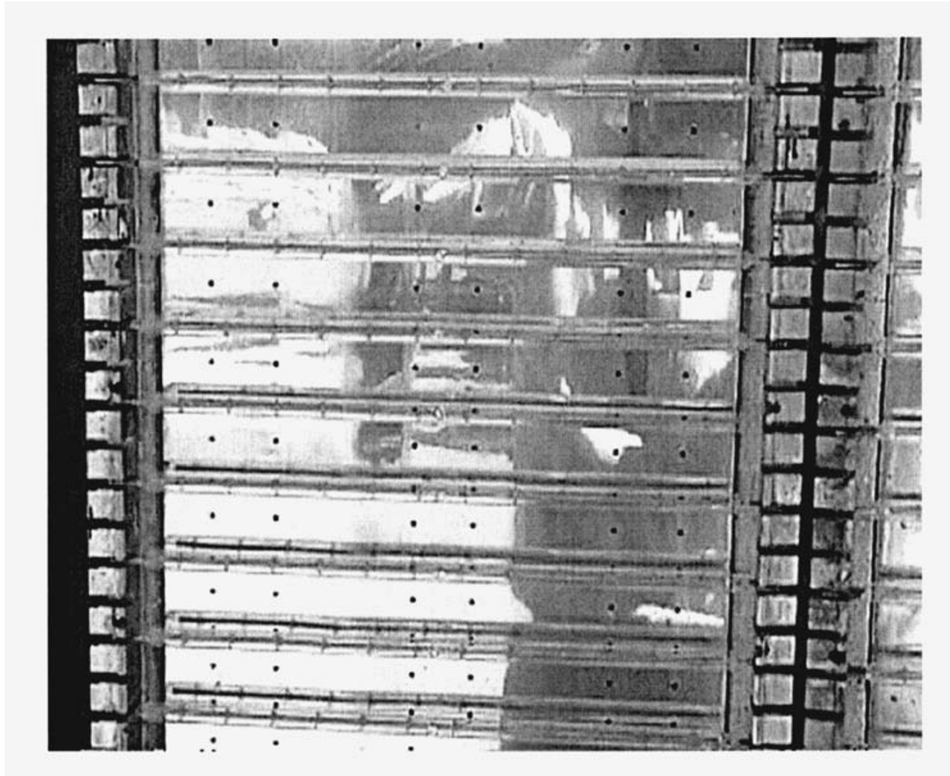


FIG. 15 Close-up of Lamps and Lamp Panel

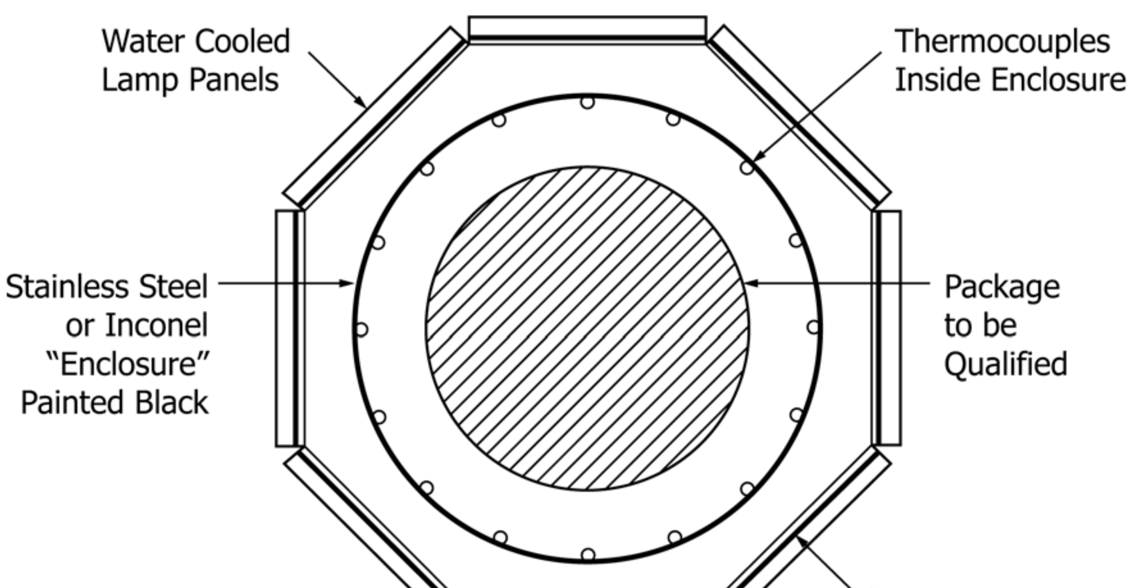


FIG. 16 Overall Plan View of Typical Radiant Heat Array

7.4.1.5 Controlling heat flux to the top and bottom of the test object is an important consideration in radiant heat testing. Heat lamp arrays and the steel enclosure are normally positioned vertically on stands around the test object, and heating of the top and bottom of the object is accomplished by extending the height of the lamp arrays and enclosure above and below the test object. The view factor from the heated steel enclosure to the top and bottom of the test object shall be considered in designing the test. In some cases additional insulated enclosure pieces are required above or below the test object to create a hot cavity completely surrounding the test object.

7.4.1.6 Radiant heat testing is especially beneficial for cases where it is desired to obtain experimental data to compare with

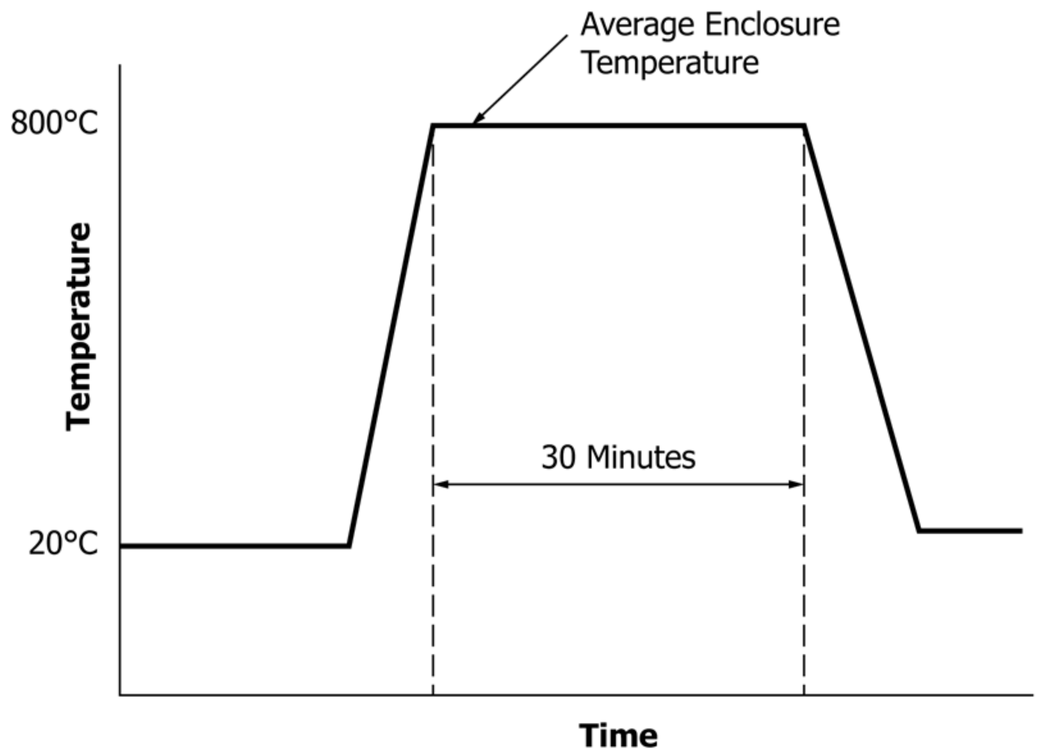


FIG. 17 Typical Enclosure Temperature Profile

thermal model predictions (see 7.1). With the well controlled environment (as compared with pool fires), radiant heat tests provide a uniform, constant boundary condition more suitable for use with comparison with model predictions. Wind effects are non-existent in radiant heat simulations. Wind plays a significant role in the heat transfer in pool fires (see 7.2).

7.4.1.7 One key limitation of radiant heat testing is startup cost. To develop the radiant heat capability requires a high power substation (Sandia's Radiant Heat Facility has a dedicated 6 MW substation), transformers, power control system, switchgear, water cooling for the lamp arrays, banks of lamp panels, and lamps. Once up and running, the facility is relatively inexpensive to operate and is competitive with open pool fire testing. Open pool fire testing often requires additional environmental approvals (for example, for the National Environmental Policy Act, NEPA), and "burn permits" if near a city with air quality restrictions. Radiant heat testing normally does not require such permits because no fuel is burned.

7.4.1.8 There are several differences in the heat transfer mechanisms between pool fires and radiant heat testing. The convective heat transfer in radiant heat tests is different than for pool fires—the latter being greater. This is usually not a problem because the overall heat transfer in fires is thought to be dominated by radiative heat transfer. Normally, the highest emissivity attainable on the enclosure via paint is $\varepsilon = 0.85$, not $\varepsilon = 0.90$ as required by the regulations. An adjustment up in enclosure temperature is often required. In the many radiant heat tests performed in the past, customers have specified a uniform circumferential and axial temperature on the enclosure. This in turn creates a uniform heating pattern on the package. This is very different than what actually occurs in open pool fires (see 7.2). Significant non-symmetric circumferential heating of a package causes larger thermal stresses than present in a symmetric circumferential heating environment. This non-symmetric heating is often difficult to reproduce in radiant heat testing. Because the steel enclosure mount is open to outside air at the bottom, natural convection draws a sufficient air supply inside the steel enclosure to support combustion of materials inside the package.

