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Standard Thermal Problem Set for the Evaluation of Heat Transfer Codes Used in the Assessment of Transportation Packages

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STANDARD THERMAL PROBLEM SET FOR THE EVALUATION OF HEAT TRANSFER CODES USED IN THE ASSESSMENT OF TRANSPORTATION PACKAGES

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ABSTRACT

The design and certification of packages used for the shipment of nuclear materials requires that well established analytical techniques are available to predict the behavior of the packagings during normal transport and hypothetical accident environments. The Organization of Economic Cooperation and Development (OECD), through the Nuclear Energy Agency's Committee on Reactor Physics (NEACRP), has established specialists' meetings in the areas of heat transfer, criticality, and shielding. The subject of this paper is the work resulting from the Specialists' Meetings on the Heat Transfer Assessment of Transportation Packages.

The heat transfer group held its first meeting in April 1985 with the purpose of defining a set of thermal benchmark problems and providing solutions. A set of six two-dimensional thermal problems has been defined and analytical solutions provided. These problems, and the corresponding solutions, are provided in this report. In addition, magnetic tapes, including computer code input and output, are being provided to the NEA Data Bank.

The codes used to provide numerical analysis range from the cask specific codes such as RIGG to general purpose codes such as Q/TRAN. These codes were all used in the two dimensional mode although many were capable of solving three dimensional problems.

PARTICIPATING ORGANIZATIONS

AEEW	Atomic Energy Establishment, Winfrith (United Kingdom)
BNFL	British Nuclear Fuel, PLC (United Kingdom)
CEA	Commissariat A L'Energie Atomique (France)
EMS	E M Systems (Sweden)
ENEA	Comitano Nazionale Per La Ricerca E Per Lo Sviluppo Dell'Energia Nucleare E Delle Energie Alternative (Italy)
ORNL	Oak Ridge National Laboratory (United States)
SNL	Sandia National Laboratories (United States)

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NOMENCLATURE

C_p = specific heat

D = distance from cask

h = convective coefficient

h_g = global heat transfer coefficient

k = thermal conductivity

k_ℓ = liquid state conductivity

k_s = solid state conductivity

L = latent heat of melting

Q = volumetric heat source

r_i = radius

T = temperature

T_i = initial temperature

T_m = melting temperature

T_s = surface temperature

T_∞ = ambient temperature of environment

t = time

Δt = time step

W = width

ε = surface emissivity

δ = shield thickness

ρ = density

Introduction

During a preparatory meeting in Paris on June 21 to 22, 1979, several Nuclear Energy Agency (NEA) member countries expressed interest in exchanging information and experience on various aspects of spent fuel transportation cask design. As a result of this meeting, working groups were established 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 numerical codes.

The problems are designated according to the proposing member (France, FR; United Kingdom, UK; and United States, US) and problem number. Hence, the problems are FR-1, UK-1, UK-2, UK-3, US-1, and US-2. During the shipment of spent fuel, numerous thermal transport mechanisms are occurring simultaneously. All spent fuel casks have a heat source (fuel) which rejects heat through a liquid or gaseous medium to the cask wall. The heat is then conducted through the cask wall and rejected at the surface through a combination of convection and radiation. During a fire, the transport of heat is reversed with the greater heat source 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. UK-1 is a simulated horizontal fuel pin array in a gas environment. FR-1 addresses the situation where the fuel is surrounded by sodium which is allowed to undergo phase changes. 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 rejection by convection at the cask surface. UK-2 simulates heat rejection by fins. US-2 is a multiple layered cask in a fire environment with a thermal shield. This configuration involves a two-dimensional radiation analysis.

Description of Thermal Codes

The thermal codes used 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 number 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 providing 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 as it affects the stability and efficiency of the solution. An explicit integration technique solves the heat transfer equation at a time, $t + \Delta t$, based only on solutions at the previous time step, t. This technique is conditionally stable and hence requires small time steps. An implicit integration technique uses the equilibrium conditions at time, $t + \Delta t$. This technique is unconditionally stable and hence allows larger time steps.

Table I: Code Matrix

	HEAT6	HEAT5	TRUMP	TEMPEST	TAG-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

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 conditions.

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 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 particular to a specific cask.

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 as an indication of ease of using with the codes.

US-1: Internal Heat Source

US-1 consists of the two-region cylindrical geometry shown in the cross sectional view provided in Figure 1. The interior region (Region I) contains a volumetric heat source with an energy generation rate representative of the internal decay heat of single 120-day-old Pressurized Water Reactor (PWR) spent fuel assembly. The internally generated heat is removed at the outer surface of the cylinder by convective cooling to the environment.

The geometrical and thermal specifications for US-1 are provided in Table II. The thermal properties were selected for calculational purposes and are not representative of cask designs or materials.

This problem has an exact analytical solution for comparison with the numerical results.

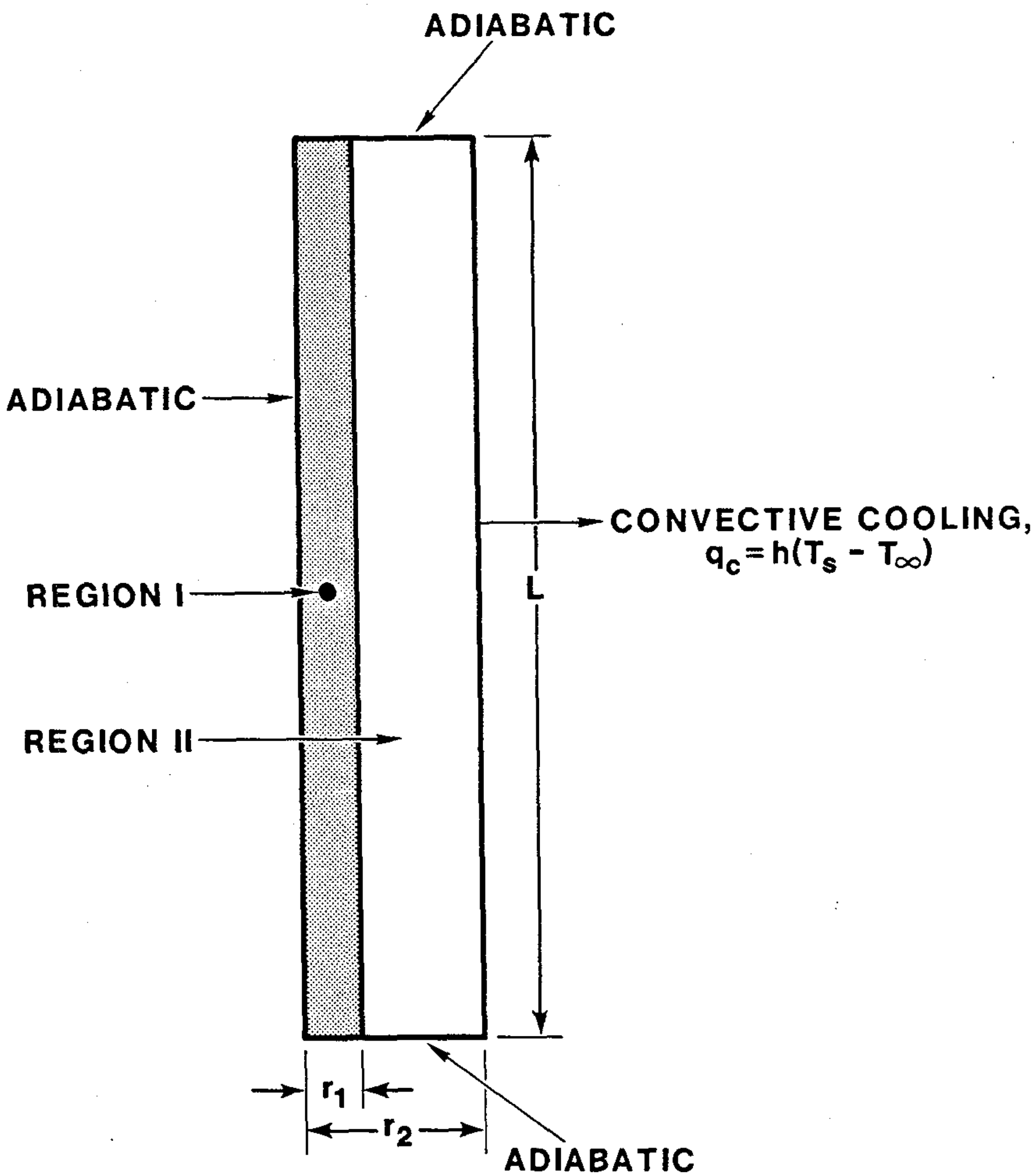

Figure 1. US 1--Cask with Internal Heat Source

Table II: US-1 Thermal Characteristics

Region	Description	Thermal Characteristics
I	Inner Region with Internal Heat Source r_1 = 27.43 cm L = 457.2 cm	ρ = 16.02 kg/m^3 C_p = 1 cal/gm-°C k = 69.2 W/m°C Q = 11,090 W/m^3
II	Outer Region r_2 = 91.44 cm L = 457.2 cm	ρ = 16.02 kg/m^3 C_p = 1 cal/gm-°C k = 34.6 W/m°C
Boundary Conditions		
Convective Coefficient		h = 5.67 W/m^2-°C
Ambient Environment		T_∞ = 54.4°C
Initial Cask Temperature		T_i = 54.4°C

The codes used in this solution include SINDA (SNL); HEATING-6 (EMS, ENEA, ORNL); Q/TRAN (SNL); DELFINE (CEA); AND TAU (AEEW, BNFL).

The exact and numerical solutions reported to 1° accuracy are given in Table III and the graphical solution reported to 0.1° accuracy in Figure 2. The numerical and exact solutions agreed within reported accuracy.

Table III: US-1 Results

	Centerline (°C)	Interface (°C)	Outer Edge (°C)
Exact	152	149	135
Mean	152	149	135

These results indicate that a broad spectrum of codes are available for performing problems involving an internal heat source with specified convective cooling at the surface.

