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# A Guide For Thermal Testing Transport Packages For Radioactive Material

## *- Hypothetical Accident Conditions -*

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# ABSTRACT

This document provides guidelines for planning, conducting, and reporting thermal tests on transport packages for radioactive material. Test conditions and acceptance criteria are for the hypothetical accident conditions specified in *Part 71 of Title 10 Code of Federal Regulations* (*10 CFR 71*). All Type B packages for transport of radioactive material must be tested to these conditions, by physical or analytical test, and meet the acceptance criteria for certification by a U.S. regulatory agency as being in compliance with federal safety standards. The principal objective of this Thermal Test Guide (TTG) is to provide an applicant with general recommendations for development of a physical test program. Also, the TTG is in accord with the general philosophy for reviewing safety analysis reports for packaging and provides a common basis for applicants and reviewers. As there can be a large variety of package designs, the TTG is not all-inclusive. An applicant should appropriately apply the TTG to ensure acceptable test conditions and results for a particular package design. Recommended test conditions are based on a proposed ruling of *10 CFR 71* that was published in the U.S. Federal Register. Thermal test conditions in the proposed ruling exceed those specified in the current ruling. Also, they are effectively equivalent to thermal test conditions specified by the International Atomic Energy Agency (IAEA) for Type B packages. Thus, by following the TTG recommendations, an applicant would be assured of meeting future *10 CFR 71* requirements and also complying with IAEA requirements.

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# GLOSSARY

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|---|---|
| $A_1$ | The maximum activity of special-form radioactive material permitted in a Type A package. ($A_1$ values are given in Appendix A of *10 CFR 71*.) |
| $A_2$ | The maximum activity of radioactive material, other than special-form radioactive material, permitted in a Type A package. ($A_2$ values are given in Appendix A of *10 CFR 71*.) |
| Applicant | The organization or person making application to a U.S. agency (e.g., the Department of Energy or the Nuclear Regulatory Commission) for certification and permit to transport radioactive material in a designated package. |
| CFR | *U.S. Code of Federal Regulations* |
| Containment system | The packaging assembly (vessel, seals, closure, valves, etc.) designed to contain radioactive material during transport in compliance with *10 CFR 71* and other applicable U.S federal regulations. |
| Contents | Material contained by the containment system. This includes radioactive material, absorbent material, spacing structures, and fluids. |
| Contents heat | The heat generated from nuclear decay, chemical activity, and other heat sources of contents. |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| Hypothetical accident | A severe transportation accident represented by package test conditions specified in *10 CFR 71*. |
| IAEA | International Atomic Energy Agency |
| NRC | U.S. Nuclear Regulatory Commission |
| Package | The packaging and its radioactive contents as presented for transport. |
| Packaging | The assembly of components necessary to ensure compliance with the packaging requirements of *10 CFR 71*. |
| Production package | The assembled package intended for transport of radioactive material. |
| Regulator | A U.S. regulatory agency that is responsible for review and approval of applications for certification of packagings. |

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| Safety Analysis Report | A document that provides a comprehensive technical evaluation and review of the design, testing, operational procedures, maintenance procedures, and quality assurance program for a package. The purpose of the report is to demonstrate compliance with the DOE regulatory safety standards equivalent to those established by the NRC for approving packagings and issuing certificates of compliance. |
| Special form | Radioactive material that satisfies the radioactive material conditions defined in *10 CFR 71.4*. |
| Subcriticality | The condition of a nuclear system in which the rate of production of fission neutrons is lower than in the previous generation due to neutron leakage and poisons. As a result of this condition, a self-supporting chain reaction cannot be maintained. |
| Test package | The package (containing simulated radioactive contents) used in the acceptance tests defined in this document. |
| Type A package | A package containing radioactive material, the aggregate radioactivity of which does not exceed $A_1$ for special-form radioactive material or $A_2$ for normal-form radioactive material. |
| Type B package | A package containing radioactive material, the aggregate radioactivity of which exceeds $A_1$ or $A_2$ levels. |
| *10 CFR 71* | *Title 10 of the Code of Federal Regulations, Part 71* |
| *10 CFR 71.73(a)* | *10 CFR 71, Section 73*, paragraph (a) |

# 1. INTRODUCTION

## 1.1 Background

Packages to be used for transport of radioactive material must be certified by federal regulators to assure protection of public health and safety. The Nuclear Regulatory Commission (NRC) regulations of *10 CFR 71* [Ref. 1], the Department of Transportation (DOT) regulations of *49 CFR 100-199* [Ref. 2], and the Department of Energy (DOE) orders of DOE 5480.3 [Ref. 3] contain standards for determining if a certificate of compliance may be issued to applicants for domestic transport of packages. Standards for packages for international transport are defined by International Atomic Energy Agency (IAEA) Safety Standards [Ref. 4], which are effectively equivalent to *10 CFR 71* regulations. The standards are based on three main considerations: (1) assurance that any release of the contents of a package during either normal or accident conditions of transport will not exceed specified limits; (2) protection of the public from external radiation; and (3) assurance that subcriticality will be maintained. An applicant must prepare a Safety Analysis Report for Packaging (SARP) that addresses these considerations and contains sufficient information to ensure that a package design satisfies all applicable U.S. regulatory safety standards. Federal regulators must review and approve the SARP before issuing a certificate of compliance.

*10 CFR 71* requires that Type B packages be subjected to specific tests (physical or analytical) that simulate conditions of a hypothetical accident. Four sequential test events defined in Section 73 of *10 CFR 71 (10 CFR 71.73)* [Ref. 1][1] must be performed with a test package. They are:

(1) a 30-ft free drop onto an unyielding surface
(2) a 40-in free drop onto a 6-in (15-cm) diameter pin
(3) a 30-min engulfing fire
(4) immersion of an undamaged package under a head of water of at least 50 ft (15 m).

The test requirements may be satisfied by analysis, by physical tests, or by a combination of these methods. An applicant may choose the most appropriate method, which may depend on package design, available analytical tools, available test facilities, and cost. This guide focuses on the 30-minute engulfing fire performed by physical testing.

## 1.2 Objective

The principal objective of this Thermal Test Guide (TTG) is to provide applicants with information that will help them plan, conduct, and report physical thermal tests performed according to the hypothetical accident conditions specified in *10 CFR 71.73*. Also, the TTG can be useful to an applicant in deciding which testing method—physical, analytical, or a combination—would be the most appropriate for a specific package. However, only physical testing should be applied to packages that cannot be modeled by analysis to adequately predict their response to hypothetical accident conditions.

[1] A proposed ruling of *10 CFR 71* includes a dynamic crush test in the hypothetical accident sequential testing. The proposed ruling of *10 CFR 71.73* is given in Appendix A. IAEA accident condition tests also require a crush test which is described in Appendix B.

## 1.3 Scope

The TTG includes general instructions for planning and performing physical thermal tests in accordance with *10 CFR 71.73(c)*. Detailed instructions or methods are not prescribed because each test will be package-design and test-facility specific. Also, selection of specific test materials, equipment, instrumentation, or methods will be dictated by availability of these items and their applicability to a specific package. Supporting analyses are recommended, but the analysis methods (e.g., equational, numerical, etc.) are to be selected by the packaging designer.

## 1.4 Hypothetical Accident Requirements

The requirements for applying thermal testing methods to a package, at hypothetical accident conditions, are contained in *10 CFR 71.73* [Ref. 1]. *NRC Regulatory Guides 7.8* and *7.9* [Refs. 5 and 6] give supporting guidance for applying these requirements. A proposed new ruling[2] for *10 CFR 71.73* submitted by the NRC is in closer agreement with IAEA Safety Standards. (See Appendices A and B.) The following is a summary of current NRC requirements for hypothetical accident thermal tests.

Test procedures - Evaluation for hypothetical accident conditions is to be based on sequential application of four tests: (1) free drop, (2) puncture, (3) thermal, and (4) immersion. (The immersion test does not affect the results of the other tests; therefore it is not discussed in this guide.)

Test conditions - The ambient air temperature before and after the tests must remain constant at that value between -29 °C (-20 °F) and +38 °C (100 °F) that is most unfavorable for the package under consideration. 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.

Free-drop test - A free drop of the package through a distance of 9 m (30 ft) onto a flat, essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected.

Puncture test - A free drop of the package through a distance of 1 m (40 in) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical, mild steel bar mounted on an essentially unyielding, horizontal surface. The bar must be 15 cm (6 in) in diameter, with the top horizontal and its edge rounded to a radius of not more than 6 mm (0.25 in) and of a length as to cause maximum damage to the package, but not less than 20 cm (8 in) long. The long axis of the bar must be vertical.

Thermal test - Exposure of the whole package for not less than 30 minutes to a heat flux not less than that of a radiation environment of 800 °C (1475 °F) with an emissivity coefficient of at least 0.9. For purposes of calculation, the surface absorptivity must be either that value that the package may be expected to possess if exposed to the fire or 0.8, whichever is greater. In addition, when significant, convective heat input must be included on the basis of still, ambient air at 800 °C (1475 °F). Artificial cooling must not be applied after cessation of external heat input, and any combustion of materials of construction must be allowed to proceed until it terminates naturally. The effects of solar radiation may be neglected prior to, during, and following the test.

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[2] Expected to become effective at a future date.

The major difference between proposed and current rulings for the thermal test is that an engulfing hydrocarbon fuel/air fire of limiting dimensions is specified in the proposed ruling. Also, convective heating is to be that value that would actually occur instead of the value from free convection of still ambient air at 800 °C. Moreover, the major difference between the proposed ruling for the *10 CFR 71.73* and the IAEA Safety Standards is that the IAEA standards require solar heating after the 30-minute heating period.

### 1.5 Acceptance Criteria

Standards for package approval are specified in Subpart E of *10 CFR 71*. Contained in the subpart are general standards for containment, shielding, and subcriticality.

<u>Containment</u> - Requirements for Type B packages subjected to the hypothetical accident conditions are defined in *10 CFR 71.51* as follows:

"...There would be no escape of krypton-85 exceeding 10 A2 in one week, no escape of other radioactive material exceeding a total amount A2 in one week, and no external radiation dose rate exceeding one rem/h (10 mSv/h) at 1 m from the external surface of the package....Compliance with the permitted activity release-limits of this section must not depend upon filters or upon a mechanical cooling system."

Packages for transporting plutonium in excess of 20 Ci must meet containment requirements as specified in *10 CFR 71.63*: "...the separate inner container must restrict the loss of its contents to not more than $A_2$ in one week." Regulations require that packages for transporting plutonium must have two containment systems.

<u>Shielding</u> - External radiation standards for all packages are defined in *10 CFR 71.47*: "...the radiation level does not exceed 20 mrem/h (2 mSv/h) at any point on the accessible external surface of the package and the transport index...does not exceed 10." Packages transported as exclusive use by rail, highway, or water, and which meet conditions given in *10 CFR 71.47*, may have radiation limits up to 1000 mrem/h (10 mSv/h).

<u>Subcriticality</u> - *Standards for subcriticality during hypothetical* accident conditions are defined in *10 CFR 71.55* through *71.65*: "A package for the shipment of fissile material must be so designed and constructed and its contents so limited that under the hypothetical accident conditions, the package would be subcritical. For this determination, it must be assumed that: (1) the fissile material is in the most reactive credible configuration consistent with the damaged condition of the package and the chemical and physical form of the contents, (2) water moderation occurs to the most reactive credible extent consistent with the damaged condition of the package and the physical and the chemical and physical form of the contents, and (3) there is reflection by water on all sides, as close as is consistent with the damaged condition of the package."

# 2. TEST PLAN

Successful execution of a thermal test program requires forethought and planning, taking into account all events that can affect the test results. A test plan document should be prepared to address the *10 CFR 71* requirements given in Section 1.4 and define how these requirements will be met. In addition, a test program must be performed under an approved QA program. Before implementation, the plans should be reviewed by independent reviewers for comment and revised as appropriate. Reviewers must possess sufficient knowledge related to the subject material to make constructive evaluations.

Should an existing thermal test facility be used, it must be capable of testing packages at conditions specified in *10 cfr 71.73*. If a developed applicable test plan exists, the existing test plan (or portions of it) may be used in lieu of developing a new plan.

Recommended topics to include in a test plan are:

(1) Scope
(2) Requirements
(3) Test method
(4) Instrumentation plan
(5) Acceptance plan
(6) Test procedure
(7) Test design
(8) Supporting analyses
(9) Hazards and safety
(10) Quality assurance plan
(11) Reporting
(12) Test organization.

Suggested content for each topic is given in Subsections 2.1–2.12.

## 2.1 Scope

Briefly describe the purpose and objective of the test, what will be tested, and how and where the test will be performed.