7.4.1.9 Simulation of convection from flame velocities of 5 to 10 m/s (11.2 to 27.4 mph) in radiant heat testing is difficult but possible. One generates 800°C (1475°F) air from an external source and ducts it to the annular space between the steel enclosure and the package, then provide an exit path for the air out of the space around the heater array. Existing radiant heat facilities have not provided this kind of convective boundary condition in past tests. This was related to the concept that almost all of the heat transfer in fires was due to radiative effects. What little was caused by the convection was accounted for by a slightly increased flame temperature (in this case the steel enclosure temperature was raised slightly). Both methods are used, but the easier method is to increase the average steel enclosure temperature because it requires less equipment.

7.4.1.10 In summary, radiant heat testing generates a very similar radiative environment, but a less severe convective environment when compared to pool fires.

7.4.2 *Test Preparation and Configuration:*

7.4.2.1 Test preparation and configuration are separated into several overall tasks:

Procedures
Setup
Calibration and uncertainty analysis

7.4.2.2 Procedures span the following areas:

(1) Environmental Documentation—If the package has a significant flammable component that generates toxic gases or radioactive debris, or other hazardous materials, NEPA (National Environmental Policy Act) approval is often required (that is, an Environmental Assessment (EA) or Environmental Impact Statement, EIS). Normally, radiant heat testing does not require an EA or EIS for NEPA approval for typical package testing (that is, without radioactive materials).

(2) Safety Procedures—Because of the lethal voltages and currents (480 V, 1000 A) encountered in large package radiant heat testing, safety procedures are very important to reduce the chance of injury or equipment damage.

(3) Quality Procedures—To ensure adherence to a quality process, QA procedures are provided so that a regulatory agency has the proper information to make a judgment as to whether an experiment was performed according to the regulations. Refer to 10 CFR71, Subpart H - Quality Assurance for a discussion of QA requirements, procedures, etc.

(4) Operational Procedures—These are step-by-step procedures written to carefully analyze the steps required to perform a radiant heat test. These often have simple instructions such as "start the water pump and ensure water is flowing," but sometimes also include safety procedures. Often, safety, quality, and operational procedures are combined into a single list of procedures where the entire experiment is analyzed and steps described. (See Appendix X2 for a description of operational procedures, sometimes called "Job Analysis Work Sheets," or JAWS.)

7.4.2.3 *Test Setup Requirements:*

(1) Determine Lamp Array Size Needed—For small packages, that is, less than about 1.2 m (4 ft) long, a single height lamp array is most commonly used. For packages longer than about 1.2 m (4 ft) but shorter than about 7.4 m (8 ft), lamp arrays made of two-high lamp panels are used. Each panel is about 30.5 cm (12 in.) wide and 1.2 m (46 in.) long. They are mounted so the long dimension is vertical, and panels are placed side-by-side to surround the steel enclosure as shown in Fig. 2. The enclosure is stainless steel or inconel because these materials withstand temperatures up to about 1200°C (2200°F), which spans the maximum temperatures normally seen in hydrocarbon fuel fires. The steel enclosure is of a sufficient diameter to provide easy installation of the package, and of the same length as the lamp panels. The enclosure is circular and formed by bending a flat plate into a circle and welding the seam. The enclosure is painted with a high emissivity black paint on both sides (ε = 0.85).

(2) Design Stand to Hold Package—This is relatively easy because stands exist from past testing, especially if the package is to be placed with the long side vertical, and because packages are often not heavy. However, if the package is to be placed with the long side horizontal, the entire lamp array is often rotated 90° from its most often used configuration, and a new stand built. Alternatively, the lamp array is kept vertical but made a larger diameter, and a larger diameter steel enclosure made to accommodate the longer horizontal dimension. Based on IAEA TS-R-1, the package shall be mounted with the shortest dimension vertical for the most uniform flame cover, unless a different orientation will lead to a higher input or greater damage, in which case such an arrangement shall be chosen. In the case of the radiant heat test, presuming the longest dimension is not too long to fit into the radiant heat array, the orientation chosen be the case with the greatest expected damage.

(3) Determine Temperature Profile Required on Enclosure—Currently, this is a constant temperature of at least 800°C (1475°F).

(4) Determine Instrumentation (for example, Thermocouples) Required to Ensure Proper Environment is Created—(See Appendix X1 for a discussion of issues related to instrumentation.) Although the radiatively heated enclosure is more uniform than a fire, the enclosure normally has a non-uniform temperature. These can range more than ±5 % about a mean. Although ±5 % temperature non-uniformity does not seem large, when taken to the fourth power (σT^4) a ±5 % uncertainty in temperature results in a ±20 % uncertainty in heat flux. This is a significant uncertainty. Depending on the customer requirements, measures are to be taken to ensure enclosure uniformity, or that the coldest regions are above the regulatory temperature.

(5) Other Tasks—This includes items such as connecting water hoses, making sure there are no leaks, checking power connections and cables, installing safety barriers, setting up data acquisition system, insulating areas that will potentially become overheated, etc. It is often beneficial to perform a "check test" of the setup as close as possible to the actual configuration with the package installed. This is accomplished with a mock package, often instrumented, to act as a surrogate for the package. In this manner one checks operation of all the experimental apparatus, pre-conditioning hardware, and the enclosure uniformity. If required, modifications are made and re-tested as necessary because the mock package is reusable.

7.4.2.4 *Calibration and Uncertainty Analysis Tasks:*

(1) Calibrate and Check Individual Thermocouples and Other Transducers as Required by QA Procedures—Thermocouples are fabricated via ASTM standards with a known maximum uncertainty (for example, ±2.2°C (4°F) or ±3/4 % depending on the temperature range, for chromel-alumel type thermocouples). Thermocouple manufacturers normally spot check the calibration of a batch of thermocouple wire to ensure its calibration is within the ASTM standard. If the wire does not meet this uncertainty level, it is not considered viable thermocouple wire. Normally, this calibration is not checked because we have found that the thermocouples received from the manufacturer are well within specifications, and because the initial calibration is normally not the largest uncertainty source. If desired, one orders calibrated thermocouples from the factory, each coming with a calibration, or they are calibrated at a test site. See Appendix X5 for further discussion about thermocouple calibrations.

(2) Perform a Pre-Test Uncertainty Analysis of the Entire Measurement System—It is important to be able to quantify the uncertainties and errors present in the entire data acquisition (data acquisition) system, from the measuring junction of the thermocouple to the output of the display device or computer file. This requires an uncertainty analysis of the entire system. If one is to compare test results with predictions from thermal

models, the uncertainties of both the model predictions and test results shall be known. Normally, the data acquisition system uncertainty is small and is quantified once and the same value used in future tests. However, it has been found that the biggest source of uncertainty in pool fire tests and radiant heat tests is due to the thermocouple measuring junction NOT being at the same temperature as the item one wishes to measure. The environments are sufficiently severe in pool fire and radiant heat tests that mineral insulated metal sheathed thermocouples are used. To fabricate the thermocouple to be robust enough to survive the fire or radiant heat test causes the measuring junction of the thermocouple to be separated from the environment, and therefore a systematic error occurs. This systematic error is because the measuring junction of the thermocouple is not at the same temperature as the package item or enclosure to be measured. Normally this difference is small (for example, 1 to 5 %), but as with the enclosure temperature, if the temperature uncertainty is ±5 %, the heat flux uncertainty is ±20 %.

(3) After performing the pre-test uncertainty analysis, one needs to confirm that the equipment selected is suitable for the uncertainty "budget" available from this test standard. For example, if the pre-test uncertainty analysis suggests an uncertainty of ±15 %, and the customer requires ±5 %, the uncertainty "budget" is exceeded and changes need to be made to resolve this issue.

(4) Perform a Pre-Test Data Validation Analysis of the Measurements Expected—This step entails tasks such as assuring that the frequency response of the transducer meets the needs of the system being measured. Does the data acquisition system have enough channels, and does the data acquisition system sample at a high enough rate? What will the results be expected to generate; for example, will temperature values be converted via analysis software to heat flux? In other words be sure that data is taken in a manner that is suitable for the requirements of the final deliverables.

(5) Perform a Pre-Test Check of Data Acquisition System—At several temperatures spanning the minimum to maximum temperatures expected, on each channel provide a voltage input from a calibrated source that mimics the output of a thermocouple at a specified temperature. This checks the entire data acquisition system from the end of the thermocouple extension cable to the output of the conversion program. The only item left to check is the thermocouple itself, see 7.4.2.4(*1*).

7.4.3 *Additional Data to be Reported:*

7.4.3.1 *Volts, Amps, Power*—It is sometimes convenient to provide a "sanity check" on heat flux values estimated from transducer data. Knowing the total voltage and current allows one to estimate the total power input. Knowing the total power input allows one to estimate the maximum heat flux to the enclosure, sometimes a useful value.

