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THE DEVELOPMENT OF AN INTERNATIONAL STANDARD PROBLEM SET FOR THERMAL CODE EVALUATION

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ABSTRACT

During a preparatory meeting in Paris on June 21-22, 1979, interest was expressed by most Nuclear Energy Agency (NEA) member countries in exchanging information and experience on various aspects of spent fuel transportation. The result of this meeting was the establishment of working groups under the auspices of the Committee on Reactor Physics (CRP) in the areas of heat transfer, criticality, and shielding.

The heat transfer group was established to define a set of cask-like thermal problems and to provide solutions. The problem set and its solutions are available to benchmark computer codes.

INTRODUCTION

During the shipment of radioactive materials, numerous thermal transport mechanisms are occurring simultaneously. All casks have a heat source (spent fuel) 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 fuel.

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 fuel pin array in a gaseous environment. FR-1 addresses the situation where the 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 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.

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 large pool 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 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.

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 final section specifies the type of code. These are 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.

Problem Descriptions

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. Since the area between the cask and shield is nonparticipating, there is also 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: i) a steady state solution to define initial conditions, ii) a 30-minute fire transient with an environmental temperature of 800°C, and iii) a cool- down period in a 54.4°C environment for 60 minutes duration.

UK-1 represents a 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.

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.

Results

The numerical results within were 10 percent when compared with closed form solutions and experimental data. Examples of these are shown in Figs. 2, 3, and 4.

Figure 2 is a plot of the closed form and numerical solutions to the cask with internal heat source (US-1). This indicates that where a convection boundary can be specified with a simple conduction problem, there are a wide spectrum of codes which can currently simulate the cask response. The agreement with the analytical solutions was within the requested operating accuracy of 1°C.

Figure 3 is a plot of the numerical results and experimental data along a line of tubes in the simulated irradiated fuel array (UK-1). This demonstrates the ability of codes to simulate internal cargo response and is in agreement with the experimental data.

Figure 4 is a plot of the fin tip response (UK-2) with standard deviation given. This is typical of problems without experimental or closed form analytical results where consensus solutions were obtained.

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.