## 2.2 *Requirements*

State the requirements of *10 CFR 71* and other applicable requirements that must be satisfied during performance of a thermal test.

## 2.3 Test Method

Describe how the package will be tested to satisfy the stated requirements. Include details of the fire facility or oven design that will be used to heat the test package and its operation methods.

## 2.4 Instrumentation Plan

List all measurements to be made during the test, location of the measurements, type of sensors to be used, signal readout devices to be used, and method of converting signals to measurement units (e.g., volts to temperature, volts to pressure, etc.). Measurement accuracies and expected induced errors should also be addressed (e.g., errors caused by heat transfer in sensor lead wires, poor thermal contact between sensors and package components, or other temperature-induced errors). Methods to be implemented for sensor calibrations should be described. (Discussions of test measurements and sensor selections are presented in Section 4.)

### 2.5 Acceptance Evaluation

Describe the method of acceptance evaluation that will be used to determine if the package design meets the acceptance criteria for containment, shielding, and subcriticality (see Sections 1.5 and 5).

### 2.6 Test Procedure

Give a detailed test procedure that includes all pre-test, test, and post-test activities. Include contingency plans for unexpected events or deviations. Include a step-by-step procedure for test personnel to follow with sufficient detail to minimize possible confusion during performance of the test.

### 2.7 Test Design

Describe all fixtures, supports, equipment, and instrumentation that will be used in the test. If contents heat must be simulated, describe the method to be applied (see Section 3.2.3). Include appropriate drawings. Give sufficient detail for test personnel to assemble the test setup.

### 2.8 Supporting Analyses

Present the method and results of analyses performed in support of the test plan. The objective of the analyses is to ensure that a thermal test can be conducted successfully and the expense of conducting a test will not be wasted. The method, degree of accuracy, and extent of the analyses are optional, but for most test parameters, approximations are sufficient. The following analyses are recommended.

- Determine the ambient air temperature between -29 °C (-20 °F) and +38 °C (100 °F) that will result in the most unfavorable initial and final conditions for the package (see <u>Test conditions</u> in Section 1.4).

- Determine if the initial internal pressure within the containment system must be the maximum normal operating pressure or must be a lower internal pressure consistent with the ambient temperature to precede and follow the test (see <u>Test conditions</u> in Section 1.4).

- Estimate the maximum pressure that will occur in the containment system of a test package during a thermal test.

- Verify that temperatures of package components are expected to remain within acceptable limits.

- Verify that the containment system will not leak during the thermal test (e.g., from stresses in closure bolts, flanges, or seals).

- Estimate heat transfer rates to the package and compare to the requirements (see <u>Thermal test</u> in Section 1.4).

- Estimate operating temperature ranges of instrumentation sensors and wires and induced measurement errors (see Section 4 for further discussions).

### 2.9 Hazards and Safety

Describe all anticipated hazards that may be present during the test program and provide a safety plan to protect test personnel, the public, equipment, and property. Particularly, hazards associated with a fire test must be addressed, if this test method is chosen. Also, provisions for terminating the fire either prematurely or at the conclusion of the heating period may be necessary. In addition, methods for protecting surrounding materials may be needed. If the package is to be removed from a fire or oven for cooling, a safe method for handling the package while it is hot must be provided.

All fluid pressures during the test must be within safe limits. Appropriate safety practices must be exercised during use and operation of pressurized systems. Also, measures must be taken to comply with applicable local, state, and federal occupational safety and health standards and environmental protection requirements.

### 2.10 Quality Assurance Plan

Present a plan that describes how the thermal test will be planned, conducted, evaluated, and documented as a test record in accordance with *10 CFR 71, Subpart H* [Ref. 1]. ANSI/ASME NQA-1 [Ref. 7] and NRC Regulatory Guide 7.10 [Ref. 8] may be used as a guide to implement a Quality Assurance Plan to satisfy regulatory requirements. The principal focus for the Quality Assurance Plan must be to assure that the test package fully represents the production packages and that all details of the test plan are correctly implemented and completed. Performance of thermal test activities and test results should be reviewed by an independent authority within the applicant's organization to ensure that all test objectives and requirements are met.

### 2.11 Reporting

Present a plan for reporting the results of all activities pertaining to the thermal test. Describe the methods to be used for recording and reporting test data and results. Define all supporting documents that will be prepared as part of the test program (see Section 6).

### 2.12 Test Organization

Prepare a list of all key personnel who are expected to participate in the thermal test program, including their specialities and their assigned responsibilities.

# 3. TEST CONDITIONS

Many conditions must be satisfied during a thermal test program to satisfy the requirements of *10 CFR 71.73*. Since the proposed ruling for *10 CFR 71* is expected to become effective in the future (see Appendix A), applicants would be prudent to comply with the proposed ruling as much as practical. Therefore, test conditions described in the following sections are based on the proposed ruling.

## 3.1 Package Conditions

A test package must be a full-scale specimen that represents all design features of the transport package being considered for certification when prepared for transport[3]. There is one exception: a test package must not contain radioactive or hazardous materials. Such materials may be replaced with suitable nontoxic surrogate materials. However, the mechanical and thermal responses of a test package to the test conditions must be nearly the same as for a transport package.

Dimensions of components of the test package should include allowed tolerances that result in the most unfavorable results of the tests.

## 3.2 Initial Conditions

The initial condition of a package can have significant influence on the results of a thermal test. Thus, conditions must be developed to satisfy those specified by *10 CFR 71.73* (see Section 1.4 and Appendix A). The initial conditions are those for the sequential drop, crush, puncture, and thermal tests under hypothetical accident conditions. In the following sections, guidance is given for developing acceptable initial conditions.

### 3.2.1 Temperature

The initial package temperatures must be at steady-state conditions resulting from an ambient temperature and equivalent contents heating. Solar insolation is not required, but can be applied, if desired, to satisfy IAEA Safety Standards (see Appendix B). An analysis should be performed to determine if the contents heating is sufficient to have a significant effect on temperatures or temperature gradients in the package during the test. If the contents heating does not have a significant effect, it may be omitted from a test package, because doing so would not enhance the capability of a test package to meet acceptance criteria for containment, shielding, and subcriticality. The analysis must use an ambient temperature between -29 °C (-20 °F) and +38 °C (100 °F), which is the most unfavorable condition for the package (see Section 2.8 for recommended supporting analyses).

If the analysis indicates that contents heat must be included, initial temperatures in the package will be higher than the environment temperature because of thermal resistances in the packaging between the contents and the environment. Heat transfer from the contents to the environment will also produce temperature gradients that will cause thermal stresses in the package. In this case, simulated contents heat (e.g., from electrical heaters) must be included. The design of heaters for simulating contents heating should be such that the contents heating distribution in the containment system is adequately duplicated (e.g., in some packages, the contents heating may be concentrated instead of uniformly distributed).

[3] The thermal response and containment leakage rates of full-scale packages cannot be satisfactorily determined from tests on scaled models.

If the analysis indicates that contents heating can be omitted, initial temperatures in the package should be nearly uniform and equal to the required ambient temperature.

In some package designs the outcome of a thermal test is not significantly influenced by varying the initial ambient temperature within the specified range (-29 to +38 °C). In such cases, the test package temperatures can come to equilibrium with an existing ambient temperature, if it is effectively steady. To accomplish this, the test package may, in some cases, have to be isolated from diurnal temperature variations.

If a specific environment temperature must be created for the test package, a method that can satisfy the required temperature and the packaging size must be used. Appropriate heating or cooling chambers or blankets can be used when steady-state temperature conditions in the test package are to be achieved. From any chosen method, nearly uniform environment temperatures on all package surfaces must be attained.

3.2.2 Containment Pressure

According to *10 CFR 71.73*, the initial internal pressure within a containment system must be the maximum normal operating pressure unless a lower internal pressure is more unfavorable. In some containment designs, a maximum internal pressure is not always the most unfavorable condition; that is, a lower pressure may result in greater leakage (see Section 1.4). For example, some containment system seals depend on an internal pressure being greater than the external pressure to maintain leak tightness. Therefore, an analysis should be performed to determine the most unfavorable pressure for containment (see Section 2.8).

Packages that are to be used for transporting plutonium must have a double containment system as specified in *10 CFR 71.63*. Pressure conditions in test packages having such containment system must be applied to both containments.

The internal pressure of a test-package containment system reaches a maximum value during a thermal test. This value must not be less than the maximum pressure that would occur in a transportation package subjected to the same test. Therefore, the initial pressure in a test package must be at a level that will result in this equivalence. In determining the required initial pressure, several possible sources of pressure increase must be considered. They include release from encapsulated materials, phase change of materials, outgassing, radiolysis, thermochemical decomposition and container closure procedures. The transportation package contents must be analyzed to determine all pressure sources and their contribution to the total internal pressure in a containment system.

If the drop, crush, and puncture tests preceding the thermal test could cause gases or materials to be released from a transportation package contents (e.g., by rupture of encapsulations), and the release would result in increased pressure in the containment system, then the selected initial pressure for the thermal test must include the effects of the release. Usually, it is necessary to assume that all encapsulations in the contents are ruptured and existing fluids are released. The worst-case accumulation of fluids in encapsulations should be assumed. However, if rupture of encapsulations during the drop, crush and puncture tests cause a reduction of pressure, the initial pressure for the thermal test must not be reduced to account for the effects of this reduction, except when the reduction causes a more unfavorable condition for containment.

The gas volume in the containment system must be equal to that gas volume that would present the most unfavorable condition for containment during the thermal test.

When feasible, the required initial pressure can be reached by pressurizing the containment system to a predetermined level with a gas and then bringing the package to the required initial temperature. At this temperature, the pressure should be at the required level. A pressure sensor may be installed to measure pressures within the containment system so that the initial condition pressure and subsequent pressures can be monitored. However, the sensor must not degrade the integrity of the packaging or significantly influence heat transfer in the packaging during the thermal test (see Section 4.2 regarding pressure instrumentation).

3.2.3 Contents

During the test sequence, the contents of the containment system must represent the actual contents intended for transport. If the package will transport a variety of contents, the contents that presents the worst condition to the package must be represented in the thermal test. Use of hazardous materials to represent the actual contents must be avoided. Materials that are selected to represent the actual contents should reproduce the following characteristics: (1) mass, (2) average specific heat, (3) heat generation rate, and (4) pressure generation.

The combination of the contents mass and average specific heat should be duplicated so that the containment system response to impact loads and temperature transients will be effectively the same as in transportation packages. If the contents heat must be included in a test package, an appropriate heat source must be installed in the containment system. The heat source must provide a heat rate and distribution that is representative of worst-case conditions in a transportation package. Displacement of contents that may occur during the mechanical test conditions (i.e., drop, crush, and puncture) should be considered. If the displacements alter the distribution of contents heat to an extent that increased stresses in the containment system would result, then the location of heat sources in a test package must account for the displacements.

A common method for simulating contents heat in a test package is to install electrical heating elements. This requires penetrations through the containment system for the electrical wires. However, care must be exercised when designing penetrations so that they do not alter the rate of heat transfer to or from the test package or degrade its leak tightness during the test. Also, the wires must be supported and protected so that they do not fail or short out during the preceeding mechanical tests.

The contents selected for a test package (liquids, solids, and gases) must cause pressures in the containment system, during a thermal test, to be at least as high as would be developed in a transportation package during a thermal test. When analyzing the contents for a transportation package, all materials that can increase the gas pressure must be considered. Containment system pressure can be increased by materials that undergo phase change, decomposition, and outgassing, and by increased temperature of contained gasses. An exception to this requirement is when containment pressures are expected to be low enough to have an insignificant effect on the outcome of a test.

Materials that are corrosive or deleterious to any of the containment system components must be excluded from test package contents.

3.2.4 Impact Damage

*10 CFR 71* requires that sequential drop, crush, and puncture tests be performed on a test package before a thermal test is performed on that package (see Section 1.4 and Appendix A). If, at the conclusion of the puncture tests, there is sufficient evidence to indicate that the containment leakage allowance is definitely exceeded, then the thermal test should be suspended until an improved package design is developed. Testing and inspecting a test package after the puncture test to determine if this condition occurred could save time and expense, though this step is optional and may not be feasible for some packages.

Inspections should also be performed to evaluate the extent of deformations or loss of thermal insulation, if any. If they are severe enough that unacceptable temperatures or stresses in the containment system will undoubtedly occur during the thermal test, then the package design should be improved.

