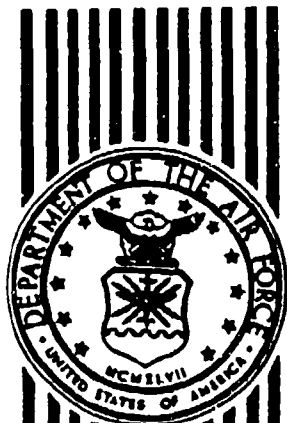AD-A243 142

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SIMULATION OF THE THERMAL RESPONSE OF EXTERNALLY COOLED ORDNANCE ENGULFED IN LARGE AVIATION FUEL FIRES

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To assess effects of the external cooling on the fire-exposed ordnance cookoff time, a validated heat transfer computer model was adopted and modified to include principles describing the external cooling effects. The new model predicts the change in ordnance cookoff time as a function of coolant application rate. Calculations demonstrate that the external cooling can delay the cookoff time.

The thermal interaction between the incident flame and ordnance, as well as the effects of coolant on cookoff time, were simulated experimentally. Specially designed calorimeters were instrumented and placed in a pool fire to measure the transient heat flux and to quantify the effects of various coolants. Effects of intumescent coating used on various ordnance were evaluated experimentally and compared with the response of the thermally unprotected ordnance. The experimental data, although inconclusive, suggest that thermally unprotected ordnance can achieve longer cookoff times than coated ordnance, when external cooling is applied.

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LARGE AVIATION FUEL FIRES

EXECUTIVE SUMMARY

Evaluation and quantification of the response time of various munitions to accidental fire impingement is an integral part of the DOD's ordnance thermal protection program. The thermal protection program involves interaction of numerous thermodynamic and heat transfer disciplines. This report presents exclusively the efforts on numerical and experimental simulations of the effects on ordnance cookoff time when external cooling is applied.

To assess effects of the external cooling on fire-exposed ordnance cookoff time, a validated heat transfer computer model was adopted and modified to include principles describing the external cooling effects. The new model predicts the change in ordnance cookoff time as a function of coolant application rate. Calculations demonstrate that external cooling can delay the cookoff time.

The thermal interaction between the incident flame and ordnance, as well as the effects of coolant on cookoff time, were simulated experimentally. Specially designed calorimeters were instrumented and placed in a pool fire to measure the transient heat flux and to quantify the effects of various coolants. Effect of an intumescent coating used on various ordnance was evaluated experimentally and compared with the response of the thermally unprotected ordnance. The limited experimental data, although inconclusive, suggest that thermally unprotected ordnance can achieve longer cookoff times than coated ordnance, when external cooling is applied.

PREFACE

This final report was prepared by the New Mexico Engineering Research Institute (NMERI), University of New Mexico, Campus Box 25, Albuquerque, New Mexico 87131, under Contract F29601-84-C-0080 (Subtask 3.10) for the Air Force Engineering and Services Center (AFESC/RDCF), Tyndall Air Force Base Florida 32403, and the Naval Air Systems Command (NAVAIR), Washington, DC 20361.
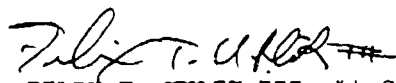
This report summarizes work done between 14 January 1985 and 30 October 1986. HQ AFESC/RDCF Program Manager was Joseph L. Walker, and NAVAIR Project Officer was Phillis Campbell.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

T :	Temperature	K
T_w :	Coolant temperature	K
T_f :	Flame temperature	K
T_s :	Surface temperature	K
ϵ :	Emissivity coefficient	
σ :	Stefan Boltzman constant	$cal/s\ m^2\ K$
q_f :	Incident heat flux from fire	$cal/s\ m^2$
q :	Internal energy generation	cal/s
U_{oa} :	Overall heat transfer coefficient	cal/s K
Q :	Heat of reaction	cal/g
C_p :	Specific heat at constant pressure	cal/g K
Z :	Collision number	liter/s
K :	Thermal conductivity	$cal/cm^2\ s\ K$
E :	Activation energy	cal/mole
ρ :	Density	g/cm^3
R :	Universal gas constant	cal/mole K
t :	Time	second
ℓ :	Current layer	
n :	Total number of layers	
m :	Number of components of the explosive	
i :	Represents the calculation node, spatial coordinate	
j :	Represents the current time, time step	
ΔF :	Fourier modulus	
Δr :	Elemental radial width	
h :	Convective heat transfer coefficient	cal/s K
R :	Radius	cm

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SECTION I

INTRODUCTION

A. OBJECTIVE

This project was conducted to calculate the response time for fire-exposed ordnance and determine how long ordnance cookoff can be delayed by application of external cooling. Different coolant types and application techniques were tested to develop pragmatic criteria for response times and cooling procedure to be used for ordnance exposed to fire.

B. BACKGROUND

The US armed forces have had a number of incidents in which ordnance exposed to fire has cooked off, causing major loss of life and property. Incidents on the USS Forrestal, USS Enterprise, and the USS Nimitz all resulted in losses of life and materiel (References 1, 2, and 3). The USAF has also had such incidents; for example, a maintenance accident at Mountain Home AFB resulted in the burning of an F-111 loaded with Mark 82 bombs. In this incident the firefighters retreated and all of the bombs cooked off, resulting in significant materiel losses.

In the event of a postcrash fire, it is likely that ordnance will be exposed to high heat fluxes. Ordnance reactions (propulsion or detonation depending on the nature of the weapon) to a fire environment can range from mild burning to violent explosion. The extent of the reaction is determined by the intensity and duration of heating, and the thermal protection of the ordnance. The ordnance may have a cookoff reaction after removal of the heat source (usually by fire extinguishment) because of self-heating from internal exothermal reactions. Firefighting efforts and the associated hazards are complicated when fire-exposed ordnance are present. Criteria are not available to accurately define the cooling/handling requirements and safe response procedures to be used for ordnance exposed to fire.

C. SCOPE

The scope of this project was to investigate and evaluate all existing ordnance response models and to modify a viable candidate to include the effects of external cooling. The modified model was to be capable of predicting the cooling required to prevent a runaway reaction and to assess the cookoff time extension resulting from external cooling. Small-scale calorimeter tests were conducted to obtain essential parameters needed to calculate cookoff time extensions which can be achieved by application of external cooling. To evaluate the effects of intumescent thermal protection on cookoff time extension, coated calorimeters were tested and the data were compared with the response data from uncoated calorimeters.

D. APPROACH

This report documents numerical modeling conducted as one component of a long range effort to reduce losses from ordnance cookoff. Numerical models which predict the transient response of ordnance exposed to heat fluxes have been developed in the past. One of these models has been updated to include external cooling and its effect on ordnance response. Testing of subscale models has been used to measure the effectiveness of various coolants, with their heat transfer rates used as input to the computer model. The change in cookoff time as a function of coolant application rate is then predicted.

SECTION II

MATHEMATICAL MODELING

A.   INTRODUCTION

The derivation of heat transfer equations describing the thermal
loading of an ordnance is based on the physical model shown in Figure 1.
In this figure various components of a typical ordnance (a Mark 82 general
purpose bomb) are shown in a sector cross section. Each layer is characterized
by its thickness and thermal properties; perfect thermal contact between each
of the layers is assumed. Internal energy generation due to chemical reaction
is allowed in any layer. The energy generation is modeled by the use of
first-order Arrhenius kinetics. The ordnance is assumed to be immersed in
a large aviation fuel fire, which is characterized by a flame temperature. The
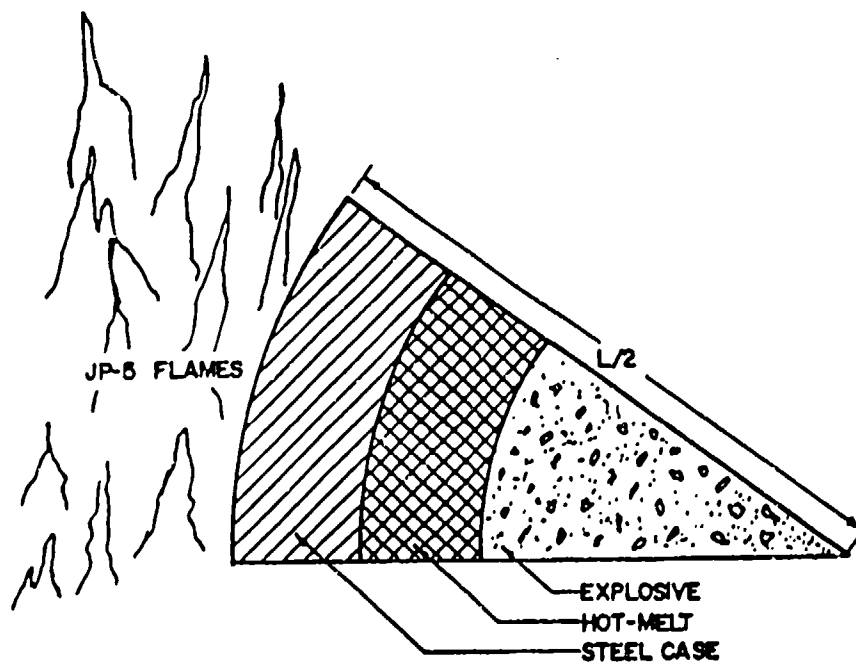
Figure 1.   Sector of Cylindrical Cross Section of a General-Purpose Bomb,
            Mark 82 (extracted from Reference 4).

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heat flux input from the fire to the ordnance is modeled with radiative and convective components. Ordnance cookoff is defined as the point where the explosive begins a thermally induced, exothermic, runaway decomposition. This process is modeled by use of the first-order Arrhenius kinetics.

B. GOVERNING EQUATIONS

The governing equations describing the overall heat transfer processes in a fire-exposed ordnance must include:

1. Equations describing the incident external heat flux.
2. Equations describing the heat transfer through various internal layers.

C. EXTERNAL HEATING

The total incident heat flux on the exterior boundary of the ordnance, q_f, is equal to the sum of radiative and convective heat flux.

$$q_f = \epsilon \, \sigma \, (T_f^4 - T_s^4) + h \, (T_f - T_s)$$

with the terms defined as follows:

T_f: flame temperature
T_s: surface temperature
ϵ: emissivity factor
σ: Stefan Boltzman constant
h: convective heat transfer coefficient

The incident flame temperature history used in the program was taken from JP-5 fire data presented by Russell and Canfield (Reference 4). The emissivity factor of the fire is assumed to be 0.99. The convective heat transfer coefficient is taken from Boyer and Russell (Reference 5). During cooling, the surface boundary condition is modeled using

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$$q - U_{oa} (T_w - T_s)$$

where U_{oa} is the overall heat transfer coefficient and T_w is the coolant temperature. The values for U_{oa} were obtained from experimental data provided by the subscale calorimeter tests.

D.   INTERNAL HEATING

Heat is transferred through various layers of munitions by conduction. The governing internal heat transfer equation is the algebraic sum of conduction and internal energy of the materials at each layer. The internal heat transfer equation in cylindrical coordinates becomes:

$$\rho_\ell \ C_{p\ell} \ \frac{\partial T_\ell}{\partial t} - k_\ell \ [\frac{1}{r^2} \ \frac{\partial}{\partial r} \ (\ r^2 \ \frac{\partial T_\ell}{\partial r} \ ) \ ] + \dot{q}_\ell \qquad \ell - 1, \ldots . n \qquad (1)$$

The terms in the energy equation are defined as follows:

ℓ: layer index

n: total number of layers

ρ: density (g/cm^3)

C_p: specific heat (cal/g K)

T: temperature (K)

t: time (seconds)

k: thermal conductivity $(cal/cm^2 \ s \ K)$

r: radius (centimeters)

$\dot{q}$:   rate of internal energy generation (cal/s)

The rate of internal energy generation ($\dot{q}$) is expressed as a first-order Arrhenius reaction:

$$\dot{q} - \rho_\ell \ \sum_{p=\ell}^{m} Q_p \ Z_p \ \exp \ (\ -E_p \ / \ R \ T_1 \ ) \qquad (2)$$

where

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m: number of components of the explosive

i: represents the calculation node

Q: heat of reaction (cal/g)

Z: collision number (liters/s)

E: activation energy (cal/mole)

R: universal gas constant (cal/mole K)

E. BOUNDARY CONDITION AND ASSUMPTIONS

The above governing equations are solved according to the following boundary conditions:

The outer boundary condition is

$$-k_\ell \frac{\partial T_\ell}{\partial r} = \epsilon \, \sigma \, (\, T_f^4 - T_s^4 \,) + h \, (\, T_f - T_s \,) \tag{3}$$

Similarly, the boundary condition for the period of cooling becomes

$$-k_\ell \frac{\partial T_\ell}{\partial r} = U_{oa}(\, T_w - T_s \,) \tag{4}$$

The boundary condition at each interface assumes that the heat flux across the boundary is equal on both sides of the interface and the temperatures are the same. This is expressed as:

$$k_\ell \frac{\partial T_\ell}{\partial r} = k_{\ell+1} \frac{\partial T_{\ell+1}}{\partial r} \tag{5}$$

and

$$T_\ell = T_{\ell+1} \tag{6}$$

Furthermore, it is assumed that the variation of the temperature at the center of the ordnance is finite, therefore

$$\frac{\partial T_\ell}{\partial r} = 0, \text{ at } r=0 \tag{7}$$

and the ordnance is initially at the ambient temperature

$$T = T_{amb} \tag{8}$$

F.   FINITE DIFFERENCING METHOD

The governing heat transfer principles and the boundary conditions described in Equations (1) through (8) are solved numerically using a finite differencing scheme. The algorithm used to obtain an approximate numerical solution is based on an explicit central differencing method (Reference 6). The spatial location of each finite element is based on the cylindrical distribution of Δr as shown in Figure 2.