7.4.3.2 *Noise Levels*—This is a very important piece of data to acquire, especially in both radiant heat and pool fire testing. In both cases electrical noise levels completely overwhelm true temperature fluctuations if the data acquisition system is not properly grounded. By providing 1-2 extra thermocouples in the same area as all other thermocouples, but not subjected to a temperature change, one obtains data before power it turned on, during the test at various power levels, and after the power has been turned off again. This is very valuable for data validation and QA purposes. If proper grounding is not done the noise levels induced into instrumentation cause data with high uncertainties. It is feasible to modify the noisy data so it is more useful, assuming the noise levels are quantified. It is important for QA purposes to be able to prove that your data is noise free, or to be able to quantify the noise level.

7.4.3.3 *Reference Junction Temperature*—In the past, separate devices called thermocouple reference junctions were used to establish a reference temperature (for example, an ice bath at 0°C). In newer data acquisition systems, the reference junction is part of the electronics and is often a thermistor embedded into the data acquisition system thermocouple "card." These thermistors have to be read at certain intervals (preferably at each time all the thermocouples are sampled). During long duration pool fire testing, the reference junction temperature is sampled at set intervals because it might change enough during a long day (for example, 24 h) from normal diurnal temperature swings to affect the overall temperature reading.

7.4.3.4 *Details of Equipment Used, Calibration Dates, etc.*—For quality assurance purposes it is prudent to record the equipment model and serial numbers, calibration dates, etc. on all the equipment used during the radiant heat test.

7.4.4 *Abnormal Events, Remediation:*

7.4.4.1 As in all endeavors, sometimes there are "abnormal" events that are unexpected and that ruin a test. For example, if the water hoses cooling the lamp arrays are not carefully insulated from the reflected light from the lamps (the light from the lamps is quite intense), the hoses develop a leak and spray water over the setup. In most cases the only safe thing to do is to terminate the test and start over. In all cases with abnormal events, personnel safety is of paramount importance.

7.4.4.2 In these cases the "JAWS" discussed in Appendix X2 are very helpful. Each step in the test is described and hazards identified. As such, before the test begins, experienced operators have knowledge of many of the abnormal events possible, and possible remediations that are initiated.

8. Report

8.1 For approval in the United States, reports addressing the thermal issues shall be included in a SARP prepared according to the format described in NRC Regulatory Guide 7.9. The test report shall be as comprehensive as possible and shall include any observations made during the test and comments on any difficulties experienced during testing. The units for all measurements shall be clearly stated in the report.

8.2 Include the following descriptive information in the test report:

8.2.1 Name and address of the testing laboratory,

8.2.2 Date and identification number of the report,

8.2.3 Name and address of the test requester, when applicable,

8.2.4 Name of manufacturer or supplier of material, product, or assembly tested,

8.2.5 Commercial name or other identification marks and description of the sample, 8.2.6 Full description of the package, including such aspects as type, form, essential dimension, mass (in g) or density, color and coverage rate of any coating,

8.2.7 Full description of test fixture construction and preparation (see 9.1 and 9.3),

8.2.8 Face of specimen tested (if applicable),

8.2.9 Conditioning of the test specimens,

8.2.10 Date of the test,

8.2.11 Test orientation and specimen mounting details,

8.2.12 Details of test conducted including test planning documents,

8.2.13 Number of tests performed,

8.2.14 Test number and any special remarks,

8.2.15 All test thermocouple and calibration data, and

8.2.16 Reference to approved QA program.

9. Precision and Bias

9.1 Package qualification is determined by a leak tightness test following completion of the entire regulatory qualification process that includes drop testing, puncture testing, crush testing (if applicable) and fire testing. For this reason, the data reported in the SARP and other regulatory documents are intended to provide evidence that the regulatory fire environment was met or exceeded. For actual testing, the precision of these measurements shall be sufficient to convince the regulatory authority that the regulatory fire conditions were met or exceeded. Measurements and calculations shall be done under a QA program accepted by the package certification authority prior to submittal of the data.

10. Keywords

10.1 furnace testing; nuclear transportation package; pool fire; radiant heat; thermal qualification

APPENDIXES

(Nonmandatory Information)

X1. ADJUSTMENT OF RESULTS FOR DIFFERENCES FROM REGULATORY INITIAL AND BOUNDARY CONDITIONS

X1.1 Adjustment Approaches

X1.1.1 When performing package tests, simultaneously achieving all the boundary and initial conditions specified by the regulations can be difficult or impossible. For example, achieving a 38°C ambient air temperature prior to a pool fire test would severely restrict testing to warm summer days, and approximating the solar insolation may not be possible on a given test day because of clouds. Under such circumstances, experimental results must be adjusted to demonstrate the package would pass the test even if the more extreme conditions were present before, during and after the test.

X1.1.2 Two analytical approaches are available to adjust experimental results to account for variations in boundary and initial conditions. Adjustment methods should be discussed with appropriate regulatory authorities before submission of the results for approval.

X1.1.2.1 The first method, based on the principle of superposition of solutions, was first developed as a method for achieving analytical mathematical solutions to complicated boundary value problems. With this method (see, for example, Arpaci, 1966), the separate solutions for several different sets of boundary conditions acting on an object are mathematically summed to give the same solution that would occur if all the boundary conditions were applied to act on the object simultaneously. Strictly speaking, this approach is valid only when material properties are constant and do not vary with temperature. If applied to experimental results, material property values that give conservative results must be used. An example would be the superposition of a steady state solution for temperatures resulting from internal decay heat of the cargo onto experimental temperature transients measured during an actual test. This yields estimates of transient internal package temperatures adjusted for the presence of a hot cargo.

X1.1.2.2 A second and more easily justified approach is to match experimental results to a detailed analytical model (finite element or finite difference), and then use the analytical computer-based model to evaluate the results that would occur with different initial or boundary conditions. If an analytical model of the package were already completed as part of the package design process, this model could also be used to interpret and extend experimental results with high confidence. Allowances for temperature dependence of material properties can be included in such models.

X1.2 Adjustment of Results for Differences from Regulatory Initial Conditions

X1.2.1 Regulatory initial conditions, from 10CFR71, are as follows: "ambient air temperature before and after the tests must remain constant at that value between -29°C (-20°F) and +38°C (+100°F) which is most unfavorable for the feature under consideration." There is a pressure initial condition as well, and it is: "The initial internal pressure within the containment system must be the maximum normal operating pressure, unless a lower internal pressure, consistent with the ambient temperature assumed to precede and follow the tests, is more unfavorable."

X1.2.2 In pool fire, radiant heat and furnace testing, a common initial condition is the maximum temperature, 38°C (100°F). Deviation from this initial condition by a small amount (that is, ±5 %) is probably inevitable. For example, to bring a package to 38°C (100°F) normally requires an air heating system and insulated enclosure surrounding the package. In such systems, temperature variations of several degrees C are common. In addition, just before the beginning of the test one has to remove the heater and any insulation surrounding the package. The package immediately begins to cool unless the ambient temperature is 38°C (100°F) as well. This in turn causes greater temperature gradients (colder on the outside, warmer on the inside). In all cases the initial condition of the package should be as close as possible to the equilibrium condition of the package including any internal heat sources. See Appendix X3 for further discussion about initial conditions.

X1.2.3 In many cases, the desired initial conditions (that is, internal decay heat, external skin temperature, internal temperature distribution) are not possible to obtain precisely. For these kinds of conditions, the testing group and regulatory group should come to an up-front understanding of what is technically feasible, and come to an agreement as to the uncertainty allowed and the post-test adjustments necessary to make the data usable.

X1.2.4 For those initial conditions where the temperature is farther away from the desired temperature, postponing the test should be considered until the proper conditioning equipment is available. For example if the initial condition is 38°C (100°F), and the initial condition is really 20°C (68°F) because the equipment malfunctioned and the temperature dropped back to ambient, then one should just wait, repair the equipment, and re-condition back to 38°C (100°F).

X1.2.5 For those conditions where the initial conditions are outside the agreed upon range including the uncertainty, one should consider use of a validated computer model to adjust the results and predict the response to the slightly out of bounds initial conditions (see 7.1).

X1.2.6 It is suggested that a model be developed for several purposes:

X1.2.6.1 Initial predictions of the package response,

X1.2.6.2 Helping to define instrumentation locations,

X1.2.6.3 Prediction of the most severe initial condition,

X1.2.6.4 Be able to adjust results for non-standard initial or boundary conditions without repeat testing,

X1.2.6.5 Simulate package content decay heat, and

X1.2.6.6 Be able to adjust the average temperature of the test environment (furnace or radiant heat) to include effects of convection anticipated in a fire.

X1.3 Adjustment of Results for Differences from Regulatory Boundary Conditions

X1.3.1 Once the test is underway, a number of unexpected events might occur that would change the desired boundary conditions. Examples in radiant heat testing include lamp burnout, slight shifting of the enclosure surrounding the package which causes uneven heating, and control thermocouple failure that causes either a rise or drop in the enclosure temperature and therefore the heat flux to the package. In any of these cases, the event that triggers a non-desirable boundary condition could occur at any time during the test. If it occurs very early, before the package heats up appreciably, then it is likely best to just terminate the test before non-reversible destruction of the package occurs, fix the problem, re-stabilize at the desired initial condition, then begin the test again.

