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STANDARD THERMAL PROBLEM SET*

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INTRODUCTION

Beginning in April 1985, a working group on heat transfer met under the auspices of the Organization for Economic Cooperation and Development's Committee on Reactor Safety to define a standard problem set which could be used to benchmark codes used to predict cask thermal response. The problem definitions and solutions which resulted from these meetings as described in "Standard Thermal Problem Set for the Evaluation of Heat Transfer Codes Used in the Assessment of Transportation Packages," R. E. Glass, et al., Sandia National Laboratories, 1988 are summarized in this paper.

The problems that were defined address each of the major heat transfer mechanisms (conduction, convection, and radiation) that occur in a cask both during normal transport and as a result of the all-engulfing fire scenario.

The problems were kept geometrically simple to minimize the resources required to obtain a solution while still addressing actual phenomena. This has resulted in a set of one- and two-dimensional problems.

The solutions to this problem set include closed form analytical solutions, experimental data, and consensus of numerical solutions. For each problem the range of numerical solutions are presented.

PROBLEM DESCRIPTION

During the shipment of radioactive materials, numerous thermal transport mechanisms are occurring simultaneously. All casks have a heat source (radioactive materials) in the cask. This heat source dissipates its energy through a liquid or gaseous medium to the cask wall. The thermal energy is then conducted through the cask wall and dissipated from the surface by free convection and radiation. During a fire the energy transport is reversed, with the greater heat source (fire) being on the outside of the cask, and the same heat transport mechanisms then work to transport heat in towards the contents.

The problems that have been defined address each of these areas. The problems are designated according to the proposing member (France, FR; United Kingdom, UK; and United States, US) and the problem number. Hence, the problems are FR-1, UK-1, UK-2, UK-3, US-1, and US-2. UK-1 is a simulated horizontal spent fuel pin array in a gaseous environment. FR-1 addresses the situation where spent fuel is surrounded by sodium which is allowed to undergo phase change. UK-3 addresses the potential for thermal stratification and pressure buildup in a water-filled cask. US-1 simulates a

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heat source with conduction through the cask wall and heat dissipation by convection at the cask surface. UK-2 simulates heat dissipation by fins. US-2 is a multiple layered cask in a fire environment with a thermal shield. This configuration forces a two-dimensional radiation analysis. The problems are shown in Fig. 1. US-1 represents a monolithic cask body with a uniformly distributed heat load during normal transport. The interior region (Region I) contains a volumetric heat source of 11,090 W/m^3, which simulates the internal decay heat of an irradiated fuel load. The internally generated heat is conducted through the stainless steel cask body then removed at the outer surface of the cylinder by convective cooling to the environment.

US-2 is based on a prototypic cask configuration consisting of several different annular regions above a thermal shield. Region I contains a volumetric heat source of 38,320 W/m^3 simulating the decay heat of a packaged spent fuel assembly. Region III is considered to be a voided neutron shield. Consequently, the single mode of heat transfer between the cask wall of Regions II and the neutron shield wall of Region IV is thermal radiation. The cask/thermal shield arrangement is presumed to transfer heat to the surrounding environment by thermal radiation. The area between the cask and shield is assumed to be nonparticipating. There is a thermal exchange between the bottom of the cask and the upper surface of the shield. The cask is subjected to the regulatory thermal event so that a three-part solution is required. Those three parts consist of: 1) a steady state solution to define initial conditions, 2) a 30-minute fire transient with an environmental temperature of 800°C, and 3) a cool down period in a 54.4°C environment for 60 minutes duration.

UK-1 represents a horizontal 16 X 16 array of heated and unheated pins simulating a PWR fuel element in a gas environment. The array is contained in an isothermal enclosure. Internally generated heat is removed by conduction and radiation to the internal surface of the enclosure. Convection contributed insignificantly to the heat transfer due to the use of helium as the heat transfer medium.