Expressed in the finite-difference form, the partial differential Equation (1) describing the energy transfer at each layer becomes

$$T_i^{j+1} = T_i^j + \frac{[\Delta F_i^j + 0.25(\Delta F_{i-1}^j - \Delta F_{i+1}^j)][r_i + 0.5\ \Delta r_1][T_{i-1}^j - T_i^j]}{r_i}$$
$$\cdot \frac{[\Delta F_i^j + 0.25\ (\Delta F_{i-1}^j - \Delta F_{i+1}^j)][r_i - 0.5\ \Delta r_1][T_i^j - T_{i+1}^j]}{r_i} +$$
$$\frac{\Delta F_i^j\ (\Delta r)^2}{(k_\ell)_i^j}\ \dot{q} \tag{9}$$

where i represents the current node and j represents the current time. The internal energy term is expressed as

$$\dot{q} = \rho_\ell \sum_{n=\ell}^{m} Q_{\ell,n} \, Z_{\ell,n} \, \exp \left(-E_n / R \, T_i^j \right) \tag{10}$$

where n represents the current reactive component, m represents the total number of reactants, and ℓ represents the current layer. The Fourier modulus, ΔF, is defined as

$$\Delta F_i^j = \frac{k_i^j \, \Delta t}{\rho_\ell \, Cp_\ell \, (\Delta r)^2} \tag{11}$$
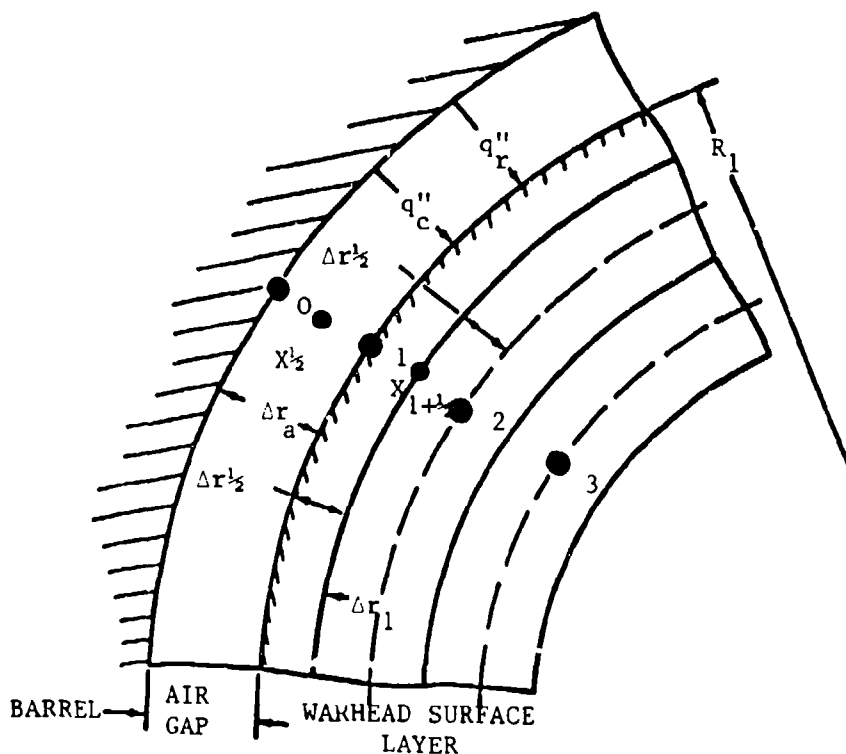
Figure 2. Elemental Surface Layer Analog.

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The surface boundary condition, Equation (3), in finite difference form is

$$T_i^{j+1} = T_i^j + \Delta F_1^j \frac{(\Delta r_1)^2}{k_i^j} \dot{q} + 2 \frac{\Delta F_1^j (r_t)(\Delta r_1)}{k_1^j (r_t - \Delta r_1/4)} [h (T_f - T_1^j) +$$

$$\epsilon \sigma (T_f^4 - (T_1^j)^4)] - \Delta F_1^j \frac{(r_t - \Delta r_1/2)}{(r_t - \Delta r_1/4)} [T_1^j - T_2^j] \qquad (12)$$

The surface boundary condition during cooling is expressed as

$$T_i^{j+1} = T_i^j + \Delta F_1^j \frac{(\Delta r_1)^2}{k_i^j} \dot{q} + 2 \frac{\Delta F_1^j (r_t)(\Delta r_1)}{k_1^j (r_t - \Delta r_1/4)} [U_{oa} (T_w - T_1^j)] -$$

$$\Delta F_1^j \frac{(r_t - \Delta r_1/2)}{(r_t - \Delta r_1/4)} [T_1^j - T_2^j] \qquad (13)$$

The interface boundary condition between layers is expressed as

$$T_1^{j+1} = T_1^j + \frac{2\theta_1 \Delta x_1}{K_1(- \frac{\Delta x_1}{4})} \cdot [x_1 \sigma F_{1-0}(T_0^j)^4 - (T_1^j)^4] +$$

$$\frac{2\theta_1 \Delta x_1}{K_1(1 - \frac{\Delta x_1}{4})} \cdot [K_1(x_1 - \frac{\Delta x_1}{2}) \cdot (\frac{T_2^j - T_1^j}{\Delta x_1}) + \frac{2\theta_1 \Delta x_1}{K_1(x - \frac{\Delta x_1}{4})} \cdot$$

$$[K_a(x_1 + \frac{\Delta x_a}{2}) (\frac{T_0^j - T_1^j}{\Delta x_1})] + \frac{2\theta_1 \Delta x_1}{K_1(x - \frac{\Delta x_1}{4})} \cdot$$

$$[(x_1 + \frac{\Delta x_1}{4})(\frac{\Delta x_1}{2}) \dot{q}'''] \qquad (14)$$

where:

$$\theta_1 = \frac{K_1 \Delta t}{\rho_1 c_1 (\Delta x_1)^2}$$

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$$x_{1+1/2} = x_1 - \frac{\Delta x_1}{2}$$

$$x_{1/2} = x_1 + \frac{\Delta x_a}{2}$$

$$F_{1-0} = \frac{1}{[\frac{1}{\epsilon_1} + (-\frac{A_1}{A_0})(\frac{1}{\epsilon_0} - 1)]}$$

The coefficient F_{1-0} is the gray-body shape factor resulting from the radiative heat transfer processes (Reference 7). The center boundary condition expressed in finite difference becomes

$$T_i^{j+1} = T_i^j + 2 \left(\frac{k_i^j \Delta t}{\rho_i \, Cp_i \, (\Delta r_i)^2} \right) (T_{i-1}^j - T_i^j) + \frac{\dot{q}_i^j}{\rho_i \, Cp_i} \qquad (15)$$

A FORTRAN program was written to solve the governing differencing Equations (9) through (15). Details of the computer model are discussed in the next section.

SECTION III

COMPUTER MODEL

A.   INTRODUCTION

The finite difference equations used to calculate the temperature profiles through the ordnance were implemented in a computer program.   A flowchart of the program is contained in Appendix A and the program listing is in Appendix B.   The program is a modified version of one originally written by Russell and Canfield (Reference 4) and later modified by Boyer and Russell (Reference 5).   The program is written in FORTRAN and consists of a driver program and several subroutines.   Each subroutine calculates one of the three temperature types (surface, interior, or interface node), or performs other tasks required by the program.   The model has been executed on a 16-bit desk-top computer.   The program is interactive; it requests the user to enter the data and output file names. Tne input data consist of dimensions, thermal properties of each of the layers, flame, and cooling parameters, and program control parameters.   The input data required by the program are listed in Appendix C.

B.   COMPARISON WITH OTHER MODELING AND EXPERIMENTAL DATA

The model was tested by executing several cases to ensure that cookoff times were predicted correctly.   All of the cookoff tests were conducted with ordnance engulfed in JP-5 fires.   The model results were first compared to results obtained by Russell and Canfield (Reference 4) with their flat-plate ordnance model.   Reference 4, Appendix B, Table 3, Case 1 was used as a baseline. Russell and Canfield predicted a cookoff time of 229.7 seconds.   The current model predicts a cookoff time of 240.2 seconds.

Russell and Canfield also presented data for Mark 82 bombs with what was then the standard hot-melt thickness. The average time for reaction for the three tests (Reference 4, Appendix B, Table 5) was 196 seconds.   Measured hot-melt layer thicknesses were not available for these tests, but radiographs were taken

of 10 bombs randomly selected from different production runs. The average of the hot-melt thicknesses for the 10 bombs was 0.33 cm. Using the value of 0.33 cm for the hot-melt thickness, the computed reaction time for a Mark 82 bomb using the current model is 184.5 seconds.

C. W. Morris (Reference 8) also presented cookoff data that were used for comparative purposes. Table 1 presents a summary of experimental and comparative predicted cookoff times for five different cases.

TABLE 1. COOKOFF TIMES FOR MARK 82 AND MARK 84 BOMBS
WITH AND WITHOUT FM-26 ABLATIVE COATING

Case	Ordnance	FM-26 thickness, mils	Hot-melt thickness, mils	Experimental cookoff time, s	Morris model time, s	NMERI model time, s
1	Mark 82	none	125	180	169	182
2	Mark 82	120	250	628	640	624
3	Mark 84	none	125	182	196	228
4	Mark 84	none	300	309	264	320
5	Mark 84	60	300	525	528	526

Agreement between the model and experimental results is generally good. For the remainder of this report, ordnance with the FM-26* ablative coating will be referred to as coated ordance, and those without will be referred to as uncoated.

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*FM-26 is an ablative coating manufactured by AVCO Corporation, Wilmington, Massachusetts 01887. This material is used as an insulator, for thermal protection on most nonpropelled Navy ordnance.

C.   EFFECTS OF COOLING

When coolant is applied to an engulfed ordnance, extension of the cookoff time can be expected. The cookoff time extension depends on many parameters. The parameters contributing most effectively to the cookoff-time extension are the overall heat transfer coefficient, cooling initiation time, and coolant temperature.

A series of calculations was made to determine the dependency of the cookoff time on the overall heat transfer coefficient and the start of cooling time. The values chosen for the overall cooling coefficient, U_{oa}, were taken from the result of the subscale calorimeter testing reported in sections IV and V. The dependency of the cookoff time on the overall heat transfer coefficient and the start of the cooling time is shown in Figures 3, 4, and 5. Each of these figures shows a composite cookoff time prediction, based on the calculation, for an uncoated ordnance.

Figure 3 is a composite illustration of the cookoff time prediction for an uncoated Mark 82 bomb. The figure shows that, for any U_{oa} greater than 10^{-5} cal/cm^2 s K, ordnance cookoff can be prevented if cooling starts at any time before about 150 seconds after fire initiation. For the same coefficient, if cooling starts 160 seconds after fire initiation, cookoff can be delayed approximately 40 seconds. If the cooling initiation is delayed another 10 seconds, i.e., until 170 seconds, the increase in cookoff time is negligible (less than 10 seconds). A similar trend is shown for the heat transfer coefficient U_{oa} of 10^{-4} cal/cm^2 s K. Cookoff can be prevented if cooling starts at any time before 155 seconds after fire initiation.

Similarly, Figures 4 and 5 illustrate the cookoff time versus cooling initiation predictions for uncoated Mark 84 general-purpose bombs with different hot-melt thicknesses. Analogous to the analysis performed on Figure 3, one can estimate the cookoff time for various values of U_{oa}. The key to safe and successful cookoff prevention is to apply the coolant before the exothermic runaway decomposition of the explosive inside the ordnance begins.
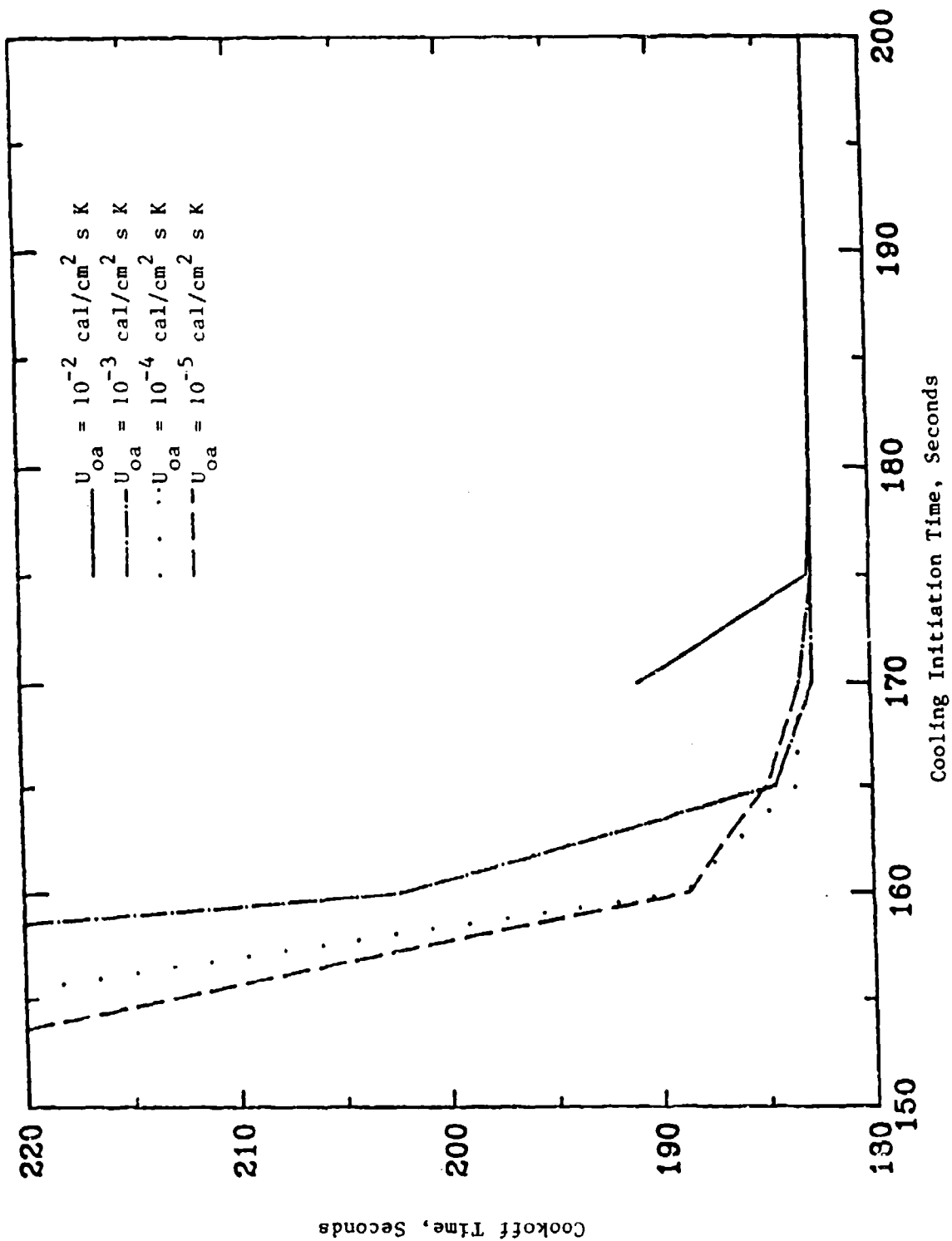
Figure 3. Cookoff Time Versus Cooling Initiation Time Profile
(Mark 82, Uncoated, Table 1, Case 1).