An applicant may choose to perform the drop, crush, or puncture tests by analysis and the thermal test by a physical test. A benefit of this approach is that only one package may be needed for testing. Otherwise, several packages may have to be tested to determine the orientations in the drop, crush, and puncture tests that yield the most unfavorable result. If the drop, crush, and puncture tests are performed by analysis, the test package should be subjected physically to the sequential drop, crush, and puncture conditions at the most unfavorable orientations (The test requirements are given in Section 1.4 and Appendix A.) This is necessary to produce the resulting deformations or other damage prior to a thermal test. The analyses may be used to determine the package orientations that must be applied during the drop, crush, and puncture conditions to produce the most unfavorable results. If, however, an applicant can clearly show that the sequential drop, crush, and puncture tests on a specific package do not significantly affect the outcome of the thermal test on the package, then subjecting the package to the sequential physical tests becomes optional.

3.2.5 Orientation

During a thermal test, a package must be positioned in the orientation (e.g., horizontal, vertical, or oblique) that provides the most unfavorable conditions for the package to satisfy the *10 CFR 71* requirements for maintaining containment, shielding and subcriticality. This orientation may be determined by analysis or test. If the test method is chosen, then more than one thermal test may be required to determine the most unfavorable orientation.

### 3.3 *Thermal Conditions*

According to *10 CFR 71.73(c)* requirements, a test package must be exposed for not less than 30 minutes to a fully engulfing, hydrocarbon fuel/air fire of defined dimensions or an equivalent environment (see Appendix A). The intent of the requirements is to expose a test package to a thermal environment that will supply a heat flux to the package surfaces that exceeds a minimum value. Components of the total heat flux from the engulfing fire environment are radiation and convection heat transfer.

$$q_{tot} = q_{rad} + q_{con} \tag{1}$$

where: $q_{tot}$ = total heat flux to the package surface ($W/m^2$)
$q_{rad}$ = radiation heat flux to the package ($W/m^2$)
$q_{con}$ = convection heat flux to the package ($W/m^2$).

An equational expression for estimating the net radiation heat flux between a radiation source and package of uniform temperatures is [Ref. 9]:

$$q_{rad} = \frac{\sigma \; (T_s^4 - T_p^4)}{(A_p/A_s)(1/\varepsilon_s - 1) + (1/\varepsilon_p - 1) + 1/F_{p\text{-}s}} \tag{2}$$

where:

$A_p$ = package surface area ($m^2$)
$A_s$ = radiation source surface area ($m^2$)
$F_{p-s}$ = view factor from package to radiation source
$T_s$ = radiation source temperature (K)
$T_p$ = package surface temperature (K)
$\varepsilon_s$ = radiation source total thermal emissivity (absorptivity) coefficient
$\varepsilon_p$ = package surface total thermal emissivity (absorptivity) coefficient
$\sigma$ = Stefan-Boltzmann radiation constant ($5.669\times10^{-8}$ $W/m^2\text{-}K^4$).

For an engulfing fire condition, the value of $A_p/A_s$ is 1.0, and $F_{p-s}$ should be equal to 1.0 during any package thermal test.

Figure 3.1 shows a curve of radiation heat flux, $q_{rad}$, versus package surface temperature, $T_p$, for *10 CFR 71*-specified minimum values of radiation source temperature (800 °C), radiation source emissivity coefficient (0.9), and package surface emissivity coefficient (0.8). However, if the effective emissivity coefficient (i.e., absorptivity) of the package surface is greater or less than 0.8, then the radiation heat flux would be changed accordingly.

As illustrated in Fig. 3.1, the radiation heat flux decreases as the surface temperature increases until surface and environment temperatures are equal. At this condition, heat transfer to a package ceases. Also, the total heat transferred (time-integrated surface heat flux times package surface area) will depend on the temperature response of package surfaces to a thermal test. This response depends not only on the environment and surface properties, but also on the package thermal characteristics. For example, package surfaces that heat up rapidly will receive less total heat than surfaces that heat up slowly. This is due to a reduction of heat flux as the surface temperature increases as indicated in Fig. 3.1.

The intent of the hypothetical accident thermal test is to simulate fire conditions of a transportation accident. A fire in this type of accident would probably be a liquid/fuel fire that could deposit combustion products on package surfaces or cause them to oxidize. The result would be that the effective thermal absorptivity of the package surfaces would be increased during the fire. If a package is thermally tested in an acceptable fire, the surface absorptivity of the package surfaces may be the value resulting from the fire. Otherwise, the absorptivity must be either that value that the package may be expected to possess in the fire or 0.8, whichever is greater (see Section 1.4). Test packages that have surface absorptivity coefficients less than that required by *10 CFR 71.73(c)*, and are to be tested by methods other than an engulfing fire, may be treated so as to achieve an acceptable absorptivity coefficient during a test. An example method for creating high-absorptivity surfaces is to coat them with a black refractory paint or other suitable coating.

An alternate method for treating packages having a surface absorptivity coefficient less than 0.8 is to compensate for the low absorptivity by providing a radiation source temperature higher than 800 °C. A relationship of surface absorptivity (i.e., emissivity) to minimum acceptable source temperature for the required radiation heat flux can be derived from Equation (2). The relationship is illustrated in Fig. 3.2 for a source emissivity equal to 0.9 and package–source area ratio equal to 1.0. Temperatures above those defined by the curve would satisfy the required heat flux while temperatures below would not.

An increase of the source temperature would also compensate for a source emissivity of less than 0.9. Again, Equation (1) can be used to derive a relationship between the source temperature and source emissivity for the required minumum radiation heat flux. Figure 3.3 illustrates the relationship for three values of package emissivity and package–source area ratio equal to 1.0.

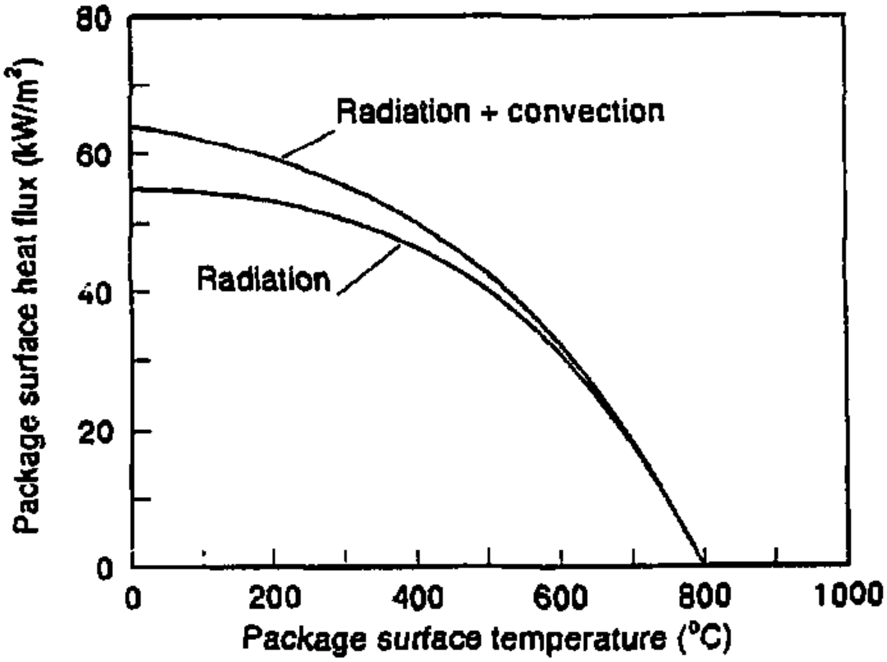


Fig. 3.1. Radiation and convection heat flux to test package surfaces for: $T_s$ = 800 °C, $\varepsilon_s$ = 0.9, $\varepsilon_p$ = 0.8, $A_p/A_s$ = 1.0, and $F_{p\text{-}s}$ = 1.0. Convection heat flux is an example only.

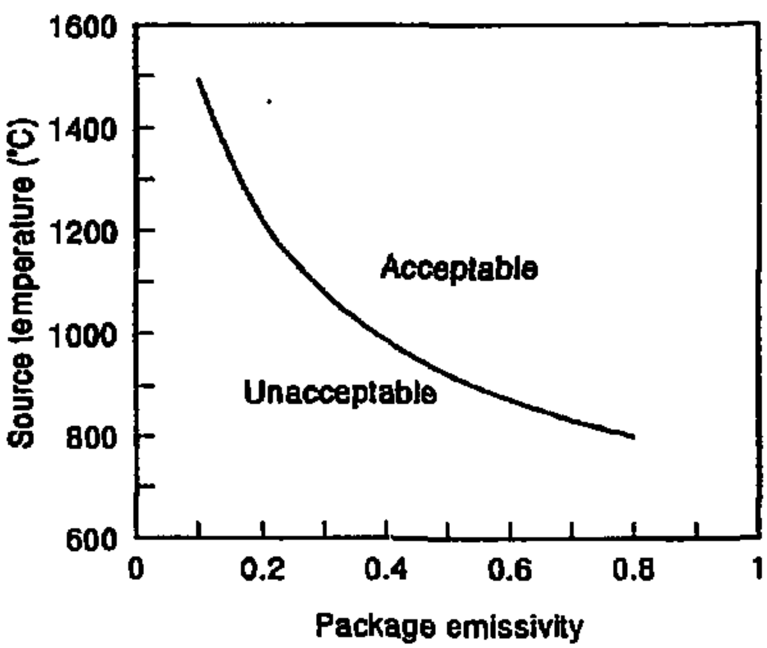


Fig. 3.2. Source temperature to exceed the minimum required radiation heat flux to a package having surface emissivity less than 0.8 and for: $\varepsilon_s$ = 0.9, $A_p/A_s$ = 1.0, and $F_{p\text{-}s}$ = 1.0.

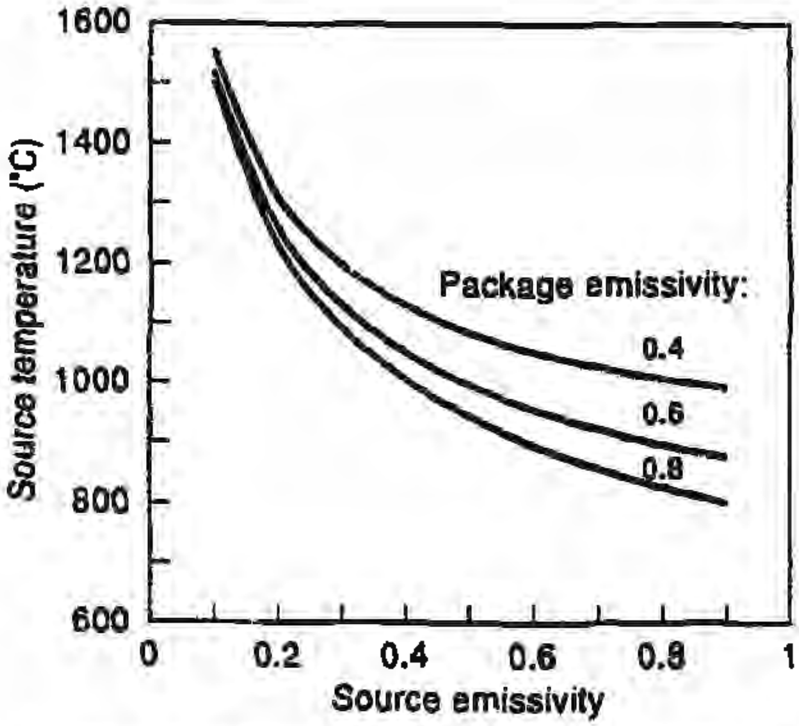


**Fig. 3.3. Source temperature to achieve minimum required radiation heat flux to a package for source emissivity less than 0.9 and for: $A_p/A_s = 1.0$, and $F_{p\text{-}s} = 1.0$.**

Note in Equation (1) that small changes of the source temperature will cause relatively large changes in heat flux. Also, the package surface-temperature must increase significantly before a significant reduction of radiation heat flux will occur. Thus, during the initial phase of heating, radiation heat flux remains effectively constant. This phenomenon is due to the fourth power relationship of temperatures.

The convection component of the total heat flux, $q_{tot}$, in Equation (1) can be estimated by the following expression:

$$q_{con} = h\,(T_f - T_p) \qquad (3)$$

where:
- $h$ = convection coefficient ($W/m^2$-K)
- $T_f$ = fire temperature near the package surfaces (K)
- $T_p$ = package surface temperature (K).

The convection coefficient specified in the proposed ruling for *10 CFR 71* is "for purposes of calculation...that value which may be demonstrated to exist if the package were exposed to the fire specified" (see Appendix A). The expectation is that the convection coefficients produced by an engulfing fire test will be at least this value. Convection heat transfer from a fire to package surfaces will occur mainly from hot-gas flow developed by buoyancy of hot gases and radial inflow of air. These conditions will produce turbulent gas flow on package surfaces and the flow structure will be similar to that of forced flow. A convection coefficient for these conditions can be estimated using published correlations appropriate to a package geometry and external fluid flow conditions. Appendix C gives example correlations for convection coefficients that may be applicable to package surfaces in fire environment.