X1.3.2 If the failure event takes place after the package has heated up and some irreversible damage has occurred, it is best to continue the test and make as many adjustments as possible to mitigate the non-desirable boundary condition. For example in a radiant heat test, if enough lamps in an array panel fail, there will be a cold spot on the stainless steel enclosure surrounding the package. This effect can be mitigated somewhat by increasing power to the lamps in adjacent panels so the effect of the burned out lamps is lessened.

X1.3.3 How to adjust results for events that generate non-desirable boundary conditions should be decided on a case-by-case basis. If the boundary condition perturbation is "small," as defined by the regulator and package owner, then perhaps no major adjustments are required. This would be the case if the package passed with abundant margin so a small boundary condition perturbation would not be enough to cause the package to fail.

X1.3.4 In the case where it is not possible to determine the effect of the perturbed boundary condition on the package response, then additional testing, or assessment by analysis is required. If one does not have a validated model to use to predict the package response, then the only recourse might be an additional test. It is recommended (see above) that a thermal model be developed for the package.

X2. TEST PROCEDURES

X2.1 Considerations in Procedure Development

X2.1.1 Conducting a pool fire, furnace or radiant heat test requires interaction with a number of organizations, each with a different view of the testing activity. The first is the package design organization. Their objective is a timely economical test that subjects the package to the required conditions. The second organization is the package certification authority, which requires that the test definitively demonstrate that the package reliably meets the acceptance criteria. Organizations require hard evidence that the package was exposed to the required environment in the form of photographs, video coverage, and instrumentation response.

X2.1.2 Other organizations have an interest in the test as well. Open burning is prohibited in most US localities with exceptions normally given specifically for fire testing of radioactive material packages. Obtaining the exception requires interaction with local Environmental Protection Agency (EPA) representatives. They need estimates of the air emissions, information on the waste stream from the test, and information about ground water contamination preventative

TABLE X2.1 Sandia Integrated Safety Management System and Documentation

ISMS Point	Documentation
Plan Work	Test Plan
Analyze Hazards	Preliminary Hazard Screen
	Hazards Analysis
	NEPA Documentation
Control Hazards	Test Procedure
Perform Work	Test Readiness Review
Feedback and Improve	Post-Test Debriefing
	Test Data Report

measures. This interaction may be at the city, county or state level and involves obtaining some kind of burn permit. Furthermore, when U.S. Government agencies are involved either as designers or testers, the National Environmental Protection Act (NEPA) reporting requirements have to be met. At a minimum, this requires preparing an Environmental Checklist/Action Description Memorandum that is reviewed within the federal agency itself. Depending on the results of the review, an Environmental Assessment or an Environmental Impact Statement could further be required that would involve public hearings.

X2.1.3 Internal to the testing organization itself, are a number of entities that have a vested interest in the test. Internal safety, accounting, and resource management groups need to understand the test in order to provide their input to the whole process. Information about the conduct of the test, manpower, materials, cost and schedule are required for their use.

X2.1.4 To meet the needs of all interested parties in the test, some degree of formality is required. It falls upon the testing organization to provide the formality, as they bridge the package designer needs, the regulatory requirements, the EPA regulations, and the impact on the testing organization's resources. Some degree of caution needs to be exercised in adopting this formality, as it can become all consuming and can drive the cost and schedule. This is particularly true when the formality is "invented" as the test preparations progress and interactions with the different interested agencies occur. A well thought out approach that is acceptable to all interested parties is needed before any test preparations begin.

X2.1.5 An example of a workable formal approach is the DOE Integrated Safety Management (ISM) program which systematically integrates safety management, work practices, and environmental issues. All agencies within the DOE complex have implemented a specific form of the program germane to their particular activities. The ISM program consists of five main points listed in Table X2.1. Also in the table is the documentation that demonstrate compliance with the points. By following through on the points and required documentation, a testing organization is assured that pertinent information is available at the right time in the acceptable format.

X2.1.6 Note that other testing organizations are not subject to DOE practices, however, some kind of formal program like ISM needs to be worked out among the interested parties before attempting a test.

TABLE X2.2 Outline of a Test Plan

- Purpose of Test
  - Background Information on Package
  - General Expectations of Test
- Description of Package
  - Overall Dimensions and Weight
  - List of Materials
  - Required Test Orientation
  - Handling Features for Damaged Package
- Proposed Setup
  - Estimates of Fire Environment
  - Fire and Package Instrumentation
  - Package and Instrumentation Support Structure
  - Expected Instrumentation and Package Response
  - Strategy for Demonstration of Compliance with 10CFR71
- Proposed Procedure
  - Package Shipping and Handling
  - Timeline for Test Setup, Performance, and Cleanup
  - Package Post-mortem Activities
- Quality Plan
  - Identify Required Documentation
  - Identify Roles and Responsibilities

X2.2 Test Plan

X2.2.1 The purpose of the test plan is to facilitate communication among the interested parties. The creation of the plan generates and summarizes information that would otherwise be available in bits and pieces in widely dispersed locations. An outline of the information required in the test plan is shown in Table X2.2.

X2.2.2 *Hazards Documentation:*

X2.2.2.1 The hazards analysis required documentation is largely a function of the testing organization's in-house requirements. However, in general there is a need for preliminary screening where hazards are identified and categorized as to being of concern to the organization's employees or to the general public. The hazards then need to be analyzed, mitigated, and assessed for risk. The following is a partial list of hazards that need to be considered for a pool fire test:

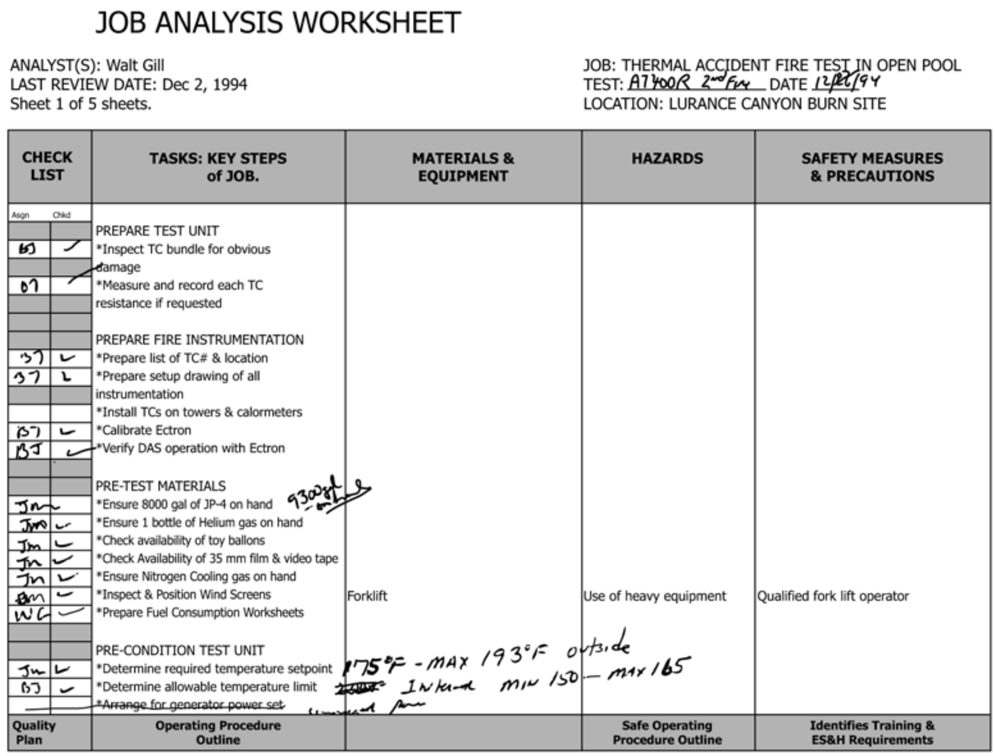
X-ray equipment
Radioactive material
Explosives
Lasers
Chemical/Hazardous Waste
Electrical Energy
Mechanical Energy
Thermal Energy
Pressure
High Noise Levels
Equipment used outside of design specifications
Use of non-commercial equipment
Environmental impacts

X2.2.2.2 If a U.S. federal agency is involved in the test, then the NEPA requirements need to be addressed. The federal agency is responsible for meeting NEPA requirements and has resources and procedures in place for doing so. However, much of the information needed would have to be furnished by the testing organization. With this in mind, Table X2.3 shows a partial list of the issues that would have to be addressed in NEPA documentation.

X2.2.3

X2.2.4 *Test Procedure:*

X2.2.4.1 A well thought out, written, and detailed test procedure is absolutely necessary for successfully conducting



JOB ANALYSIS WORKSHEET

ANALYST(S): Walt Gill
LAST REVIEW DATE: Dec 2, 1994
Sheet 1 of 5 sheets.