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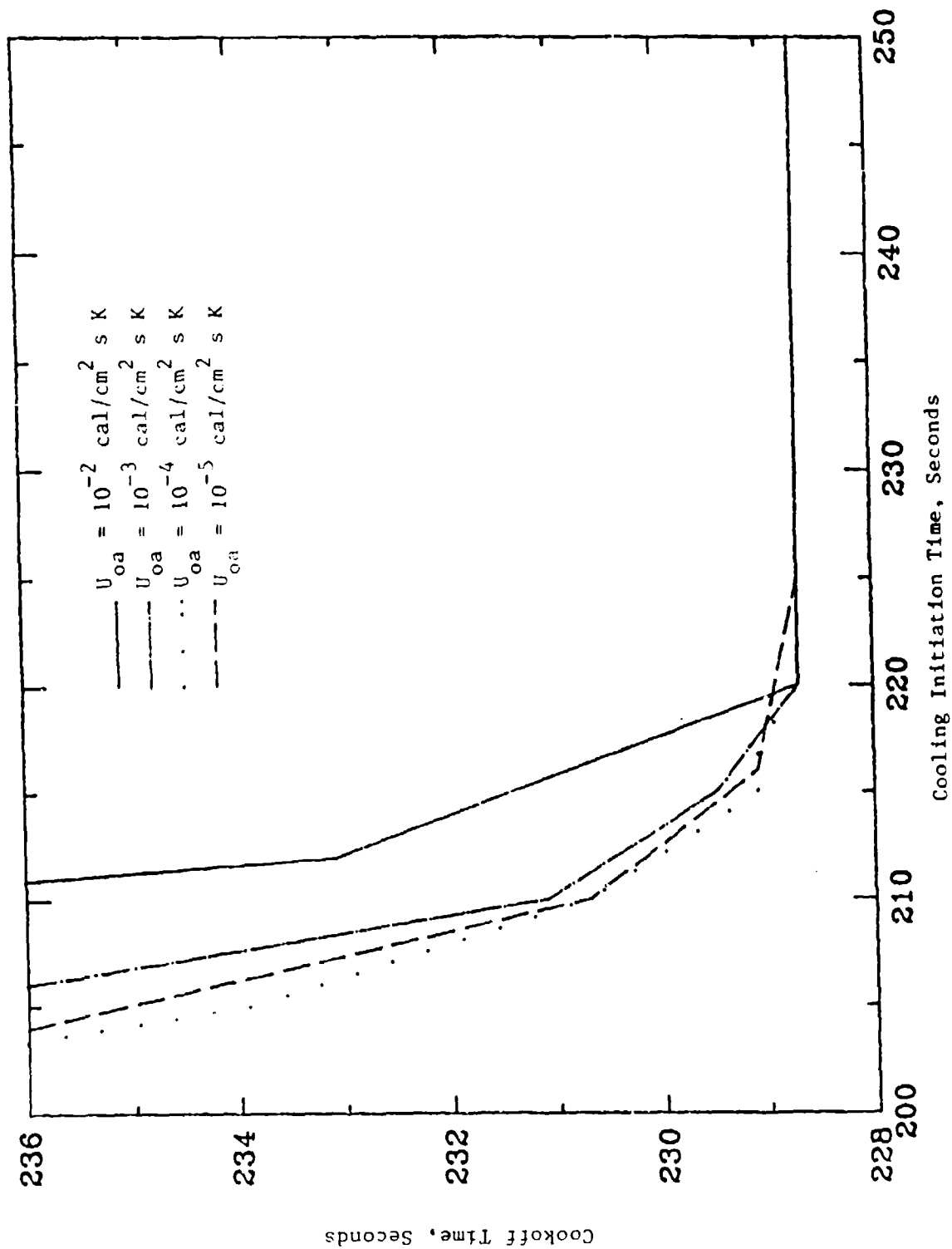
Figure 4. Cookoff Time Versus Cooling Initiation Time Profile
(Mark 84, Uncoated, Table 1, Case 3).

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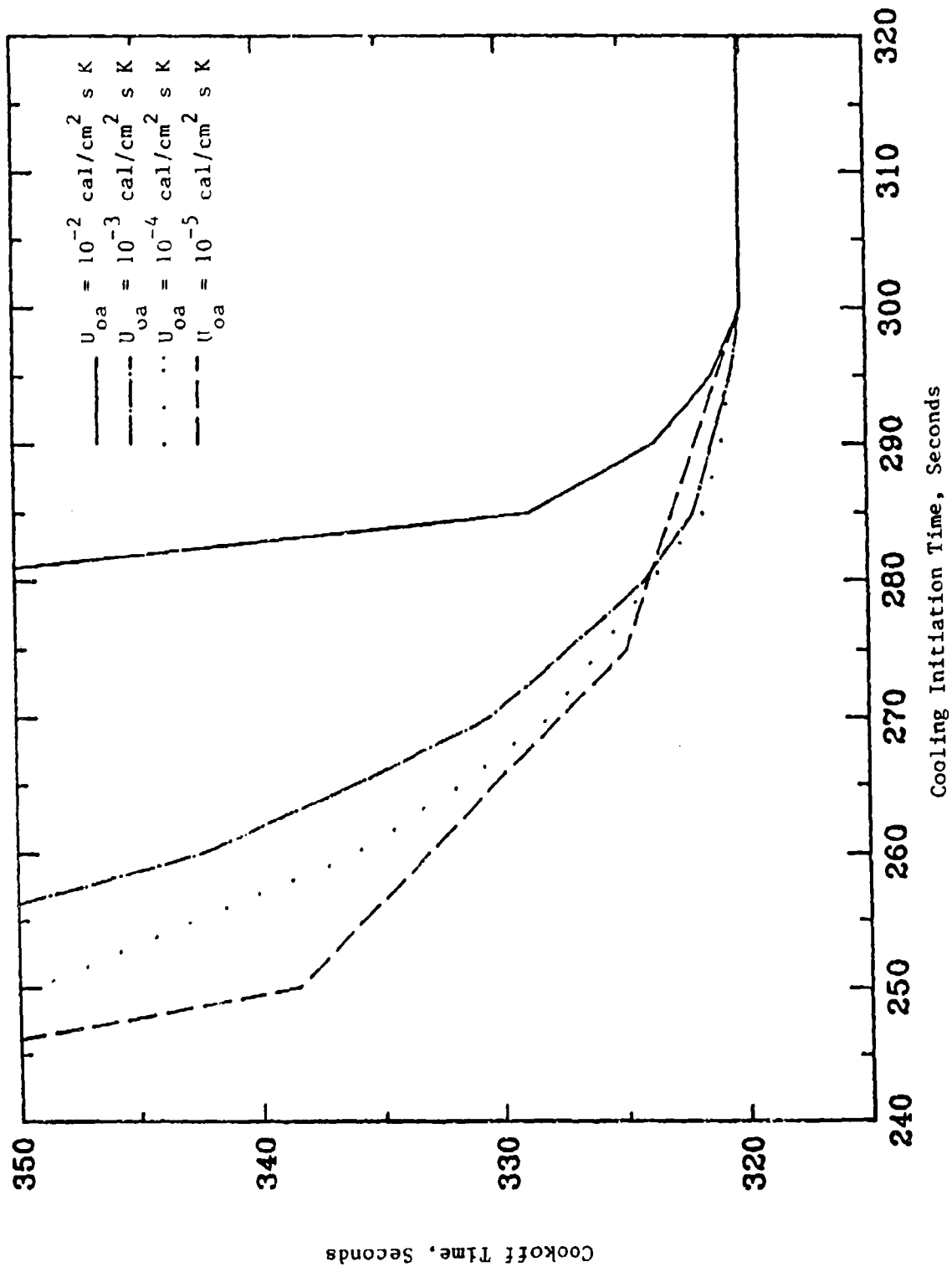
Figure 5. Cookoff Time Versus Cooling Initiation Time Profile (Mark 84, Uncoated, Table 1, Case 4).

SECTION IV

SUBSCALE TESTING

A. INTRODUCTION

Specially designed calorimeter tests were conducted to obtain overall
heat transfer coefficients essential to the cooling module of the computer
model. The tests were also designed to validate the performance of the
model. The calorimeters were placed in turbulent fires from a stagnant pool
and cooled with various cooling agents.

Water, AFFF, Halon 2402, and liquid nitrogen were investigated as
cooling agents. Water was chosen as a baseline agent because of its cooling
capacity and its use in previous cooling studies. AFFF was chosen because
it provides a blanket which covers and secures the fuel instead of carrying
it to other areas as water does (Reference 9). AFFF is also the most likely
agent to be used in a real fire situation. Studies show that AFFF does not
cool as effectively as water. However, it extinguishes the fire while
cooling the ordnance, and may be a better overall control agent for that
reason (Reference 10). Halon 2402 was tested because of its superior
ability to provide rapid knockdown, three-dimensional effectiveness, and
slight cooling capacity. It was thought that the Halon 2402 would
extinguish the fire rapidly while providing the initial cooling. Liquid
nitrogen was chosen as a cooling agent for coated ordnance because the
traditional cooling agents (water and AFFF) were unable to provide any
significant cooling to coated ordnance during earlier test programs.

B. PREVIOUS WORK

Experimental and theoretical studies of the response (cookoff time) of
uncoated ordnance when exposed to pool fires have been reported by many
investigators (References 9, 10, 11, 12, 13, and 14). Specifically, Hontgas
(Reference 9) has reported a series of tests in which inert ordnance were

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engulfed in pool fires and cooling was provided with water and AFFF using handlines and deck nozzles. Included in the documentation are the temperature history curves of various locations within the inert ordnance. Multiple parameters were varied in each test making it impossible to get correlation of the data at different coolant flow rates or handline locations relative to the ordnance. This study indicates that application of AFFF would not cool the ordnance until the fire had been extinguished.

Cragin, Pakulak and Vernon (Reference 10) calculated a heat transfer parameter from heated ordnance to water and AFFF using inside skin temperature of the ordnance. The procedure used during this study was to heat inert ordnance with a propane burner rack to a specified temperature, turn the burner rack off, and begin cooling. An extensive series of photographs was included in this report to document the effectiveness of the coolant coverage over the ordnance. They show that the most effective coverage of the ordnance is provided when the coolant is dispersed in a fog pattern. The study shows that AFFF cannot completely cover the surface of uncoated ordnance (especially the bottom of the back side), although it can cover coated ordnance. This study also concluded that if the fire engulfing a coated Mark 82 is extinguished within 7 minutes the ordnance will not cook off, even if uncooled.

C. TEST SETUP, INSTRUMENTATION, AND MATRIX

Testing was performed by suspending a calorimeter 0.91 meters above a pool of burning JP-4. The pool size area ranged from 91.4 m^2 to 274 m^2.

The calorimeter consisted of three cylinders divided into five circumferential sections each. The cylinders and sections were thermally insulated from each other to allow quantification of the heat transfer rates to various areas of the calorimeter. Each of the circumferential sections in two of the three cylinders (the middle and one end cylinder) were instrumented with thermocouples to measure the transient temperatures experienced during the fire and subsequent cooling. The third section was not instrumented because it was symmetric with the first end section. The area with the highest heat flux is the bottom of the ordnance. Since it is not always possible to cover the bottom of the back side (the near side is

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where the coolant stream was directed) of the ordnance with coolant, this area is of critical importance. This quadrant of the calorimeter was split to have two temperature measurements in this area. The construction of the calorimeters is shown in Figures 6 through 8.

Testing was first conducted using water, AFFF, and Halon 2402 to cool an uncoated calorimeter. The calorimeter was then coated with 0.406 cm of FM-26 and retested with water, AFFF, and liquid nitrogen. The temperatures were read by a datalogger at 5-second intervals and stored on floppy disks. The data were later reduced using a desk-top computer. All of the tests were filmed with a video camera. Table 2 shows the test matrix used to evaluate the various coolants.

TABLE 2.   COOLING TEST MATRIX

Calorimeter Type	Coolant	Cooling Flow Rate	Application Method
uncoated	water[a]	341 L/min	stream
uncoated	water[a]	341 L/min	fog
uncoated	water[a]	170 L/min	fog
uncoated	AFFF[a]	341 L/min(water)	fog
uncoated	Halon 2402[b]	2.5 kg/s	stream
coated	water[a]	341 L/min	fog
coated	water[a]	170 L/min	fog
coated	AFFF[a]	341 L/min(water)	fog
coated	liquid nitrogen[c]	---	---

[a]The water and AFFF were dispensed using a variable-cone, variable-flow-rate nozzle attached to a 3.81-cm handline.

[b]The Halon 2402 was dispensed from a pressurized system through a standard USAF 0.71-cm halon nozzle.

[c]During the liquid nitrogen tests the Dewar was pressurized to 1000 kPa. The liquid discharge valve was then opened and the nitrogen flowed at whatever rate the Dewar could maintain. By the time the nitrogen reached the discharge of the feed pipe (1.83 meters long by 2.54 cm diameter), almost all of it had vaporized and the calorimeter was engulfed in vapor.