UK-2 represents a plane surface with a uniform array of parallel rectangular fins attached. The problem represents three phases in a fire test. The first is the pretest, steady state condition where heat is transferred by natural convection from an internal fluid at a fixed temperature to the plane inside wall. Heat is conducted through the wall and dissipated by radiation and natural convection from the outside wall and fin surfaces to constant temperature surroundings. The second phase is the fire transient where heat is supplied by radiation and forced convection from a hot external fluid. After conduction through the fins and the body, it is rejected by natural convection to the internal fluid. The third phase is the cool down period where heat absorbed during the fire transient is rejected to the surroundings by the same process as used to derive the initial steady state condition. Two magnitudes of surface emissivity are considered to assess the ability of the calculation methods to treat heat transfer between reflecting surfaces.

UK-3 represents a sealed container, part filled with water, subject to external heating approximating the regulatory thermal test. The external heat flux is simplified to avoid unnecessary external boundary condition complexity. The container is assumed to be sealed thereby suppressing boiling in the water. Natural convection is also simplified to enable relatively simple heat transfer codes to be used. Heat flow by convection is simulated by using an artificially large horizontal component of thermal conductivity for the water while the vertical component is the actual conductivity of water. In this way the effects of stratification are represented. The calculation is in two parts: an initial steady state is defined (in this case a uniform temperature of 38°C) followed by a heating transient with a constant heat flux of 10 kW/m and finally a cool down transient when heat is rejected from the curved outer surface by radiation and convection.

FR-1 is taken from the transport method used in France to ship the "monitored" fuel pin assemblies from Super Phenix to laboratories for analysis. The model consists of a radial section of a cask containing a sheath filled with sodium in which is placed the irradiated assembly. The residual power is dissipated to the environment through a finned surface. In the initial state the sodium is completely solidified. The calculation is then performed in a transient state where the cask is subjected to a temperature of 800°C. A simplifying assumption is made that the sodium volume is constant during phase change.

DESCRIPTION OF THERMAL CODES

The thermal codes in the intercomparison for each problem were selected by the user. This results in different codes being used for each problem. These codes range from those developed for a specific purpose, such as fuel pin simulation (RIGG), to the large multipurpose heat transfer code (Q/TRAN).

The selection of codes used indicates that a variety of thermal codes are available to select from and that a given problem can be solved using a variety of tools. This makes a standard problem set particularly valuable in evaluating the available codes.

The codes used in this exercise are summarized in Table I. This table presents the advertised capabilities of each of the codes. The geometry section addresses the number of dimensions and coordinates systems that the codes can handle. In the standard problem set, only one- and two-dimensional problems are presented for ease in modeling, although many of the codes are capable of solving the three-dimensional problems that arise in practice.

The temporal section addresses whether the codes solve steady state or transient problems and further whether they use an explicit or implicit integration technique in the transient solutions. The ability to solve steady state problems directly, as opposed to converging a transient solution, is significant to the cost of providing solutions. This is most applicable to solving normal transport problems or in establishing the initial temperature distribution prior to a thermal transient, such as exposure for 30 minutes to an 800°C ambient. The explicit versus implicit technique is of interest to the stability and efficiency of obtaining the solution.

The section on physics identifies the physical phenomena that can be simulated with the code. These include the basic heat transfer phenomena of conduction, convection, and radiation as well as heat generation, phase change, and variable material properties. There are additional fluids-related capabilities, such as phase change with convection currents or volume change, which are not addressed because they are either not generally used or are cask specific needs.

The section on the type of code specifies finite difference, finite element, and thermal network analogy. This information is often needed to select pre- and post-processors and provides an indication of the ease of using the codes.

The boundary condition section addresses whether a code can address problems with a variety of boundary conditions, such as fixed temperature, heat flux, convection, and radiation. This identifies the type of problem that can be solved and what approximations must be made in simulating the actual boundary condition.

RESULTS

This problem set includes problems based on closed form analytical solutions, experimental data, and a consensus of numerical solutions. In all cases the numerical solutions were within 10 percent of the closed form solutions and experimental data. This summary of results focuses on an example of each. Table II lists the problems and the codes used. As stated earlier, the thermal codes used for the intercomparison were selected by the users.

US-1, which represents normal transport conditions, has a closed form analytical solution. The results are shown in Fig. 2. The temperature varies from 152°C at the centerline to 135°C at the outer edge. Both the closed form and numerical solutions agree within the 1°C accuracy requested for reporting for a broad range of codes (SINDA, HEATING-6, Q/TRAN, DELFINE, and TAU).