JOB: THERMAL ACCIDENT FIRE TEST IN OPEN POOL
TEST: A7400R 2nd Fire DATE 12/DEC/94
LOCATION: LURANCE CANYON BURN SITE

CHECK LIST	TASKS: KEY STEPS of JOB.	MATERIALS & EQUIPMENT	HAZARDS	SAFETY MEASURES & PRECAUTIONS
Asgn / Chkd				
	PREPARE TEST UNIT			
	*Inspect TC bundle for obvious damage			
	*Measure and record each TC resistance if requested			
	PREPARE FIRE INSTRUMENTATION			
	*Prepare list of TC# & location			
	*Prepare setup drawing of all instrumentation			
	*Install TCs on towers & calormeters			
	*Calibrate Ectron			
	*Verify DAS operation with Ectron			
	PRE-TEST MATERIALS			
	*Ensure 8000 gal of JP-4 on hand	9300 gal		
	*Ensure 1 bottle of Helium gas on hand			
	*Check availability of toy ballons			
	*Check Availability of 35 mm film & video tape			
	*Ensure Nitrogen Cooling gas on hand			
	*Inspect & Position Wind Screens	Forklift	Use of heavy equipment	Qualified fork lift operator
	*Prepare Fuel Consumption Worksheets			
	PRE-CONDITION TEST UNIT			
	*Determine required temperature setpoint	175°F - MAX 193°F outside		
	*Determine allowable temperature limit	Intake min 150 — max 165		
	~~*Arrange for generator power set~~			
Quality Plan	Operating Procedure Outline		Safe Operating Procedure Outline	Identifies Training & ES&H Requirements

FIG. X2.1 Job Analysis Worksheet

any test. As pointed before, once the test starts, the commitment is total. The only recourse for recovering from forgotten steps is repeating the entire test sequence up to and including the actual test.

X2.2.4.2 The actual format of the procedure is dependent on in-house requirements. However, there are basic requirements that a procedure should provide. The procedure should clearly state the purpose of the test, identify roles and responsibilities of the individual participants, set a up logical time sequence of steps to be followed (and signed off as having been completed), identify necessary equipment and associated hazards, and specify the required records to be kept. The procedure needs to be a controlled recoverable document, as it will become part of the material submitted to the regulatory authority as evidence that the test was properly executed.

X2.2.4.3 At a pre-meeting, all parties shall agree on the steps for conducting the test. For purposes of example, a radiant heat test is considered here. The approach is then formalized, and a test plan prepared by the testing organization.

X2.2.5 *Test Readiness Review:*

X2.2.5.1 The test readiness review is a presentation by the test organization to the package design organization. The purpose of the presentation is to insure that all objectives of the test will be met, and as such, participation by the other interested parties is also needed. The testing organization makes the presentation to representatives of the package design organization, in-house environmental safety and health groups, and any interested outside oversight group.

X2.2.5.2 A partial agenda of the review is given in Table X2.4. The documentation consists of a memorandum stating the review occurred and list of action items. A second memorandum is needed documenting the closeout of the actions items.

X2.2.6 *Post-Test Debriefing:*

X2.2.6.1 During the post-debriefing, the testing organization presents their interpretation of the outcome of the test with respect to meeting the accident environment described in the regulations. The quality of the data, occurrence of abnormal events, and lessons learned are discussed. A memorandum documents the meeting.

X2.2.7 *Test Data Report:*

X2.2.7.1 The testing organization generates a test data report that ultimately becomes part of the evidence presented to the regulatory authority. An outline of the material that needs to be included in the report is given in Table X2.5.

X2.3 Organization

X2.3.1 The process of preparing and configuring for a pool fire test is shown in Table X2.6. In the table, the various roles that must be played are indicated in the columns. The role players can range from entire organizations to a small task groups or individuals. The tasks required of the role players are shown in the table rows in more or less chronological order; the order being determined by the degree of interaction between the various tasks.

X2.4 Example Procedure

X2.4.1 The worksheets shown in Fig. X2.1 are taken from a completed procedure where two shipping containers were

Sheet 2 of 5 sheets.

CHECK LIST Asgn	CHECK LIST Chkd	TASKS: KEY STEPS of JOB.	MATERIALS & EQUIPMENT	HAZARDS	SAFETY MEASURES & PRECAUTIONS
		FACILITY CHECKOUT			
		*Check Fire Set operation	Fire Set	High Voltage	Use Fire Set OP
		*Check Fuel Valve Operation			
		*Check extension cords for breaks & kinks			
		*Verify GFI systems to be used			
		*Check operation of sight glass video			
		~~*Verify "Critical Equipment" connected to UPS~~ No UPS	DAS, Sight Glass Video, Fuel Valve Power Supply, Fuel Valve Air Solenoids		
		*Check operation cooling water pump			
		*Checkout video equipment and 35 mm camera			
		TEST SETUP			
		*Install test item in pool	Crane	Use of heavy equipment	Qualified crane operators
		*Insulate TC bundle from test unit	Ladders, steel wire, insulation & flexible conduit	Insulation fibers, cuts & high places	Use gloves, face mask, eye protection read MSDS for insulation
		*Connect TCs to DAS per setup sheet			
	NOTE	connect each TC one at a time and record channel #			
		*Verify and record TCs condition with DAS, temperature & resistance			
		*Photograph test setup			
		*Install heater on test unit	Heaters, Controller, Generator	Temporary Electrical Installation	Inspect cables and connectors
		*Start DAS at required sample rate			
		*Start heating process - note time			
		~~*Arrange generator refueling~~			
		*Arrange for heater monitor			
Quality Plan		Operating Procedure Outline		Safe Operating Procedure Outline	Identifies Training & ES&H Requirements

Sheet 3 of 5 sheets.

CHECK LIST Asgn	CHECK LIST Chkd	TASKS: KEY STEPS of JOB.	MATERIALS & EQUIPMENT	HAZARDS	SAFETY MEASURES & PRECAUTIONS
		DAY BEFORE TEST			
		Verify ES&H documentation			
		~~*TOR~~			
		*Burn permit			
		*DOE approval			
		*Inform Air Quality Monitors			
		*Check weather prediction and record wind velocity			
		*Make notification calls and record time and person contacted			
		~~*Make arrangements for fire truck or water tanker if required~~	Not required; Fire fighting equipment	Forest fire	Standby fire truck
		DAY OF TEST			
		*Check weather prediction and record wind vel & amb temp			
		*Setup video system			
		*Fill pool with 24" of water			
		*Launch helium filled ballons	Helium gas bottle & regulator	High gas pressure	Hazard Communication Training Module Six "Compressed Gases"
		#1 time ___ direction ___			
		#2 time ___ direction ___			
		#3 time ___ direction ___			
		*Unplug heaters			
		*Remove test unit heaters			
		*Turn on cooling water			
		*Close Wind Screens			
Quality Plan		Operating Procedure Outline		Safe Operating Procedure Outline	Identifies Training & ES&H Requirements

FIG. X2.1 Job Analysis Worksheet *(continued)*

subjected to a pool fire test. The activities began several days before the actual fire, because the test units were pre-conditioned to a desired initial temperature. This was accomplished by heating the test units in place over the pool with barrel heaters.

X2.4.2 As can be seen in reading through the procedure, test materials were gathered, equipment checked out, and the pre-conditioning began. On the day before the test, a general announcement of the intention to test was made to interested parties. On the day of the test, the test personnel were brought in at first light and wind conditions began to be monitored. When it was apparent that the wind was going to follow the predicted pattern, preparations for conducting the test started. This involved removing the barrel heaters from the test units and fueling the pool. The pool was filled with only enough fuel to burn approximately half the required time. The fuel consumption was monitored, and a linear fuel level recession rate was established on a level versus time plot. The slope of the

Sheet 4 of 5 sheets.

CHECK LIST Asgn	CHECK LIST Chkd	TASKS: KEY STEPS of JOB.	MATERIALS & EQUIPMENT	HAZARDS	SAFETY MEASURES & PRECAUTIONS
		*Call County Fire Marshall 345-5600 KAFB Command Post 846-6432 Sandia Security 845-5134			
		*Take Documentation Photos			
		TEST CONDITION "GO"			
		*Clear pool arena of all personell			
		*Announce presence of fuel hazard			
		*Fill 20 × 20 pool with JP-4 fuel to desired depth 3''	Fuel	Flammable JP-4 fuel Toxic Fumes	Hazard Communication Training Module Five "Chemical Carcinogens" NO open flames within 50 FT
		*Turn on video equipment			
		*Verify DAS operation System recording Set 10 sec Scan rate			
		*Calibrate Velocity Probes			
		*Start 2nd DAS if required			
		POOL IGNITION			
		*Set hazard zone		High pressure in test unit Noxious Fumes	Maintain hazard zone until unit has cooled to ambient temperature
		*Turn on cooling gas			
		*Follow insert from "Operating Procedure For Fuel Ignition System". Sections 1.3, 1.4	Spark Ignition System	High Voltage	Follow Ignition OP
		*Record ignition time Time ______			
Quality Plan		Operating Procedure Outline		Safe Operating Procedure Outline	Identifies Training & ES&H Requirements

Sheet 5 of 5 sheets.