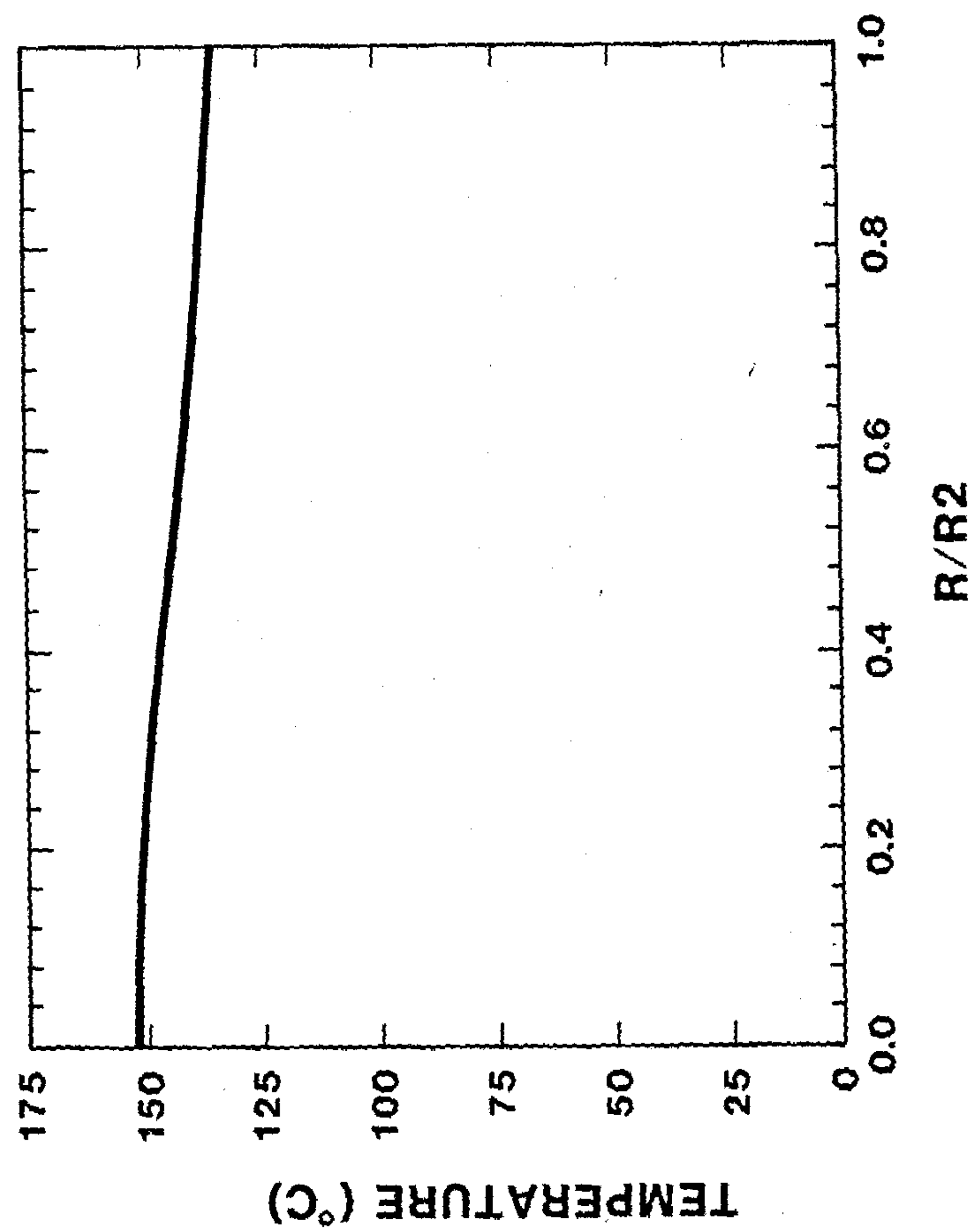

Figure 2. US-1--Temperature Versus Normalized Radial Position

US-2: Cask with Annular Regions and Shield

US-2 is based on a cask configuration consisting of several different annular regions. The multiregion geometry for US-2 is shown in Figure 3, while the thermal and geometric description of each region is provided in Table IV. Region I contains a volumetric heat source simulating the decay heat of a spent fuel assembly. Region II is a monolithic steel wall providing gamma shielding and structural integrity. Region III is considered to be a voided neutron shield. Region IV is the outer wall of the neutron shield. The single mode of heat transfer between Regions II and IV is thermal radiation. The cask/shield arrangement is assumed to transfer heat to the surrounding environment by thermal radiation only. Since the area between the cask and shield is transparent to thermal radiation, there is also a thermal radiation exchange between the bottom of the cask and the upper surface of the shield.

A three-part solution was generated for US-2. Those three parts consist of: i) a steady state solution to define initial conditions generated during normal transport, ii) a 30-minute fire transient with an environment temperature of 800°C, and iii) a cool-down period in an ambient environment for 60 minutes duration.

The tabular results are given in Table V, and the mean value graphical results are given in Figure 4.

The largest deviation from the mean temperatures was 15°C at Location T3 after 90 minutes. The codes used in analyzing this problem were SINDA (SNL), Q/TRAN (SNL), TAU (AEEW, BNFL), DELFINE (CEA), and HEATING-6 (ORNL, ENEA, EMS).

This same problem, when analyzed with only one-dimensional radiation models, produced a 50°C temperature deviation at T3, where the cask body faces the shield. This is due to the lack of radiant energy interacting with the cask from the fire.

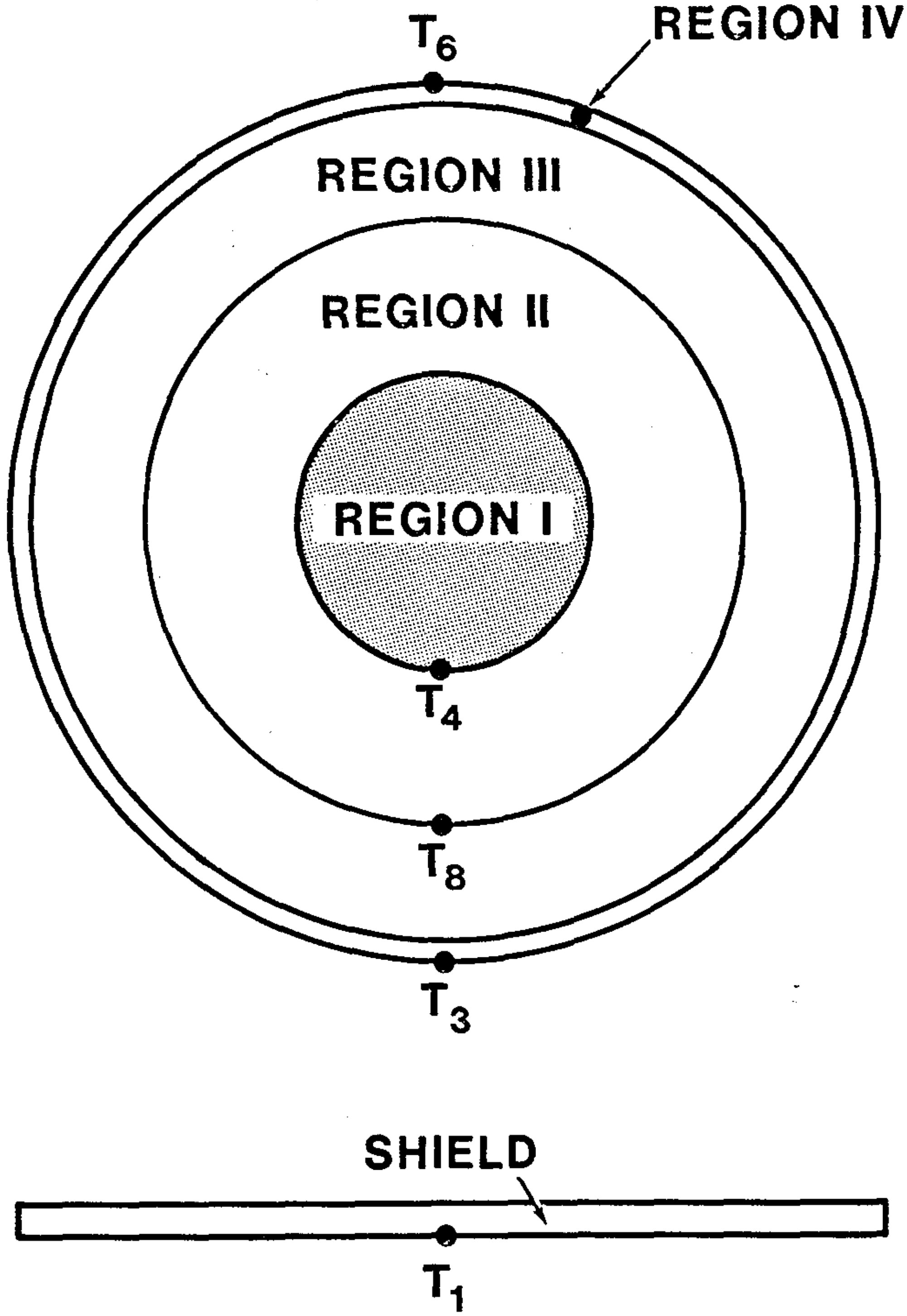

Figure 3. US-2--Cask with Annular Regions and Shield

Table IV: US-2 Thermal Characteristics

Region	Description	Thermal Characteristics
I	Inner Region with Internal Heat Source, $r_1 = 16.51$ cm	$\rho = 2707$ kg/m^3 $C_p = 0.214$ cal/gm-°C $k = 242.$ W/m°C $Q = 38{,}320$ W/m^3
II	Gamma Shield, Steel Construction, $r_2 = 38.74$ cm	$\rho = 7832.8$ kg/m^3 $C_p = 0.113$ cal/gm-°C $k = 45.$ W/m°C
III	Neutron Shield, Voided Region, $r_3 = 53.98$ cm	Voided, Annular Enclosure, Nonparticipating Media, Radiant Exchange Between Regions II and IV
IV	Neutron Shell, Steel Construction $r_4 = 54.61$ cm	ρ, C_p, k Same as Region II
Shield	Intervening Radiation Shield, Steel $w = 109.2$ cm $\delta = 2.54$ cm $D = 30.48$ cm	ρ, C_p Same as Region II

Environment Temperature

Ambient Environment, Steady-state:	$t = 0$	$T_\infty = 54.4$°C
Fire Environment, Transient:	$0 < t < 30$ min	$T_\infty = 800$°C
Ambient Environment, Transient:	$30 < t < 90$ min	$T_\infty = 54.4$°C

Radiation Properties

$\varepsilon = \alpha = 1$ (All surfaces and environment considered black)

Table V: US-2 Results - Temperatures at Specified Locations

Time (Minutes)	T1	T3	T4	T6	T8
0	88	146	217	139	207
30	765	664	261	689	350
90	205	242	314	203	301

FR-1: Transport in Sodium

The proposed model, FR-1, as shown in Figure 5 is taken from the transport method used in France to ship the "monitored" fuel pin assemblies from Super Phenix to laboratories for analysis.

The goal of the proposed model is to verify, on a simplified geometry, the validity of the numerical formulation implemented in the codes which take into account phase change phenomena.