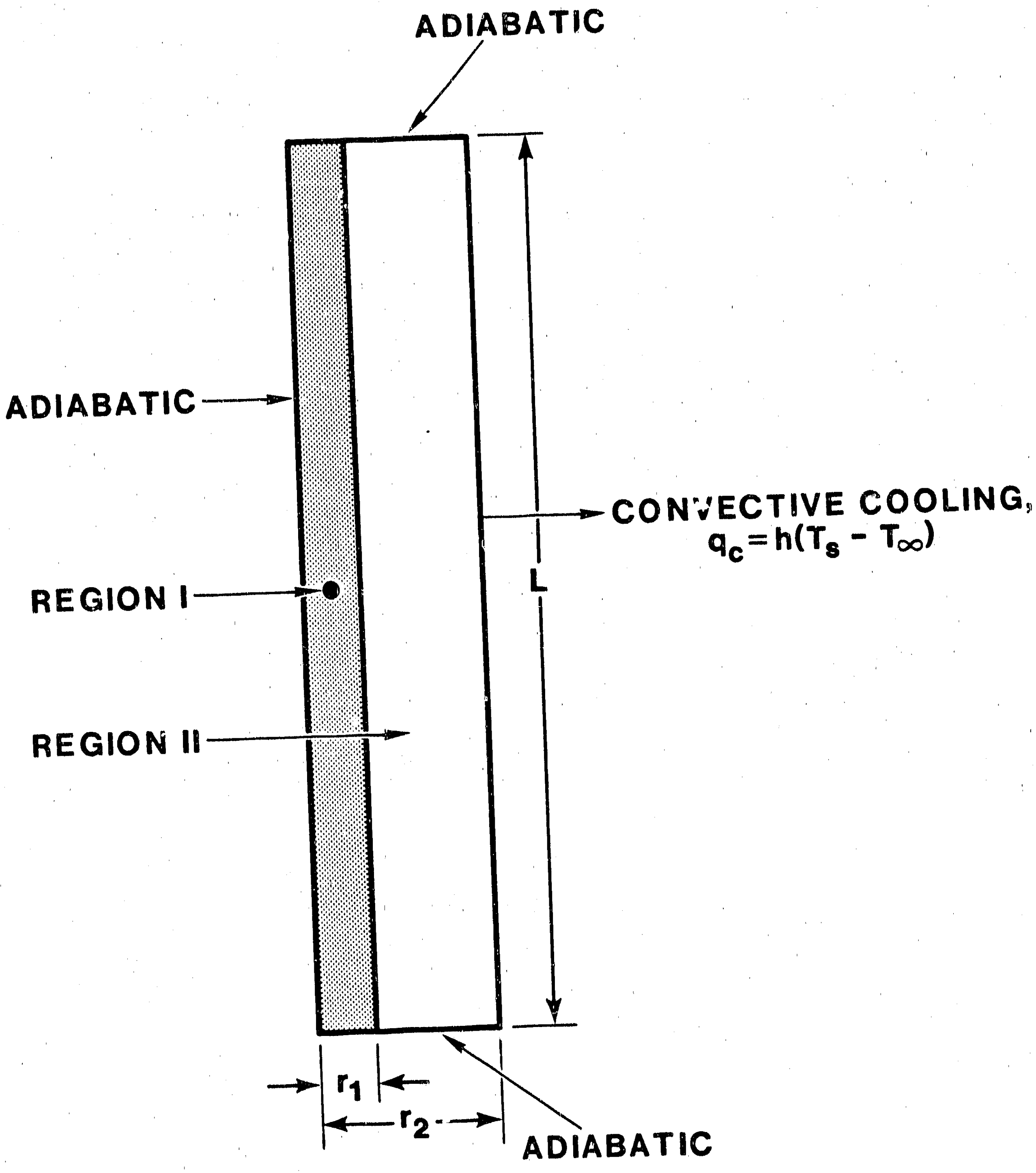

Figure 1. US 1--Cask with Internal Heat Source

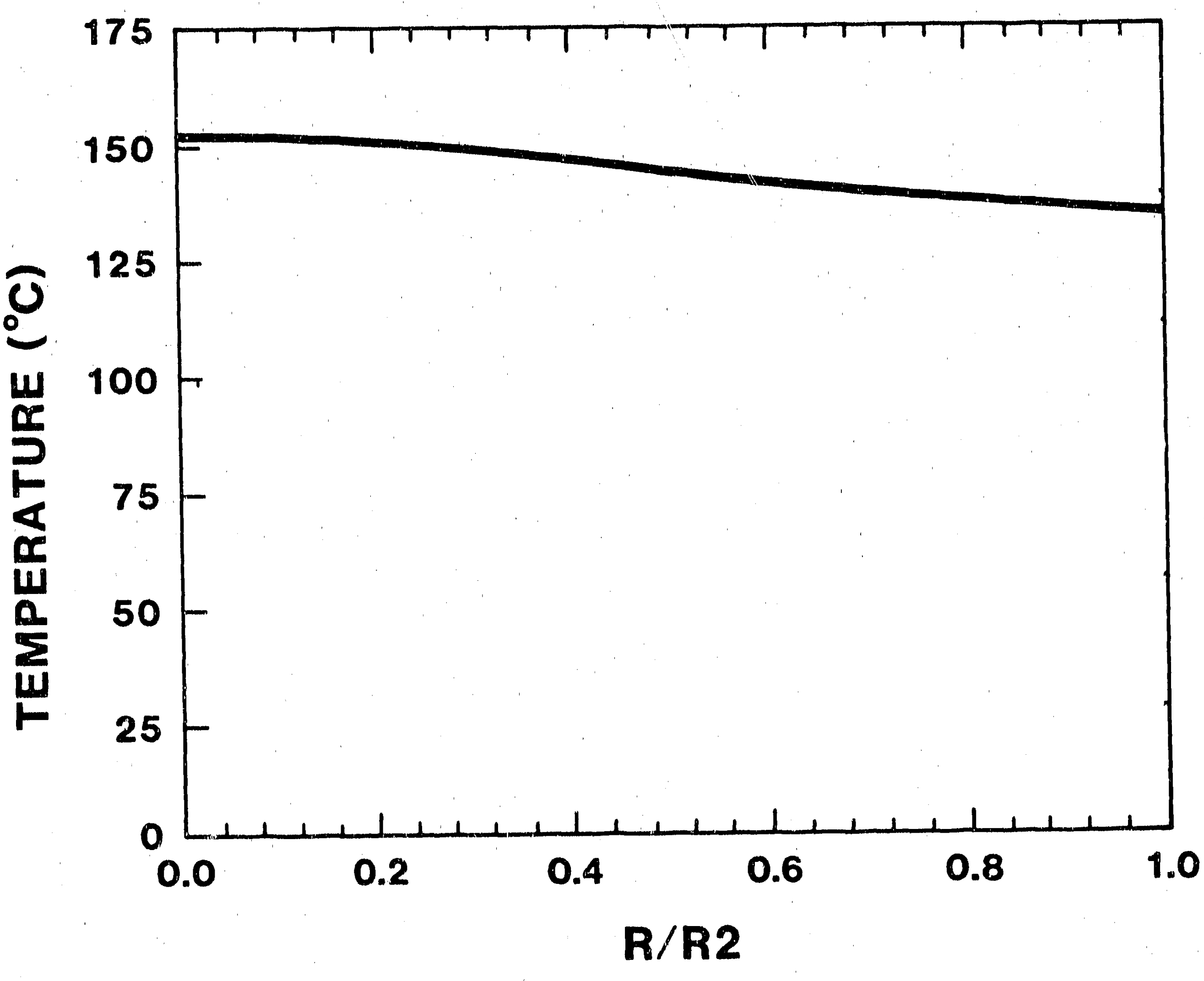

Figure 2. US-1--Temperature Versus Normalized Radial Position