UK-1, which represents an irradiated fuel element, is based on experimental data. The results along Line A-B are given in Fig. 3. The greatest deviation between experimental data and the analytical envelop was 6 percent. The largest absolute variation in the analytical solutions (HEATING-6, RIGG, COBRA, Q/TRAN) was 20°C at the array center.

FR-1, representing a sodium phase change problem, is based on a consensus of numerical solutions. The temperature histories are given in Fig. 4. The maximum variation from the mean of these temperatures was 2.3°C. The codes used were HEATING-6, TAU, DELFINE, and SINDA.

CONCLUSIONS

This paper summarizes the development of an international standard thermal problem set. The problem set contains six problems and their corresponding analyses. These problems span the thermal phenomena associated with internal heat generation and dissipation (US-1), a two-dimensional thermal radiation environment (US-2), phase change in a cooling medium (FR-1), fuel pin interaction (UK-1), fin heat dissipation (UK-2), and thermal stratification and vapor pressure buildup (UK-3).

These problems require simulation of conduction, radiation, and a specified convection boundary. Natural convection was simulated using an anisotropic thermal conductivity.

The main thermal components of a cask were simulated including a fuel assembly as a heat source, cooling media of sodium and water, conducting cask walls, radiating gaps representing voided neutron shields, and heat dissipation fins.

The results of the analyses indicated that there are several general purpose thermal computer codes (TAU, SINDA, Q/TRAN, DELFINE, HEATING-6) capable of simulating cask thermal response as well as at least two special purpose codes (RIGG, COBRA) able to model fuel assembly response.

When compared with analytical or experimental solutions, the results were within 10 percent. The intercomparison of the numerical results were also within 10 percent.

In general, this set of problems provides broad coverage of the thermal phenomena of interest to cask designers and regulators. The agreement with analytical and experimental solutions, as well as the consistent results in intercomparison of codes, provides confidence that these solutions can be used in benchmarking other thermal codes.

Table I. Code Matrix

	HEAT6	Q/TRAN	SINDA	TAU	RIGG	FLUFF	DELFINE	COBRA
<u>Geometry</u>								
1-D	Y	Y	Y	Y	N	Y	Y	Y
2-D	Y	Y	Y	Y	Y	N	Y	Y
3-D	Y	Y	Y	Y	N	N	Y	N
Cartesian	Y	Y	Y	Y	Y	Y	Y	Y
Cylindrical	Y	Y	Y	Y	N	N	Y	N
Irregular	N	Y	Y	Y	N	N	Y	N
<u>Temporal</u>								
Steady State	Y	Y	Y	Y	Y	Y	Y	Y
Transient Implicit	Y	Y	Y	Y	N	Y	Y	N
Transient Explicit	Y	Y	Y	N	N	N	N	Y
<u>Physics</u>								
Conduction	Y	Y	Y	Y	Y	Y	Y	N
Radiation	Y	Y	Y	Y	Y	Y	Y	Y
Heat Generation	Y	Y	Y	Y	Y	N	Y	Y
Variable Properties	Y	Y	Y	Y	Y	-	Y	N
Phase Change	Y	Y	Y	N	N	N	Y	N
<u>Type</u>								
Finite Element Method	N	N	N	Y	N	N	Y	N
Finite Difference Method	Y	N	Y	N	Y	Y	N	Y
Thermal Network Analogy	N	Y	N	N	N	N	N	N
<u>Boundary Conditions</u>								
Transient	Y	Y	Y	Y	Y	Y	Y	N
Temperature	Y	Y	Y	Y	Y	Y	Y	N
Heat Flux	Y	Y	Y	Y	Y	Y	Y	N
Convection	Y	Y	Y	Y	Y	Y	Y	Y
Radiation	Y	Y	Y	Y	Y	Y	Y	Y
Calculation of View Factors	N	N	N	Y	Y	Y	N	Y