The geometry and thermal specifications are provided in Table VI. The model consists of a radial section of a cask containing a sheath filled with sodium in which the irradiated assembly is placed. 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.

Two variations of this problem were analyzed. The first variation (FR-1a) included a steady-state solution to determine the initial condition followed by a 1-hour transient where the cask is subjected to an 800°C ambient environment. These conditions are given in Table VII. The temperature dependent conductivity of air is given in Table VIII. This problem is solved using the codes HEATING-6 (EMS, ENEA); TAU (AEEW, BNFL); and DELFINE (CEA). The temperature histories are given in Figure 6.

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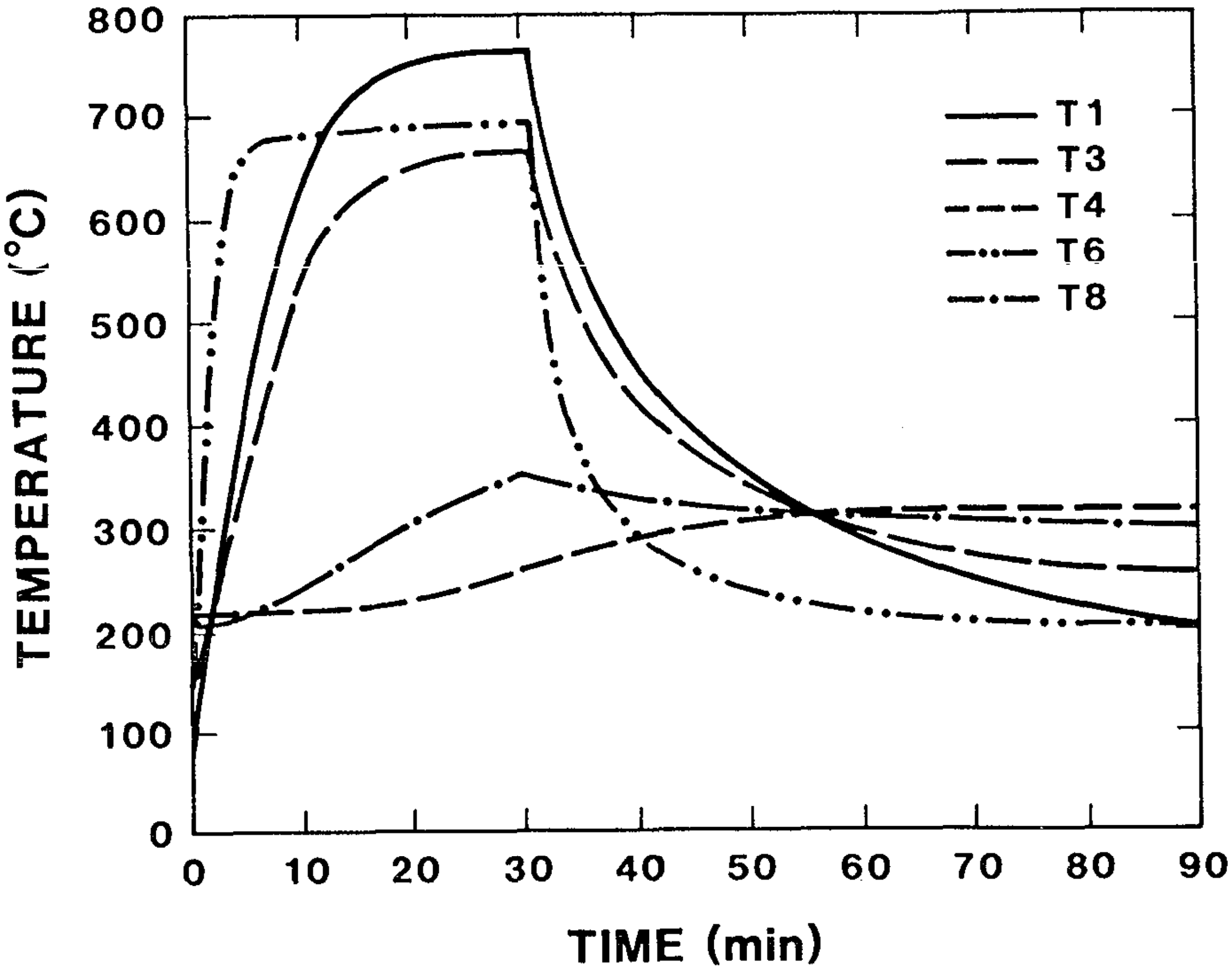

Figure 4. US-2--Temperature Versus Time

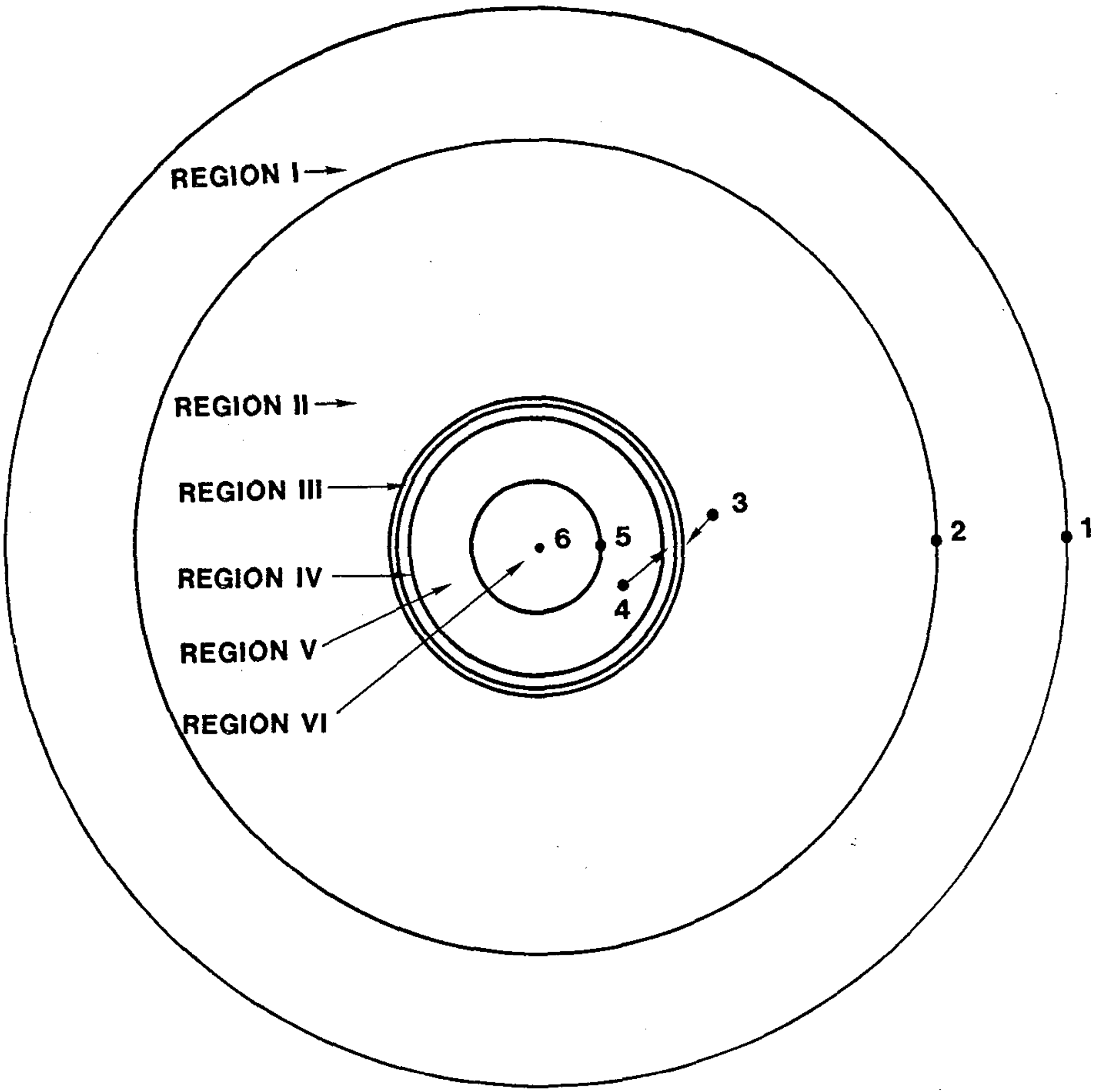

Figure 5. FR-1--Transport in Sodium

Table VI: FR-1 Thermal Characteristics

Region	Description	Thermal Characteristics
I	Shield Region r_I = 0.65m	k = 20 W/m°C ρC_p = 2,500J/m^3°C
II	Steel Container r_{II} = 0.5m	k = 65 W/m°C ρC_p = 3.2 x 10^6 J/m^3°C ε = 0.5
III	Air Gap r_{III} = 0.175m	
IV	Stainless Steel Sheath r_{IV} = 0.1745m	k = 20 W/m°C ρC_p = 3.9 x 10^6 J/m^3°C ε = 0.5
V	Sodium r_V = 0.1725m	T_m = 97°C k_s = 135.529 - 0.1673T W/m°C k = 90.6038 - 0.048523T W/m°C ρ = 890 kg/m^3 C_p = 1338 J/kg°C L = 113.5 x 10^3 J/kg
VI	Fuel r_{VI} = 0.075m	k = 5 W/m°C ρC = 3 x 10^6 J/m^3°C Q = 2800 W/m

Table VII: FR-1a Initial and Boundary Conditions for One-Hour Transient

Steady State

Time, 0
Ambient temperature, 0°C
Global heat transfer coefficient (convection + radiation), 20 W/m^2°C
Surface emissivity, 0.5
Heat transfer in annular region between the sheath and container is by radiation and conduction in air

Transient

Time, 0-60 minutes
Ambient temperature, 800°C
Global heat transfer coefficient, 200 W/m^2°C

Table VIII: Temperature Dependent Conductivity of Air

Temperature (°C)	Conductivity (W/m°C)
0	.02422
100	.03182
200	.03868
300	.04494
400	.05077
500	.05629
600	.06150

The second variation assumed a 30-minute transient as defined in Table IX followed by a 1-hour cool down. The solutions to this problem were obtained using HEATING-6 (ORNL) and SINDA (SNL) and are given in Figure 7.