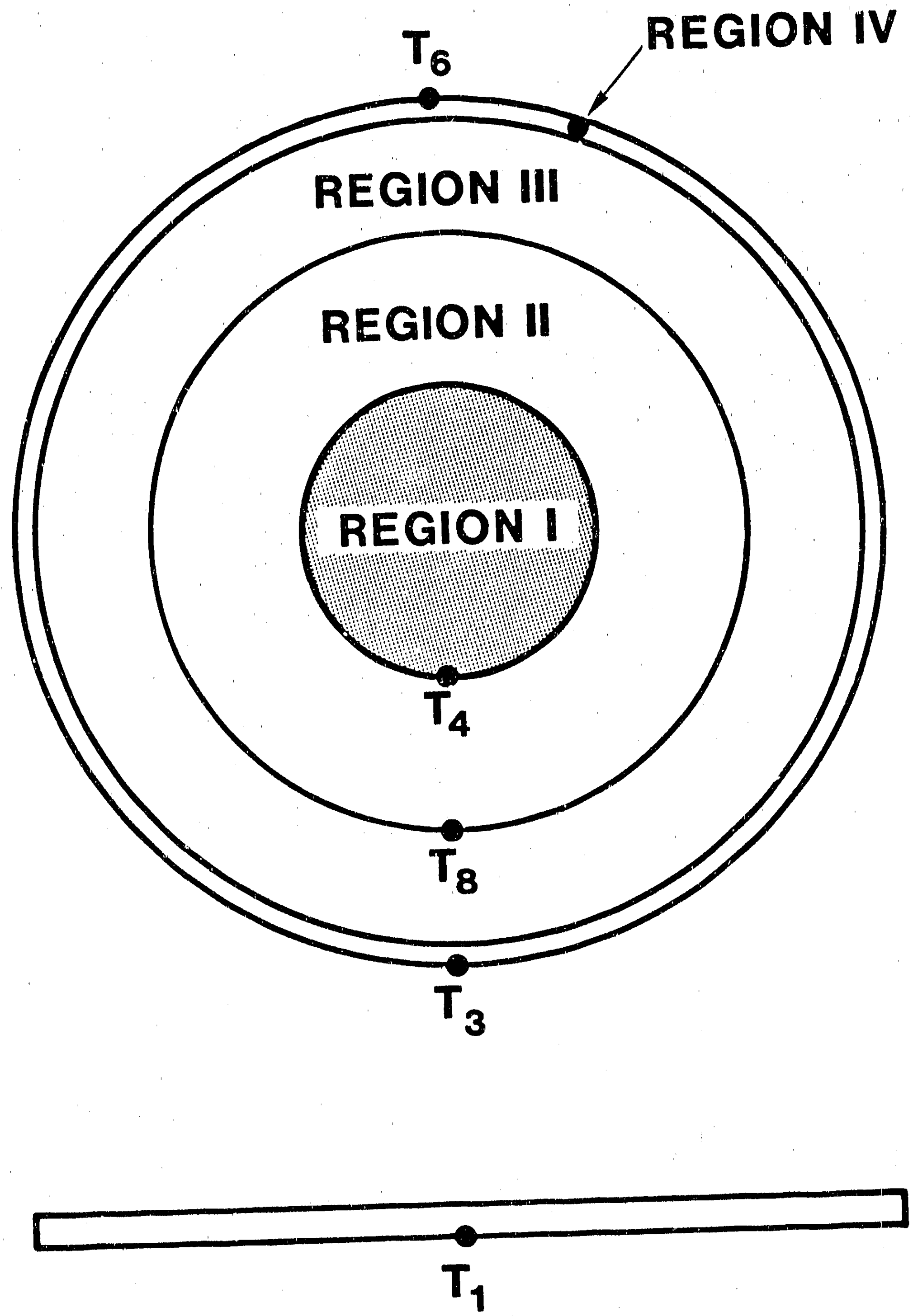

Figure 3. US-2--Cask with Annular Regions and Shield

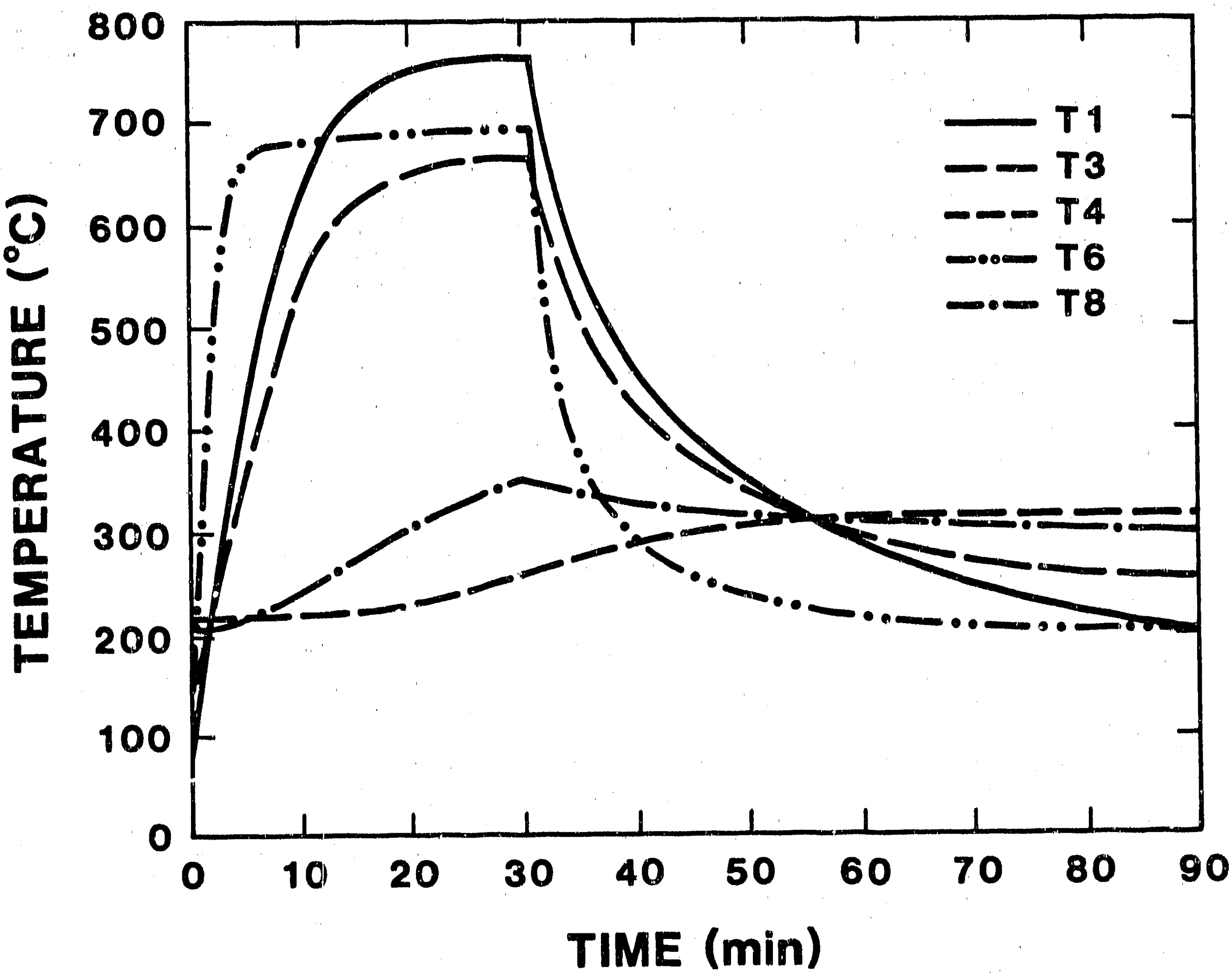

Figure 4. US-2--Temperature Versus Time