5x¼-28 UNF-2B
I.50±.06@6.194BC

BOTH ENDS BEFORE SPLITING

5x∅.250/.257@6.194BC
V∅.404/.412x45° FARSIDE
COUNTER BORE ∅.281x.275
DEEP

FRONT SIDE

2x22½

DRILL THRU
∅ PER ± N TABLE

Use A 1/16" Blade
To Split Item 2
Only

5 Places As Shown

45°

VIEW B-B

-B-

6"
SCH 80

B

.600
±.05

-A-

12.00
±.10

B

3

1

2

1/8"

3x∅.250/.257@4.000BC

1" NPT
PIPE
COUPLING

3x45°
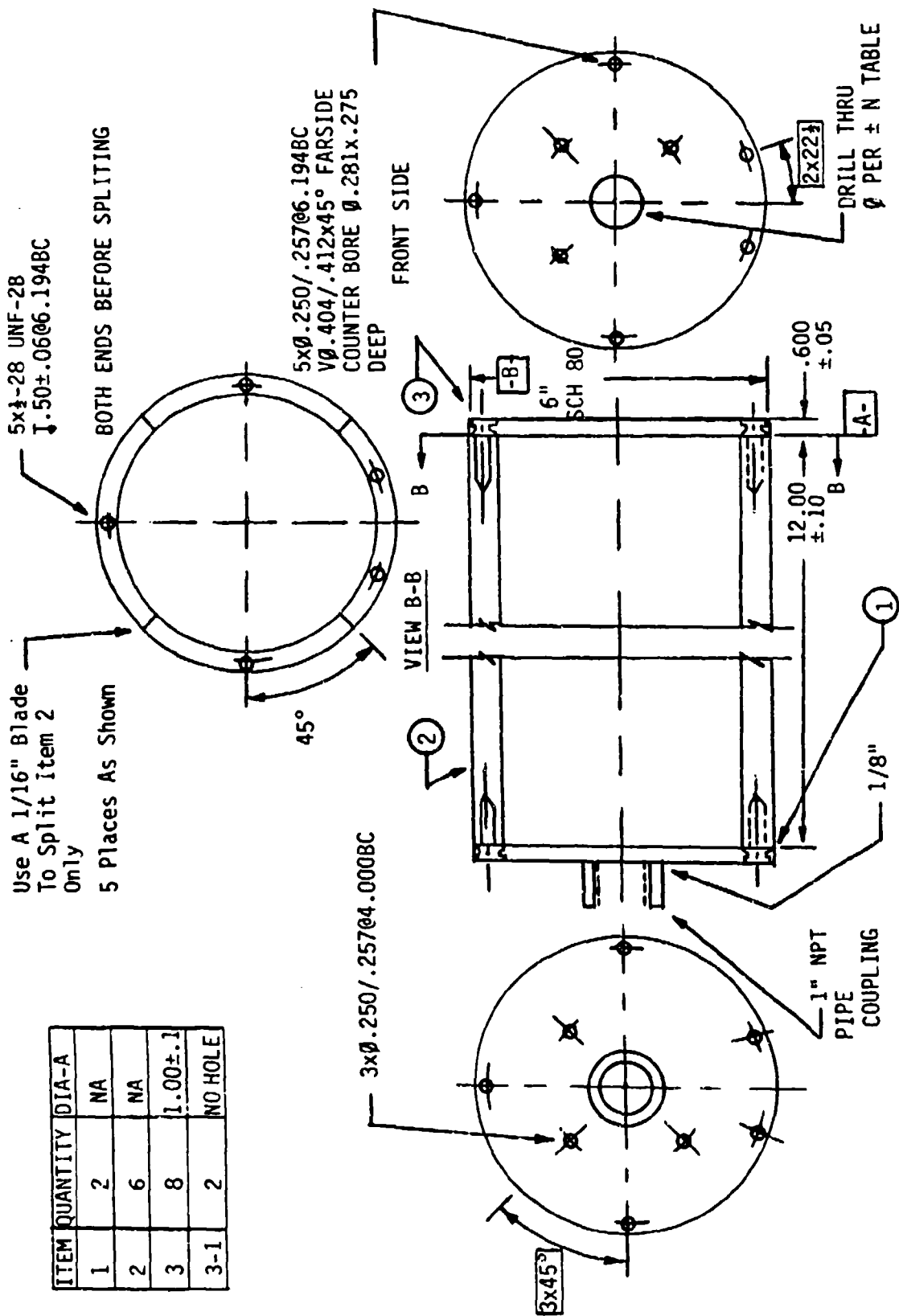
ITEM	QUANTITY	DIA-A
1	2	NA
2	6	NA
3	8	1.00±.1
3-1	2	NO HOLE

Figure 6. Calorimeter Engineering Drawing.

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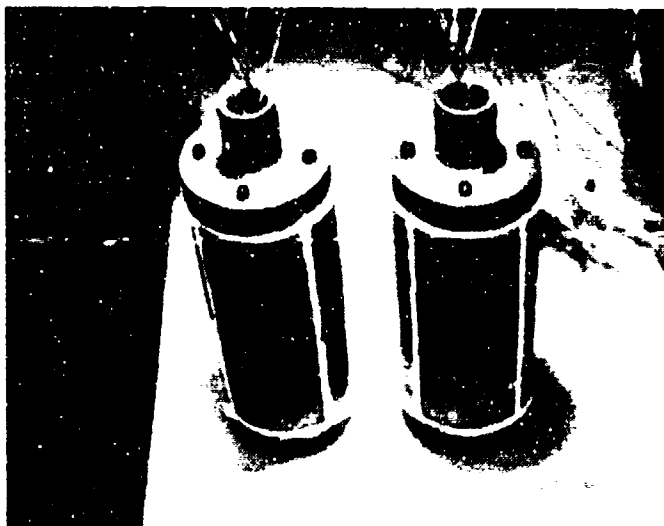
(a) Half-Scale Calorimeter.

(b) Calorimeter Thermocouple Placement.

Figure 7. Calorimeter Fabrication.
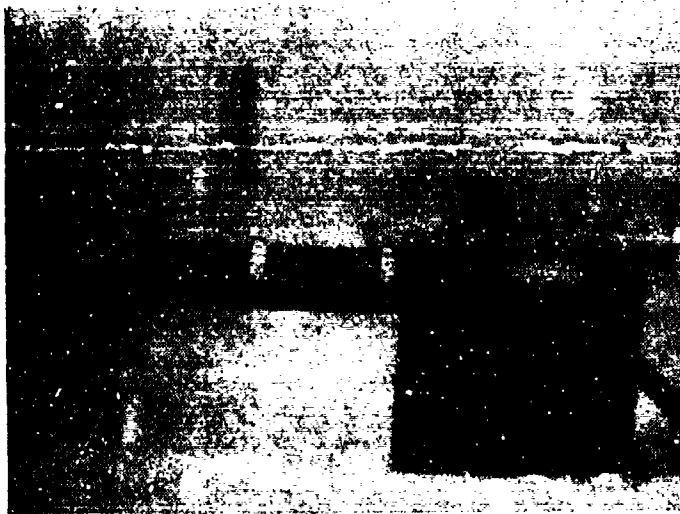
(a) Large-Scale Calorimeter on Test-Bed.

(b) Fire, Coolant, and Calorimeter Interaction.

Figure 8. Calorimeter Assembly and Testing.

D. OVERALL HEAT TRANSFER COEFFICIENT

The overall heat transfer coefficient can be calculated from equating the convective heat transfer with the conductive heat losses at the calorimeter surface;

$$U_{oa}(T_w - T_s) = K \frac{dT}{dr} \qquad (16)$$

In Equation (16) the variable U_{oa} represents the overall heat transfer coefficient, and T_w and T_s are coolant and surface temperature, respectively. In the right-hand side, K is the thermal conductivity and $\frac{dT}{dr}$ is the spatial temperature gradient across the calorimeter wall and can be calculated from the Fourier Conduction Law. However, the total heat loss from the calorimeter during the cooling period is given by

$$q = \rho C_p \frac{\partial T}{\partial t} \qquad (17)$$

where ρ and C_p are density and the heat capacity respectively, which are known quantities for the calorimeter. The term $\frac{\partial T}{\partial t}$ is the slope of the temperature history profile, which is known at any time. Since all parts of Equation (17) are known, the heat loss rate, q, can be calculated. Substituting q from Equation (17) into the Fourier Conduction Law, one obtains

$$q/A = K \frac{dT}{dr} \qquad (18)$$

The left-hand side of Equation (18) is known and Equation (16) can be written as

$$U_{oa}(T_w - T_s) = K \frac{dT}{dr} = q/A \qquad (19)$$

A computer program was written to calculate U_{oa} from the temperature history profiles and is presented in Appendix C.

Figure 9 illustrates the calorimeter's cross section and the location of thermocouples. The arrows specify the direction in which the coolant was applied. Effects of various coolants were tested experimentally. Figures 10 and 11 show typical temperature/time profiles for heating and cooling. In this case the cooling agent is water. The temperature profiles resulting from other coolants are given in Appendix D. Discussion of each coolant follows.

The test results showed that of the two water flow rates tested, the higher the water flow rate the more effective the cooling. The overall heat transfer coefficients for the different segments of the calorimeter for a water flow rate of 341 L/min ranged from 10^{-2} to 10^{-3} cal/cm^2 s K, while they ranged from 10^{-2} to 10^{-5} cal/cm^2 s K for a water flow rate of 170 L/min. This is reflected in the temperature profiles. The temperature profiles for the 341 L/min flow rate show an immediate and dramatic temperature reduction for all parts of the calorimeter (Figures D-1 and D-2). The temperature profiles for the 170 L/min flow rate show rapid and dramatic temperature reductions only at the point where the water struck the calorimeter (Figures 10, 11, D-3, and D-4). There was a delay in the onset of the temperature drop in other parts of the calorimeter and the temperature drop rate was not nearly as high as with the 341 L/min case. The cooling was ineffective on some parts of the calorimeter.

AFFF rapidly extinguished the fires during testing. It then cooled the calorimeters, although at a rate much lower than that of water (Figures D-5 through D-8). The AFFF was incapable of providing cooling to some parts of the calorimeter. The overall heat transfer coefficients for AFFF at 341 L/min ranged from 10^{-4} to 10^{-5} cal/cm^2 s K. The overall heat transfer coefficients for 170 L/min were similar.

24

Thermocouple
Numbers

B-B

Thermocouple
Numbers

A-A

Dummy
Section

Middle
Section

End
Section

Side View

Coolant

Flow

Top View

Coolant

Flow

End View
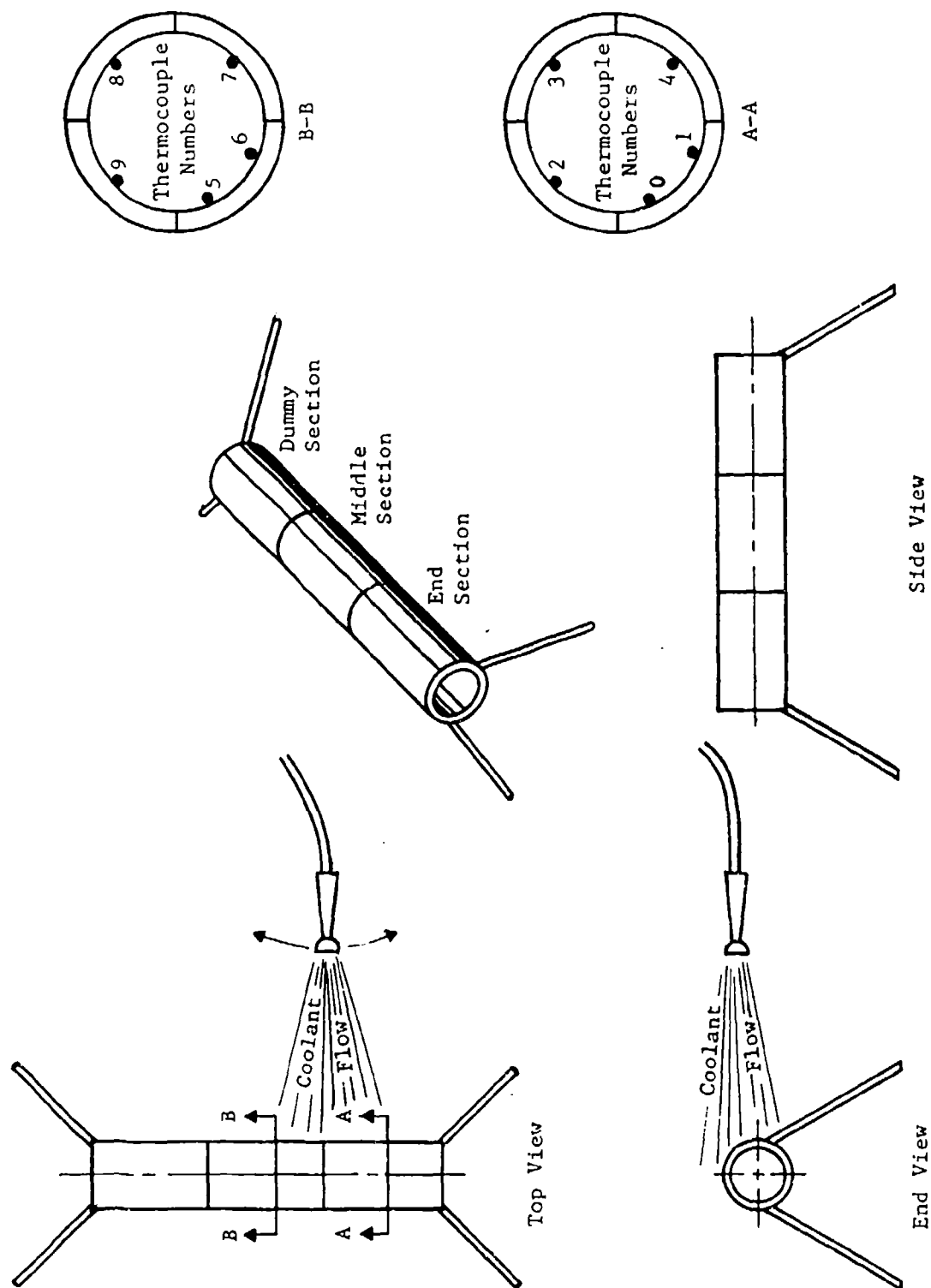
Figure 9.   Calorimeter Test Configuration.

25
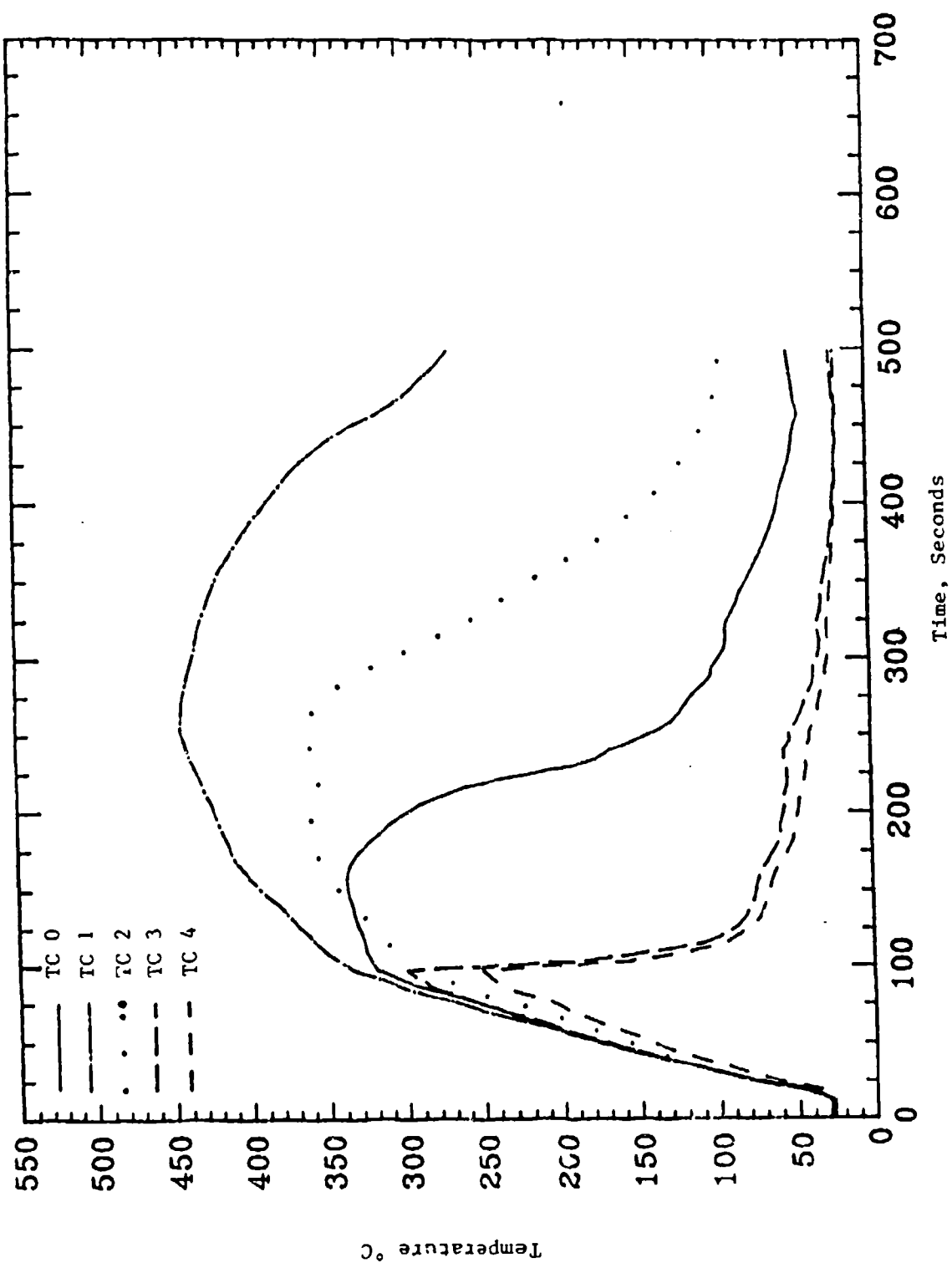
Figure 10. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).