Table IX: FR-1b Initial and Boundary Conditions for 30-Minute Transient

Steady State

Time, 0
Ambient temperature, 0°C
Global heat transfer coefficient 30 $W/m^2 °C$
Surface emissivity, 0.5
Heat transfer in annular region between the sheath and container is by radiation and conduction in air

Transient

Time, 0-30 minutes
Ambient temperature, 800°C
Global heat transfer coefficient, 200 $W/m^2 °C$

Cool Down

Time, 30-90 minutes
Ambient temperature, 0°C
Global heat transfer coefficient, 30 $W/m^2 °C$

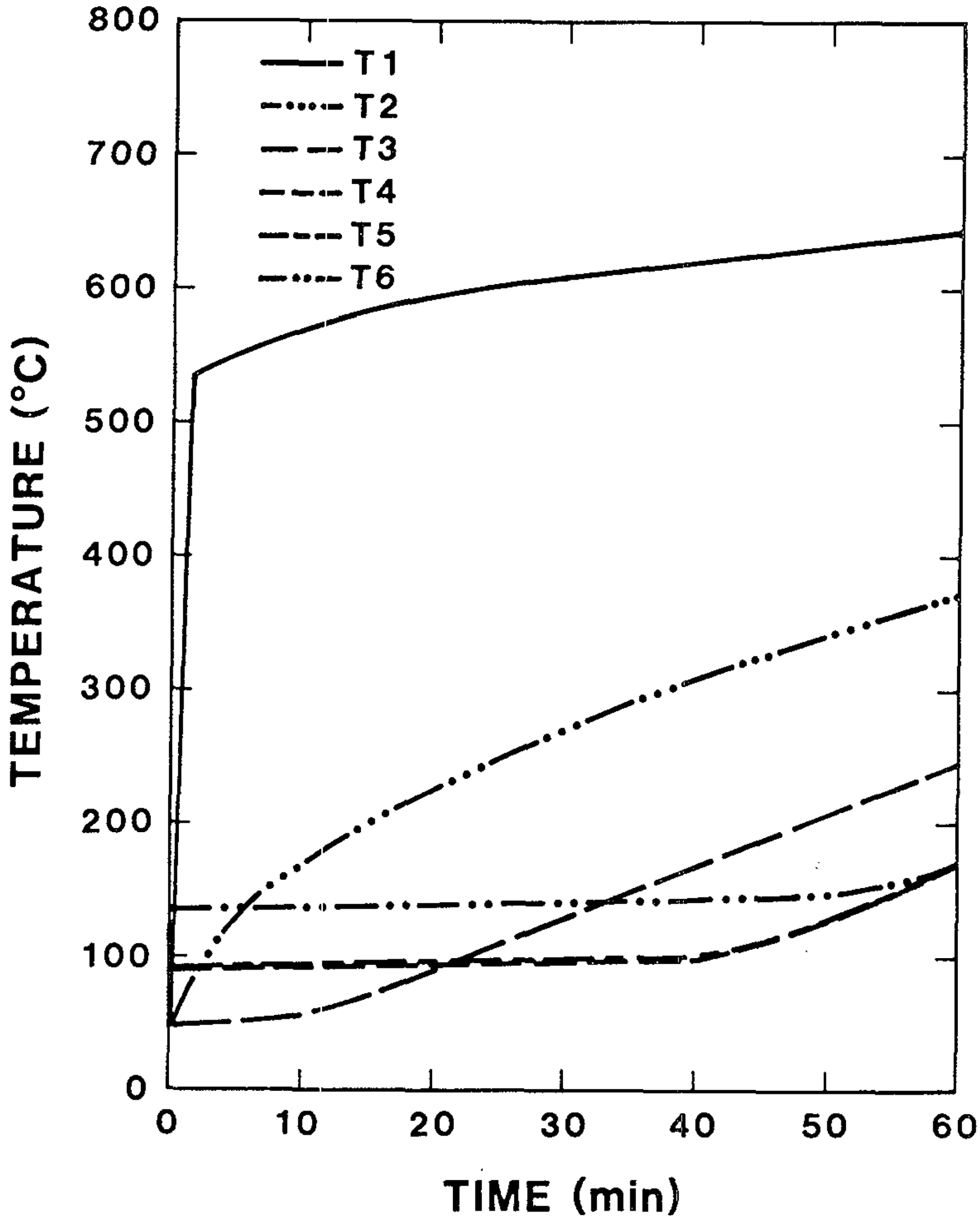

Figure 6. FR-1a Temperatures Versus Time

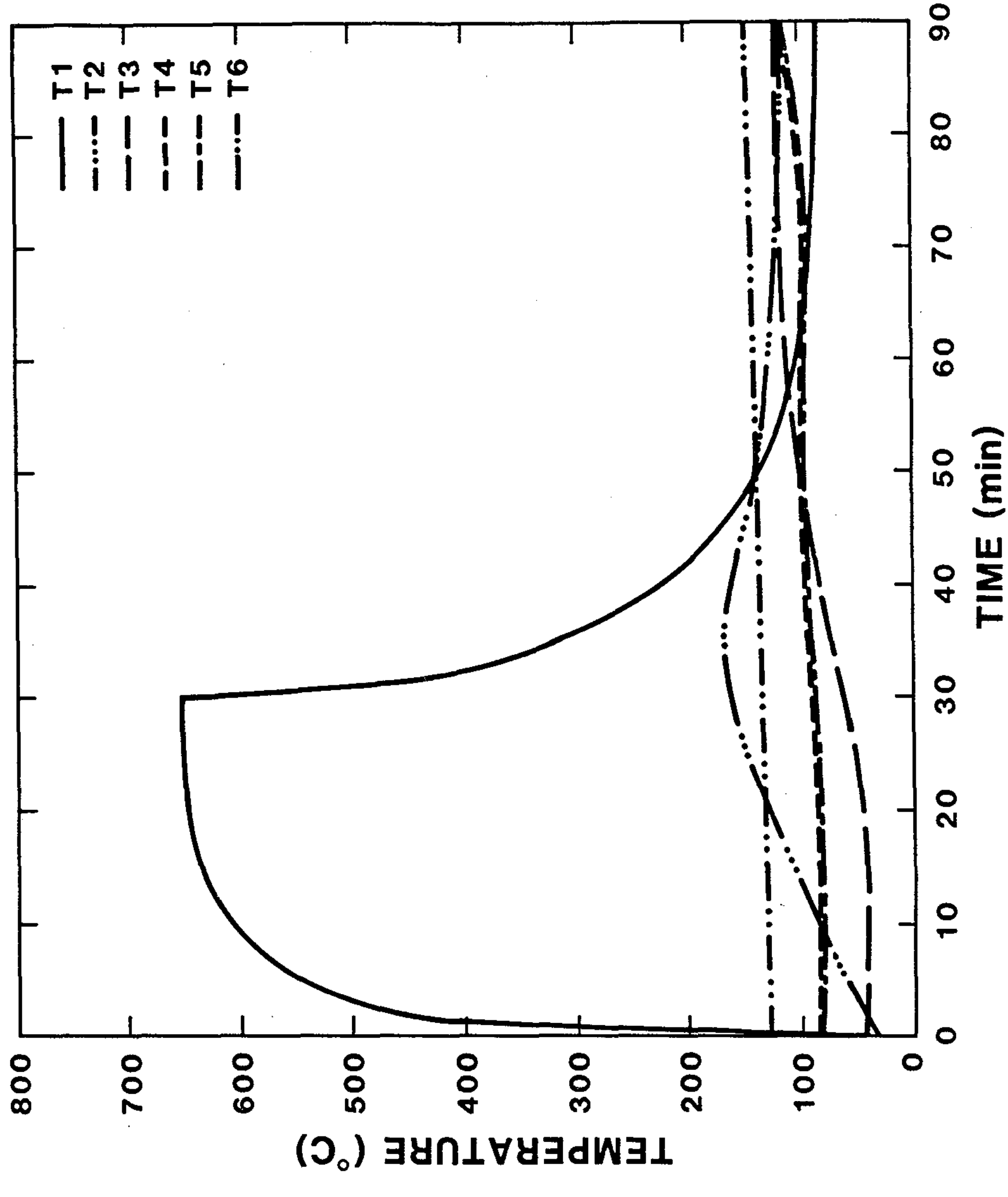

Figure 7. FR-1b Temperatures Versus Time

The maximum variation from the mean temperature for each of these problems was 2.3°C at T4 at 3,600 seconds. This indicates that even with phase change, the codes are able to produce consistent results.

UK-1: Irradiated Fuel Element in a Gas Environment

UK-1 represents a simulated PWR fuel element in a gas environment. Figure 8 shows the 16 x 16 array of heated and unheated pins simulating the fuel and control rod positions. The array is contained in an isothermal enclosure. The internally generated heat is removed by conduction and radiation to the internal surface of the enclosure.

The dimensions and material properties are given in Table X. This problem is based on an experiment performed by BNFL. The steady state analytical and experimental results are given in Figures 9 and 10 where analytical results are enveloped by the shaded region. The codes used to perform the analyses were HEATING-6 (ORNL); RIGG (AEEW, BNFL); COBRA (CEA); and Q/TRAN (SNL).

The greatest deviation between experiment and the analytical envelop was 6 percent. The largest absolute variation in the analytical solutions was 20°C at the array center. This represents a 6 percent variation in analytical results but only 4 percent maximum variation from experiment. These figures indicate that the analytical results are consistent and in good agreement with experimental data.

UK-2: Plane Finned Surface

UK-2, shown in Figure 11, 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.