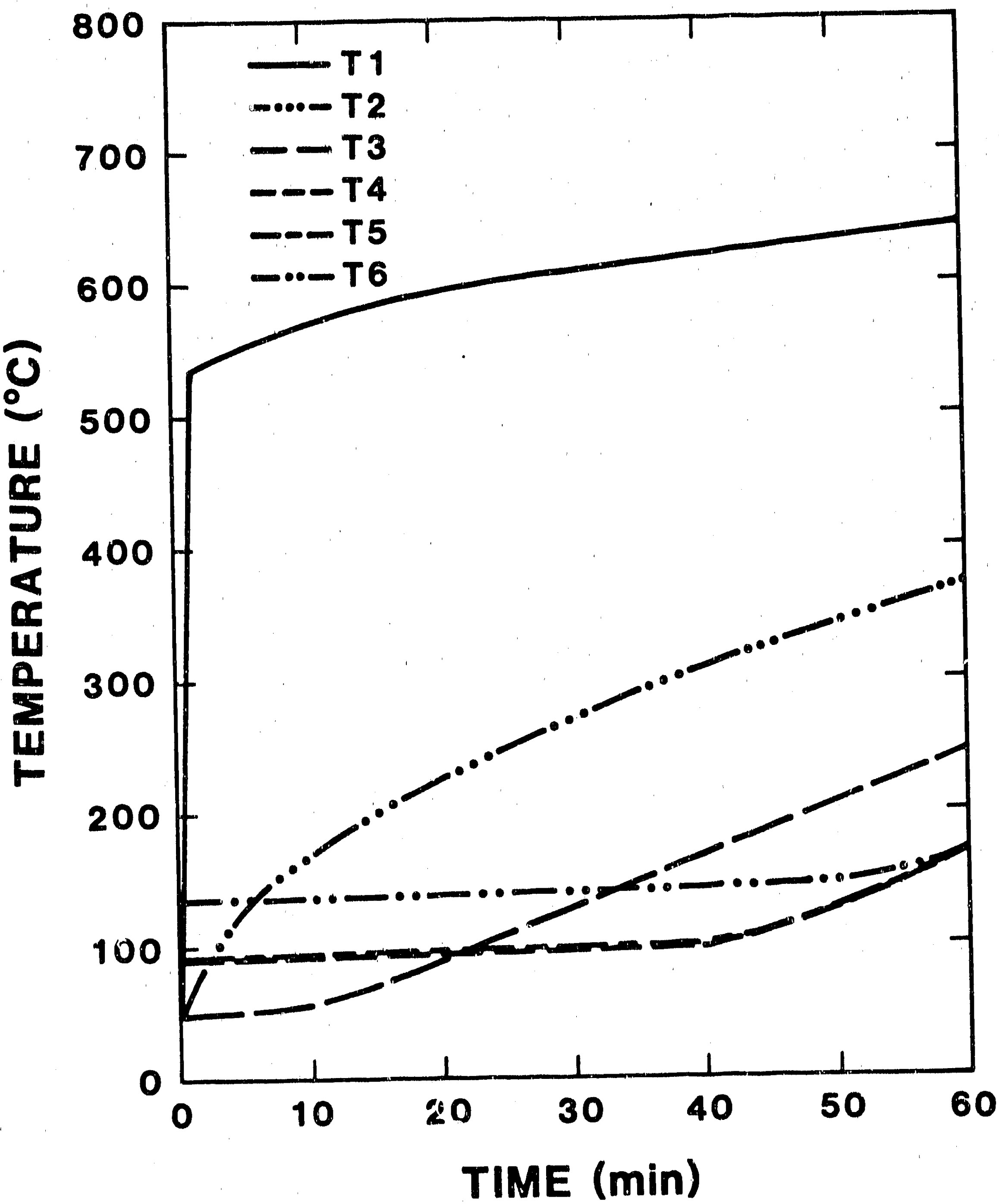

Figure 5. FR-1a Temperatures Versus Time

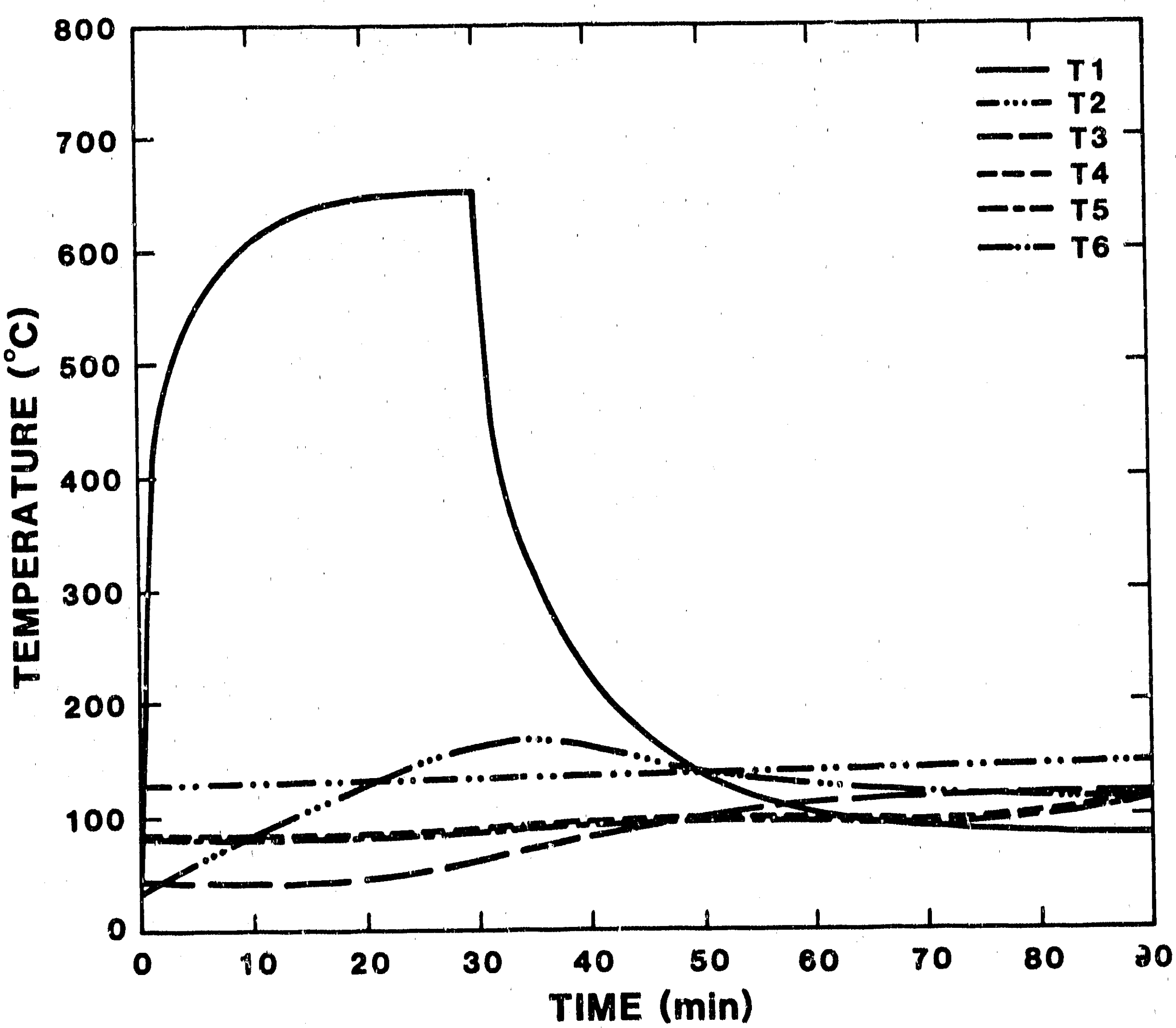

Figure 6. FR-1b Temperatures Versus Time