Table II. Code Use by Problem

	US-1	US-2	UK-1	UK-2	UK-3	FR-1
HEATING-6	Y	Y	Y	Y	Y	Y
Q/TRAN	Y	Y	Y	Y	N	N
SINDA	N	Y	N	N	Y	Y
TAU	Y	Y	N	Y	Y	Y
RIGG	N	N	Y	N	N	N
FLUFF	N	N	N	N	N	N
DELFINE	Y	Y	N	Y	Y	Y
COBRA	N	N	Y	N	N	N

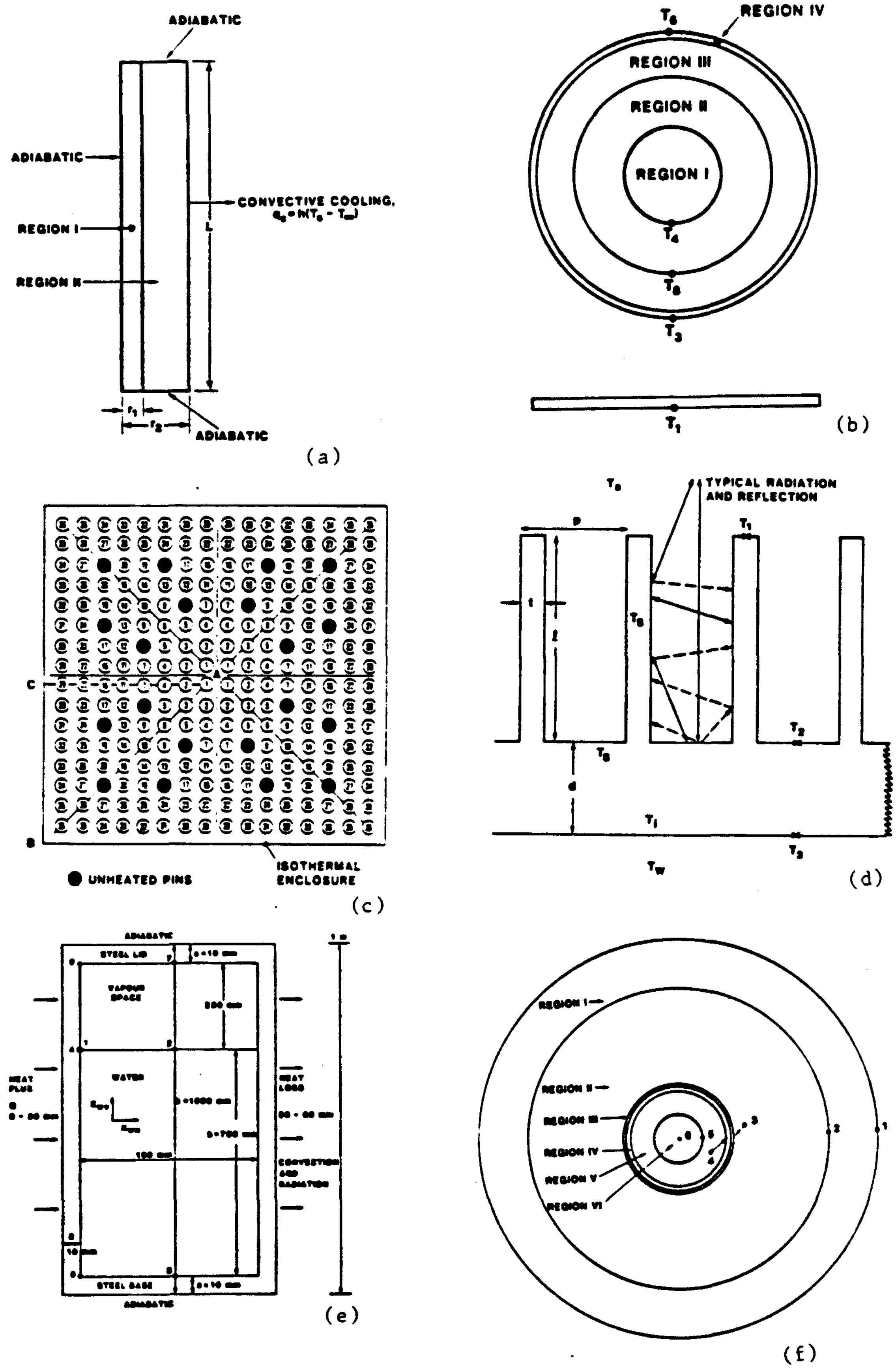

Figure 1. Standard thermal problem set: (a) US-1, (b) US-2, (c) UK-1, (d) UK-2, (e) UK-3 (f) FR-1.