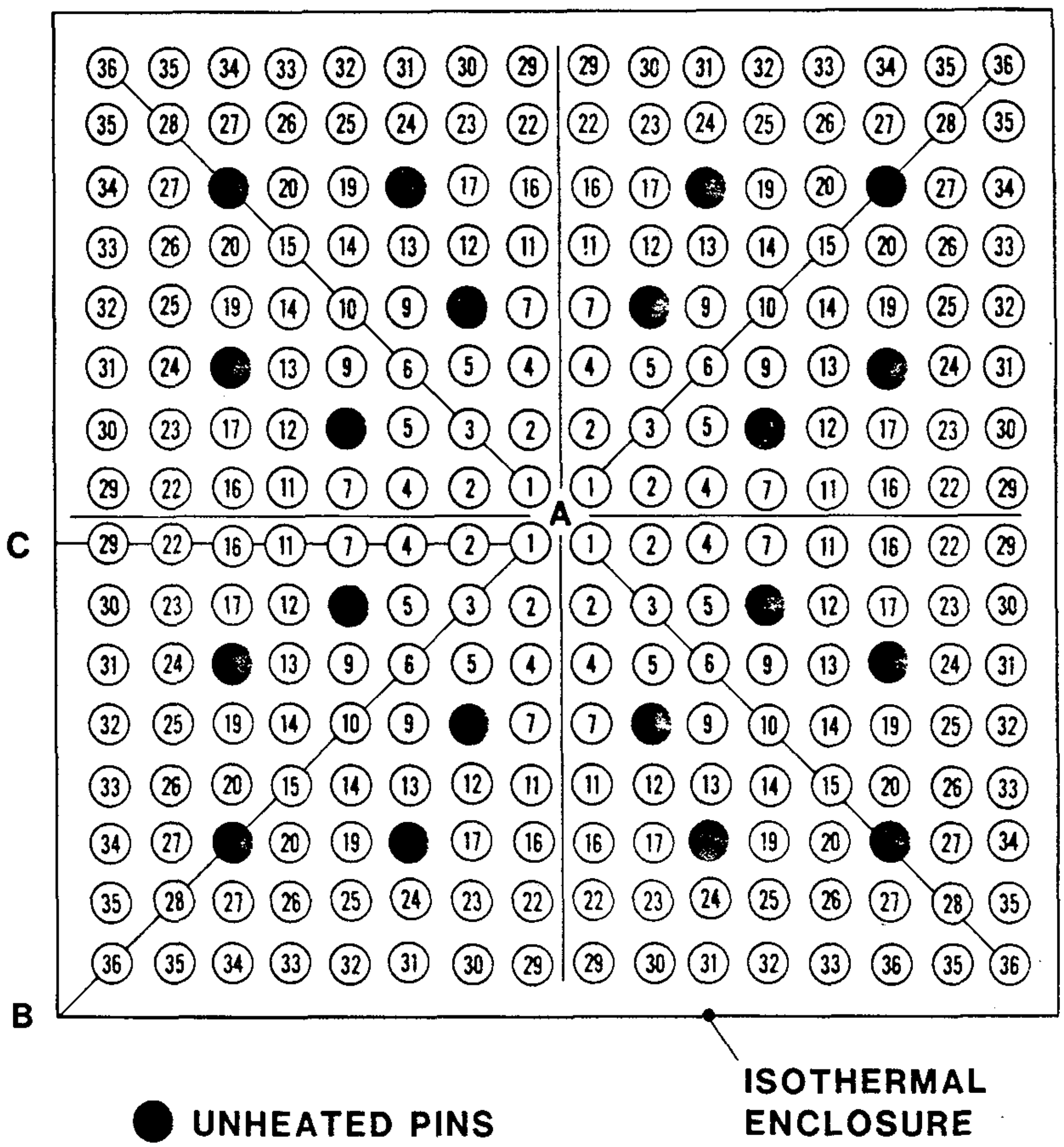

Figure 8. UK-1 Irradiated Fuel Element in a Gas Environment

Table X: UK-1 Dimensions and Thermal Characteristics

<u>Geometry and Dimensions</u>	
Enclosure:	
Internal dimension	242.7 x 242.7 mm
Pin array:	
Pin layout	16 x 16 square pitch
Number of heated pins	236
Number of unheated pins	20
Pin outside diameter	10.75 mm
Clad thickness	0.725 mm
Pin pitch	14.30 mm
<u>Material Properties</u>	
Enclosure:	
Surface emissivity	0.38
Pin cladding:	
Conductivity	19.0 W/m-°C
Emissivity	0.8
Pin filler (power source):	
Conductivity	0.0982 W/m-°C
Power per pin	8.156 W/m
Ambient gas:	
Material	99% helium and 1% air
Conductivity	$(0.14426 + 3.42\times10^{-4}T - 7.147\times10^{-8}T^2)$ W/m-°C where T is in °C

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. The dimensions and material properties are given in Table XI, and boundary conditions are given in Table XII.