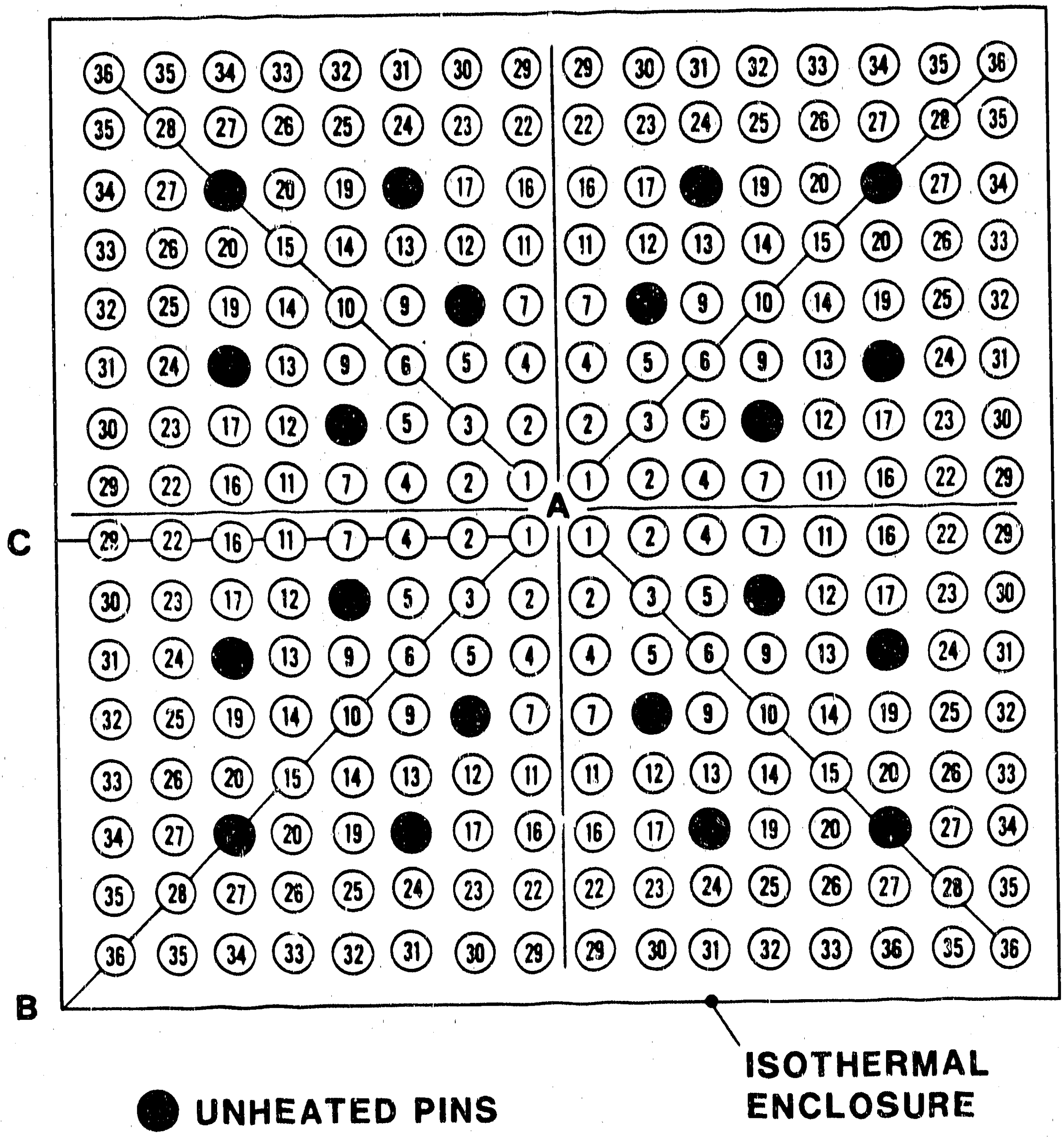

Figure 7. UK-1 Irradiated Fuel Element in a Gas Environment

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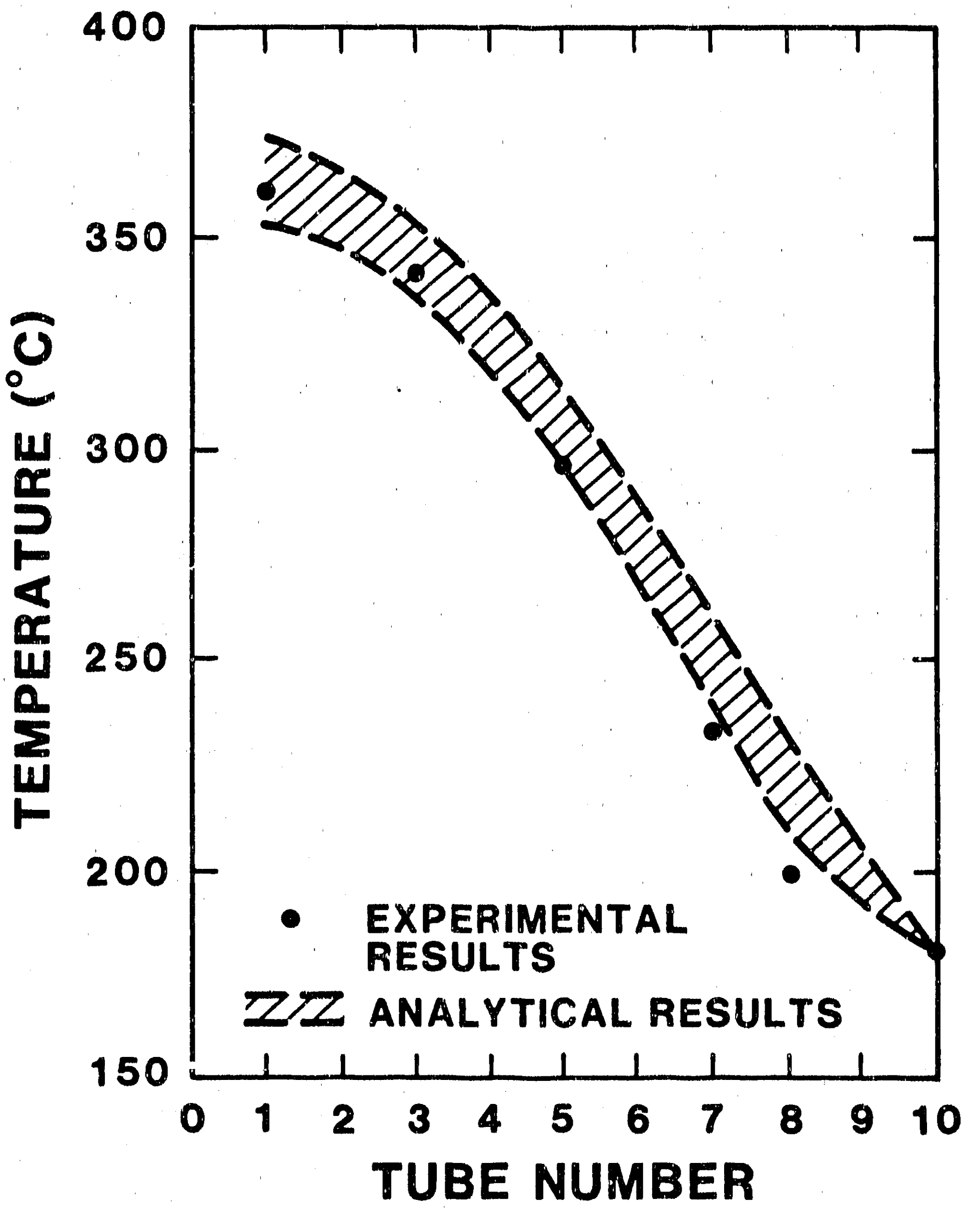