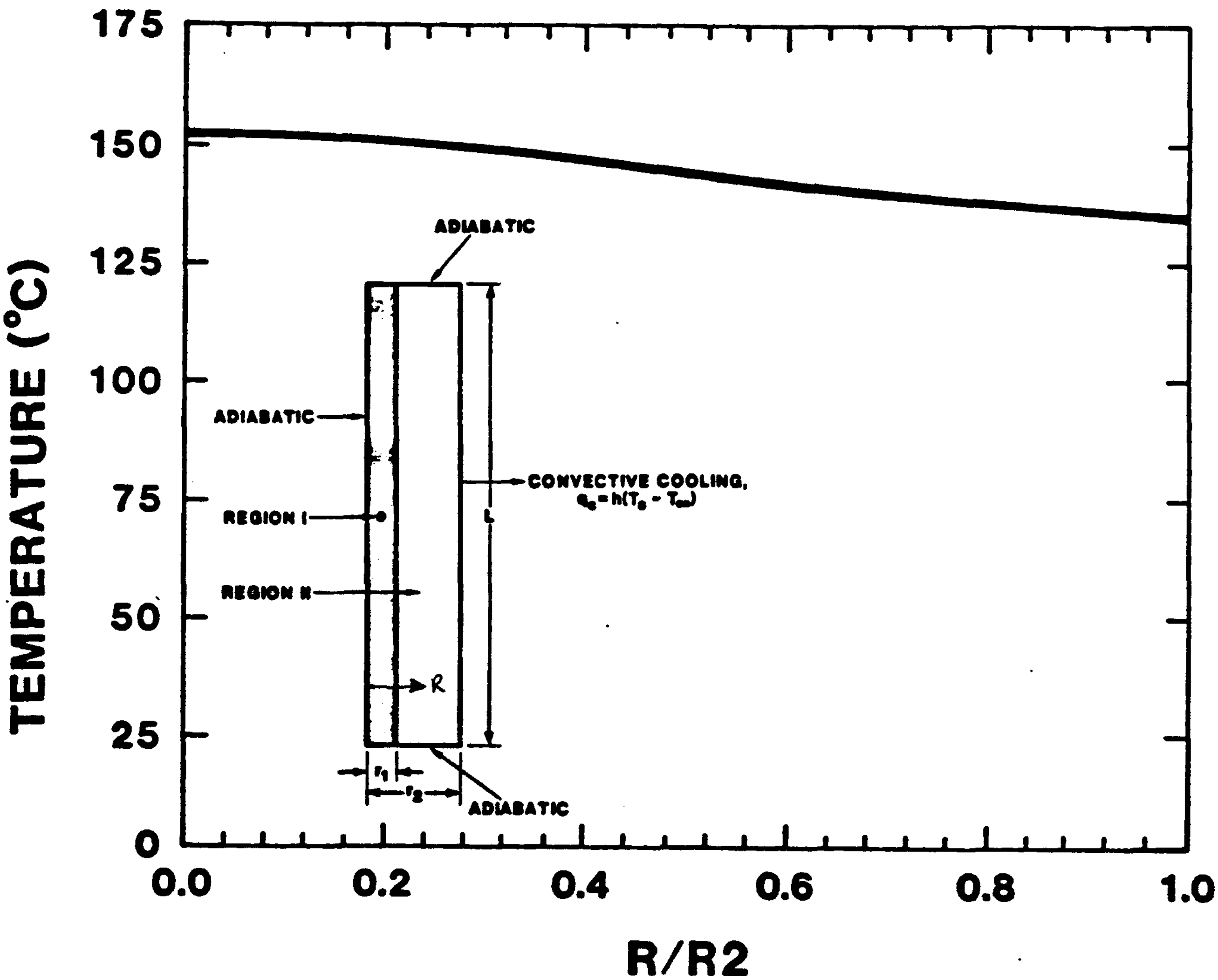

Figure 2. US-1: closed form analytical solution and numerical analysis.