An example of convective heat flux values for a package surface is shown in Fig. 3.1. Note that the convection component of the total heat flux is significant in the example and should not be omitted from heat transfer analyses. However, the value of convective heat flux is dependent on package design, orientation, and surface and environment temperatures. Thus, every test package should be independently evaluated to estimate a convective heat flux for each surface.

The required heat flux to a test package can possibly be accomplished by several methods, such as oven heating, liquid fuel fires, or gas fuel fires. Selection of a suitable method can depend on the package size and design and on available heating methods. For example, fire facilities or ovens must satisfactorily accommodate a package size and develop the required thermal conditions.

### 3.3.1 Fire Heating

Fire can be used to thermally test a package. The fire must be from air/fuel combustion of a hydrocarbon fuel such as gasoline, kerosene, aviation jet fuel, diesel fuel, or liquefied gases. Temperatures in air-combustion fires using these fuels are typically more than 800 °C (1475 °F). However, a fire must be controlled to an extent that it sufficiently engulfs a test package and develops at least the required minimum heat flux to the package. Properly controlled fires of jet or diesel fuels can provide acceptable test conditions. These fires can have a relatively high density of entrained carbon particles to provide for a sufficiently high thermal emissivity coefficient.

Gaseous-fuel fires, such as combustion of natural gas or liquefied gas (e.g., propane), have relatively low emissivity coefficients because the quantity of entrained particulates in these fires is low. If a gaseous-fuel fire should be used, the fire temperature may have to be much greater than 800 °C to develop the required test conditions. Flame temperatures can sometimes be increased by controlling air/fuel mixtures.

The proposed ruling for *10 CFR 71* (and IAEA Safety Standards) specifies that "The fuel source shall extend horizontally at least 1 m, but shall not extend more than 3 m, beyond any external surface of the package, and the package shall be positioned 1 m above the fuel surface" (see Appendices A and B). This applies particularly to pool fires of jet or diesel fuels. At least 1 m of fire thickness is needed to achieve sufficient opacity for developing an acceptable flame emissivity in these fires. Pool fires extending more than 3 m may inhibit natural air flow to the fire center and thereby reduce flame temperatures adjacent to a package. However, low-opacity fires may need to be thicker than 3 m and have enhanced air flow to achieve the minimum required heat flux to a package.

Before using a fire for thermal testing, the basic mechanics of fire behavior should be understood. Numerous published references contain descriptions of fire behavior. For example, the characteristics of large, open-pool fires are described in Refs. 10 and 11. This type of fire contains large-scale turbulence that produces random temporal and spatial fluctuations of temperature and velocity. The fire is also characterized by three descriptive vertical zones illustrated in Fig. 3.4 for a JP-4 fuel. They are:

(1) the persistent flame zone (orange/red color) where there is an accelerating flow of burning gases (a characteristic radial pinch occurs in this zone, caused by strong radial inflow of air)
(2) the intermittent flame zone (orange/black color) where there is intermittent flaming and a near-constant flow velocity
(3) the buoyant plume (black color) where gas velocity and temperature decrease.

An example pool fire is reported in Ref. 10. The fire was developed by combustion of JP-4 fuel, and it had a 9-m (30-ft) diameter base. According to correlations given in Ref. 11, the persistent

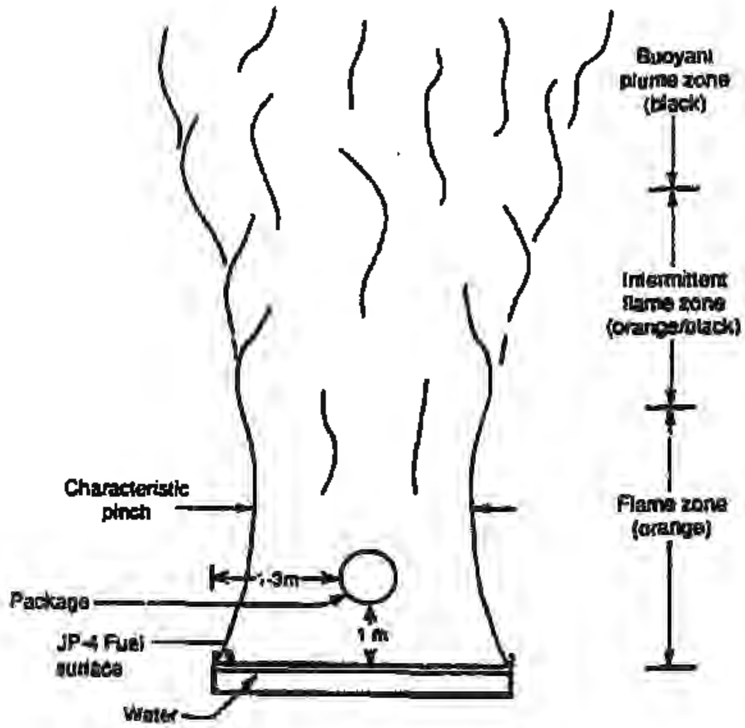


**Fig. 3.4. Test package position in a typical JP-4 fire in quiescent wind conditions.**

zone height was 14.7 m (48 ft), the intermittent zone was to 36.6 m (120 ft), and the buoyant plume reached at least 91.4 m (300 ft). The observed pinch occurred at approximately 2.5 m (8 ft) and was approximately 20% of the fire base.

Natural convection, open-pool fires (<10 m diameter) have been created by burning a liquid fuel while it is floating on a pool of water. A typical recession rate of a fully-developed JP-4 fuel pool fire is 6.4 mm/min (0.25 in/min) [Ref. 10]. Enhanced convection pool fires have been created by providing air flow through pipes to the fuel surface so that combustion occurs effectively throughout the fuel surface [Ref. 12]. Examples of these two pool-fire methods are described in Appendix D. Both of these example fires would satisfy current and proposed *10 CFR 71* requirements.

Gaseous-fuel fires can also be created by using air-fuel mixing burners. However, many burners may be needed to develop a flame volume that adequately engulfs a test package and provides the required heat flux over all package surfaces.

If thermal testing is to be performed outside, the test period must be during quiescent ambient conditions, i.e., when winds are calm and when no precipitation occurs. Modest breezes (a few km/h) can greatly tilt a flame column (e.g., as much as 20° [Ref. 11]) and possibly reduce the flame depth on some portions of a package. In fact, large fires can create modest local winds caused by the inflow of free convection air. However, appropriate shields may be used to minimize the effects of wind on a test package, such as the chimney illustrated in Appendix D. If wind shields are to be used, it must be shown that they do not reduce the thermal heat flux on the test package below required levels.

Consideration must also be given to ambient temperature. Fire temperatures and evaporation rates of liquid fuels are effected by ambient air temperature. Thus, a fire test should not be conducted during extremely cold conditions, such as when ambient temperature is less than -15 °C (5 °F).

A means for supporting a test package in a fire must be carefully designed. If a structure that is not an integral part of a package design is used to support a test package, then the support structure must not significantly interfere with a fire reaching package surfaces or conduct significant quantities heat to or from a package.

The duration of the fire test is measured from the initial time the test package becomes fully engulfed in the fire until it is not fully engulfed in the fire. The time for the fire to become fully developed must not be included in the test duration. A package should be in a fully engulfing fire for a duration that is sufficient to ensure that the requirements of *10 CFR 71.73(c)* are satisfied.

Termination of fire heating can be accomplished by moving a package out of the fire. Radiation shields may be required to prevent any further heat transfer from the fire to the package if it remains in the vicinity of the fire. Sometimes, the duration of pool fires can be sufficiently controlled by the quantity of fuel allowed into the pool. Fire heating may also be terminated by interrupting the fuel or air supply and leaving the package in place. If this method is chosen, the test must be designed to ensure that the package is neither cooled nor exposed to a source of heat that would significantly alter natural cooling of the package. Also, any combustion of package materials must not be inhibited and combustion must be allowed to continue until it terminates naturally.

3.3.2 Oven Heating

A package may be thermally tested in an oven (or furnace) if acceptable conditions in the oven can be achieved. An oven must be able to supply at least the minimum required heat flux to all surfaces of a package and allow natural combustion of package materials throughout a test. Some ovens can provide a nearly uniform temperature environment; however some ovens are not uniformly heated and may not provide a uniform temperature environment for a test package. Also, some ovens may inhibit combustion of package materials. Before using an oven to thermally test packages, it should be subjected to qualifications tests to demonstrate it can satisfy the requirements of *10 CFR 71.73* [Ref. 13].

A common difficulty in using an oven is achieving an acceptable heat flux to a test package throughout the test. If the oven volume is not large compared to the package volume, the oven wall temperature may significantly decrease after a package is inserted into the oven. This would be caused by transient heat transfer from the oven walls to the package. It would be an unacceptable condition if the total heat transfer to all package surfaces during the test fell below the required minimum. To help avoid this potential problem, an oven test-zone volume should be at least 5 times the volume of a test specimen so that the oven will have sufficent thermal mass to keep its wall temperatures above a required minimum [Ref. 14]. The acceptability of a particular oven for thermally testing packages must be evaluated on the basis of an oven's capability to develop and maintain the required conditions for a specific package.

The thermal emissivity coefficients of oven walls are usually less than 0.9. A surface emissivity that is too low can be compensated by increasing the oven wall temperature until the required surface heat flux to a package is achieved. This is illustrated in Fig. 3.3. An alternate compensation method is to have a sufficiently large ratio of oven wall area to package surface area as indicated in Equation (2). Figure 3.5 illustrates this relationship for package emissivity equal to 0.8. When oven-wall-to-package-surface area ratios are greater than those defined by the curve, then the heat flux to a package should be more than the required minimum.

Equation (2) can be used to estimate radiation heat flux to packages in ovens that have uniform interior temperatures and do not contain non-transparent gases. Should non-transparent gases (e.g., carbon dioxide or water vapor) be present, they will participate in the radiation heat transfer. This participation should be accounted for when correctly estimating heat fluxes to a package. For oven conditions that provide uniform wall and gas temperatures, spectrally gray gases, and an area ratio and package-to-oven view factor equal to 1.0, the radiation heat flux can be estimated by the following equation [Ref. 15]:

$$q_{rad} = \frac{\sigma \varepsilon_p \{[E_w + \varepsilon_g(1/\varepsilon_w - 1)](T_g^4 - T_p^4) - (T_g^4 - T_w^4)\}}{E_w[1 + (1 - \varepsilon_g)(1 - \varepsilon_w)E_p]} \qquad (4)$$

where:
$E_w$ = $[\varepsilon_g(1 - \varepsilon_w) + \varepsilon_w]/[(1 - \varepsilon_g)\varepsilon_w]$
$E_p$ = $[\varepsilon_g(1 - \varepsilon_p) + \varepsilon_p]/[\varepsilon_g(1 - \varepsilon_p) + \varepsilon_w]$
$T_g$ = gas temperature (K)
$T_p$ = package temperature (K)
$T_w$ = oven wall temperature (K)
$\varepsilon_g$ = gas thermal emissivity coefficient
$\varepsilon_p$ = package surface thermal emissivity coefficient
$\varepsilon_w$ = oven wall thermal emissivity coefficient
$\sigma$ = Stefan-Boltzmann radiation constant ($W/m^2$-$K^4$).

The contribution that a participating gas in an oven can make to radiation heat transfer is illustrated in Fig. 3.6. Package surface heat flux curves are shown for three gas-emissivity values when the oven wall and package surface emissivities are equal to 0.9 and 0.8, respectively. (Clean-burning fuels, such as natural gas, have an emissivity value that is typically equal to 0.1.) The curves indicate that a participating gas can augment the heat flux to a package. High concentrations of some gases that contain opaque materials, such as smoke or certain products of combustion or dissociation, may shield a package from radiation and reduce its surface heat flux. Thus, this condition should be avoided. Sometimes, ovens can be vented to keep the concentration of undesirable gases at acceptable levels and to supply sufficient air to allow natural combustion of package materials. However, venting must not be so strong that heat transfer to the test package is significantly reduced.

For many ovens, radiation heat transfer to a test package cannot be adequately estimated using simple equations such as Equations (2) or (4). Non-uniform temperatures and other conditions may exist that are not consistent with the assumptions in the two equations. In such cases, suitable computer heat transfer codes may be used. If such codes are not available, one may be developed based on a radiation network method of formulation [Ref. 9].