26
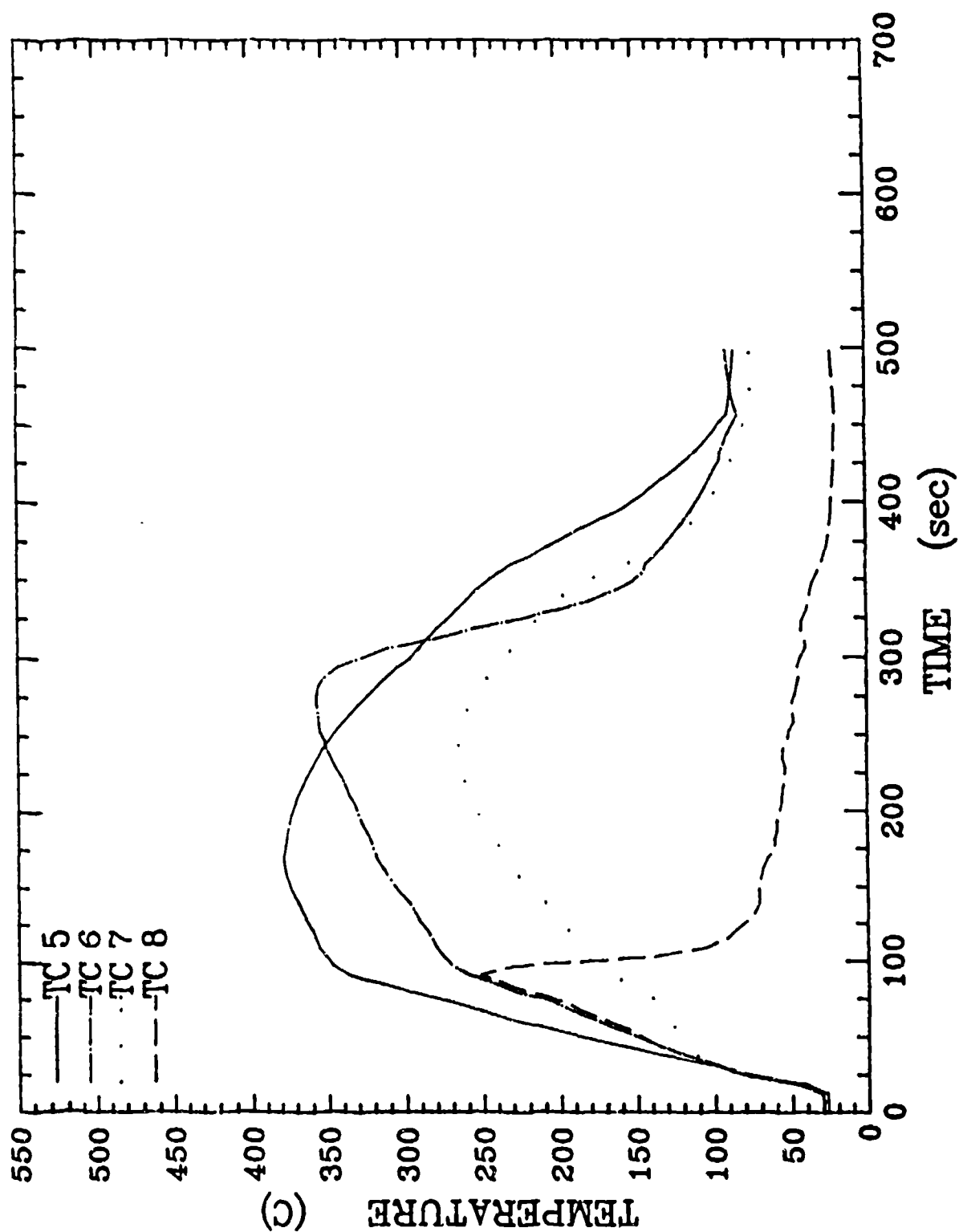
Figure 11. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).

The Halon 2402 was ineffective as a coolant. It was able to stop the temperature rise at the points where it struck the calorimeter, but was unable to cool other areas (Figures D-9 and D-10). The overall heat transfer coefficients ranged from 0 to 10^{-4} cal/cm^2 s K. The Halon 2402 did not extinguish the fire since was not sprayed at the base.

The testing on coated calorimeters showed the remarkable insulating ability of the FM-26 coating. Before cooling was initiated, the temperature rise was a fraction of that for the uncoated calorimeter (Figures D-11 through D-14). The insulating ability of the FM-26 also dramatically slows down the rate of energy removal. The overall heat transfer coefficient with a water coolant flow rate of 341 L/min ranged from 10^{-3} to 10^{-4} cal/cm^2 s K.

The liquid nitrogen provided very effective cooling in the area where the nitrogen impinged on the calorimeter (Figure D-15). The fixed-pipe feed system for the liquid nitrogen did not allow it to be spread over the calorimeter surface, although the nitrogen did provide more effective cooling than the water on the impinged area. The overall heat transfer coefficients for the liquid nitrogen ranged from 10^{-2} to 10^{-5} cal/cm^2 s K.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Response of ordnance to accidental flame impingement was studied experimentally as well as numerically. Calculations were made to quantify the effect of the various coolants on cookoff times. Experiments were conducted to assess the fire interaction with ordnance to quantify effective coolant application rates, to evaluate various cooling agents, and to provide baseline heat transfer coefficients essential to cookoff prediction calculations.

Calculations show that extension of the cookoff time can be obtained when coolant is applied to the ordnance as long as the temperature of the explosive has not reached the critical point, that is, the point where an irreversible exothermic reaction begins. It is concluded that cookoff time extension strongly depends on the overall heat transfer coefficient and the cooling initation time.

The effects of various coolants on cookoff time were evaluated experimentally. Water, AFFF, Halon 2402, and liquid nitrogen were investigated as cooling agents. Although AFFF does not cool as effectively as water, it extinguishes the fire while cooling the ordnance and may be considered a superior agent. Ordnance with intumescent coatings were compared with uncoated ordnance. Limited experimental data suggest that FM-26 coating is effective initially in preventing heat from transferring in, but, at the same time, the char layer formed when the coating is heated hinders removal of heat by the coolant and does not significantly alter the cookoff time.

It is recommended that additional studies be conducted to further evaluate the effectiveness of water and AFFF on cookoff time of coated ordnance in terms of the physical properties of various coating materials. This would require a combination of predictions using the computer codes developed and carefully instrumented tests using live ordnance.

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APPENDIX A
PROGRAM
FLOWCHART

MAD PROGRAM (REFERENCE 5)

SUBROUTINE

COMMON BLOCK

F(X)= FUNCTION FOR THERMAL CONDUCTIVITY

G(X)= FUNCTION FOR THERMAL CONDUCTIVITY

DO 250   L1=1,K   DO LOOP ON # OF LAYER

L2=L1+1   L2 IS NEXT LAYER

YES   IS
          THIS OUTER   NO
            LAYER
              ?

OUTER LAYER   IF(L1.67.\)
                               GO TO 750
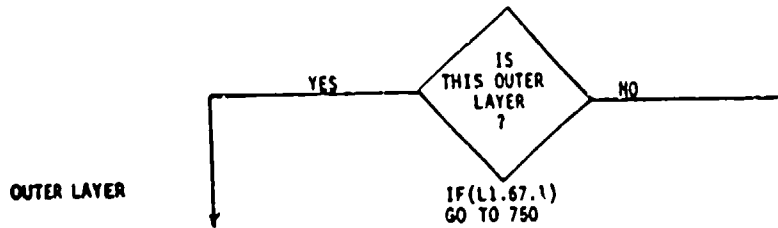
TB = A0+···CALCULATE GUN BARREL TEMP
TSTE= AVG TEMP OF NODE H2
AE = 0 INITIALIZE INTERNAL ENERGY GENERATION

                    IS
                 THIS A ONE
IF (K.NE.1)   LAYER ORDNANCE   YES
GO TO 237   WITH LAYERS
                EXPLOSIVE
                    ?

                                    CALCULATE INTERNAL ENERGY
                                    GENERATED BY EXPLOSIVE

              NO   DO 238
                                    238 AE=AE+···

              237
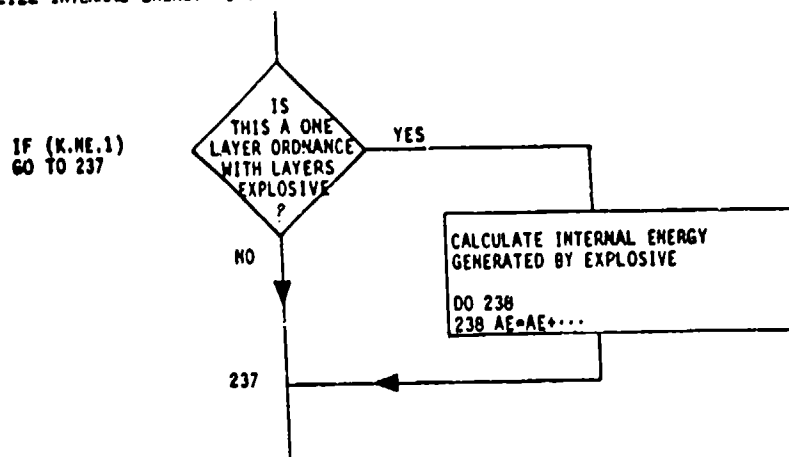
TSTAR= AVG TEMP NODES 1 & 2 (°F)

CALCULATE THERMAL CONDUCTIVITY   IF
                                  CX4=
                                  60 TO 240
                              239 CX4=

34

240

IS
TSURF.LT.
TMELT
?

YES
145

NO

IS
QM.LE.
0.0
?

NO

YES
147

IS
QM.G.E.
HMELT
?

QM(1)=QM(1)+···

T(1,2)=T(1,1)+···

CALCULATE MELTING ENERGY
THIS TIME STEP & SUM
QM(1)=QM(1)+···

IS
QM.LT.
0.0
?

NO

IS
QM(1).GE.
HMELT
?

NO

YES
152

DID
MELTING
ENERGY
EXCEED HM
?

YES
152

IS
ENERGY ABSORBED
NEGATIVE
?

NO

T(1,2)=T(1,1)

T(1,2)=T(1,1)+...
CALCULATE TEMP RISE
FROM EXCESS QM
QM(1)=HM(1)

NO TEMP
CHANGE (MELTING)

T(1,2)=T(1,1)+
QM(1)=0

T(1,2)=T(1,1)

7E0 CONTINUE

M = M + IPT (L1)

IS
THIS OUTER
LAYER
?

YES
121

CALCULATE LOWEST RATE
# IN THIS LAYER
I=I+2

TST1=   CONVERT SURROUNDING
TST2=   NODE TEMPS TO
TST3=   °F

CALCULATE THERMAL CONDUCTIVITIES
AND FOURIER MODULII FOR
TST1&TST2

431

RESET THERMAL CONDUCTIVITIES
AND FOURIER MODULII FOR
NEXT NODE,

433

CALCULATE THERMAL CONDUCTIVITY
AND FOURIER MODULUS FOR TST3

116

116

IS THIS LAYER EXPLOSIVE ? — NO / YES 713

IS T(I).LT. TMELT ? — NO / YES 435

IS QM(I).LE. 0.0 ? — NO / YES 139

IS QM(I).GE. HMELT ? — YES 139 / NO

IS THIS ELEMENT NEXT TO INTERFACE I.EQ.M ? — YES 131 / NO

IS THIS ELEMENT NEXT TO INTERFACE I.EQ.M ? — YES 159 / NO

QM(I)=QM(I)+···

QM(I)=QM(I)+···

151

IS THIS ELEMENT NEXT TO INTERFACE (I.EQ.M) ? — YES 132 / NO

132
QM(I)=QM(I)+···

QM(I)=QM(I)+···

T(1,2)=T(I,1)+···
CALCULATE TEMP RISE IF NO MELTING

T(I,2)=T(I),1)+···

IS T(1,2)-TO .LE.0.01 ? — YES / NO

60 TO 400

IS QM(I).GE. 0.0 ? — YES 135 / NO

IS T(1,2)-TO .LE. 0.01 ? — NO / YES

GO TO 400

IS QM(I).GE. HMELT ? — NO / YES

T(1,2)=T(I,1)
NO TEMP RISE MELTING

133

IS QM(I).GT. HMELT ? — YES 163 / NO

163

153
T(I,2)=T(I,1)+···
QM(I) = HM(I)
TEMP RISE FROM EXCESS ENERGY ABOVE H MELT

T(1,2)=T(I,1)+···
NEW TEMP DURING RESOLIDIFICATION
QM(I)=0

IS QM(I).LE. 0.0 ? — YES /

RESOLIDIFYING 135
T(1,2)=T(I,1)+···
QM(I)=0.

IS THIS ELEMENT TO INTERFACE I.EQ.M ? — YES / NO

T(I,2)=T(1,2)
NO TEMP RISE MELTING

GO TO 125

I=I+1
GO TO 431

INCREMENT TO NEXT NODE

GO TO INTERFACE WITH NEXT LAYER

37

125

```
TBEFORE AVG TEMP(°F) L1 SIDE
CALCULATE THERMAL CONDUCTIVITY
      L1 SIDE CK4=
TAFTER AVE TEMP(°F) L2 SIDE
CALCULATE THERMAL CONDUCTIVITY
      L2 SIDE CKO=
```

INTERFACE TEMP
CALCULATION
(NON-EXPLOSIVE)

IS
LAYER L2
EXPLOSIVE
(L1.EQ.L3)
?