CHECK LIST Asgn	CHECK LIST Chkd	TASKS: KEY STEPS of JOB.	MATERIALS & EQUIPMENT	HAZARDS	SAFETY MEASURES & PRECAUTIONS
		*Record final burnout time TIME ______			
		~~*Re-Calibrate Velocity Probes~~			
		*Call County Fire Marshall, Command Post & Security			
		*Post hazard signs if required			
		~~*Reset DAS scan rate for coo~~l down			
		*Record data until Project Engineer determines peak temperature is reached without artificial cooling			
		*Photograph package on test stand			
		POST TEST ACTIVITIES			
		*Slow extension cords			
		*Drain fuel from supply line			
		*Pump out pool	Pump	Over flow of water storage tank	Follow Pool Pumpout JAWS
		*Reclaim test item	Test item, Fork lift, Crane	Damaged test item with decomposed hazardous materials	Seek advice from Test Engineer before handling
Quality Plan		Operating Procedure Outline		Safe Operating Procedure Outline	Identifies Training & ES&H Requirements

FIG. X2.1 Job Analysis Worksheet *(continued)*

plot was transferred to intersect desired ending time (Figure 7.2.6 in main text).

TABLE X2.4 Possible NEPA Concerns

Use and Storage	Chemicals
	Petroleum/fuel products
	High energy sources/explosives
	Pesticides/herbicides
Waste	Solid waste
	Hazardous waste
	Radioactive waste/materials
	Mixed waste (radioactive + hazardous)
Emissions	Air emissions
	Liquid effluents
Health and Safety Issues	Radiation exposure
	Chemical exposure
	Noise levels
	Transportation of hazardous materials/waste
Land Issues	Clearing or excavation
	Archaeological/cultural resources
	Special status species/environment
	Real estate issues
	Related off-site activities
Special Issues	Asbestos
	Utility system modifications
	Environmental Restoration Site

TABLE X2.5 Agenda for Test Readiness Review

- Overview of the Test
  - Strategy for demonstrating compliance with 10CFR71
  - Instrumentation
    - Expected Response
    - Demonstration of Calibration
- Walk-through Procedure
  - Discussion of Hazards
  - Mitigation of Hazards
  - Post-Test Cleanup
    - Disposal of Test Unit
    - Disposal of test waste material
- Presentation of Required Documentation
  - Permits
  - Safe Operating Procedures
- List of Action Items

TABLE X2.6 Outline of Test Data Report

- Introduction
  - Identification of Test Item
  - Description of Test setup
- Overview of the Instrumentation
- Data Acquisition
- Test Procedure
  - Summary of Events
- Test Unit Thermal Response
- Fire Instrumentation Response
  - Temperature
  - Heat Flux
- Weather Conditions
- Visual Records
  - Video
  - Photographs
- Assessment of Thermal Environment
- Appendices
  - Instrumentation Calibration
  - Completed Procedure Checklist
  - Copies of Permits

TABLE X2.7 Process for a Fire Test

Customer	Administration	Engineering	Operations	Regulators
Initiate Request	Cost Estimate	Generate Preliminary Test Plan		10CFR71
Supply Funding	Allocate Funding to Resources			
Review and Concur with Test Plan		Finalize Test Plan		
		Design Test	Calibrate Instrumentation	NIST
	File Environmental Documentation	Perform Hazards Analysis		In-house Environmental Organization
	Obtain Open Burn Permits			Local EPA Air Quality Board
			Implement Test Setup	
		Prepare Test Procedure	Walk Through Procedure	In-house Safety Organization
	Initiate Public Notification		Conduct Full Dress Rehearsal	Local EPA Air Quality Board
Review and Concur with Test Procedure		Conduct Test Readiness Review		
Provide Test Unit	Shipping and Handling		Execute Test	
Review Draft Test Data Report		Draft Test Data Report		
		Conduct Post-Test Debriefing	Perform Post-Test Cleanup	In-house Waste Management Organization
Accept Final Report	Closeout Funding Account	Finalize Test Data Report		

X3. COMPARISON OF 10 CFR 71.73 AND IAEA TS-R-1

TABLE X3.1 Conditions for the Thermal Portion of a Hypothetical Accident

Condition	10 CFR 71.73	IAEA SS TS-R-1
Initial Temperature, °C	–29<T<38	38
Initial Insolation	May be neglected	Yes
Content Decay Heat	Yes	Yes
Environment Emissivity	>0.9	>0.9
Package Emissivity	>0.8	>0.8
Environment Temperature, °C	>800	>800
Test Time, min	30	30
Facility	Fire	Fire
Post-test Temperature, °C	–29<T<38	38
Post-test Insolation	Implied	Yes

X3.1 The conditions for the thermal portion of the hypothetical accident (10 CFR 71.73) [2000] and IAEA TS-R-1 [1996] are given in Table X3.1.

X3.2 The initial thermal conditions of a package prior to the thermal portion of a hypothetical accident are, under 10 CFR 71.73, similar to those used to estimate the package surface temperatures for 10 CFR 71.43(g), for example, in 38°C still air without insolation. The initial thermal conditions of a package prior to the thermal portion of a hypothetical accident are, under IAEA TS-R-1, §728, identical to those used to estimate the temperatures of the package for normal conditions of transport under 10 CFR 71.71(c)(1), for example, in 38°C still air with insolation.

X3.3 The application of insolation to a package during the post-test cool down is unspecified in 10 CFR 71.73 [2000], but the Federal Register (Vol 60, No.188, pg. 50257, [September, 1995]) noted that "NRC adopts the view of the thermal experts who participated in developing the IAEA regulations. Those experts thought the effects of solar radiation may be neglected before and during the thermal test but such effects should be considered in the subsequent evaluation of the package response."

X3.4 The difference in the initial conditions prescribed by 10 CFR 71.73 and IAEA TS-R-1 result in different temperature implications for a given package. Some packages, with the surface heat flux from the content decay much less than the insolation, may have lower internal temperatures during a 10 CFR 71.73 test than for normal conditions of transport. Conversely, for all packages the IAEA TS-R-1 tests will result in the maximum internal temperatures being greater than for normal conditions of transport. For no loss of thermal effectiveness and with insolation, the steady state post-test temperatures will be the same for the 10CFR 71.73 and the IAEA TS-R-1 tests. For no loss of thermal effectiveness, with insolation, and with no change in emissivity, the steady state post-test temperatures will be the same for the 10CFR 71.73 and the IAEA TS-R-1 tests and equal to that of the normal conditions of transport.

X3.5 The application of the current version of IAEA TS-R-1, §728 [1996] may result in greater internal package temperatures from the thermal hypothetical test than will result from the application of the current version of 10 CFR 71.73 [2000].

X4. THERMAL CODES

X4.1 A number of thermal analysis codes are available to perform the thermal qualification analyses of radioactive material transportation packages. A few are described in this appendix for the reader's benefit. Codes not mentioned herein may be equally adequate to perform thermal qualification of packages to regulatory requirements. No comparison or benchmarking of codes is done in this document.

X4.2 Older thermal codes include TAP-A, SINDA, ANSYS and HEATING. More recently developed codes are COSMOS/M, MSC Patran Thermal and Thermal Analysis System (TAS). The general characteristics of three thermal codes are given below.

X4.3 *HSTAR:*

X4.3.1 The HSTAR module of COSMOS/M, developed by Structural Research and Analysis Corporation (SRAC), Los Angeles, CA, is a general purpose heat transfer analysis code. It provides a simple approach for performing thermal analysis.

X4.3.2 When modeling thermal problems, HSTAR enables the user to model real-world time and temperature dependent loads and boundary conditions. HSTAR models heating and cooling effects, material phase changes caused by conduction, convection and radiation under steady state and transient conditions. The matrix solver performs the analysis without introducing any approximation in the result calculation.

X4.4 *MSC Patran Thermal:*

X4.4.1 MSC Patran Thermal, developed by MSC Software in Costa Mesa, CA, supports a wide range of boundary conditions such as nodal, surface, and volumetric heat sources, nodal temperatures, convective surfaces, radiative surfaces, and advective flows. Earlier versions of this code were called qtran, and benchmarking documents often refer to it by that name.

X4.4.2 Radioactive packaging models may be constructed in MSC Patran using native geometric entities or models can be imported directly from all major CAD packages including ProE, Catia, or Unigraphics.

X4.4.3 All boundary conditions may be input as constant, time or temperature dependent, or spatially varying and can be defined by combinations of built-in tabular or analytic functions or Fortran user-subroutines. An exact mathematical representation of the model is assured by creating a resistor-capacitor network using all finite element cross-derivative terms. The element library includes two-dimensional, three-dimensional, and axisymmetric elements.

X4.4.4 MSC Patran Thermal includes a radiation view-factor algorithm for accurately computing and modeling thermal radiation interchange among radiative surfaces.

X4.4.5 All files required for the MSC Patran Thermal analysis of radioactive packaging are created seamlessly and automatically from the MSC Patran graphical user interface. All files are accessible as text files for manual user intervention and modification, if desired.

X4.4.6 Output from MSC Patran Thermal is in the form of a nodal result file. It contains all nodes in the model and the temperatures at the nodes. The nodal files are read into MSC Patran. Results can be viewed from within MSC Patran as fringe plots, contour plots, or as text reports. Data analysis of results can be performed within MSC Patran by combining or algebraically manipulating result sets within the graphics interface.

X4.4.7 The MSC Patran interface has built-in translators to SINDA, TRASYS, and NEVADA and provides an interface to structural analysis codes like MSC Nastran through the use of self-interpolating temperature results fields.

X4.5 *TAS:*

X4.5.1 Thermal Analysis System (TAS) developed by Harvard Thermal, Harvard, MA, provides a single graphical interface for generating the model, solving it for temperatures and viewing the results. The finite element style of model generation allows the user to generate complex three-dimensional models.