The convection component of heat flux for package surfaces in an oven can be estimated using Equation (3). The $T_f$ value in Equation (3) is replaced by the oven atmosphere temperature, and the convection coefficient is estimated for free convection conditions. The mean coefficient will be dependent on fluid properties, surface geometry, and the convection velocity. Conditions in an oven during a thermal test are expected to develop free-convection turbulent flow on oven-wall and package surfaces. Heat will be transfered from oven walls to a package by the free convection flow. Correlations of free convection coefficients for regular geometries can be found in published references such as Refs. 16 and 17. (Included in Appendix C are correlations found in Ref. 16.) However, an applicant must derive coefficent values that are appropriate for a proposed combination of test package and oven. Should this task become too difficult, an

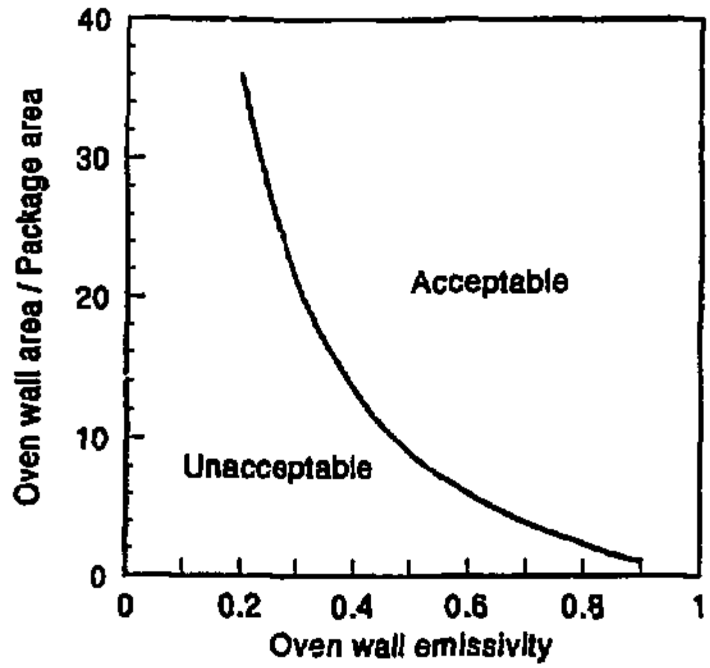


**Fig. 3.5. Ratio of oven wall area to package surface area needed to achieve minimum required radiation heat flux to a package for $\varepsilon_w$ less than 0.9 and for $\varepsilon_p = 0.8$.**

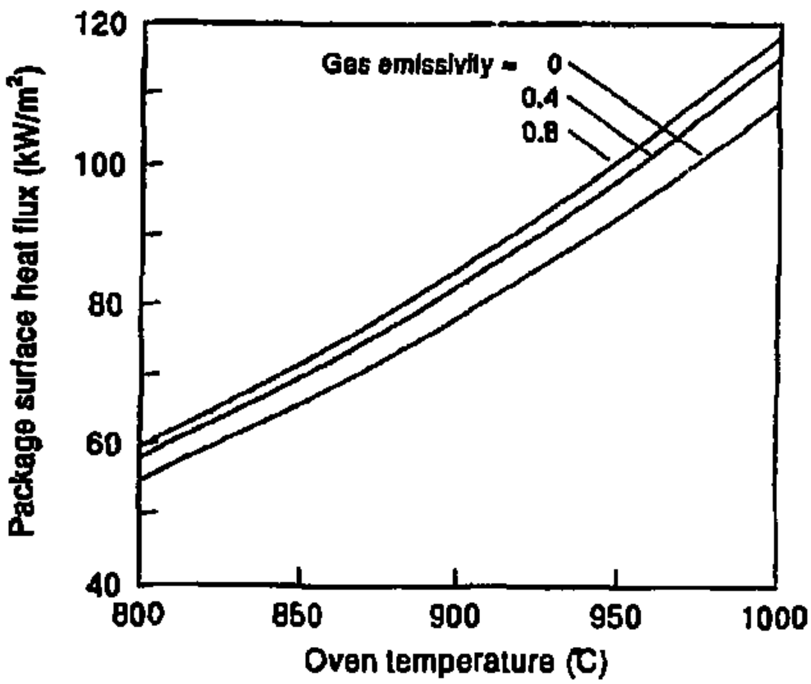


**Fig. 3.6. Radiation heat flux to a package in an oven containing a radiation participating gas for: $T_g = T_w$, , $\varepsilon_w = 0.9$, $\varepsilon_p = 0.8$, and $A_p/A_w = 1.0$.**

applicant may choose, instead, to verify that minimum heat flux requirements are satisfied by measuring these values during a thermal test or assuming that convection does not occur.

Gas velocities over package surfaces in a fire test would probably be greater than in an oven test. Thus, convection heat transfer to a package in an oven test would probably be less than convection heat transfer to a package in a fire test. Therefore, the oven temperature must be augmented enough to compensate for this difference.

If a package is tested in an oven or furnace, an oxidizing atmosphere must be maintained throughout the thermal test so that oxidation and combustion of package materials can occur naturally as they would in a fire test. Also, the discussions in Section 3.3 on package surface treatment and Section 3.3.1 on package support system apply to oven tests.

### 3.4 Final Conditions

After heating a package in a fire or oven, the package must be left to cool naturally (i.e., without artificial cooling such as water spray or forced air flow) in the same ambient air temperature as at the beginning of the test (see Section 1.4). Also, it must be shielded from the fire or oven so that only cooling by ambient air occurs. In addition, the test package must be protected from atmospheric precipitation and winds greater than 5 km/h (3 mph).

The motion of a package during removal from a fire or oven should be slower than the velocity of natural air circulation over the package when its surfaces are at 800 °C (typically 1 to 2 m/s). This will enssure that the motion of the package does not create artificial cooling.

According to *10 CFR 71.73(c)*, "...any combustion of materials of construction must be allowed to proceed until it terminates naturally." Also, care must be taken to support the package so that the natural cooling ability of the surrounding air is not significantly altered. Any support structure, included only for the test, must not significantly enhance or degrade cooling on any portion of the package.

The package must be left to cool until all temperatures in the package are effectively at steady state. For large packages, this may require several days. During this period, containment system temperatures may continue to increase before they begin to decrease. This behavior is caused by heat transfer to the containment system from exterior portions of a package where temperatures may be higher.

# 4. MEASUREMENTS

Sufficient measurements must be taken during a thermal test program to demonstrate that the required test conditions occurred. Measurements that monitor the response of the package and contents to a thermal test are not required by *10 CFR 71*, but they are recommended to enhance the evaluation of test results. The measurements may be continuous or periodic during the heating and cooling phases of the test to determine the maximum values and to determine steady-state conditions. Pretest and post-test measurements may also be necessary to verify acceptable test conditions and test results. Typical measurements that may be taken are temperature, pressure, heat flux, and strain. Appropriate sensors should be selected on the basis of their ability to provide reliable measurements within required ranges and with required accuracies, and to function in the required environment.

Installation of sensors, connectors, tubes, or wires must not significantly alter the thermal or mechanical response of a package to the tests or degrade containment of contents. Heat conduction in wires connected to sensors should be minimized so that measurement errors and spurious heating effects can be minimized. This may be accomplished by using small-diameter wires, thermally insulating them, and routing the wires through isothermal zones whenever possible. Also, instrumentation wires should be protected or routed so that the insulation is not damaged to an extent that electrical shorts would occur.

Some of the instrumentation for demonstrating that a package has been thermally tested in accordance with the requirements of *10 CFR 71.73*, and to quantify the response of package components to the thermal test, may have to be installed in the package prior to the sequence of tests prescribed in *10 CFR 71.73(c)*. Thus, not only must this instrumentation survive the prescribed mechanical tests, but it must also survive the thermal test. This requirement may place constraints on the type of sensors that can be used as well as on the method of sensor output transmission. Sensors should be calibrated in accordance with an Instrumentation Plan (see Section 2.4). Also, all measurements must be conducted in accordance with an approved Quality Assurance Plan (see Section 2.10).

Tests and measurements in addition to those for a thermal test may be required to determine that the *10 CFR 71* acceptance criteria for containment, shielding, and subcriticality are satisfied (see Sections 1.4 and 5).

## 4.1 Temperature

Location of temperature measurements should be on or near bolts, gaskets, valves, and other containment system boundaries as well as throughout the package [Ref. 6]. The choice of measurement locations should be based upon judgment, experience, and analysis. Recommended overall locations include: the outer package and containment system surfaces at both ends and the middle, and in any materials that could possibly change phase. Several locations around the outer surface should be included to enssure that the required heat flux is transferred to all package surfaces (see Fig. D.1.3 in Appendix D for example locations).

If fire heating is employed, measurements should be taken at several locations within the fire to determine the magnitude, constancy, and variation of temperatures around the package. If oven heating is employed, temperature should be measured at several locations on the oven walls for the same purpose.

Typical temperature sensors include thermocouples and resistance thermometers [Refs. 16 and 18]. The sensor must be well attached to a material to accurately measure its temperature.

Surface temperature sensors, like those on outer package surfaces, may require shielding from convective or radiation heating. Small, metal-foil radiation shields placed over, but not contacting, the sensors can be used, provided the shielding does not significantly change the surface temperature. However, if the sensor is embedded in the material, shielding may not be required. As recommended in Section 2.8, an analysis of the sensor conditions should be performed to estimate induced errors and expected accuracies. Equations for estimating these errors can be found in available publications [Ref. 19].

To properly measure fire or oven atmosphere temperatures, sensors must be shielded from thermal radiation and also be well ventilated so that only the gas temperature is measured. If oven wall temperatures are to be measured, surface sensors must also be shielded from radiation.

Color-changing and fusible temperature indicators can be used to determine attained temperatures of surfaces. These indicators are specially formulated materials that change color or melt when heated to a defined transition temperature [Ref. 16]. They can be applied as paint, attached strips, or as a rub-on solid, and they can indicate temperatures from 100 to 1300 °C, in 50-°C and 100-°C increments, and within 1% accuracy. These indicators cannot be used in place of continuously indicating temperature sensors, but they can be used in conjunction with them. If a color-changing indicator is to be subjected to surface deposits, such as fire soot, a removable coating may have to be applied over the indicator to permit acceptable post-test inspection. Such coating must not affect the response of the package or the indicator to the test conditions.

### 4.2 Pressure

If feasible, the containment system pressure should be measured during a thermal test. This can sometimes be accomplished by connecting a pressure transducer to an appropriate containment system penetration via a small diameter metal tube that is long enough to allow remote placement of the transducer. If desirable, the tube can be connected to an existing penetration (e.g., for a relief valve), provided the connection does not interfere with, or adversely influence, the intended function of any package component. The gas volume in the pressure measuring system must be small relative to the gas volume in a package container (e.g., <5%) so that a pressure change in the container will not be significantly affected by the gas in the pressure-measuring system. Also, to protect package materials from additional heating, the tubing should be routed and thermally insulated in the same manner as temperature sensor wires.

Pressure transducers may, in some cases, be installed within a package, provided they function properly while experiencing the conditions produced by a thermal test. Ordinarily, pressure transducer calibrations are sensitive to temperature change. However, this type of installation would entail routing wires, instead of a tube, to pressure-indicating instruments.

### 4.3 Heat Flux

Measurements can be made to verify that heat flux on the package surfaces exceed the required minimum. Heat flux can be measured by using total flux meters (radiative plus convective), radiometers (radiative), or calorimeters.

Water-cooled, Gardon-type meters are commonly used for total or radiative flux metering [Ref. 16]. These meters may be placed on or near a package to measure heat flux at several locations. However, care must be taken not to influence the package surface heating. Also, condensation or soot deposition on these meters can cause measurement errors. Thus, this of type meter would probably not be suitable for fire environments.

Calorimeters (heat-flux integrating devices) have been used for estimating surface heat flux of packages [Ref. 10]. The temperature history at several calorimeter/wall locations and the calorimeter thermal properties are used with special computer codes or derived equations to calculate average and local heat flux values. If the calorimeter is of similar size, shape and heat capacity to a test package and the thermal environment conditions are equivalent, then it is acceptable to presume that the relationship between heat flux and surface temperature for the two objects is approximately equal. In some cases, calorimetry may be the preferred method to certify fire or oven conditions as capable of delivering the required heat flux to a package. However, sufficient supporting analyses and tests are necessary to demonstrate that a chosen calorimeter design will yield acceptable results. An example calorimeter is shown in Appendix D.

The location of heat-flux measuring devices placed in fires or ovens must be carefully selected to obtain good data. Sensors placed close to a test package may significantly influence its surface heat flux if the sensor is large enough to significantly shadow the package from radiation heating. However, sensors placed too far from a test package would probably measure a heat flux that is much different from that on a package surface. For example, at locations approaching the outer edge of a fire, the radiant heat flux decreases. Thus, heat flux sensors should not be placed in this zone, unless a survey of fire properties is being performed. A similar condition can occur in ovens at locations approaching unheated walls.