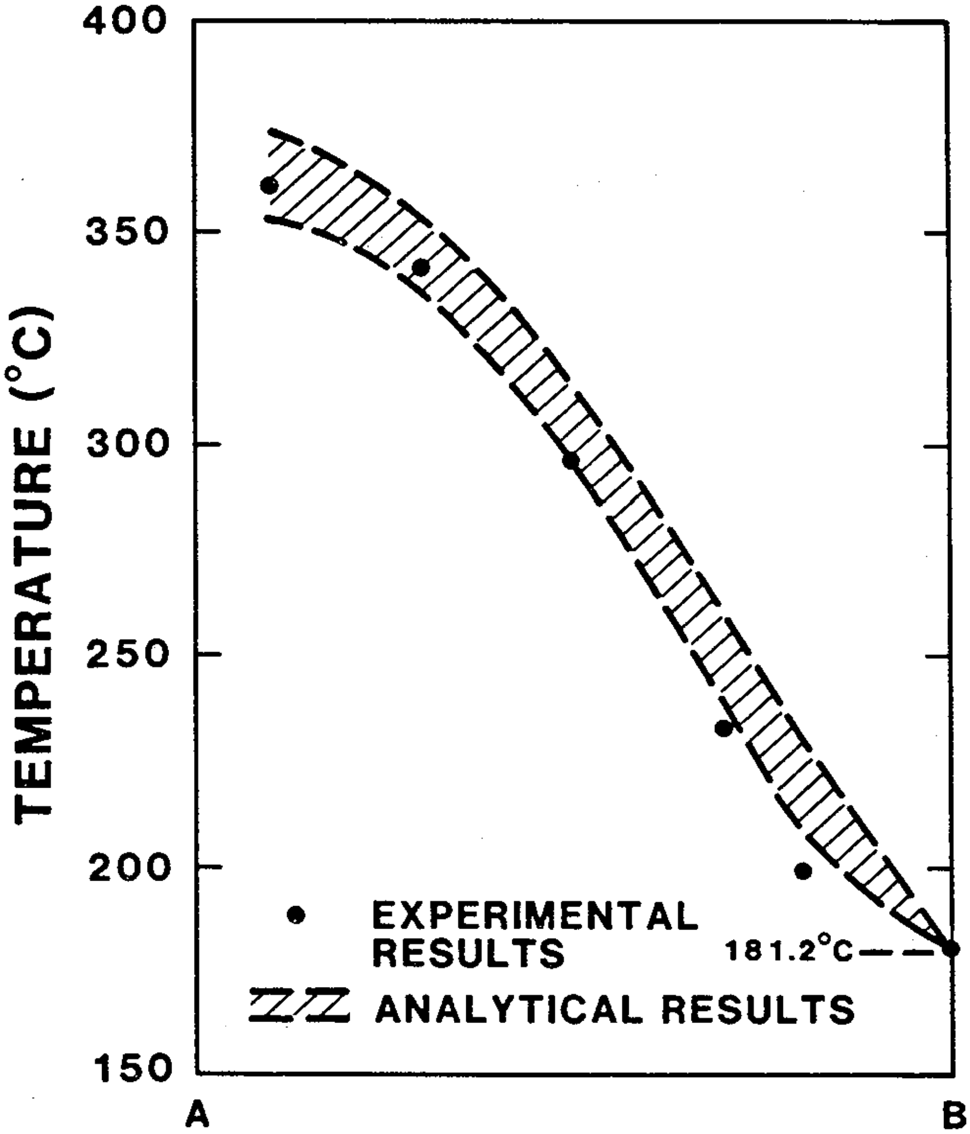

Figure 9. UK-1 Temperatures Along Line A-B

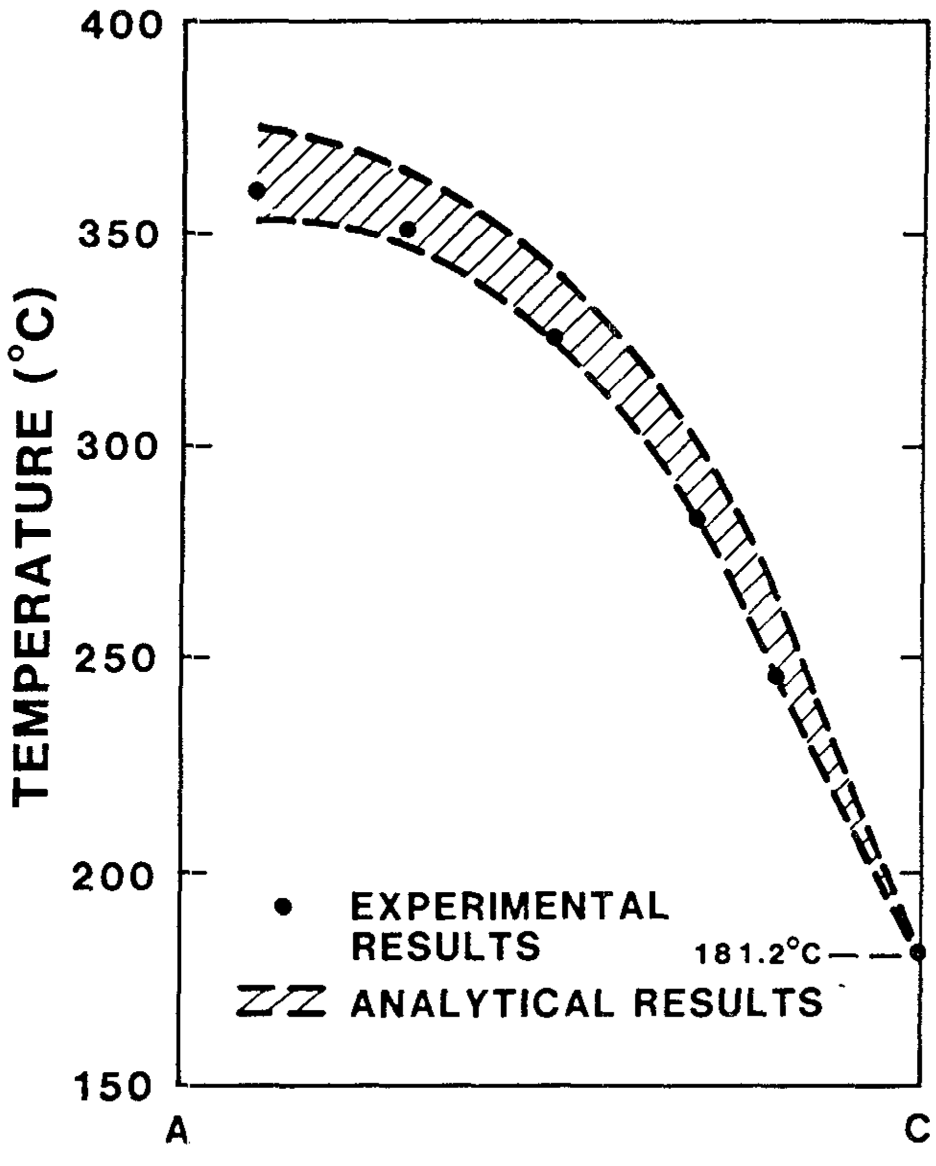

Figure 10. UK-1 Temperatures Along Line A-C

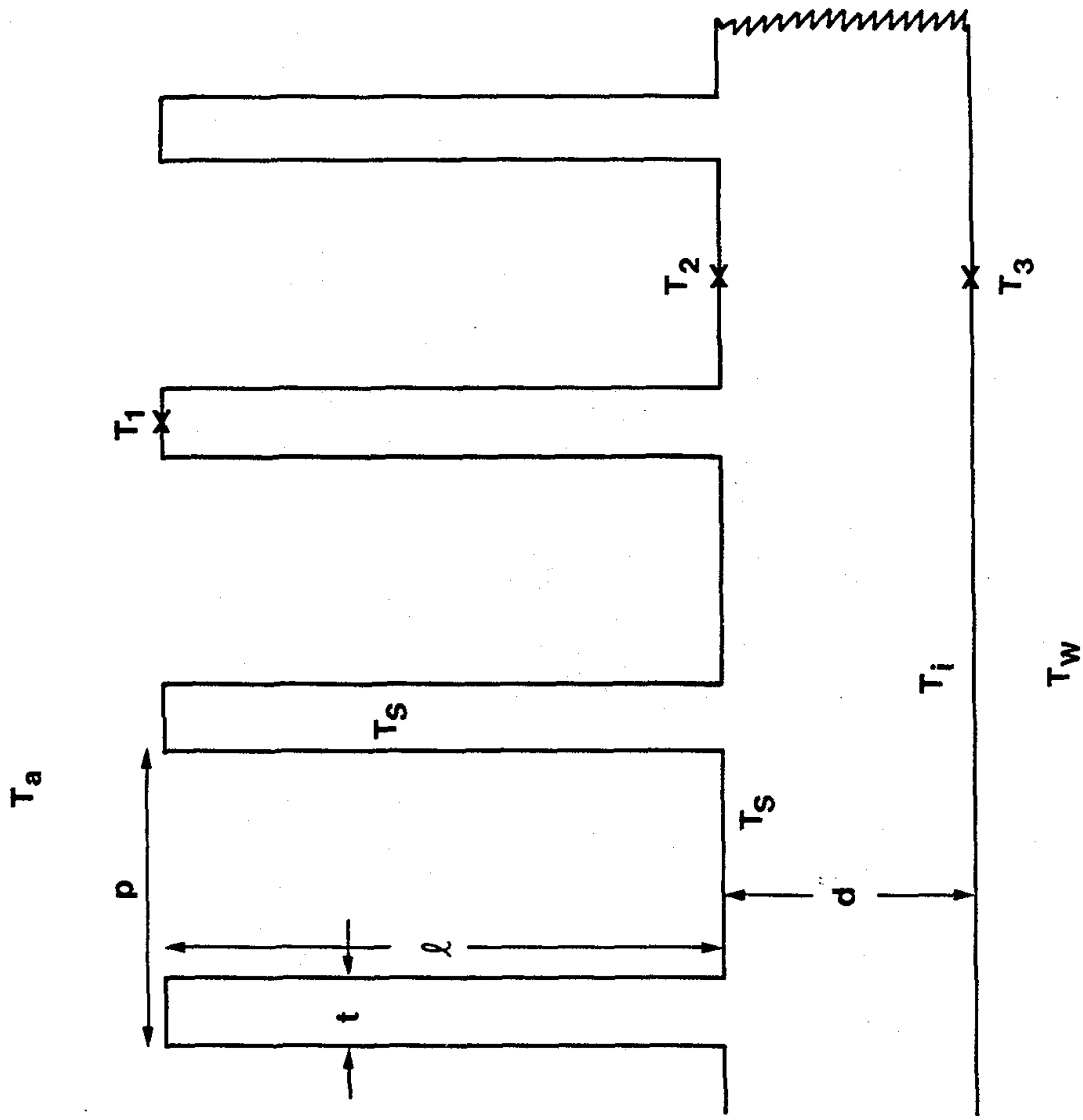

Figure 11. UK-2 Plane Finned Surface

Table XI: UK-2 Dimensions and Material Properties

Fin Thickness	t = 10 mm
Fin Pitch	p = 60 mm
Fin Length	= 150 mm
Base Thickness	d = 100 mm
Material - all mild steel with the following properties:	
Thermal Conductivity	K = 50 w/mK
Specific Heat Capacity	C = 500 J/kgK
Density	ρ = 7.8 te/m^3

The codes used to analyze this problem were TAU (AEEW, BNFL); HEATING-6 (ORNL, ENEA, EMS); Q/TRAN (SNL); and DELFINE (CEA).

The results are given in Figures 12, 13, and 14. The plots are all from the results of the TAU code with standard deviations and greatest deviations derived from the other analyses indicated. Figure 12 shows the comparison for the fin tip temperature of the results for the two emissivities. Figure 13 shows the fin root and internal surface temperatures. The temperature distribution around the fin perimeter is given in Figure 14.

The steady state temperatures shown in Table XIII are very closely spaced. If the different results are averaged, then the spread, represented by a standard deviation, is at most 0.3°C at the fin root.

At the end of the fire transient (i.e., 30 minutes), the standard deviation on the mean has increased to 6.6°C at the fin root. This is, however, only 5 percent of the temperature rise and, thus, an acceptable accuracy for most purposes.

At the end of the cool down period, all temperatures are approaching the initial, steady state values so the scatter is again small. The standard deviation is less than 1°C (fin tip) or 2 percent of the difference from ambient. At this point, there is little difference between the temperatures predicted using the two different emissivities.

Table XII: UK-2 Boundary Conditions

(a) Initial Steady State Conditions

External - Ambient Temperature $T_a = 38°C$
Environment Emissivity $\varepsilon_a = 1.0$
Heat Transfer Coefficient $h_a = 2.0\theta_s^{1/3}$ w/m^{2}K
$\theta_s = T_s - T_a$ K
T_s = local surface temperature
Surface Emissivity $\varepsilon_s = 1.0$ and 0.8
Radiation exchange between all surfaces with finite view factors (fin-to-fin, fin-to-root area).
Gas within the fin cavity does not absorb, emit, or scatter radiation.

Internal - Fluid Temperature $T_w = 100°C$
Heat Transfer Coefficient $h_w = 500\ \theta_i^{1/3}$ w/m^{2}K
$\theta_i = T_i - T_w$ K
T_w = inside wall temperature.

(b) Fire Test Transient Conditions - Duration 30 Minutes

Initial temperatures from (a) above

External - Ambient Temperature $T_a = 800°C$
Environment Emissivity $\varepsilon_a = 1.0$
Heat Transfer Coefficient $h_a = 10.0$ w/m^{2}K
Surface Emissivity $\varepsilon_a = 1.0$ and 0.8
Otherwise as (a) above.

Internal - as for (a) above.

(c) Cool Down Transient Conditions - Duration 60 Minutes

Initial temperatures from end of transient (b) above

External and internal boundary conditions as for (a) above.

An important temperature for a wet flask application is the internal surface temperature at the end of the fire transient. This, in the example considered here, is very close to the peak internal temperature and would yield the highest vapor pressure contribution to internal pressure. In this case the average temperatures are about 34°C above the internal water temperature, and the 1.1°C standard deviations corresponds to 3 percent on this temperature difference.

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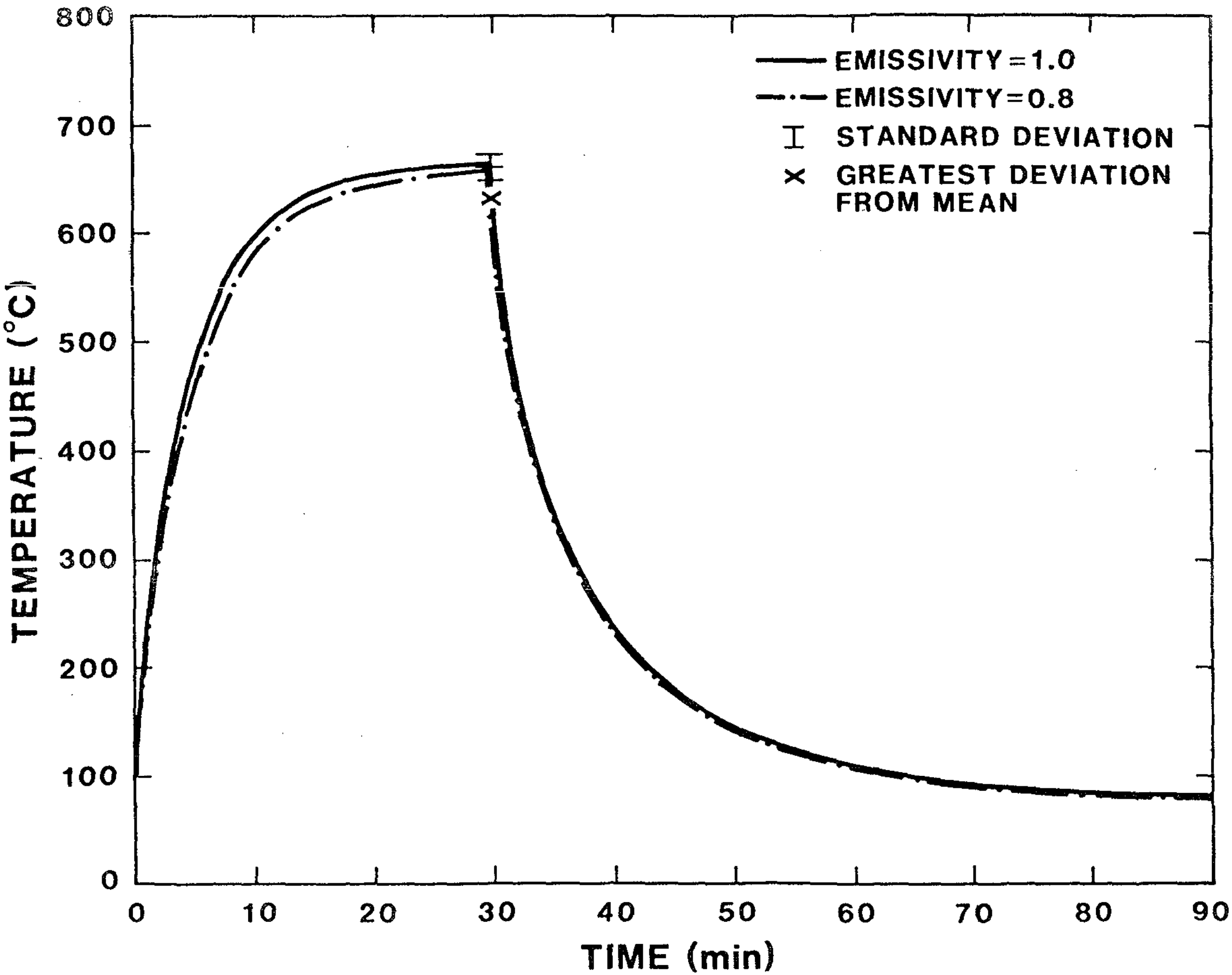