X4.5.2 TAS is a general-purpose commercially available tool used to computer-simulate thermal problems. The program provides an integrated, graphical and interactive environment to the user. A single environment provides model generation, execution and post-processing of the results. Models are generated using a set of elements. Full three-dimensional geometry can be created using two-dimensional plate and three-dimensional brick and tetrahedron elements. Convection, radiation and fluid flow elements are provided. Resistance can be added using resistor elements. Properties can be temperature, temperature difference, time and time cyclic dependent. Heat loads can be added on a nodal, surface or volumetric basis.

X4.5.3 Models generated can be subjected to various environments and thermal loads. The models can be used to determine the adequacy of a design or to determine problem areas. Geometry, thermal properties and parameters of the model can be easily changed to determine their effect. The design can be thermally optimized and characterized before incurring the expense of building and testing a prototype.

X4.5.4 TAS contains a finite difference solver. This technique performs a heat balance at each node in the model. This entails calculating the node temperature based on the resistance and the temperatures of all nodes attached to the node in question.

X4.5.5 The model is generated interactively with the screen graphics thus the user does not have to keep track of element and node numbers. Convection, radiation, heat loads and temperature boundaries are added to complete the model. The finite difference solution allows temperature and time-dependent properties and boundary conditions, convection and radiation to be easily handled.

X4.5.6 The element library includes two-dimensional plate elements, three-dimensional brick elements and three-dimensional tetrahedron elements.

X5. INSTRUMENTATION CONCERNS AND POTENTIAL ISSUES

X5.1 Thermocouple Calibration

X5.1.1 There has been considerable discussion regarding thermocouple calibration in the literature, and this appendix does not intend to repeat those discussions. Suffice it to say that to calibrate a thermocouple in practical terms, one inserts the thermocouple into an oven of a known temperature, and the thermocouple output is measured. If the thermocouple output is within ±0.75 % or ±2.2°C (±4°F) (depends on temperature level) of the oven temperature, the thermocouple is within ASTM specifications. Assuming one has a "good" thermocouple, the calibration can be measured to a tighter tolerance than ±0.75 % or ±2.2°C (±4°F).

X5.1.2 However, in reality one has only calibrated that section of thermocouple wire in the temperature gradient. If the thermocouple is used in an environment where the "calibrated" section of thermocouple wire is in no temperature gradient, then the calibration performed is of no use. Thermocouples generate output only in those sections of wire where there is a temperature gradient. Because calibrations do not specify where the temperature gradient was on the length of the wire, the calibrations are normally not useful. The only case where a calibration is useful is if the entire length of the wire is checked for inhomogeneous sections. If all parts of the wire are calibrated, and the results show errors less than ±0.75 % or ±2.2°C (±4°F), then one can conclusively say the thermocouple is calibrated to a tolerance less than the ASTM standard.

X5.1.3 One consideration for large tests is to specify during purchase that all thermocouples to be used are to be made from the same batches of thermocouple wires. This increases confidence that limited calibrations can be applied to all data.

X5.2 Instrumentation Survival

X5.2.1 Instrumentation survival is easier to accomplish in radiant heat testing than in pool fire testing. Experience has shown that the tips of inconel sheathed, type K (chromel-alumel) thermocouples are actually damaged in an intense hydrocarbon fuel fire (for example, one with high winds). This is not observed in a radiant heat or furnace testing except when the local temperature rises above the melting temperature of the thermocouple.

X5.3 Typical Thermocouple Types and Heat Conduction Errors

X5.3.1 Thermocouples used in radiant heat, pool fire and furnace testing are typically 1.6 mm (0.0625 in.) diameter and 3 to 6 m (10 to 20 ft) long. It is important to keep the first few wire diameters (about 20) in an isothermal condition so heat conduction along the thermocouple wires does not induce a non-negligible error. If the thermocouple is in a large gradient, one should estimate the errors (based on the literature), and include a correction in the data reduction process.

X5.4 Thermocouple Shunting

X5.4.1 Thermocouple "shunting" is a concern for pool fires and other thermal tests. Shunting is a source of error induced when the electrical resistivity of the magnesium oxide (or other mineral insulation) drops at high temperatures. The electrical resistivity of mineral insulations used in mineral-insulated, metal sheathed thermocouples drops with temperature, by several orders of magnitude. If the purity of the insulation is low enough (for example, 96 % rather than 99 %) and the sheath temperatures reach to over 800°C (1475°F), shunting can occur and cause a non-negligible error in the thermocouple reading. The shunting error is often exhibited as erratic, rapid, wide temperature swings that appear to be very large amplitude random noise. Discussions of magnesium oxide purity with the thermocouple supplier are in order when the thermocouples are ordered.

X5.4.2 A test for thermocouple shunting can be conducted prior to a large test by routing a portion of a thermocouple sheath (away from the tip) through a tube furnace or similar hot zone to simulate the cold-hot-cold profile that creates shunting problems in actual tests. By controlling furnace temperature and observing the thermocouple output, the temperatures at which shunting becomes a problem can be determined.

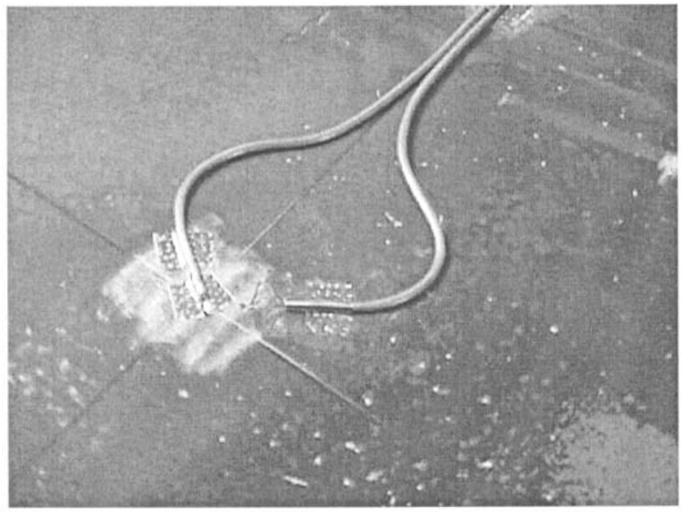
X5.4.3 For fire tests, thermocouples measuring the temperature of the internal parts of the package exit the package into the fire region before exiting to cooler areas. The area after exiting the package and before entering the pool is normally directly in the fire. This is the area where electrical shunting of the insulation in the thermocouple sheath occurs. Shunting can be prevented but normally requires that the thermocouple sheaths be heavily insulated and in some cases actively cooled. (Active cooling is not normally required for 30 min fires if the thermocouples are sufficiently well insulated.) Neither of these instrumentation issues is normally important for radiant heat or furnace testing. Also, thermocouple lengths are shorter for radiant heat or furnace tests.

X5.5 Pre-Test Checks

X5.5.1 One key element of initial checkout, especially for mineral insulated, metal sheathed thermocouples is to perform resistance checks and connector checks. Resistance checks confirm wire size and viability, and that resistance to sheath is sufficiently high. Connector checks are important because sometimes the connectors are wired backwards.

X5.6 Instrumentation Intrusion

X5.6.1 Care has to be taken to ensure there is minimal intrusion by the instrumentation on the package. One always



NOTE 1—The themocouple on the left is a sheated thermocouple. The thermocouple on the right is an intrinsic thermocouple with wires directly attached to the surface of the test object.

FIG. X5.1 Typical Thermocouple Attachment with Nichrome Strips

wants to minimize the changes in the response of the package if the instrumentation were not present. For example, if the package had holes drilled to allow the thermocouple leads to exit from the interior of the package, pressurization of the package might not occur unless the instrumentation penetrations were properly sealed. If there were flammable materials inside the package, and sufficient oxygen, there could be a fire inside the package, and the combustion products could exit the instrumentation hole (this has occurred).

X5.6.2 For cases where the instrumentation intrusion is unavoidable, one should include the effect of such intrusions on the overall uncertainty analysis by additional data validation experiments, or by analysis.

X5.7 Thermocouple Type and Mounting

X5.7.1 Most thermal testing to qualify packages involves the use of thermocouples. Thermocouples are rugged, readily available, and cost effective, but are to be used with care. The important fact to keep in mind when placing thermocouples is that they only indicate the temperature near the junction, which is not necessarily the same as the temperature of the surface to which they are attached. In a testing environment a thermocouple attached to a package surface or a test chamber wall receives a mix of thermal conduction from the underlying surface with possible influence from contact resistance, thermal radiation from the testing heat source, and convection from the surrounding gases. In addition, because sheathed thermocouples and their attaching material have a finite mass, they do not respond instantaneously to surface temperature changes. For these reasons thermocouples must be firmly attached to a surface and shielded from direct thermal radiation if they are to give a good estimate of surface temperature. Thermocouple errors are discussed by Nakos, et al, 1989, Sobolik, et al, 1989, and Son, et al, 1989.