### 4.4 Strain

Mechanical strain sensors may be used on components to estimate local stresses. However, strain measurement in high-temperature environments is usually difficult, and reliability of the results may therefore be questionable. Usually, the sensitivity of strain gauges is temperature dependent. Also, attachment of strain gauges can become weakened at high temperatures. Thus, strain measurements may have to be limited to moderate temperature conditions. Generally, strain measurements are not needed if reliable containment system temperature and pressure data are obtained and valid material mechanical properties are available. Stresses in components such as closure bolts, flanges, and the containment vessel can usually be estimated using these data with appropriate analysis methods.

### 4.5 Leakage

Containment system leakage rates must be measured to determine if they are within the *10 CFR 71* limits (see Section 1.4). The leakage rates should be measured using a nontoxic tracer gas instead of a radioactive material. However, a correlation must be developed to determine the amount of radioactive material leakage that would be represented by a measured tracer gas leakage. This can be developed by analysis or test methods. A suitable leakage measurement method, and a required instrument sensitivity, may be selected in accordance with the guidelines contained in Refs. 20 and 21.

Containment requirements must be met under all conditions, including the thermal test. Leakage measurements during a thermal test are usually not feasible. Therefore, measurements should be made before and after the test sequence defined in *10 CFR 71.73(c)*. A preferred leak test method includes measuring leakage rates while the containment system pressure is higher than occurred during the thermal test (to provide a safety margin). If this method is impractical, the containment system may be leak tested to show no leakage. A helium leakage rate of $10^{-7}$ standard cc/s at 1-atmosphere gauge pressure is generally accepted as zero leakage condition for packages.

### 4.6 Photographic Records

Photographic methods should be used to record test events, conditions, and results. For example, photos of assemblies or parts taken before and after the thermal test can be useful in explaining any changes that may have occurred. Also, a video record of a fire test can be very useful in establishing that acceptable fire conditions occurred. A video record should cover continuous elapsed time.

### 4.7 Auxiliary Tests

Independent tests may be performed on selected items, such as components or subassemblies, to demonstrate that an item can successfully survive the thermal test conditions. For example, relief valves, rupture discs, pressure gauges, gaskets, O-rings, or containment materials are items that may be candidates for independent, controlled tests. The objective of the tests may be to determine material stability or compatibility of items or to measure leak-tightness of seals when subjected to selected ranges of pressure and temperature. Demonstrating the performance of items in pretests can help establish confidence that they will perform satisfactorily during a package thermal test.

# 5. ACCEPTANCE

Packages must always satisfy three principal criteria: (1) containment, (2) shielding, and (3) subcriticality. The intent of *10 CFR 71* is to ensure that certified packages be able to exceed all acceptance criteria by reasonable safety margins, provide for uncertainties, and establish confidence in the package design.

## 5.1 Containment

The acceptance criteria for containment is based on a maximum-allowed leakage rate. Tests must be performed to establish that containment leakage rates are within the limits specified by *10 CFR 71* and *Regulatory Guide 7.4* (Ref. 21). Guidelines contained in Section 4.5 and Ref. 20 are recommended for performing leakage acceptance tests. As there are many possible methods for measuring leakage, an applicant must chose one that is appropriate to the package design and test method. In establishing equivalence of leak test and package contents leakage rates, an applicant should use standards given in Ref. 20 with approval of the regulatory agency.

## 5.2 Shielding

The criteria for shielding are defined in *10 CFR 71.47* [Ref. 1] which specifies maximum-allowed radiation levels on all external surfaces of packages.

The adequacy of a package design to attenuate external radiation to acceptable levels can be demonstrated by analyses or physical tests. If analysis is the chosen method, a suitable nuclear computer code should be used, one that is mature and extensively tested. Example codes are MCNP [Ref. 22] and MORSE [Ref. 23].

If physical testing is used to demonstrate acceptable shielding, a complete test program should be developed and reviewed for acceptability.

## 5.3 Subcriticality

The subcriticality of contents that includes fissile material must not be degraded by the consequences of the hypothetical accident tests. At the conclusion of a thermal test, the test package should be inspected for deformations and other changes that could contribute to an decrease in the contents subcriticality. For some test packages, disassembly of package components may be necessary. The effects of all relevant changes must be reintroduced into the criticality design analyses to estimate a new subcriticality level. Only suitable computer codes that are mature and extensively tested should be used to perform criticality analyses. Example codes are MCNP [Ref. 22] and KENO [Ref. 23]. Acceptance criteria for subcriticality are found in *10 CFR 71.55* through *71.65*.

## 5.4 Post-Test Examination

When appropriate, the test package should be inspected after a thermal test to establish that adequate safety margins were maintained. Disassembly and sectioning of selected subassemblies may be necessary to apply appropriate inspection methods.

# 6. REPORTING

After completing a thermal test program, all test activities and results must be documented for future reference and review. Material must also be assembled for inclusion in the Safety Analysis Report for Packaging (SARP). Topical reports may also be prepared as supporting information and to accompany the SARP.

## 6.1 Final Report

A final report containing detailed descriptions of the test program and results should be prepared. The report can be a valuable future reference for evaluating the test methods and results. Recommended topics to include are:

- Item tested
- Place and date of the test
- Test organization and observers
- Test method
- Test design
- Test procedure
- Measurements, instrumentation, and accuracies
- Results and evaluations.

## 6.2 Safety Analysis Report

Test methods and results must be included in the SARP and prepared in accordance with the format described in the *NRC Regulatory Guide 7.9* [Ref. 6].

## 6.3 Supporting Reports

Supporting topical reports may be prepared to present greater detail than in the Final Report or the SARP. Subjects addressed in the Test Plan are candidates for topical reports (see Section 2).

## 6.4 Notification

It is recommended that an applicant advise the appropriate U.S. regulatory agency of the time and place that a thermal test will be conducted. This provides the agency, or a representative of the agency, an opportunity to observe the test.

# 7. REFERENCES


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7. American Society of Mechanical Engineers, *ANSI/ASME NQA-1: Quality Assurance Program Requirements for Nuclear Facilities, 1983 Edition*, The American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, NY (July 1983).

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# APPENDIX A:

# PROPOSED RULING FOR *10 CFR 71.73*

The NRC published a proposed ruling of *10 CFR 71* in the *Federal Register*[4] for public comment. The following text is Section 71.73 (Hypothetical Accident Conditions) of the proposed ruling.

(a) *Test procedures.* Evaluation for hypothetical accident conditions is to be based on sequential application of the tests specified in this section, in the order indicated, to determine their cumulative effect on a package or array of packages. An undamaged specimen may be used for the water immersion tests specified in paragraphs (c) (5) and (6) of this section.

(b) *Test conditions.* With respect to the initial conditions for the tests, except for the water immersion tests, to demonstrate compliance with the requirements of this part during testing, the ambient 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. 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.

(c) *Tests.* Tests for hypothetical accident conditions must be conducted as follows:

(1) *Free Drop.* A free drop of the specimen through a distance of 9 m (29.5 ft) onto a flat, essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected.

(2) *Crush.* Subjection of the specimen to a dynamic crush test by positioning the specimen on a flat, essentially unyielding, horizontal surface so as to suffer maximum damage by the drop of a 500 kg (1,100 lbs) mass from 9 m (29.5 ft) onto the specimen. The mass must consist of a solid mild steel plate 1 m (3.28 ft) by 1 m and must fall in a horizontal attitude. The crush test is required only when the specimen has a mass not greater than 500 kg (1,100 lbs), an overall density not greater than 1,000 kg/m$^3$ (62.4 lb/ft$^3$) based on external dimensions, and radioactive contents greater than 1,000 $A_2$ not as special form material.

(3) *Puncture.* A free drop of the specimen through a distance of 1 m (39.4 in) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical, mild steel bar mounted on an essentially unyielding, horizontal surface. The bar must be 15 cm (5.91 in) in diameter, with the top horizontal and its edge rounded to a radius of not more than 6 mm (0.238 in) and of a length as to cause maximum damage to the package, but not less than 20 cm (7.[illegible] in) long. The long axis of the bar must be vertical.

(4) *Thermal.* Exposure of the specimen fully engulfed, except for a single support system, in a hydrocarbon fuel/air fire of sufficient extent and in sufficiently quiescent ambient conditions to provide an average emissivity coefficient of at least 0.9, with an average flame temperature of at least 800 °C (1,472 °F) for a period of 30 minutes, or any other thermal test which provides the equivalent total heat input to the package and which provides a time averaged environmental temperature of 800 °C. The fuel source shall extend horizontally at least 1 m (3.28 ft), but shall not extend more than 3 m (9.84 ft), beyond any external surface of the specimen, and the specimen shall be positioned 1 m (3.28 ft) above the surface of the fuel source. For purposes of calculation, the surface absorptivity coefficient must be either that value which the package may be expected to possess if exposed to the fire specified or 0.8, whichever is greater, and the convective

[4] *Federal Register*, Vol. 53, No. 110 (Wednesday, June 8, 1988), pp. 21550-21581.

coefficient must be that value which may be demonstrated to exist if the package were exposed to the fire specified. Artificial cooling must not be applied after cessation of external heat input and any combustion of materials of construction must be allowed to proceed until it terminates naturally.

(5) *Immersion - all packages.* A separate, undamaged specimen must be subjected to water pressure equivalent to immersion under a head of water of at least 15 m (50 ft). For test purposes, an external pressure of water of 150 kPa (21.7 lb/in$^2$) gauge is considered to meet these conditions.

(6) *Immersion - fissile material.* For fissile material subject to § 71.55, in those cases where water inleakage has not been assumed for criticality analysis, immersion under a head of water of at least 0.9 m (3 ft) in the attitude for which maximum leakage is expected.

# APPENDIX B:
# IAEA ACCIDENT CONDITIONS

The following text is taken from IAEA Safety Series 6[5] and defines the IAEA requirements for demonstrating the ability of a package to withstand accident conditions during transport.

626. The specimen shall be subjected to the cumulative effects of the tests specified in para. 627 and para. 628, in that order. Following these tests, either this specimen or a separate specimen shall be subjected to the effect(s) of the water immersion test(s) as specified in para. 629 and, if applicable, para. 630.

6.27. *Mechanical test:* The mechanical test consists of three different drop tests. Each specimen shall be subjected to the applicable drops as specified in para. 548[6]. The order in which the specimen is subjected to the dr : shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to the maximum damage in the thermal test which follows.

(a) For drop I, the specimen shall be dropped onto the target so as to suffer the maximum damage, and the height of the drop measured from the lowest point on the specimen to the super surface of the target shall be 9 m. The target shall be as defined in para. 618[7].
(b) For drop II, the specimen shall be dropped so as to suffer the maximum damage onto a bar rigidly mounted perpendicularly on the target. The height of the drop measured from the intended point of impact of the specimen to the upper surface of the bar shall be 1 m. The bar shall be of solid mild steel of circular section, (15.0 ± 0.5) cm in diameter, and 20 cm long unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum damage shall be used. The upper end of the bar shall be flat and horizontal with its edges rounded off to a radius of not more than 6 mm. The target on which the bar is mounted shall be as described in para. 618.
(c) For drop III, the specimen shall be subjected to a dynamic crush test by positioning the specimen on the target so as to suffer maximum damage by the drop of a 500 kg mass from 9 m on to the specimen. The mass shall consist of a solid mild steel plate 1 m by 1 m and shall fall in a horizontal attitude. The height of the drop shall be measured from the underside of the plate to the highest point of the specimen. The target on which the specimen rests shall be as defined in para. 618.

628. *Thermal test:* The thermal test shall consist of the exposure of a specimen fully engulfed, except for a simple support system, in a hydrocarbon fuel/air fire of sufficient extent and in sufficiently quiescent ambient conditions to provide an average emissivity coefficient of at least 0.9, with an average flame temperature of a least 800 °C for a period of 30 minutes, or shall be any other thermal test which provides the equivalent total heat input to the package. The fuel source shall extend horizontally at least 1 m, and shall not extend more than 3 m beyond any external surface of the specimen, and the specimen shall be positioned 1 m above the surface of the fuel source. After the cessation of external

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5 IAEA Safety Series No. 6, *Regulations for the Safe Transport of Radioactive Material*, 1985 Ed. (as amended 1990), International Atomic Energy Agency, Vienna (1990).