Figure 12. UK-2 Fin Tip Temperatures (T_1) as a Function of Emissivity

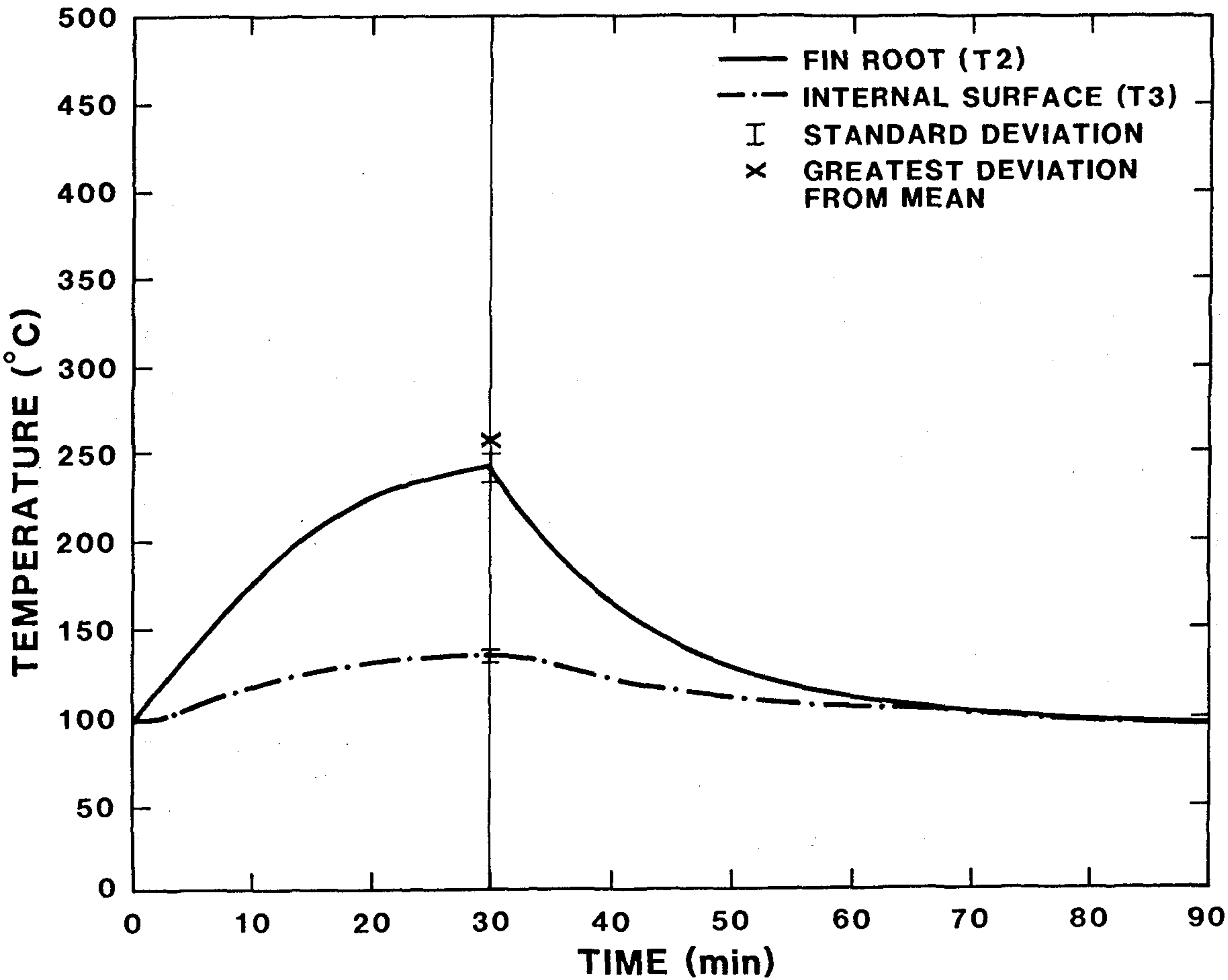

Figure 13. UK-2 Fin Root (T_2) and Internal Surface Temperatures (T_3)

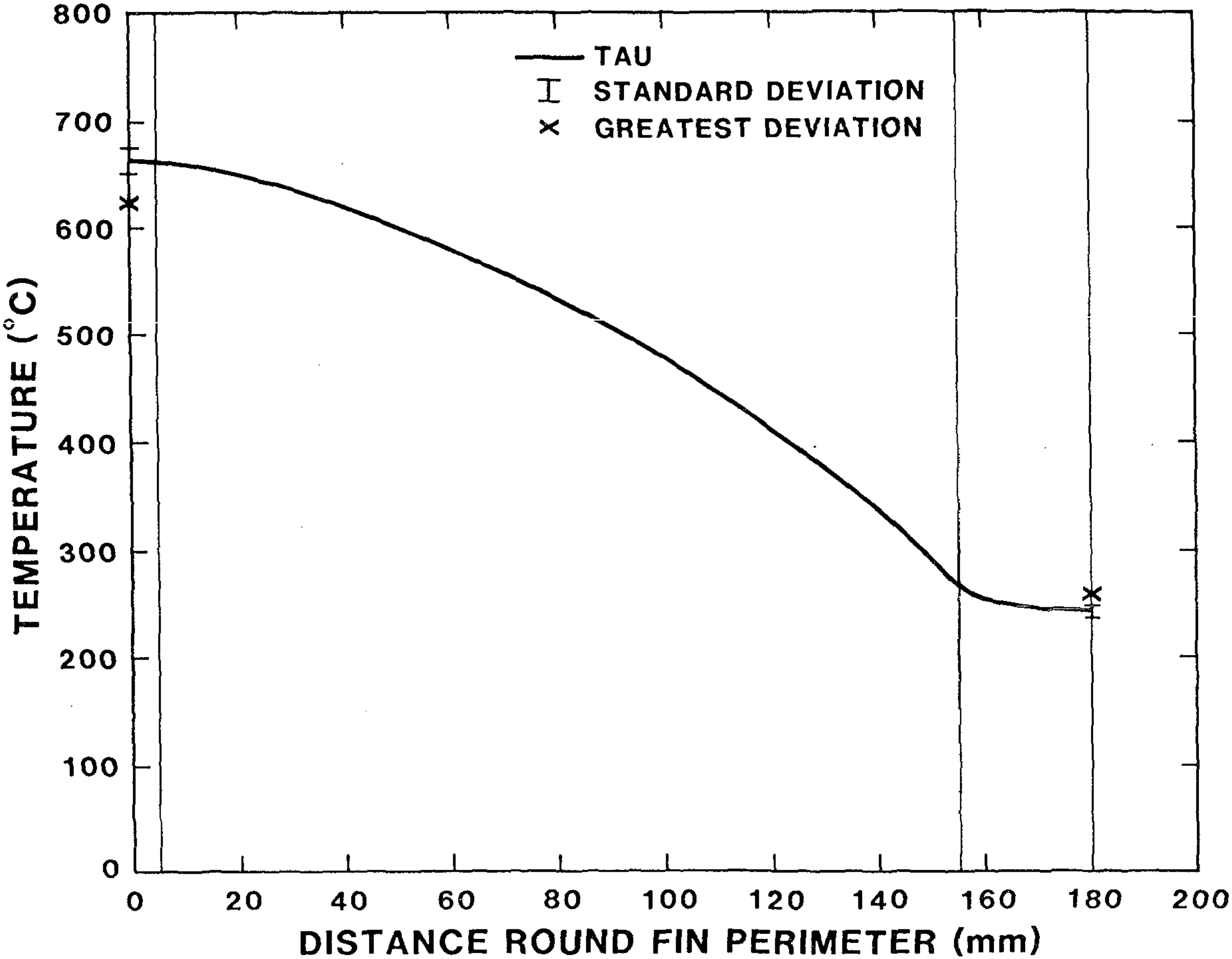

Figure 14. UK-2 Fin Perimeter (moving along the fin from T_1 to T_2) Temperature Distribution at End of Fire

Table XIII: UK-2 Summary of Results

Temperature of:		Fin Tip (T_1)		Fin Root (T_2)		Inside Surface (T_3)	
Surface emissivity		1.0	0.8	1.0	0.8	1.0	0.8
Initial Conditions, Steady State, 0.0 Minutes							
Participant	Code						
AEEW	TAU	75.3	75.9	92.9	93.0	96.9	97.0
	FLUFF/TAU	75.8	76.0	92.4	92.4	96.9	96.9
BNFL	TAU	75.4	75.8	92.9	93.1	96.9	97.0
SANDIA	Q/TRAN	75.3	75.6	92.9	92.9	96.9	96.9
ORNL	HEATING-6	76.0	76.2	93.2	93.3	97.3	97.3
ENEA	HEATING-6	75.4	75.6	92.9	92.9	96.9	96.9
CEA	COCO/ DELFINE	75.4	75.6	92.9	93.0	97.0	97.0
EMS	HEATING-6	75.5	75.6	92.8	92.8	96.9	96.9
	Mean	75.5	75.8	92.9	93.0	97.0	97.0
Standard	Deviation	±0.2	±0.2	±0.2	±0.3	±0.1	±0.1
End of Fire, 30.0 Minutes							
AEEW	TAU	664.5	657.1	242.4	236.9	134.7	133.9
	FLUFF/TAU	661.6	652.5	252.7	248.7	135.1	134.3
BNFL	TAU	657.7	640.3	239.9	224.5	134.1	131.2
SANDIA	Q/TRAN	664.4	652.0	243.4	240.2	134.9	134.3
ORNL	HEATING-6	662.8	654.3	245.3	240.6	135.3	134.5
ENEA	HEATING-6	660.2	652.4	245.7	240.9	135.3	134.5
CEA	COCO/ DELFINE	661.1	652.3	238.7	234.5	133.8	133.0
EMS	HEATING-6	658.7	657.0	245.7	241.9	134.9	134.2
	Mean	661.4	652.2	244.2	238.6	134.8	133.7
Standard	Deviation	±2.3	±4.9	±4.0	±6.6	±0.5	±1.1
End of Cool Down, 90.0 Minutes							
AEEW	TAU	79.9	80.2	95.7	95.8	98.3	98.3
	FLUFF/TAU	79.8	80.2	94.9	95.0	98.1	98.1
BNFL	TAU	81.3	81.9	96.6	96.7	98.8	98.8
SANDIA	Q/TRAN	79.3	79.7	95.3	95.4	98.1	98.1
ORNL	HEATING-6	79.7	80.0	95.4	95.5	98.2	98.2
ENEA	HEATING-6	79.5	79.8	95.4	95.5	98.1	98.2
CEA	COCO/ DELFINE	80.4	80.8	96.1	96.1	98.5	98.5
EMS	HEATING-6	79.8	79.8	95.5	95.5	98.3	98.3
	Mean	79.9	80.4	95.8	95.7	98.4	98.4
Standard	Deviation	±0.6	±0.7	±0.5	±0.5	±0.2	±0.2

UK-3: Partially Water-Filled Flask

UK-3, shown in Figure 15, represents a sealed container, partially filled with water, subject to external heating approximating the IAEA 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 in a cost effective way using readily available codes. A sample calculation, with a fluid-flow code with three-dimensional capability, shows that the temperature predictions are of an acceptable accuracy using the anisotropic conductivity simulation.