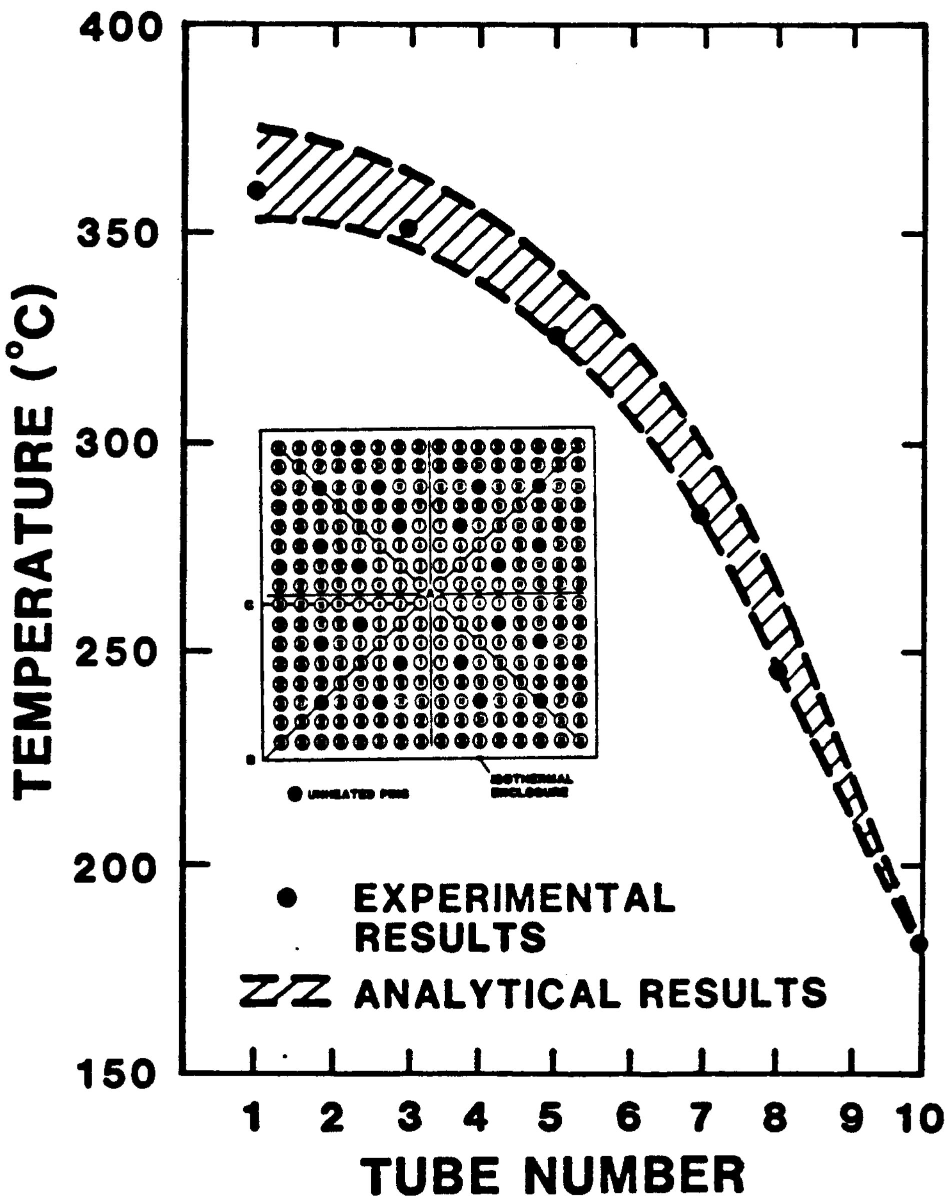

Figure 3. UK-1: Experimental data and numerical analysis

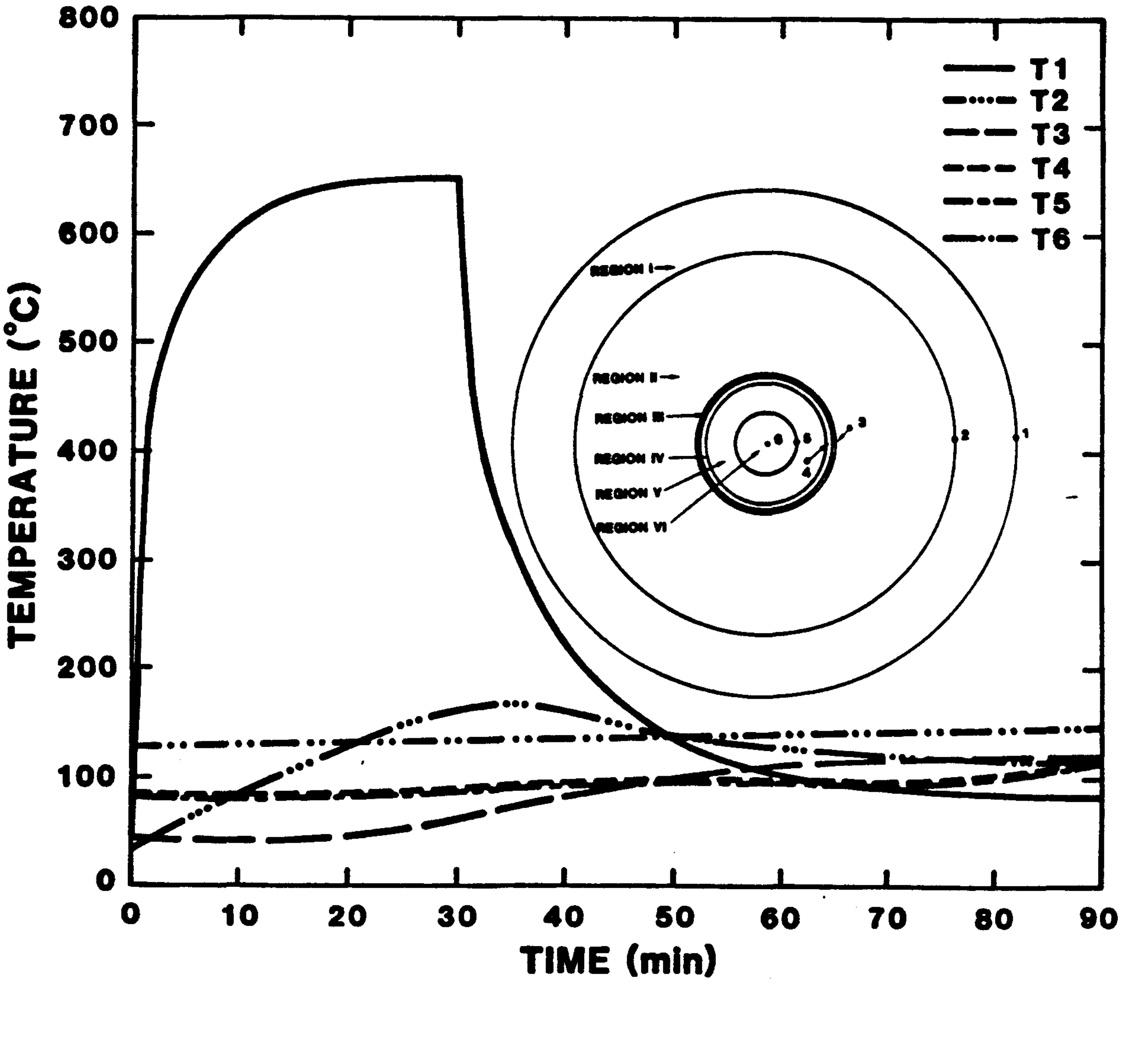

Figure 4. FR-1: Consensus of numerical analyses.

REFERENCES

Glass, R. E., et al. "Standard Thermal Problem Set for the Evaluation of Heat Transfer Codes Use in the Assessment of Transportation Packages," SAND88-0380, Sandia National Laboratories, Albuquerque, NM 87185 (1988).