6 Para. 548 specifies the test in para. 627(c) is required when the package has a mass not greater than 500 kg, and an overall density not greater than 1000 kg/m$^3$ based on the external dimensions, and radioactive contents greater than 1000 $A_2$ not as special-form radioactive material, or the test in para 627(a) for all other packages.

7 A flat, horizontal surface of such a character that any increase in its resistance to displacement or deformation upon impact by the specimen would not significantly increase the damage to the specimen.

heat input, the specimen shall not be cooled artificially and any combustion of materials of the specimen shall be allowed to proceed naturally. For demonstration purposes, the surface absorptivity coefficient shall be either 0.8 or that value which the package may be demonstrated to possess if exposed to the fire specified; and the convective coefficient shall be that value which the designer can justify if the package were exposed to the fire specified. With respect to the initial conditions for the thermal test, the demonstration of compliance shall be based upon the assumption that the package is in equilibrium at an ambient temperature of 39 °C. The effects of solar radiation may be neglected prior to and during the tests, but must be taken into account in the subsequent evaluation of the package response.

629. *Water immersion test:* The specimen shall be immersed under a head of water of at least 15 m for a period of not less than eight hours in the attitude which will lead to maximum damage. For demonstration purposes, an external gauge pressure of at least 150 kPa (1.5 $kgf/cm^2$) shall be considered to meet these conditions.

630. *Water immersion test for packages containing irradiated nuclear fuel:* The specimen shall be immersed under a head of water of at least 200 m for a period of not less than one hour. For demonstration purposes, an external gauge pressure of at least 2 MPa (20 $kgf/cm^2$) shall be considered to meet these conditions.

# APPENDIX C:
# CONVECTION COEFFICIENTS

Should a packaging be subjected to a thermal test by methods other than by an engulfing hydrocarbon fire, evaluation of the convection heating component will be necessary. Total heat transfer to a test package must be not less than would occur from an 800 °C engulfing fire having an effective thermal emissivity of 0.9 and onto package surfaces having an effective thermal absorptivity of 0.8. To estimate the convective heat transfer in the specified fire and in other test methods, suitable values of the convection coefficient are needed. They will depend on a test package's geometry and orientation, the convecting gas properties and the nature of fluid flow over package surfaces.

Hydocarbon fuel/air fires that are sufficiently large to engulf a test package will include relatively high-velocity turbulent gas flows over the package surfaces as described in Section 3.3.1. Usually, correlations of convection heat transfer coefficients for forced flow over selected surfaces can be applied to estimating coefficient values for package surfaces. However, estimates of appropriate gas properties and velocity will be required.

Packages that are thermally tested in ovens will typically be subjected to turbulent-free convection of oven gases. Correlations of free convection heat transfer coefficients for flow over selected surfaces are ususally applied to estimating coefficient values for the package surfaces. Using these coefficients, the convective heat transfer can be estimated. If necessary, the radiative component can be augmented by increasing the oven temperature until the combined convective and radiative heat transfer to a package satisfies the *10 CFR 71.73* requirements.

Given in the following sections are example correlations of mean convection heat transfer coefficients for forced and free convection, turbulent fluid flow over some common geometry surfaces. These correlations may be applicable to many test packages; however, it is the responsibility of the package designer to find the most suitable correlation for a specific test package.

## C.1 Forced Flow Correlations

Turbulent flow normal to a cylinder axis [Ref C-1]:

$$Nu_D = 0.26\, Pr^{0.37}\, Re_D^{0.60}\, (Pr/Pr_s)^{0.25} \qquad \text{(C-1)}$$

where: $Nu_D$ = Nusselt number, based on diameter D
$Pr$ = Prandtl number at fluid temperature, $0.6 < Pr < 10$
$Pr_s$ = Prandtl number at surface temperature
$Re_D$ = Reynolds number, based on diameter D, $1{,}000 < Re_D$ 200,000.

Turbulent flow parallel to a flat surface of length L or a cylinder axis of length L [Ref. C-2]:

$$Nu_L = (0.037\, Re_L^{0.8} - 871)\, Pr^{0.33} \qquad \text{(C-2)}$$

## C.2 Free Convection Correlations

The following correlations are found in Ref. C-1.

Horizontal cylinders of diameter D:

$$Nu_D = \left\{0.60 + \frac{0.387\, Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2, \quad 10^{-5} < Ra_D < 10^{12} \qquad \text{(C-3)}$$

Vertical flat plates of length L:

$$Nu_L = (Nu_l^6 + Nu_t^6)^{1/6}, \quad 1 < Ra_L < 10^{12} \qquad \text{(C-4)}$$

$$Nu_l = \frac{2.8}{\ln[1 + 2.8/(C_l\, Ra_L^{1/4})]} \qquad \text{(C-5)}$$

$$Nu_t = C_v\, Ra_L^{1/3} \qquad \text{(C-6)}$$

$$C_l = \frac{0.671}{[1 + (0.492/Pr)^{9/16}]^{4/9}} \qquad \text{(C-7)}$$

$$C_v = \frac{0.13\, Pr^{0.22}}{(1 + 0.61\, Pr^{0.81})^{0.42}} \qquad \text{(C-8)}$$

where: $Nu_L$ = Nusselt number, based on L
$Ra_L$ = Rayleigh number, based on L
$Pr$ = Prandtl number.

Upward heated or downward cooled plates:

$$Nu_L = (Nu_l^{10} + Nu_t^{10})^{1/10}, \quad Ra_L > 1 \qquad \text{(C-9)}$$

$$Nu_l = \frac{1.4}{\ln[1 + 1.677/(C_l\, Ra_L^{1/4})]} \qquad \text{(C-10)}$$

$$Nu_t = 0.14\, Ra_L^{1/3} \qquad \text{(C-11)}$$

$C_l$ = (Equation C-7)

L = (plate surface area)/(plate perimeter)

Downward heated or upward cooled plates:

$$Nu_L = C_h\, Ra_L^{1/5}, \quad 10^5 < Ra_L < 10^{10} \qquad \text{(C-12)}$$

$$C_h = \frac{0.527}{[1 + (1.9/Pr)^{9/10}]^{2/9}} \qquad \text{(C-13)}$$

Vertical cylinders of length L and diameter D:

$$Nu_L = \text{(Equation C-4)}$$

$$Nu_l = Cf\,\text{(Equation C-5)}$$

$$C_f = \frac{1.8\,\Phi}{\ln[1 + 1.8\,\Phi]} \tag{C-14}$$

$$\Phi = \frac{L/D}{C_l\,Ra_L^{1/4}} \tag{C-15}$$

$$C_l = \text{(Equation C-7)}$$

$$Nu_t = \text{(Equation C-6)}$$

## C.3 Example Heat Tranfer Rates

To illustrate the magnitude of convective heat transfer rates to package surfaces, heat flux values are computed using Equations C-1 and C-3, which are for forced and free convection flow normal to horizontal cylinders. The chosen conditions are 800 °C air, 1-m-diameter cylinder and 5 m/s forced-flow velocity. Temperature dependent air properties are also included. Results are given in Fig. C.1, which shows curves of surface heat flux relative to package surface temperature.

Velocities in large open pool type fires are reported in Ref. C-3. Vertical velocities are related to distance above the fuel surface and total heat release by the fire. The reference includes measured velocities in a JP-4 fuel fire from a 9 X 18 m pool. At 1.4 m above the fuel, the mean gas velocity was approximately 5 m/s. Turbulence caused significant velocity variations from the mean.

## C.4 References

C-1 E.C. Guyer, *Handbook of Applied Thermal Design* (McGraw-Hill Book Company, New York, NY, 1989).

C-2 S. Kakac, R.K. Shah, and W. Aung, *Handbook of Single-Phase Convective Heat Transfer* (John Wiley & Sons, New York, NY, 1987).

C-3 M.E. Schneider and L.A. Kent, "Measurements of Gas Velocities and Temperatures in a Large Open Pool Fire," *Fire Technology*, Vol. 25, No. 1, Feb. 1989, pp. 51-58.

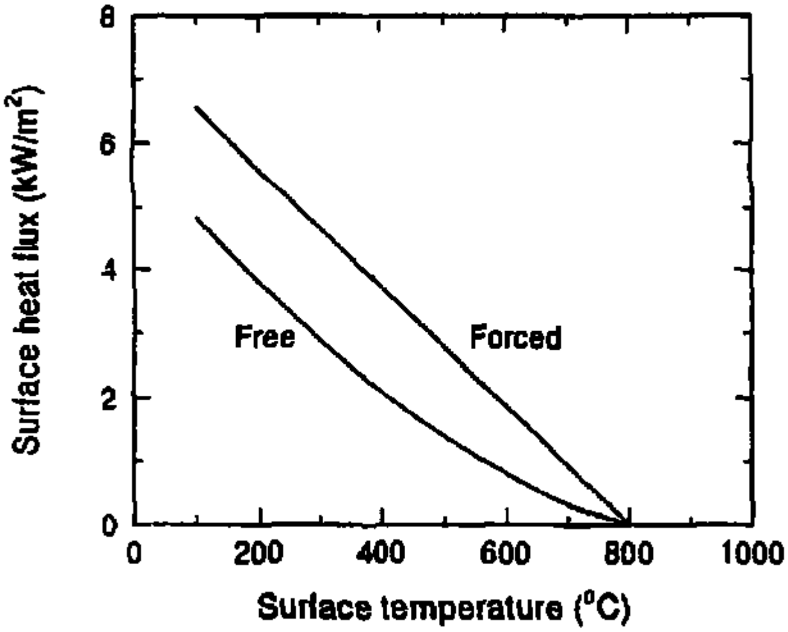


**Fig. C.1. Surface heat flux on a horizontal cylinder for forced flow (from Equation C-1) and free convection flow (from Equation C-3). Air temperature = 800 °C, cylinder diameter = 1 m, forced flow velocity = 5m/s.**

# APPENDIX D:
# EXAMPLE TEST FACILITIES

Numerous hydrocarbon fuel fires that satisfy the thermal test conditions have been produced. Two example fires are described in this appendix.

### D.1 Natural Convection Fire

A series of pool fire tests were conducted by the Sandia National Laboratories to study the thermal response of large cylindrical calorimeters to the regulation fire defined in *10 CFR 71.73* [Refs. D-1 and D-2]. A JP-4 jet-fuel fire was established on a pool of water contained by a 9.1 X 18.3 X 0.9 m (30 X 60 X 3 ft) concrete pool (see Figs. D.1.1 and D.1.2). A 22 cm (8.5 in) layer of fuel on 66 cm (26 in) of water burned for approximately 35 minutes in quiescent atmospheric conditions.

Large and small calorimeters were placed in the fire to measure their temperature and heat flux response to the fire. Surface heat flux was computed using measured temperatures at the inner and outer surfaces of a calorimeter wall (see Fig. D.1.3) and the calorimeter dimensions and thermal properties in a numerical calculation code. Example values of measured fire temperature and calorimeter surface heat flux and temperature are given in Fig. D.1.4.