Figure 8. UK-1 Temperatures Along Line A-B

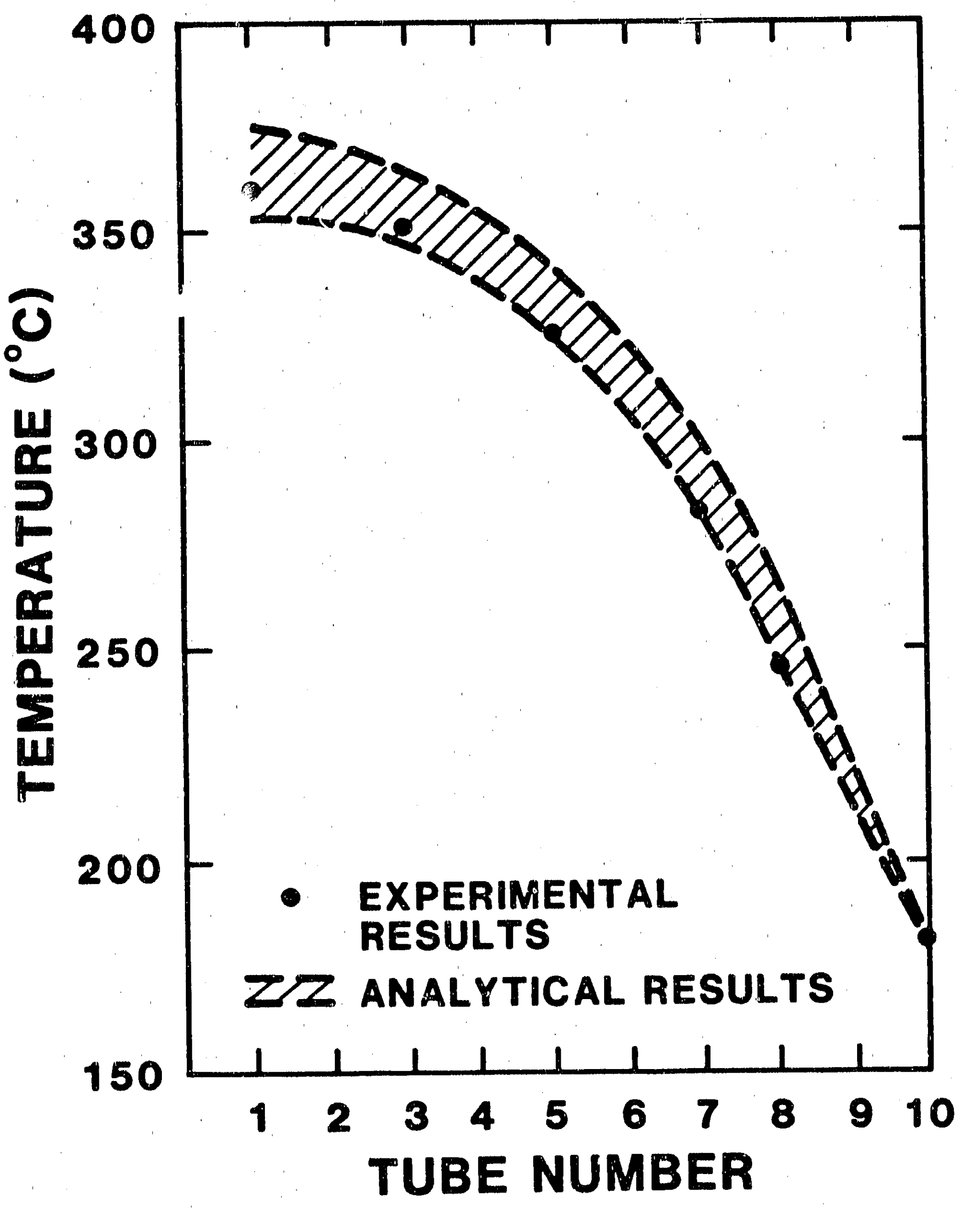

Figure 9. UK-1 Temperatures Along Line A-C

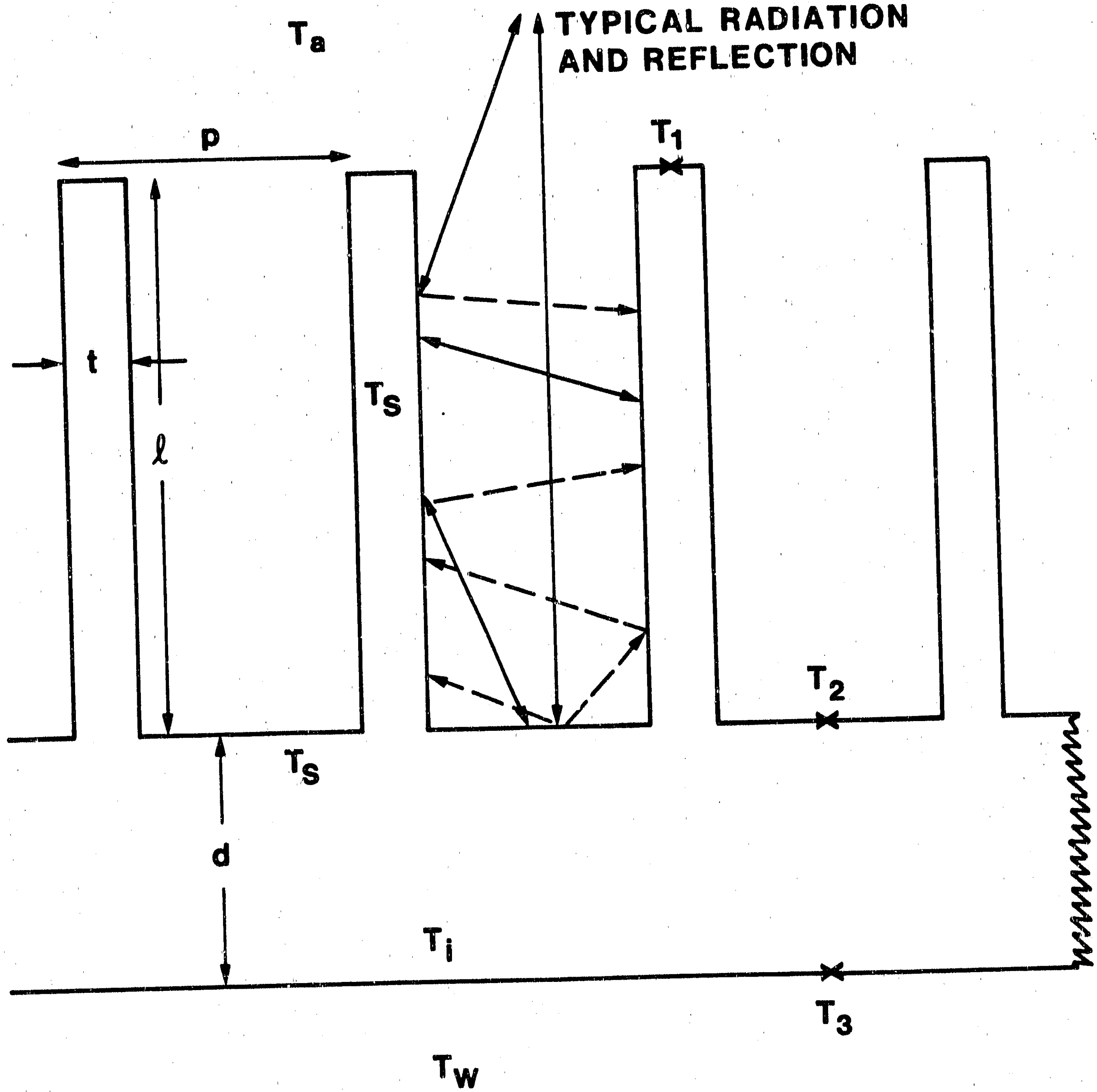

Figure 10. UK-2 Plane Finned Surface

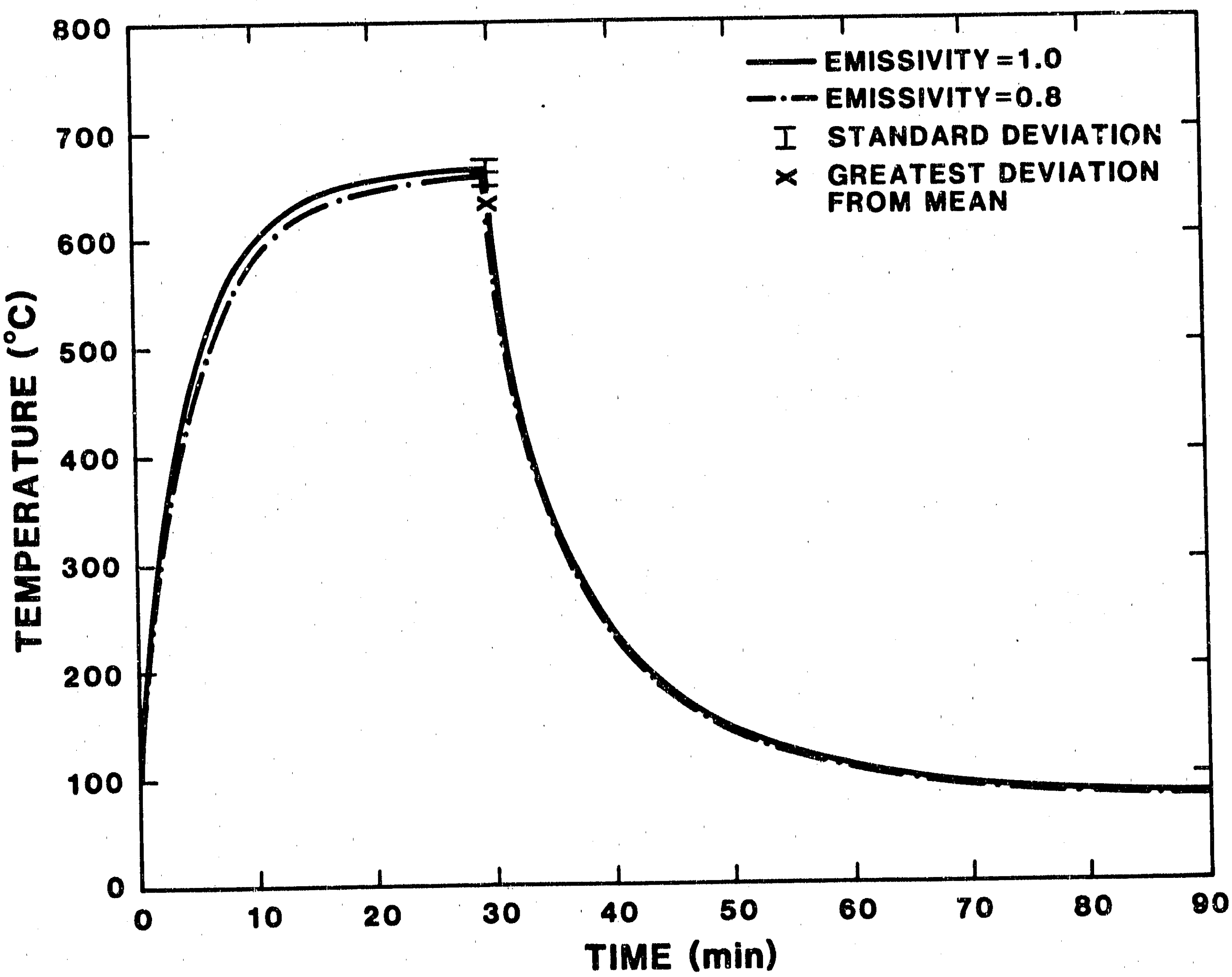

Figure 11. UK-2 Fin Tip Temperatures as a Function of Emissivity

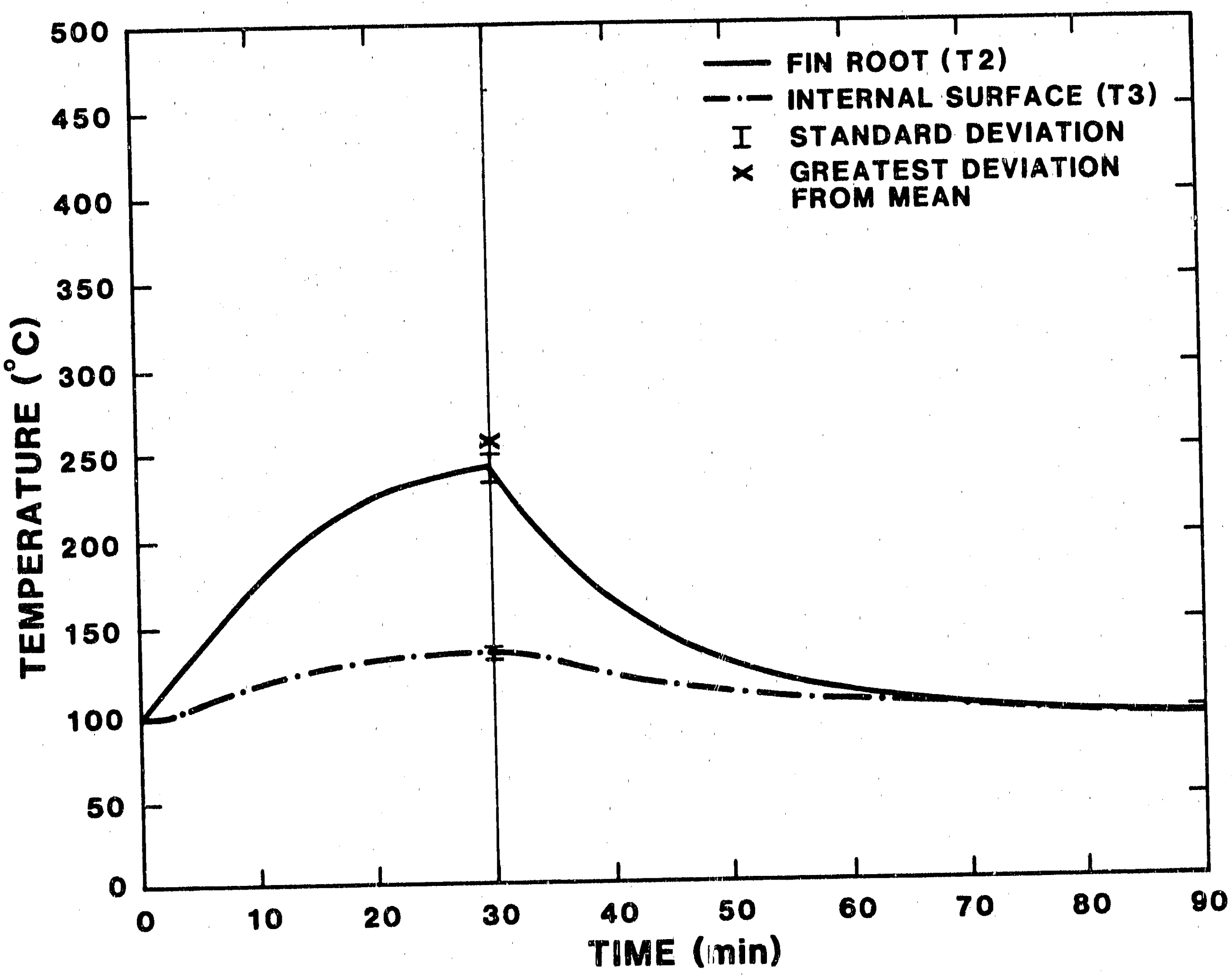

Figure 12. UK-2 Fin Root and Internal Surface Temperatures

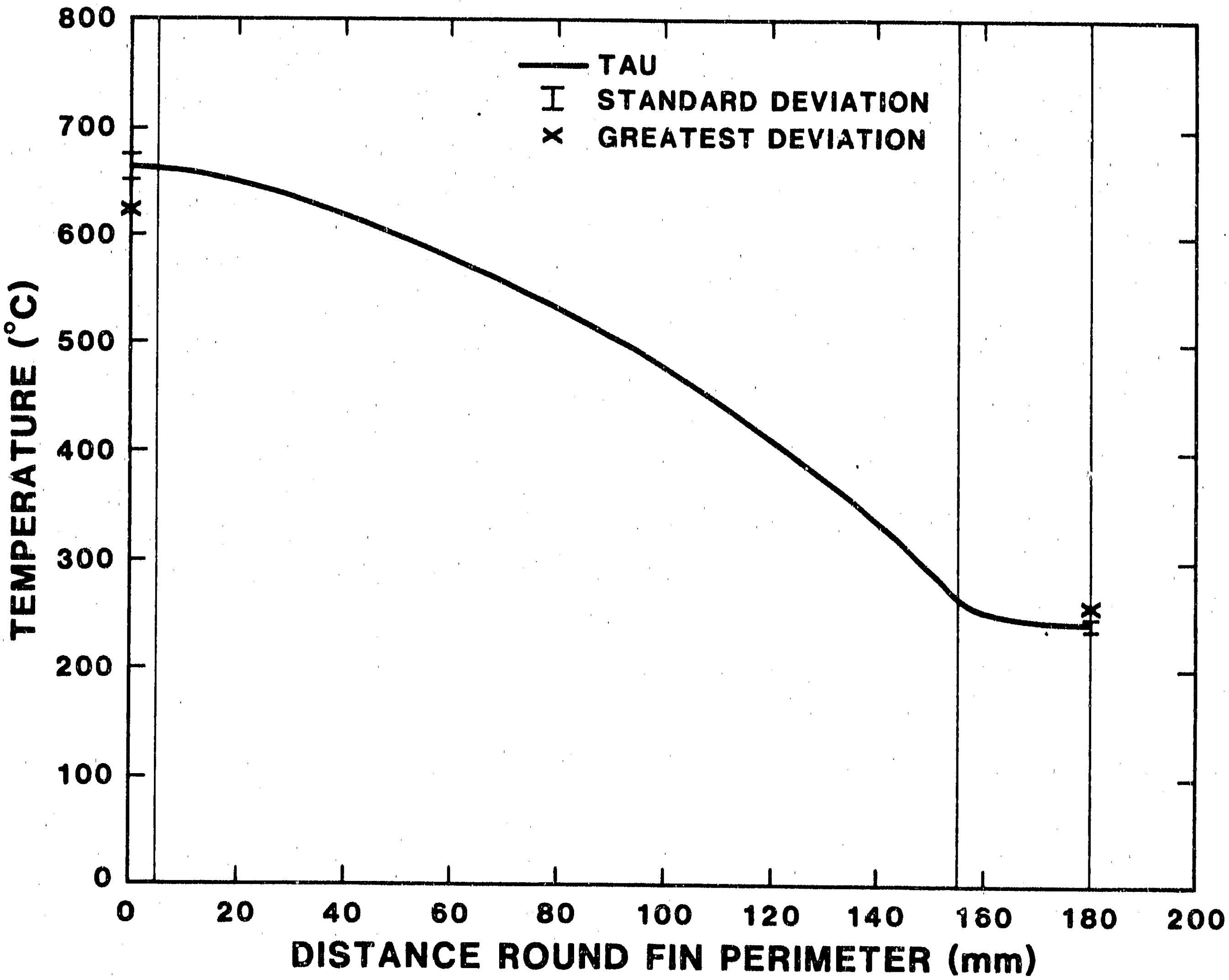

Figure 13. UK-2 Fin Perimeter Temperature Distribution

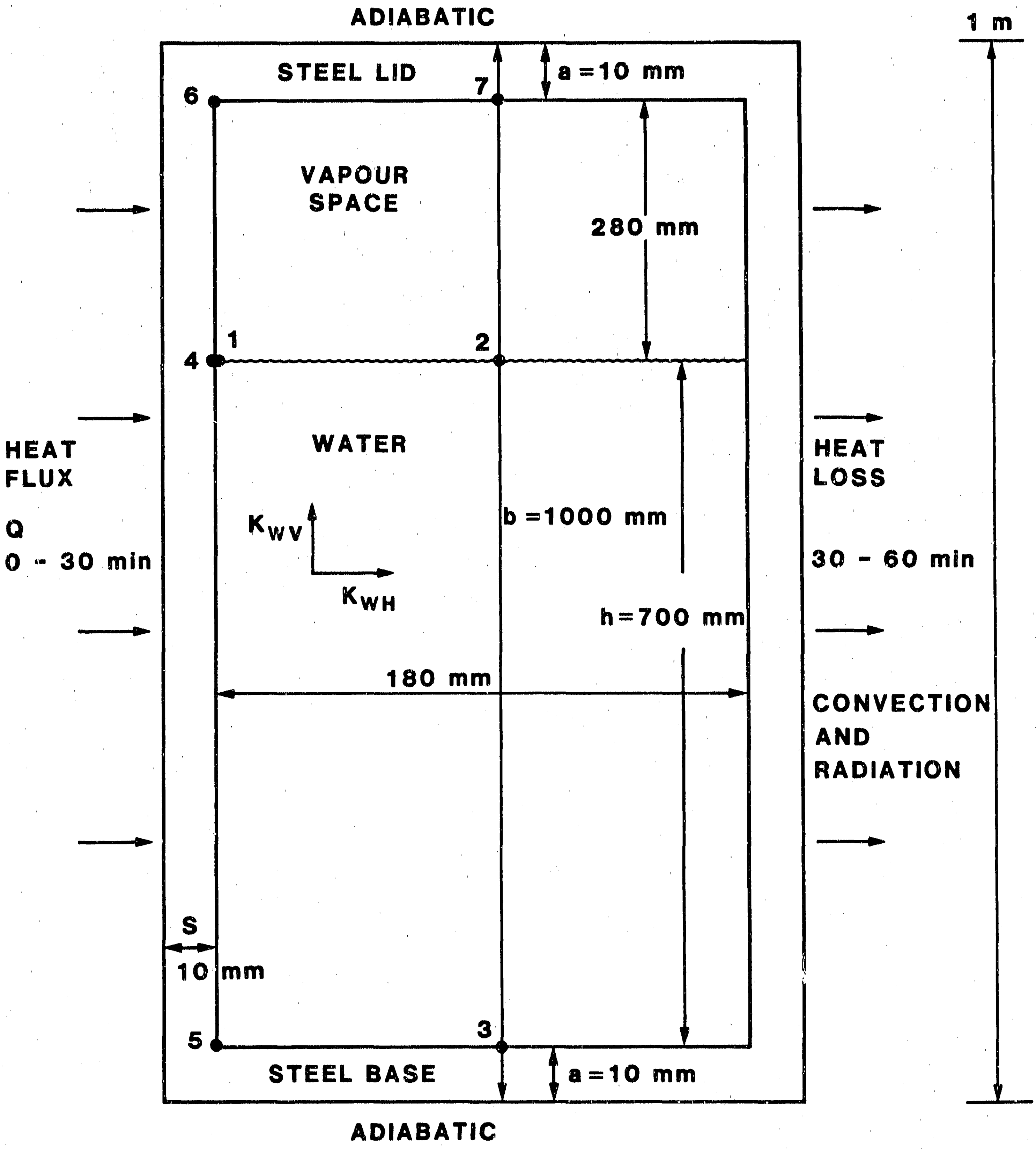

Figure 14. UK-3 Partially Water-Filled Flask

Table I: Code Matrix

	HEAT6	HEAT5	TRUMP	TEMPEST	TAC-2D	COYOTE	Q/TRAN	SINDA	TAU	RIGG	FLUFF	DELFINE	COBRA
Geometry													
1-D	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y
2-D	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
3-D	Y	Y	Y	Y	N	N	Y	Y	Y	N	N	Y	N
Cartesian	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cylindrical	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N
Irregular	N	N	Y	N	N	Y	Y	Y	Y	N	N	Y	N
Temporal													
Steady State	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Transient Implicit	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N
Transient Explicit	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y
Physics													
Conduction	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Radiation	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y
Heat Generation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Variable Properties	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	N
Phase Change	Y	Y	Y	N	N	N	Y	Y	N	N	N	Y	N
Type													
Finite Element Method	N	N	N	N	N	Y	N	N	Y	N	N	Y	N
Finite Difference Method	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	N	Y
Thermal Network Analogy	N	N	N	N	N	N	Y	N	N	N	N	N	N
Boundary Conditions													
Transient	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Temperature	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Heat Flux	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Convection	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Radiation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Calculation of View Factors	N	N	N	N	N	N	N	N	Y	Y	Y	N	Y

END

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