The calculation is in two parts: an initial steady state is defined (in this case a uniform temperature distribution) followed by a heating transient with a constant heat flux on curved external surfaces (i.e., the lid and base are adiabatic surfaces) and finally a cool down transient when heat is rejected from the curved outer surface by radiation and convection.

The dimensions and material properties are given in Table XIV. The heat transfer characteristics are given in Table XV.

Three solutions were based on finite element models (TAU and DELFINE) and the other four on finite difference codes (HEATING-6 and SINDA). Each utilized radiation view factors for heat transfer across the nonparticipating void above the water. Constant geometry was specified, so no allowance for thermal expansions or water level changes were necessary.

The individual tabular results are given in Table XVI. The mean and standard deviations are given in Table XVII.

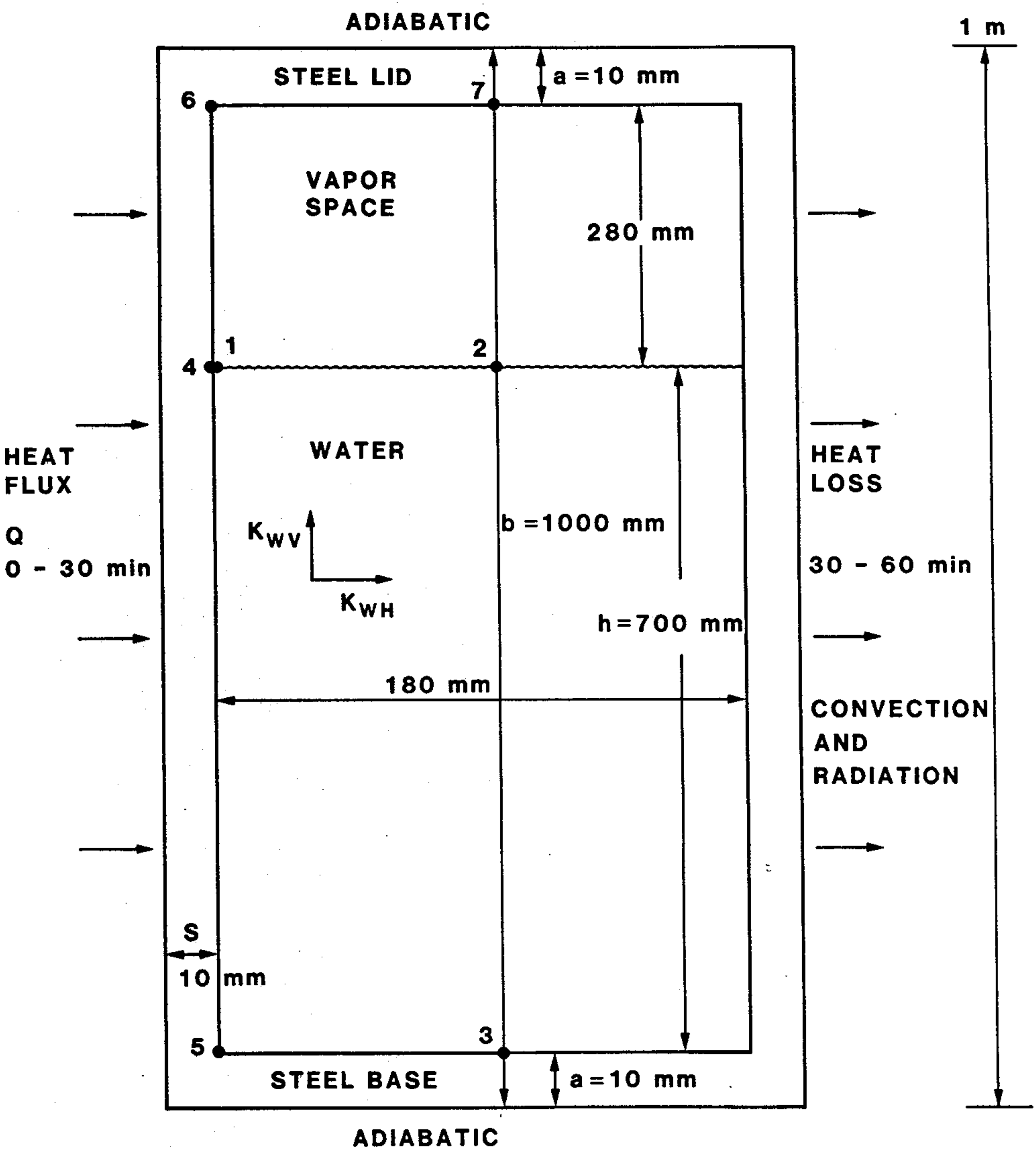

Figure 15. UK-3 Partially Water-Filled Flask

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Table XIV: Dimensions and Material Properties

Dimensions		
The model comprises a closed cylindrical vessel, partially filled with water, with the axis vertical.		
	External height	b = 1.0 m
	Wall thickness	s = a = 10.0 mm
	Outside diameter	d = 200 mm (Radius 100 mm)
	Inside diameter	180 mm (Radius 90 mm)
	Water level above base	h = 700 mm
	Height of dry wall	280 mm
Material Properties		
Steel vessel -	Thermal Conductivity	K_s = 50 w/m
	Heat Capacity	C_s = 500 J/kg K
	Density	ρ_s = 7.8 Te/m^3
Water contents -	Thermal Conductivity	K_{WH} = 5000 w/m K (Horizontal)
		K_{WV} = 0.6 w/m K (Vertical)
	Heat Capacity	C_W = 4200 J/kg K
	Density	ρ_W = 1.0 Te/m^3

The uncertainty in the water surface temperature is reflected in the corresponding uncertainty in the vapor pressure which is obtained using the water surface temperature. The standard deviation is 2.4 percent of the mean surface water temperature (2[a]) but 9.5 percent of the vapor pressure. This uncertainty must be reflected in design safety margins for water-filled cavities.

Conclusions

This report 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).

Table XV: UK-3 Heat Transfer Characteristics

Intial temperature - 38°C uniform

0 to 30 minutes

Uniform heat flux q = 10 kW/m
Lid and base outside surfaces are adiabatic
Natural convection coefficient:

$H_W = 500\ \Theta_W^{1/3}\ w/m^2K$
$\Theta_W = Ts - Tw\ K$
T_S = local vessel inside surface temperature (K)
T_W = local water temperature (K)

There is no heat transfer by conduction or convection in the vapor space above the water, but radiation exchange takes place between the surfaces of the vessel and the water.

$\varepsilon_S = 0.80$ vessel surface emissivity
$\varepsilon_W = 1.00$ water surface emissivity

30 to 60 minutes

$H_E = 1.3\ \Theta_E^{1/3}\ w/m^2K$ Convection coefficient
$\varepsilon_E = 0.80$ Surface emissivity
$\Theta_E = T_S - T_A\ K$
T_S = local vessel outside surface temperature (K)
T_A = ambient temperature (311.2 K)

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.

Table XVI: Temperatures Calculated for UK-3

Contributor	AEEW	BNFL	ORNL	SNL	CEA	ENEA	EMS
Code	TAU	TAU	HEATING-6	SINDA	DELFINE	HEATING-6	HEATING-6
Water Temperatures (°C)							
1(a) Surface Edge							
30 min	248.1	250.0	239.4	238.3	243.3	250.9	236.5
1(b) (R = 0.09, Z = 0.71)							
60 min	163.7	162.7	163.8	163.6	160.8	163.9	159.2
2(a) Surface Center							
30 min	249.8	251.1	239.3	238.3	243.3	250.9	236.5
2(b) (R = 0.0, Z = 0.71)							
60 min	164.0	162.1	163.8	163.6	160.8	163.9	159.2
3(a) Bottom Center							
30 min	127.3	127.7	126.5	123.1	126.4	123.6	124.4
3(b) (R = 0.0, Z = 0.01)							
60 min	115.5	116.2	115.5	115.9	110.1	116.0	116.5
Metal Temperatures (°C)							
4(a) Water Level							
30 min	248.9	252.1	249.4	238.3	248.9	250.5	242.2
4(b) (R = 0.09, Z = 0.71)							
60 min	157.7	157.0	158.1	163.6	154.6	158.0	154.1
5(a) Bottom Corner							
30 min	132.0	133.2	132.1	132.0	132.1	131.8	131.9
5(b) (R = 0.09, Z = 0.01)							
60 min	114.4	115.4	114.6	114.3	109.2	114.6	115.1
6(a) Top Corner							
30 min	374.9	374.1	380.4	395.1	379.2	379.2	380.1
6(b) (R = 0.09, Z = 0.99)							
60 min	178.9	178.7	177.8	172.8	181.2	177.6	174.7
7(a) Lid Center							
30 min	348.3	349.0	354.1	354.6	350.9	352.1	354.7
7(b) (R = 0.0, Z = 0.99)							
60 min	188.4	188.2	186.4	187.1	191.0	186.3	183.2
8 Vapor Pressure (Bar)							
30 min	38.5	39.8	33.1	32.6	35.5	40.5	31.5

Table XVII: Statistical Values for UK-3

Position	Mean (°C)	Standard Deviation (°C)
1(a)	243.8	4.7
1(b)	162.5	1.7
2(a)	244.2	5.9
2(b)	162.5	1.7
3(a)	125.6	1.7
3(b)	115.1	2.1
4(a)	247.2	4.6
4(b)	157.6	2.9
5(a)	132.2	0.4
5(b)	113.9	2.0
6(a)	380.4	6.4
6(b)	177.4	2.6
7(a)	352.0	2.1
7(b)	187.2	2.2
8	35.9 (bar)	3.4 (bar)

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

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.

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