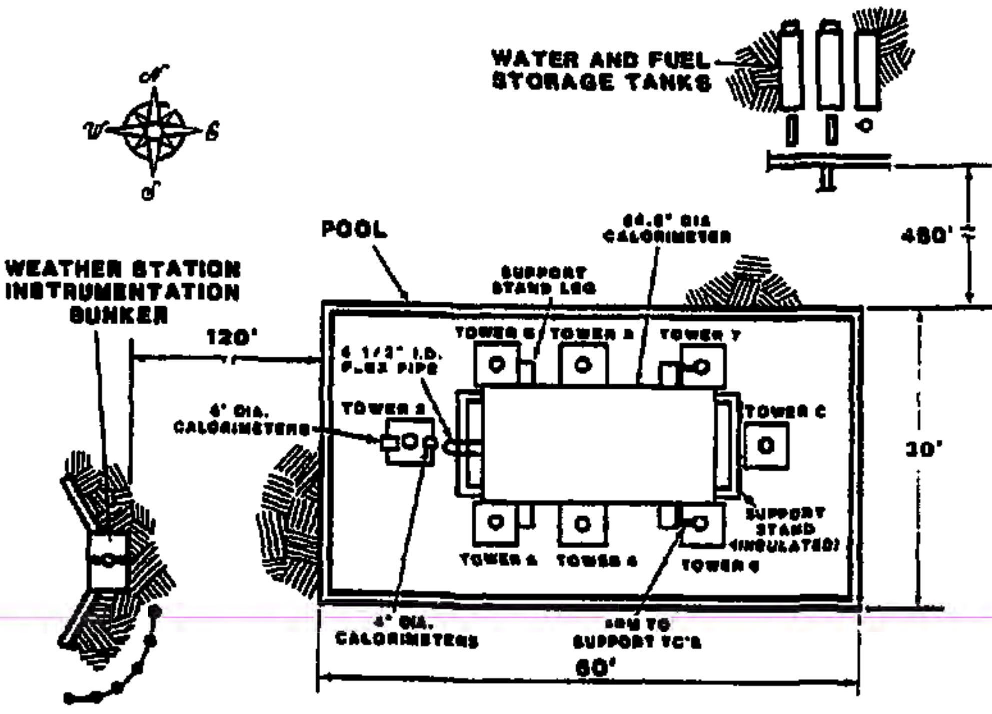


**Fig. D.1.1. Layout of Sandia fire test pool, large calorimeter, and instrumentation towers [Ref. D-1].**

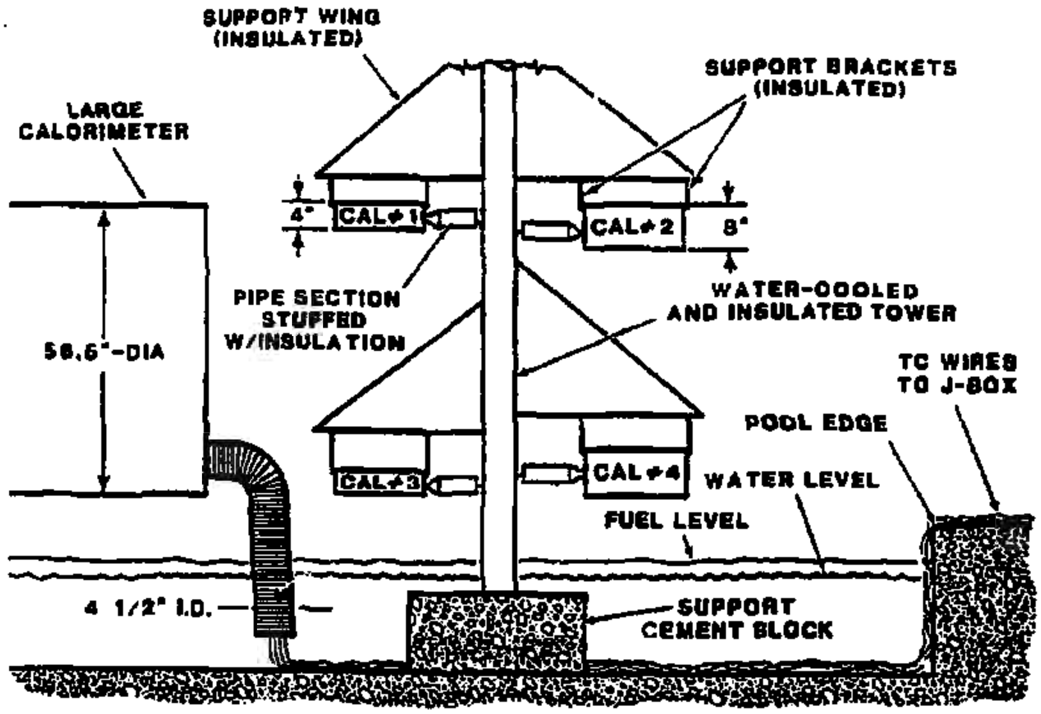


Fig. D.1.2. Section view of Sandia fire test pool, calorimeters, and instrumentation towers [Ref. D-1].

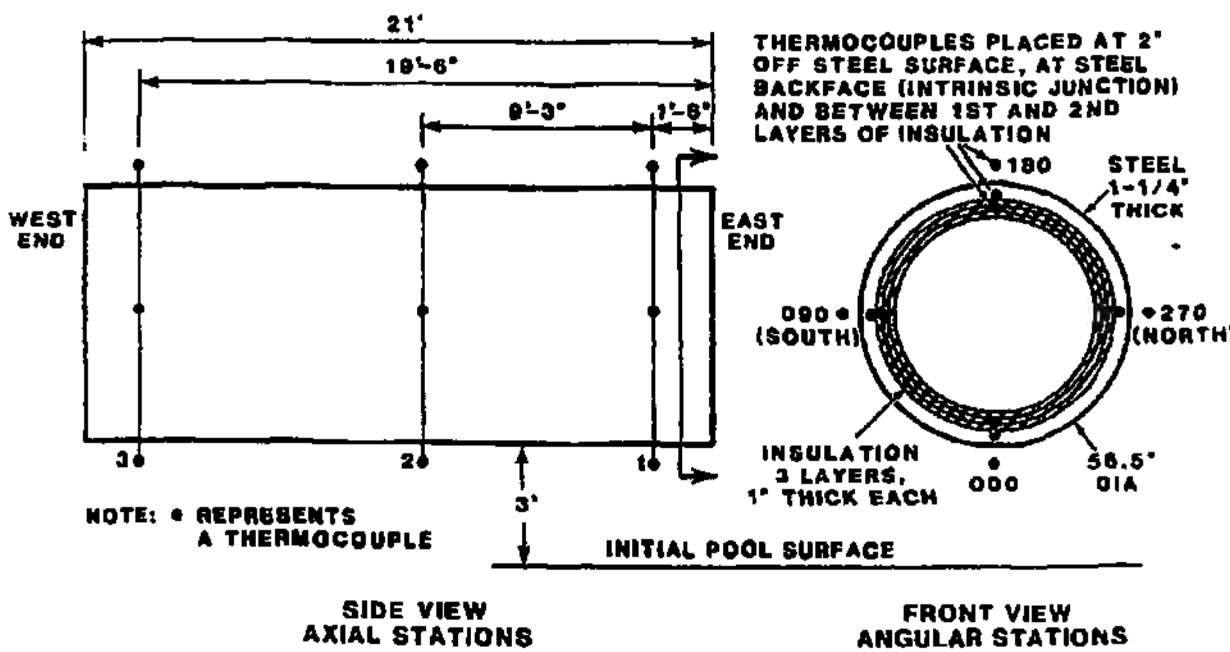


Fig. D.1.3. Side and front views of Sandia large calorimeter with thermocouple locations shown [Ref. D-1].

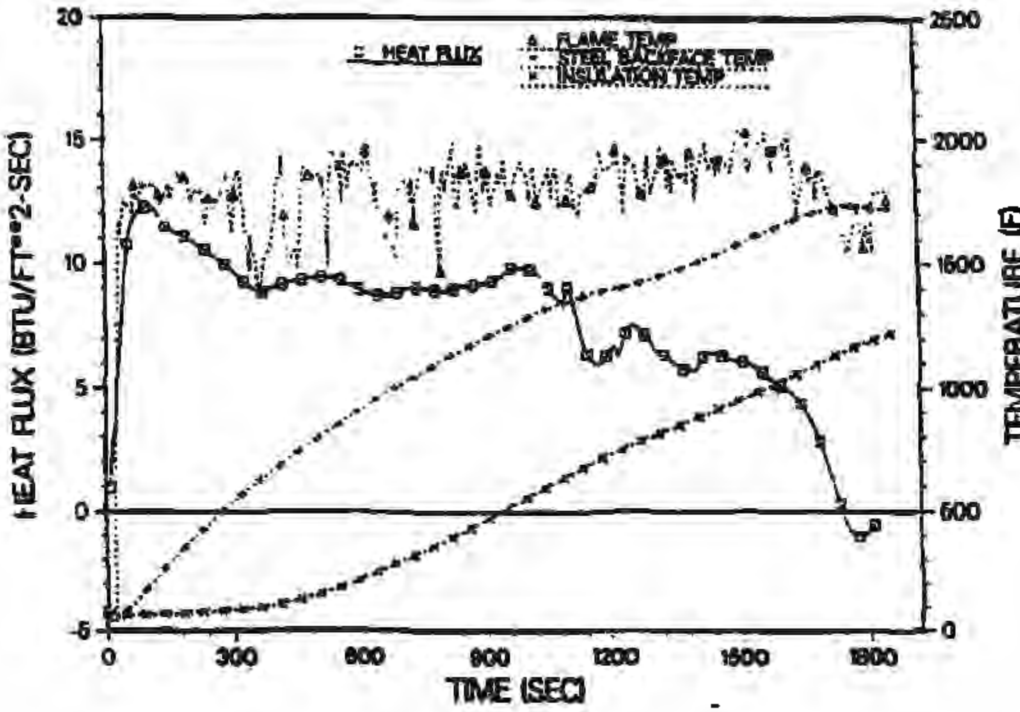


**Fig. D.1.4. Measured fire temperature and large calorimeter temperatures and heat flux [Ref. D-1].**

## D.2 Controlled Convection Fire

Another fire test facility constructed at Sandia National Laboratories, for testing packages and other items, provided a means for supplying air to the center of a pool fire [Ref. D-3]. The facility (illustrated in Fig. D.2.1) included a pool of JP-4 fuel floating on water contained in 3-m-diameter steel tub. A controlled supply of air was delivered to the fire through a symmetric pattern of nineteen 48-cm-diameter air pipes, which passed from an underground plenum upward through the water and fuel. The air supply was controlled with inlet-tunnel louvers that responded to feedback from a control thermocouple at the level of the item being tested. Test items rested above the fuel on a test stand that was centered in the burn tub. An 8-m-high by 5-m-diameter steel chimney shielded test items from ambient winds and enhanced air draft development. Flame temperatures exceeding 1000 °C (1832 °F) and lasting longer than one hour were produced during tests.

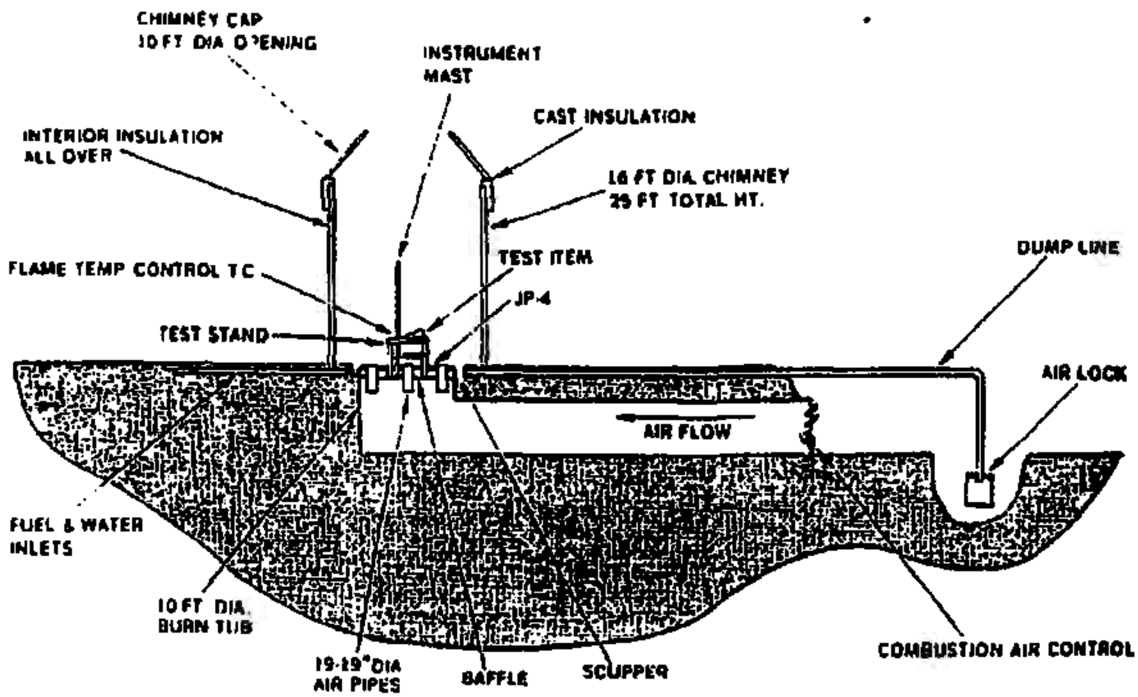


**Fig. D.2.1. Sandia fire test facility that includes enhanced air feed to a pool fire [Ref. D-3].**

## D.3 References


D-1 J.J. Gregory, R. Mata, and N.R. Keltner, *Thermal Measurements in a Series of Large Pool Fires*, Sandia National Laboratories, Albuquerque, NM, SAND85-0196, TTC-0659, UC-71 (August 1987).

D-2 United States Nuclear Regulatory Commission, *Packaging and Transportation of Radioactive Material, Title 10 Code of Federal Regulations, Part 71 (10 CFR 71)*, Office of the Federal Register, National Archives and Records Administration, January 1992. (Available from U.S. Government Printing Office, Washington, D.C. 20402.)

D-3 J.A. Andersen, et al., *PAT-2 (Plutonium Air-Transportable Model 2) Safety Analysis Report*, Sandia National Laboratories, Albuquerque, NM, SAND81-0001 (July 1981).