YES
136

IS
TINT.LT
TMELT(L2)
?

YES
247

IS
QM(INT)
.LE.0.0
?

NO

YES
248

NO

IS
QM(INT).GE.
HMELT(L2)
?

QM(INT)=QM(INT)+···

IS
QM(INT)
.LT.0

NO

YES
244

QM(INT)=QM(INT)+···

IS
QM(INT)
.GE.HMELT
(L2)
?

```
T(INT,2)+T(INT,1)+···
CALC TEMP RISE W/NO
MELTING
```

IS
QM(INT).GT.
HMELT(L2)
?

NO   YES

117

```
T(INT,2)=T(INT,1)+···
QM(INT)=HM(INT)
CALC TEMP RISE FROM
ENERGY ABOVE MELTING
ENERGY
```

IS
QM(INT).LE.
0.0
?

NO   YES
            244

```
T(INT,2)=T(INT,1)
MELTING, NO TEMP
RISE
```

244

```
T(INT,2)=T(INT,1)+···
QM(INT)=0
CALCULATE TEMP DROP
FROM RESOLIDIFICATION
```

GO TO 250

713

```
AE=0      SUM INT
DO 727    ENERGY
727 AE=AE+ GENERATED
```

IS
T. LT.
TMELT
?

YES 126   NO

IS
QM.LE.
0.0
?

NO   YES 714   YES 714

IS
QM.GE.
HMELT
?

NO

```
QM=QM+...
SUM MELTING ENERGY
```

```
QM=QM+...
SUM MELTING ENERGY
```

```
T(2)=T(1)+...
CALC TEMP CHG IF NO MELTING
```

IS
QM.GE.
HMELT
?

YES 711

IS
QM.GT.
HMELT
?

NO   YES 711

```
T(2)=T(1)
NO TEMP RISES
MELTING
```

IS
T(2)-TO
.LE.
0.01
?

YES 127   NO 712

IS
QM.LE.
0.0
?

YES 710   NO

```
T(2)=T(1)+...
QM=0
CALC TEMP CHANGE
FROM RESOLIDIFICATION
```

```
T(2)=T(1)
NO TEMP RISE;
MELTING
```

```
T(2)=T(1)+...
QM=HMELT
CALCULATE TEMP RISE
FROM EXCESS MELTING
ENERGY
```

712

IS
THIS POINT
NEXT TO
INTERFACE
?

YES 128   NO

```
I=I+1
T(1,2)=F02...
CALCULATE CENTER
TEMP
127
```

```
I=I+1
INCREMENT
TO NEXT NODE
```

GO TO 431

```
M2= NODE# OF EXPL
INTERFACE
DO 137
IF (T.LT.TC) GO TO 137   CHECK TO SEE
ICRIT=1                  IF ANY NODE
GO TO 400                IS AT CRITICAL
137 CONTINUE             TEMP.
```

```
250 CONTINUE
400 RETURN
END
```

39

```
                    ┌─────────────────────────┐
                    │            136           │
                    │ TSTE = AVG TEMP EXPLOSIVE │
                    │     SIDE OF INTERFACE     │
                    │  AE=0     SUM INT         │
                    │  DO726    ENERGY GENERATED│
                    │ 726 AE=AE+ BY EXPLOSIVE   │
                    └─────────────────────────┘
```

IS T(INT).LT. THMELT(EXPL) ? 701

IS QM(INT).GE. HMELT(EXPL) ? 707

IS QM(INT).LE.0.0 ? 707

QM(INT)=QM(INT)+···

QM(INT)=QM(INT)+···

T(INT,2)=T(INT,1)+···
CAL TEMP RISE, NO MELT

IS QM(INT).GT.HMELT(EXPL) ? 702

IS QM(INT).LT.0.0 ? 706

IS QM(INT).GE. HMELT(EXP) ? 702

702
T(INT,2)=T(INT,1)+···
QM(INT)=HMELT(EXPL)
CALC. TEMP RISE FROM
EXCESS MELTING ENERGY

IS QM(INT).LE.0.0 ? 706

T(INT,2).EQ.T(INT,1)
NO TEMP RISE; MELTING

T(INT,2)=T(INT,1)
NO TEMP RISE,
MELTING

T(INT,2)+T(INT,1)+···
Q(INT)=0
CALCULATE NEW TEMP
WITH
RESOLIDIFYING

GO TO 250

40

APPENDIX B

PROGRAM LISTING

```fortran
      program mad
$storage:2
$nofloatcalls
      real hm,hml,hm2
      character*10 matl(5),explid,weapid,title(8)
  common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
  common / tp / ckl,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
  common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layrout,irestart,icool,timcool,uoa,tw
  iread - 0.
10 call readinpt(iread)
  if ( k .eq. 0 ) go to 80
  if ( irestart .ne. 1 ) go to 20
  go to 30
20 call fourier
   call initlize
c----------------evaluate temperatures in layers and interfaces-------
      lpt - 1
30     do 60 mj-lpt,maxt
      i-2
      tim -tim+dt
      m-0
      call layer
      if (icrit .eq. 1) call prntcrit
  if (icrit .eq. 1) go to 70
c------------------check for printout time----------------------------
      if(amod(ctr,v)) 50,40,50
40     call prntrslt
50     ctr-ctr+1.
      do 60 iset-1,n
      t(iset,1)-t(iset,2)
60     continue
70     go to 10
80     stop
      end
  subroutine readinpt(iread)
  character*64  file7, file6, file9
      character*10 matl(5),explid,weapid,title(8)
  common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
  common / tp / ckl,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
  common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layrout,irestart,icool,timcool,uoa,tw
```

```
c---------------read in computation requirements-------------------
c                    k - number of layers, v - calc./printout
c                    time - max. time for calc.
c                    dt - time increment
 if ( iread .ne. 0. ) go to 200
 iread - 1.
 write(*,100)
100 format(' Enter name of input data file: '\)
 read(*, '(a)') file7
 write('',110)
110 format(' Enter name of file for output data: '\)
 read(*,'(a)') file6
 write(*,120)
120 format(' Enter name of restart data file: '\)
 read(*,'(a)') file9
 open(7,file-file7,status-'old')
 open(6,file-file6,status-'new')
200    read(7,*) k, r
       if (k.eq.0) return
       read (7,*) irestart,icool,layrout
 if ( irestart .ne. 1 ) go to 5
 open(9,file-file9,status-'old')
 go to 8
5 open(9,file-file9,status-'new')
8      read(7,1) (title(j),j-1,8)
       read(7,*) v, time, dt, inc
       do 10 j - 1,k
       read(7,1) matl(j)
10     read(7,*) dam(j),rho(j),c(j),kk(j),pt(j),hm(j),tm(j)
       do 20 j - 1, k
       read(7,*) cone(j),first(j),second(j),third(j),fourth(j)
 read(7,*) ctwo(j), fifth(j), sixth(j),tmid(j)
       read(7,*) cthree(j),sevnth(j),eighth(j),thigh(j)
20     continue
       read(7,*) t0,tc,epsilon,di,tflame,tbld
       rt - di / 2.
       read(7,1) explid
       read(7,1) weapid
 do 30 ki - 1,k
       j - 1
       read(7,*) e(ki,j),z(ki,j),xm(ki,j),q(ki,j)
 if (kk(ki) .eq. 0 ) go to 30
 do 25 j - 2,kk(ki)
25     read(7,*) e(ki,j),z(ki,j),xm(ki,j),q(ki,j)
30     continue
       if ( icool .ne. 1) go to 40
       read(7,*) timcool,uoa,tw
40     if( irestart .ne. 1 ) return
       read(9,2) n,tim,maxt,lpt
       read(9,3) (t(1,1),1-1,n)
1      format (8a10)
2      format(1h ,i10,5x,f7.3,5x,i10,5x,i10)
3      format(1h ,8(1x,f9.5))
 return
```

```fortran
      end
      subroutine initlize
          character*10 matl(5),explid,weapid,title(8)
      common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
      common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
      common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layrout,irestart,icool,timcool,uoa,tw
          icrit =0
          ctr =0.0
          sigma = 1.356e-12
          maxt =ifix(time/dt)
          tim=-dt
          l3 = k-1
          do 10 ml=1,l3
10        rcx(ml)=2.*dt/(rho(ml)*c(ml)*dx(ml)+rho(ml+1)*c(ml+1)*dx(ml+1))
          do 20 kl=1,k
          hml(kl)=rho(kl)*dx(kl)*.5*hm(kl)
20        hm2(kl) = 2.*hml(kl)
c-----------------evaluate radius at every point---------------------
          rad(1) = rt
          l5=1.
          l6=0.
          do 160 i4=1,k
          l6=ipt(i4)+l6
          do 165 mp=l5,l6
165       rad(mp+1)=rad(mp)-dx(i4)
160       l5=l6+1
c-----------------set temperatures initially to a constant-----------
          do 201 init=1,n
          qm(init)=0.
          t(init,2)=t0
 201      t(init,1)=t0
          do 1609 ii=1,20
1609      thighst(ii) = 0.0
      return
      end
      subroutine fourier
          character*10 matl(5),explid,weapid,title(8)
      common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
      common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
      common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layrout,irestart,icool,timcool,uoa,tw
```

```
c----------------evaluate and stablize fourier modulus--------------
45      tl - t0*1.8 -460.
        hc - 0.00134*(21.666/(rt*2.))**.195
        n-1.0
        do 15 j-1,k
        ck(j)-(cone(j)+first(j)*tl+second(j)*tl*tl+third(j)*tl*tl*tl+
       1fourth(j)*(tl**4))/241.9
        alpha(j)-ck(j)/(rho(j)*c(j))
        ipt(j) - ifix(pt(j))
42      dx(j)-dam(j)/pt(j)
        if(dt.ne.0)go to 27
        do 28 ij-1,k
        if(ij.eq.1)go to 41
        ck(ij)-(cone(ij)+first(ij)*tl+second(ij)*tl*tl+third(ij)*tl*tl*tl
       1+fourth(ij)*(tl**4))/241.9
        alpha(ij)-ck(ij)/(rho(ij)*c(ij))
        ipt(ij)-ifix'pt(ij))
        dx(ij)-dam i `/pt(ij)
        d(ij)-0.2*(dx(ij)**2)/alpha(ij)
        go to 39
41      bi-hc*dx(1)/ck(1)
        d(ij)-0.5*(dx(1)**2)/((1.+bi)*alpha(1))
39      if(d(1).le.d(ij))go to 28
        d(1)-d(ij)
28      continue
        dt-d(1)
27      theta(j)-alpha(j)*dt/(dx(j)**2)
        rfk(j)-theta(j)/ck(j)
        if(j.eq.1) go to 20
        go to 21
20      bi-hc*dx(1)/ck(1)
        if(theta(1)-0.5/(1.+bi)) 112,112,22
21      if(theta(j).le.0.2) go to 112
22      theta(j)-0.75*theta(j)
        dx(j)-sqrt(alpha(j)*dt/theta(j))
        ipt(j)-ifix(dam(j)/dx(j))
        pt(j)-float(ipt(j))
        go to 42
112     n-n+ipt(j)
15      continue
        return
        end
        subroutine layer
        character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hm1(5),hm2(5),k,
       & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
       & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
       & v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
       & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
       & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
       & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
       & thighst(20),layout,irestart,icool,timcool,uoa,tw
```

```fortran
      do 100 11-1,k
      12 - 11 + 1
      if ( 11 .gt. 1 ) go to 10
      call tsurf
10    m - m + ipt(11)
      if ( 11 .eq. 1 ) go to 20
      i - i + 2
20    call thermprp
      keyeqn - 0
      if ( t(i,1) .lt. tm(11) ) keyeqn - 1
      if ( qm(i) .ge. hm2(11) ) keyeqn - 1
      call newtemp
      dtmin - f02 * 0.01
      if ( abs( t(i,2) - t(i,1) ) .le. dtmin ) go to 60
30    if ( i .eq. m) go to 40
      i - i + 1
      go to 20
40    if( 11 .eq. k ) go to 50
      call tintface
      go to 60
c *** calculate temperature of center of bomb ***********************
50    i - i + 1
      t(i,2) - f02 * ( ( dx(11)**2 ) * ae / ck2 + 2. * t(i-1,1) +
     &     ( 1. / f02 - 2. ) * t(i,1) )
c *** check to see if bomb has cooked off ***************************
60    if ( 11 .ne. k) go to 100
      m2 - m - ipt(11) + 1
      do 70 11 - m2,m
      if ( t(11,2) .lt. tc ) go to 70
      icrit - 1
      return
70    continue
100   continue
      return
      end
      subroutine tsurf
          character*10 matl(5),explid,weapid,title(8)
      common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     &   kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     &   ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     &   v,time,t0,jjj(16)
      common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     &   c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     &   sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     &   ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
      common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     &   thighst(20),layrout,irestart,icool,timcool,uoa,tw
      f(x,a,b,c,d,e) - ( a + b*x + c*x*x + d*x*x*x + e*(x**4) ) /241.9
      g(x,a,b,c,d) - ( a + b*( 1. - exp((c-x)/d) ) ) / 241.9
      zz(x,a,b,c) - ( a + b/(x*x) + c/(x**4) ) / 241.9
c *** calculate internal energy generated at surface ****************
      if ( tim .ge. tbld ) go to 5
      tf - ( tflame - t0 ) * ( tim**3 / tbld**3 ) + t0
      go to 7
```