X5.7.2 Typical thermocouples used are ungrounded, mineral insulated, metal sheathed, type K (chromel-alumel) thermocouples with magnesium oxide insulation, and are commercially available from several vendors. They are normally 1.5 mm (0.0625 in.) diameter but can be as small as 0.5 mm (0.020 inches) and larger (for example, 3 mm or 0.125 in.) and have an inconel or stainless steel sheath. They are attached (see Fig. X5.1) to weldable materials via thin (0.08 mm [0.003 in.] thick by 6 mm [¼ in. wide]) nichrome strips tack welded to the material (but not to the thermocouple). The measuring junction is covered with the nichrome strip to effect better thermal contact with the surface. In cases where the temperature is low enough (for example, below 1000F), intrinsic thermocouples are made wherein the individual chromel and alumel wires are individually welded to the material being tested. Intrinsic thermocouples provide a measurement with less error, but are not as robust as sheathed thermocouples and so often do not survive the test environment.

X6. HOMOGENIZATION OF SPENT NUCLEAR FUEL ASSEMBLIES AND BASKET COMPONENTS FOR TRANSPORTATION CASKS

X6.1 Spent nuclear fuel transportation casks present significant challenges for the thermal analyst because they include numerous internal components as well as significant internal heat generation. Detailed modeling of spent fuel assemblies, including individual spent fuel rods, grid straps, top and bottom nozzles, and the spent fuel basket internal to a cask with finite element (FE) methods is difficult, and can overwhelm available computer resources.

X6.2 When analyzing spent nuclear fuel transportation casks, a common practice among analysts is the homogenization or "smearing" of spent fuel properties within a FE model to simplify the analysis by reducing the number of elements and nodes. Homogenization of fuel assemblies is done by determining an effective thermal conductivity, density, and heat capacity for a fuel assembly, and applying these values to a solid representation of the fuel assembly (either a square in 2 dimensions or a rectangular solid in 3 dimensions). The solid representation will have less detail and therefore fewer elements and nodes than would a detailed fuel assembly model. Some analysts will go one step further and homogenize the entire fuel region including the basket structure. This practice will be successful in estimating bounding fuel region temperatures, but is not as accurate for determining precise fuel cladding temperatures.

X6.3 The challenge to the analyst is to accurately determine the effective properties of the solid homogenized fuel assembly models, and assure that the model is a correct representation of the actual fuel assembly thermal characteristics. There are several different methods for determining the effective properties for analytic fuel models, some of which will be reviewed here. The reference list for this section provides several references that describe the different methods in depth.

X6.4 In general, a successful homogenization of fuel assemblies will be based on successful benchmarks against temperature data taken from actual spent nuclear fuel assemblies stored in storage casks with the effects of orientation taken into consideration. The basic steps for creating a homogenized fuel model are as follows:

X6.5 *Overall Approach for Developing Homogenized Models of Fuel Assemblies:*

X6.5.1 First, a detailed model of the fuel assemblies (including fuel pellets, fuel cladding and rod fill gasses) and the fuel basket is developed to account for all heat transfer mechanisms involved, including conduction, radiation and, where appropriate, convection. This model shall be verified against spent fuel temperature data to ensure that it provides an accurate fuel assembly and basket temperature distribution.

X6.5.2 The next step is to calculate an effective conductivity for the simplified geometry (usually a square area or a rectangular volume) that will replace the detailed fuel assembly model. This is commonly done by varying the temperature of the basket cell wall in which the fuel assembly resides and using the temperature difference between the hottest fuel rod and the cell wall to calculate the effective conductivity. Density and specific heat are often averaged and then applied to the area or volume representing the homogenized fuel assembly.

X6.5.3 Finally, the effective conductivity and average density region shall be modeled to assure that the temperature profile closely matches that of the original detailed fuel model. Note that when fuel is homogenized the temperature estimates made for fuel cladding are less accurate than with a detailed fuel model. This shall be taken into account when attempting to draw conclusions about peak fuel cladding temperatures from homogenized fuel models.

X6.6 *Methods for Determining Fuel Temperatures and Effective Conductivity Values:*

X6.6.1 One of the older correlations for determining peak fuel cladding temperatures and effective thermal conductivity values for spent fuel is the Wooton-Epstein (W-E) correlation (See Wooten and Epstein, 1963). Introduced in 1963, this correlation has been used by many cask designers since that time. The W-E correlation is based upon experiments conducted on a single fuel assembly in air, made up of 306 solid stainless steel tubes (0.34 in. in diameter) arranged in a 17 × 18 assembly on 0.422 in. centers. The assembly was approximately 8 ft long. The tubes were heated via resistance heating to simulate a decay heat of 8 kW (equivalent to 3 months of cooling). The assembly was centered in a steel pipe with an inside diameter of 1 ft. An annulus outside the pipe was filled with coolant to maintain a constant wall temperature. In their paper, Wooton and Epstein stated that for a given assembly decay heat, the correlation would over-predict the fuel cladding temperature. Currently the W-E correlation is considered to be more conservative than necessary for thermal analysis of spent fuel assemblies under most conditions of storage.

X6.6.2 Manteufel and Todreas, 1994, describe a method for determining the effective thermal conductivity of spent fuel assemblies by defining a unique effective thermal conductivity for interior and edge regions of individual fuel assemblies. This model is based on conduction and radiation within the fuel assembly. Convection effects are added to the correlation for certain temperature regimes. The model is applied to both PWR and BWR fuel assemblies. The model is compared with five sets of data for experimental validation, as well as with predictions generated by the engine maintenance, assembly, and disassembly (E-MAD) and W-E correlations.

X6.6.3 Thomas and Carlson, 1999, present an informative discussion of heat transfer within a fuel assembly and between a fuel assembly and its surrounding environment. The study in their paper presented a discussion of the Fuel Temperature Test (FTT) experimental series (Bates, 1986) which was conducted for a single Westinghouse 15 × 15 fuel assembly with a decay heat load of 1.17 kW, in vacuum, air, and helium backfill conditions.

X6.6.4 The authors used the TOPAZ3D finite element analysis (FEA) code to model the test set-up by determining an effective thermal conductivity for the fuel region, first for the vacuum case. They then used those values to determine the helium and air backfill cases. They adjusted the conductivity values of the air and helium to account for any convection that might be present, to closely match the values presented in the FTT experiments. Results and a discussion of those results are provided in their report.

X6.6.5 The authors included a comparison of the results with the effective thermal conductivity model of Manteufel and Todreas and determined that their model produced slightly lower (more conservative) effective thermal conductivity values for the same conditions present in the FTT experiments. The correlation that was developed by the authors was developed for specific spent fuel parameters, and would not be applicable to spent fuel types with different values for parameters such as burn-up, cooling time, decay heat, etc.

X6.6.6 In a report prepared for the Department of Energy, Bahney and Lotz, 1996, review current techniques for fuel homogenization and describe a method of determining fuel effective thermal conductivity with the use of FEA. Detailed models of fuel elements were developed for several PWR and BWR fuel assembly sizes and analyzed for a range of heat loads and fuel basket temperatures. Effective thermal conductivity values were then determined for individual assemblies from the fuel temperature results. This paper provides a substantive discussion of the W-E correlation, and includes a calculation of peak cladding temperatures with use of the correlation. The fuel cladding temperatures calculated with the W-E correlation were found to be greater than those calculated with the FE method for the same geometry and heat load values. The paper provides the derivation of a formula for effective conductivity of a homogenized fuel assembly, and provides values for different fuel element sizes. These effective conductivity values are compared to conductivity values derived from the W-E correlation. For the most part, the W-E conductivity values were lower (more conservative) than the values calculated based on the FE method.

X6.6.7 In the 1980's a series of tests was conducted on spent fuel storage casks at the Idaho National Engineering Laboratories (INEL). The Pacific Northwest Laboratories (PNL) in cooperation with the Electrical Power Research Institute (EPRI) conducted the tests and published the results. Several different casks were tested including the Castor-V/21 (Dziadosz, et al, 1986), the Transnuclear(TN)-24P (Creer, et al, 1987), the VSC-17 (McKinnon, et al, 1992) and the MC-10 (McKinnon, et al, 1987). These casks contained spent nuclear fuel assemblies of various sizes and burn-ups, removed from an operating nuclear reactor. Temperature measurements were taken with the casks in different orientations and using different fill gasses. PNL used this data to validate their COBRA-SFS code, which is a best-estimate finite difference code that provides accurate spent fuel cladding temperatures for almost any type of spent fuel assembly in a cask. The data from these tests has been used by other analysts to develop accurate homogenized spent fuel assembly thermal models.

X6.6.8 Sanders, et al, 1992, described a method of determining spent fuel effective thermal conductivity that utilized the TOPAZ 2D finite element code. Data from the EPRI reports mentioned above was used to develop a fuel pin model and then a full fuel element model. From the fuel element model, an effective thermal conductivity was developed and used to predict maximum fuel cladding temperatures. The predicted temperatures were only slightly above those reported in the EPRI reports for a similar fuel assembly.

X6.7 *Conclusion*—Homogenization of spent fuel for thermal analysis is a fairly straightforward process that yields significant savings in analysis time, while providing accurate results. The methods described in this appendix provide the analyst with the tools to build an accurate FE model for spent fuel assemblies. A careful review of the methods summarized here is encouraged, as the details of each method need to be understood by the analyst if they are to be successful in building accurate homogenized fuel models. Models developed by an analyst shall be verified against the best available data for a given fuel assembly. Verification will provide the necessary support for an analysis that will be reviewed by a regulatory body.

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