46

```
5 tf = tflame
7 tavg = ( t(1,1) + t(2,1) ) / 2.
  ae = 0
  do 10 ii = 1,kk(11)
10 ae = ae + xm(11,ii) * q(11,ii) * z(11,ii) *
   & exp(-e(11,ii))/(r*tavg)
  ae = ae * rho(11)
c *** calculate thermal properties of first two nodes *****************
  tlf = t(1,1) * 1.8 - 460.
  t2f = t(2,1) * 1.8 - 460.
c *** account for reaction of ablative coating ***********************
  if( layout .ne. 1 ) go to 14
  if ( tlf . lt. thighst(1) ) go to 11
  thighst(1) = tlf
  go to 12
11 tlf = thighst(1)
12 if (t2f .lt. thighst(2) ) go to 13
  thighst(2) = t2f
  go to 14
13 t2f =thighst(2)
14 avgts = ( tlf + t2f ) / 2.
  if ( avgts .ge. tmid(11) ) go to 16
     cka = f(avgts,cone(11),first(11),second(11),third(11),fourth(11))
  go to 20
16 if ( avgts .ge. thigh(1) ) go to 18
  cka = zz( avgts, ctwo(11), fifth(11), sixth(11) )
  go to 20
18 cka = g(avgts,cthree(11),sevnth(11),thigh(11),eighth(11))
c *** branch to proper temperature calculation **********************
20 if ( t(1,1) .lt. tm(1) ) go to 30
  if ( qm(1) .ge. hml(1) ) go to 30
c *** melting temperature and energy calculation *******************
  if ( icool .ne. 1 .or. tim .lt. timcool ) go to 25
  qm(1) = qm(1) + dt * dx(1) * ae / 2. +dt * (uoa * (tw - t(1,1))-
     2 (rt - dx(1) / 2.) * cka * ( t(1,1) - t(2,1) ) / ( dx(1) * rt ) )
  go to 28
25 qm(1) = qm(1) + dt * dx(1) * ae / 2. +dt * ( hc * (tf - t(1,1))+
     1 epsilon * sigma * ( tf**4 - t(1,1)**4 ) -
     2 (rt - dx(1) / 2.) * cka * ( t(1,1) - t(2,1) ) / ( dx(1) * rt ) )
28 if ( qm(1) .gt. hml(1) ) go to 40
  if ( qm(1) .lt. 0.0 ) go to 50
  t(1,2) = t(1,1)
  return
c *** calculate new temp rise from external heat fluxes *************
30 if ( icool .ne. 1 .or. tim .lt. timcool ) go to 35
  t(1,2) = t(1,1) + rfk(1) * ( dx(1)**2 ) * ae +
     & 2. * rfk(1) * ( rt * dx(1) * ( uoa * ( tw - t(1,1) ) ) -
     & ( rt - dx(1) / 2.) * cka * ( t(1,1) - t(2,1) ))/ ( rt - dx(1)/4.)
  return
35 t(1,2) = t(1,1) + rfk(1) * ( dx(1)**2 ) * ae +
     & 2. * rfk(1) * ( rt * dx(1) * ( hc * ( tf - t(1,1) ) +
     & epsilon * sigma * ( tf**4 - t(1,1) ** 4 ) ) -
     & ( rt - dx(1) / 2.) * cka * ( t(1,1) - t(2,1) ))/ ( rt - dx(1)/4.)
  return
```

```fortran
c *** calculate temp rise from excess energy above melting energy ***
40 t(1,2) = t(1,1) + 2. * ( qm(1) - hml(1)) / (rho(1) * c(1)*dx(1))
 qm(1) = hm(1)
 return
c*** calculate temp drop from endothermic reaction ******************
50 t(1,2) = t(1,1) + 2. * qm(1) / ( rho(1) * c(1) * dx(1) )
 qm(1) = 0.0
 return
 end
 subroutine thermprp
       character*10 matl(5),explid,weapid,title(8)
 common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
 common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
 common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layrout,irestart,icool,timcool,uoa,tw
 f(x,a,b,c,d,e) = ( a + b*x + c*x*x + d*x*x*x + e*(x**4) ) /241.9
 g(x,a,b,c,d) = ( a + b*( 1. - exp((c-x)/d) ) ) / 241.9
 zz(x,a,b,c) = ( a + b/(x*x) + c/(x**4) ) / 241.9
c *** this subroutine calculates thermal conductivities (ck),
c *** fourier modulii (fox) for each node point and
c *** internal energy generation (ae) for the current calculation node.
 if ( keytherm .ne. 0 ) go to 50
 temp1 = t(i-1,1) * 1.8 - 460.
 temp2 = t(i,1) * 1.8 - 460.
 if ( l1 .ne. 1 .or. layrout .ne. 1 ) go to 6
 if ( temp1 .le. thighst(i-1) ) go to 4
 thighst(i-1) = temp1
 go to 6
4 temp1 = thighst(i-1)
6 if ( temp1 .ge. tmid(l1) ) go to 8
 ck1 =f(temp1,cone(l1),first(l1),second(l1),third(l1),fourth(l1))
 go to 20
8 if ( temp1 .ge. thigh(l1) ) go to 10
 ck1 = zz ( temp1, ctwo(l1), fifth(l1), sixth(l1) )
 go to 20
10 ck1 = g(temp1,cthree(l1),sevnth(l1),thigh(l1),eighth(l1))
20 f01 = rfk(l1) * ck1
 if ( l1 .ne. 1 .or. layrout .ne. 1 ) go to 23
 if ( temp2 .le. thighst(i) ) go to 22
 thighst(i) = temp2
 go to 23
22 temp2 = thighst(i)
23 if ( temp2 .ge. tmid(l1) ) go to 25
 ck2 =f(temp2,cone(l1),first(l1),second(l1),third(l1),fourth(l1))
 go to 40
25 if ( temp2 .ge. thigh(l1) ) go to 30
 ck2 = zz( temp2, ctwo(l1), fifth(l1), sixth(l1) )
 go to 40
```

```fortran
   30 ck2 - g(temp2,cthree(ll),sevnth(ll),thigh(ll),eighth(ll))
   40 f02 - rfk(ll) * ck2
      go to 60
   50 ck1 - ck2
      ck2 - ck3
      f01 - f02
      f02 - f03
   60 ae - 0.
      do 70 ii - 1,kk(ll)
   70 ae - ae + xm(ll,ii) * q(ll,ii) * z(ll,ii) *
     &   exp(-e(ll,ii)/(r*t(i,1)))
      ae - ae * rho(ll)
      temp3 - t(i+1,1) * 1.8 - 460.
      if ( ll .ne. 1 .or. layout .ne. 1 ) go to 76
      if ( temp3 .le. thighst(i+1) ) go to 74
      thighst(i+1) - temp3
      go to 76
   74 temp3 - thighst(i+1)
   76 if ( temp3 .ge. tmid(ll) ) go to 78
      ck3 -f(temp3,cone(ll),first(ll),second(ll),third(ll),fourth(ll))
      go to 90
   78 if ( temp3 .ge. thigh(ll) ) go to 80
      ck3 - zz( temp3, ctwo(ll), fifth(ll), sixth(ll) )
      go to 90
   80 ck3 - g(temp3,cthree(ll),sevnth(ll),thigh(ll),eighth(ll))
   90 f03 - rfk(ll) * ck3
      return
      end
      subroutine newtemp
         character*10 matl(5),explid,weapid,title(8)
      common / a / t(1000,2),tm(5),qm(1000),hm(5),hm1(5),hm2(5),k,
     & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
      common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
      common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layout,irestart,icool,timcool,uoa,tw
      if ( keyeqn .ne. 0 ) go to 30
   c *** calculate melting energy and new temperature if finishes melting
      qm(i) - qm(i) + dt * ( ( ck2 + .25 * ( ck1 - ck3 ) ) *
     & ( rad(i) + .5 * dx(ll) ) * ( t(i-1,1) - t(i,1) ) -
     & ( ck2 - .25 * ( ck1 - ck3 ) ) * (rad(i) - .5 * dx(ll) ) *
     & ( t(i,1) - t(i+1,1) ) ) / ( rad(i) * dx(ll)) + dt * dx(ll) * ae
      if ( qm(i) .gt. hm2(ll) ) go to 10
      if ( qm(i) .lt. 0.0 ) go to 20
      t(i,2) - t(i,1)
      return
   10 t(i,2) - t(i,1) + ( qm(i) - hm2(ll) ) / (rho(ll) * c(ll)*dx(ll))
      qm(i) - hm2(ll)
      return
   20 t(i,2) - t(i,1) + qm(i) / ( rho(ll) * c(ll) * dx(ll) )
```

```fortran
      qm(i) = 0.0
      return
30    t(i,2) = t(i,1) + ( ( f02 + .25 * ( f01 - f03 ) ) *
     &  ( rad(i) + .5 * dx(11) ) * ( t(i-1,1) - t(i,1) ) -
     &  ( f02 - .25 * ( f01 - f03 ) ) * ( rad(i) - .5 * dx(11) ) *
     &  ( t(i,1) - t(i+1,1) ) ) / rad(i) + rfk(11) * ae * ( dx(11)**2 )
      return
      end
      subroutine tintface
          character*10 matl(5),explid,weapid,title(8)
      common / a / t(1000,2),tm(5),qm(1000),hm(5),hm1(5),hm2(5),k,
     &  kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     &  ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     &  v,time,t0,jjj(16)
      common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     &  c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     &  sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     &  ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
      common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     &  thighst(20),layout,irestart,icool,timcool,uoa,tw
      f(x,a,b,c,d,e) = ( a + b*x + c*x*x + d*x*x*x + e*(x**4) ) /241.9
      g(x,a,b,c,d) = ( a + b*( 1. - exp((c-x)/d) ) ) / 241.9
      zz(x,a,b,c) = ( a + b/(x*x) + c/(x**4) ) / 241.9
c *** calculate thermal and heat generation properties **************
      tbfor = ( ( t(m,1) + t(m+1,1) ) / 2. ) * 1.8 - 460.
      if ( tbfor .ge. tmid(11) ) go to 5
      ck4 =f(tbfor,cone(11),first(11),second(11),third(11),fourth(11))
      go to 20
5     if ( tbfor .ge. thigh(11) ) go to 10
      ck4 = zz ( tbfor, ctwo(11), fifth(11), sixth(11) )
      go to 20
10    ck4 = g(tbfor,cthree(11),sevnth(11),thigh(11),eighth(11))
20    aebfor = 0.
      do 30 ii=1,kk(11)
30    aebfor =aebfor + xm(11,ii) * q(11,ii) * z(11,ii) *
     &  exp(-e(11,ii)/(r*tbfor))
      aebefor = aebefor * rho(11)
      tafter = ( ( t(m+1,1) + t(m+2,1) ) / 2. ) * 1.8 - 460.
      if ( tafter .ge. tmid(12) ) go to 35
      ck0=f(tafter,cone(12),first(12),second(12),third(12),fourth(12))
      go to 50
35    if ( tafter .ge. thigh(12) ) go to 40
      ck0 = zz ( tafter, ctwo(12), fifth(12), sixth(12) )
      go to 50
40    ck0 = g(tafter,cthree(12),sevnth(12),thigh(12),eighth(12))
50    aeaftr = 0.
      do 60 ii = 1,kk(12)
60    aeaftr = aeaftr + xm(12,ii) * q(12,ii) * z(12,ii) *
     &  exp(-e(12,ii)/(r*tafter))
      aeaftr = aeaftr * rho(12)
c *** branch to proper equation to calculate new temperature ********
      if ( t(m+1,1) .lt. tm(12) ) go to 90
      if ( qm(m+1) .gt. hm(12) ) go to 100
c *** calculate melting energies **********************************
```

```fortran
      qm(m+1) - qm(m+1) + dt *
     & (ck4 * (rad(m+1) + .5 * dx(11)) * (t(m,1) - t(m+1,1)) / dx(11) -
     & ck0 * (rad(m+1) - .5 * dx(12)) * (t(m+1,1) - t(m+2,1)) / dx(12)
     & + ( rad(m+1) - .25 * dx(12) ) * dx(12) * .5 * aeaftr ) / rad(m+1)
      if ( qm(m+1) .gt. hml(12) ) go to 70
      if ( qm(m+1) .lt. 0.0) go to 80
      t(m+1,2) - t(m+1,1)
      return
c *** calculate temperature rise from excess energy above melting energy
70 t(m+1,2) - t(m+1,1) + ( qm(m+1) - hml(12) ) * rcx(11) / dt
      qm(m+1) - hml(12)
      return
c *** calculate temperature drop from resolidification ****************
80 t(m+1,2) - t(m+1,1) + qm(m+1) * rcx(11) / dt
      qm(m+1) - 0.
      return
90 if ( qm(m+1) .le. 0.0 ) go to 100
c *** calculate melting energy ******************************************
      qm(m+1) - qm(m+1) + dt *
     & (ck4 * (rad(m+1) + .5 * dx(11)) * (t(m,1) - t(m+1,1)) / dx(11) -
     & ck0 * (rad(m+1) - .5 * dx(12)) * (t(m+1,1) - t(m+2,1)) / dx(12)
     & + ( rad(m+1) - .25 * dx(12) ) * dx(12) * .5 * aeaftr ) / rad(m+1)
      if ( qm(m+1) .lt. 0.0 ) go to 80
      if ( qm(m+1) .ge. hml(12) ) go to 70
      t(m+1,2) - t(m+1,1)
      return
c *** calculate temperature rise (no melting or re-solidification) ****
100 t(m+1,2) - t(m+1,1) + rcx(11) *
     & ( ck4 * (rad(m+1) + .5 * dx(11)) * (t(m,1) - t(m+1,1)) / dx(11)
     & -ck0 * (t(m+1,1) - t(m+2,1)) * (rad(m+1) - .5 * dx(12)) / dx(12)
     & + ( rad(m+1) - .25 * dx(12) ) * aeaftr * .5 * dx(12) ) / rad(m+1)
      return
      end
      subroutine prntrslt
        character*10 matl(5),explid,weapid,title(8)
        dimension b(16),pos(16)
      common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
      common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
      common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layrout,irestart,icool,timcool,uoa,tw
c------------------output point control    j(1)   thru  j(16)-----------
      if ( ctr .ne. 0 ) go to 167
        jjj(1)-1
        do 839 m6-2,16
        jjj(m6)-jjj(m6-1)+inc
839   continue
        write(6,1) (title(i1p),i1p-1,8)
1 format(8a10)
```

```
      write(6,10) explid,weapid,rt
      write(6,18) dt
      write(6,106)
      write(6,17)
      write(6,23)
      do 171 i9-1,k
      write(6,19)  i9,matl(i9),dam(i9),pt(i9),dx(i9),rho(i9),c(i9),
     lck(i9),alpha(i9),theta(i9),tm(i9),hm(i9)
171   continue
      write(6,24)
24    format(1h0,70hconductivity equations   (temp. coeff. units in "f ,
     lck(i) units in "k))
      do 172 i7-1,k
      write(6,32)i7,cone(i7),first(i7),second(i7),third(i7),fourth(i7)
172   continue
32    format(1h0,3hck(,i2,5h) - (,f10.4,2h -,e13.5,4h*t +,e13.5,6h*t*t -
     1,e13.5,8h*t*t*t +,e13.5,16h*(t**4)) / 241.9)
      write(6,26)
26    format(///20h boundary conditions)
      write(6,34)
      write(6,35)t0,epsilon,hc,tc
35    format(1h ,3x,f7.1,9x,f5.2,8x,f8.5,6x,f8.1)
34    format(1h0,12hinitial temp,5x,7hepsilon,
     15x,12hconvec coeff,5x,9hcrit temp/3x,7h(deg k),19x,
     215h(cal/sec-cm2-k),7x,3h(k))
      if ( icool .ne. 1 ) go to 341
      write (6,342)
342   format(///1h ,12hTime Cooling,12x,8huoa,13x,6htw,
     &/1h ,12hStarts (sec),9x,15h(cal/cm2-sec-K),9x,7h(deg K))
      write(6,343) timcool,uoa,tw
343   format(1h ,3x,f5.1,16x,f8.6,13x,f5.1)
341   write(6,33)
      write(6,36) v,time,dt
      if(k.eq.1) go to 86
      do 85 m2-1,13
      m3 - m2 + 1
85    write(6,31) m2,m3 ,rif
86    continue
33    format(/// 21h interface properties,45x,22hcomputation parameters)
36    format(1h0,3x,8hlocation,12x,12hconductivity,30x,4hv - ,f10.6,2x,
     17htime - ,f7.2,2x,5hdt - ,f12.8/15h (between lyrs),12x,6hcoeff./)
31    format(1h ,3x,2(i3),18x,f6.4)
      write(6,37)
do 999 k9 - 1,k
      write(6, 113) k9,kk(k9)
113   format(1h ,'layer number ',i1,5x,18hnumber ind. comps.,19x,i3//)
      write(6,107) (e(k9,k5),k5-1,kk(k9))
107   format(1h0,30hactivation energy  (cal/mole) ,5(1x,e15.5))
      write(6,108) (z(k9,k5),k5-1,kk(k9))
108   format(1h ,30hcollision number    (1./sec)  ,5(1x,e15.5))
      write(6,109) (xm(k9,k5),k5-1,kk(k9))
109   format(1h ,13hmass fraction,17x,5(6x,f10.5))
      write(6, 110) (q(k9,k5),k5-1,kk(k9))
110   format(1h ,30hheat of reaction     (cal/gm) ,5(6x,f10.5))
```

```
999     continue
        write(6,11)
        do 111 j7-1,16
        j6-jjj(j7)
111     pos(j7)=rad(1)-rad(j6)
        write(6,12)  (pos(j6),j6-1,16)
167     continue
        do 168 18-1,16
        j1-jjj(18)
168     b(18)-t(j1,1)
        write(6,13) tim,tf,(b(18),18-1,16)
        write(9,1013) n,tim,maxt,mj
        write(9,1014) (t(1,2),1-1,n)
1013    format(1h ,i10,5x,f7.3,5x,i10,5x,i10)
1014    format(1h ,8(1x,f9.5))
        rewind (9)
11      format(62h1the following table is a temperature history of the exp
        llosive///)
12      format(12h depth (cm.),5x,16(2x,f5.2)//3x,10htime    free/2x,13h(sec
        l.) stream/9x,5hflame/9x, 8htemp("k)/)
13      format(1h ,f7.2,2x,f6.1,1x,16(1x,f6.1))
17      format(1h0,127hlayer material  thickness   pts    dx     density    s
        lpec.heat     therm. con.     alpha     fourier mod. melt.temp.    heat
        2 of fusion)
23      format(1h ,18x,5h(cm.),10x,5h(cm.),2x,7h(gm/cc),2x,26h(cal/gm "k)(
        lcal/sec cm "k),11h(cm*cm/sec),18x,4h("k),9x,8h(cal/gm)/)
10      format(1h0,2x,24hexplosive identification,a10//2x,
        121hweapon identification,4x,a10//2x,9hradius - ,
        2f10.6,4h cm.)
18      format(1h0,2x,16htime increment -,f7.5,2x,3hsec)
19      format(1h ,i3,3x,a10,1x,f7.4,1x,f5.1,1x,f7.5,2x,f7.4,1x,2(3x,f7.5,
        14x ),2(2x,f6.3,4x),2x,f7.2,7x,f7.3)
37      format(///21h explosive properties)
106     format(///20h material properties)
        return
        end
        subroutine prntcrit
        dimension zx(16),b(16)
        character*10 matl(5),explid,weapid,title(8)
        common / a / t(1000,2),tm(5),qm(1000),hm(5),hm1(5),hm2(5),k,
        & kk(5),11,12,13,m,1,pt(5),1pt(5),rad(1000),d(5),keyeqn,icrit,
        & ctr,maxt,dx(5),dam(5),n,1pt,weapid,explid,matl,inc,r,title,
        & v,time,t0,jjj(16)
        common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
        & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
        & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
        & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
        common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
        & thighst(20),layout,irestart,icool,timcool,uoa,tw
        do 10 jj-1,16
        j1-jjj(jj)
        zx(jj)-t(j1,1)
10      b(jj)-t(j1,2)
        timb-tim-dt
```

```
      write(6,20) timb,tf,(zx(i8),i8=1,16)
      write(6,20) tim,tf,(b(i8),i8=1,16)
      write(6,30) rad(k3),tim,timb
20    format(1h ,f7.2,2x,f6.1,1x,16(1x,f6.1))
30    format(///65h a critical temp has been reached within the explosiv
     le at radius=,f5.2,18h and between time=,f7.2,4h sec,10h and time=,
     2f7.2,4h sec)
      return
  end
```

APPENDIX C

PROGRAM HTCOEFF

```fortran
      program htcoeff
      dimension tcool(5), temp1(5), temp2(5), uoa(5)
      character*1 answer
      character*15 file5, file6
c *** layer 1 is the steel, layer 2 is the FM-26 (if app) *************
      data rhocp1 / 1.069 /, ck1 / 0.109 /, ck2 / 3.5E-04 /
      data dr1 / 0.432 /, dr2 / 0.406 /
      data tcool / 63., 91., 21., 113., -118. /
         write(*,5)
5     format(' Enter name of input data file: '\)
      read(*,'(a)') file5
      write(*,6)
6     format(' Enter name of output data file: '\)
      read(*,'(a)') file6
      open(5,file=file5)
      open(6,file=file6,status='new')
      write(*,8)
8     format(' Is this case for a calorimeter with FM-26? (y or n) '\)
      read(*,'(a)') answer
      write(*,7)
7     format(' Enter the number corresponding to the coolant: '/
     & '      1: Water fog,'/'      2: Streaming water,'/'      3: AFFF,'/
     & '      4: Halon 2402 or'/'      5: Liquid nitrogen')
      read (*,*) iz
      icount = 0
      if ( icount .ne. 0 ) go to 20
      read(5,*) time1, (temp1(i), i= 1,5)
10    icount = icount + 1
20    read(5,*,end=60) time2, (temp2(i), i= 1,5)
c **** calculate overall heat transfer coefficient *******************
      do 40 i = 1,5
      dtdt = ( temp1(i) - temp2(i) ) / ( time1 - time2 )
      q = rhocp1 * dtdt
      if ( answer .eq. 'y' ) go to 30
      ts = q / (dr1 * ck1) + temp2(i)
      go to 40
30    tint = q / (dr2 * ck2) + temp2(i)
      ts = q / (dr1 * ck1) + tint
40    uoa(i) = q / ( tcool(iz) - ts )
c *** print out answers ********************************************
      write(6,45) time2, ( uoa(i) ,i= 1,5)
      write(*,45) time2, ( uoa(i) ,i= 1,5)
45    format(' ',3x,f4.0,5(9x,e12.6))
c *** reset variables for next time step ***************************
      do 50 j = 1,5
50    temp1(j) = temp2(j)
      time1 = time2
      go to 20
60    stop
      end
```

APPENDIX D

CALORIMETER TEMPERATURE/TIME PROFILES

FOR VARIOUS COOLANTS
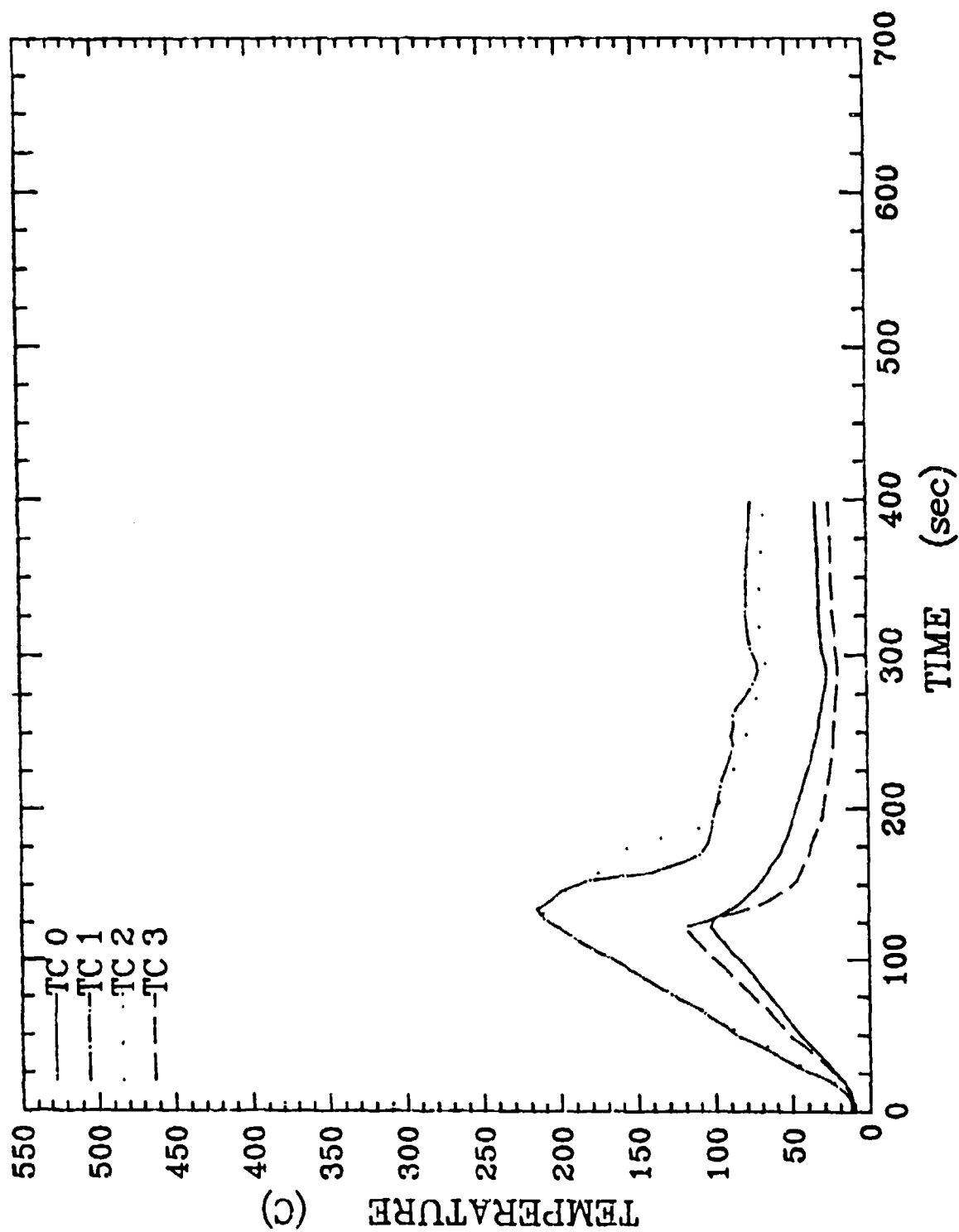
Figure D-1. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 341 L/min).

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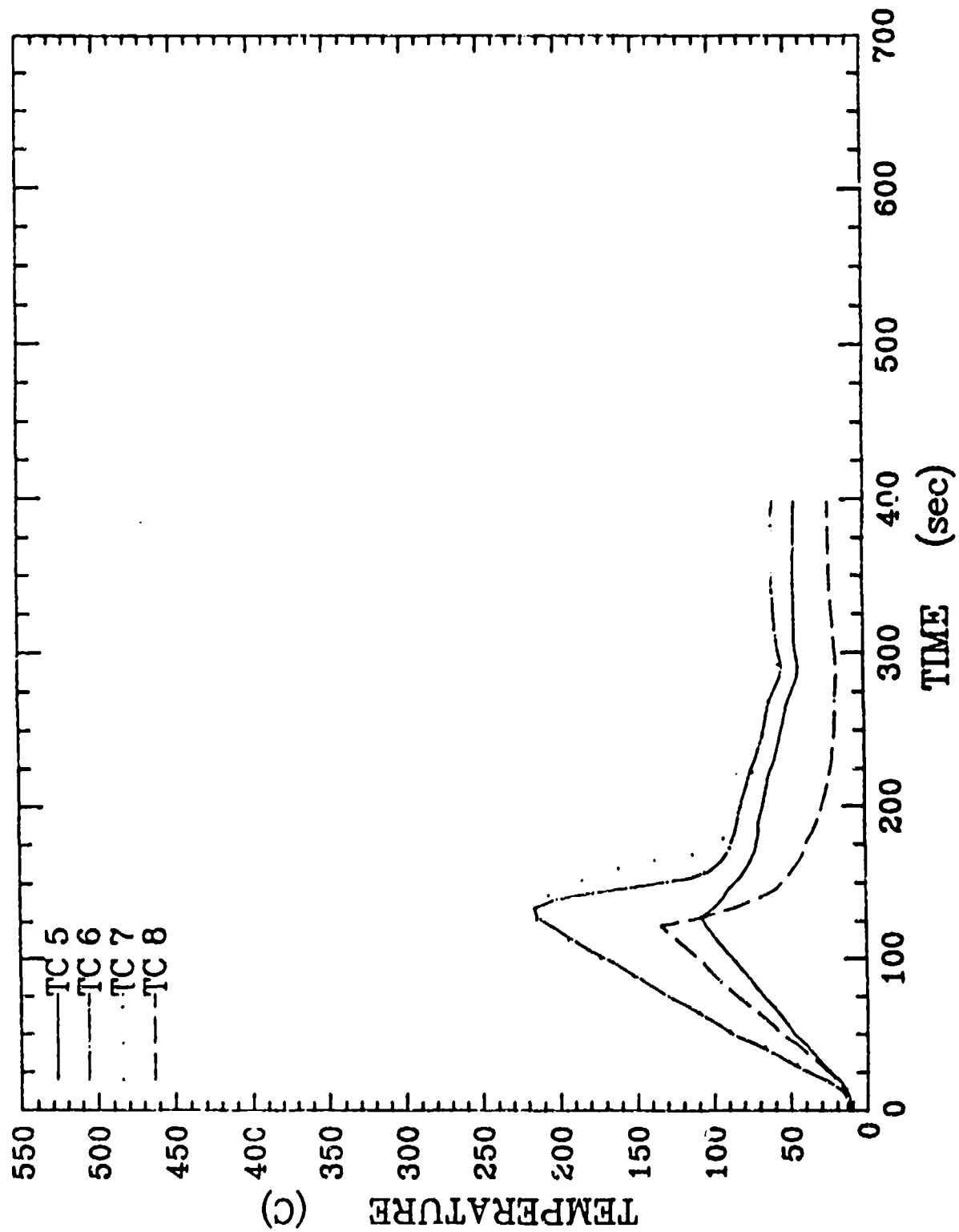
Figure D-2. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 341 L/min).
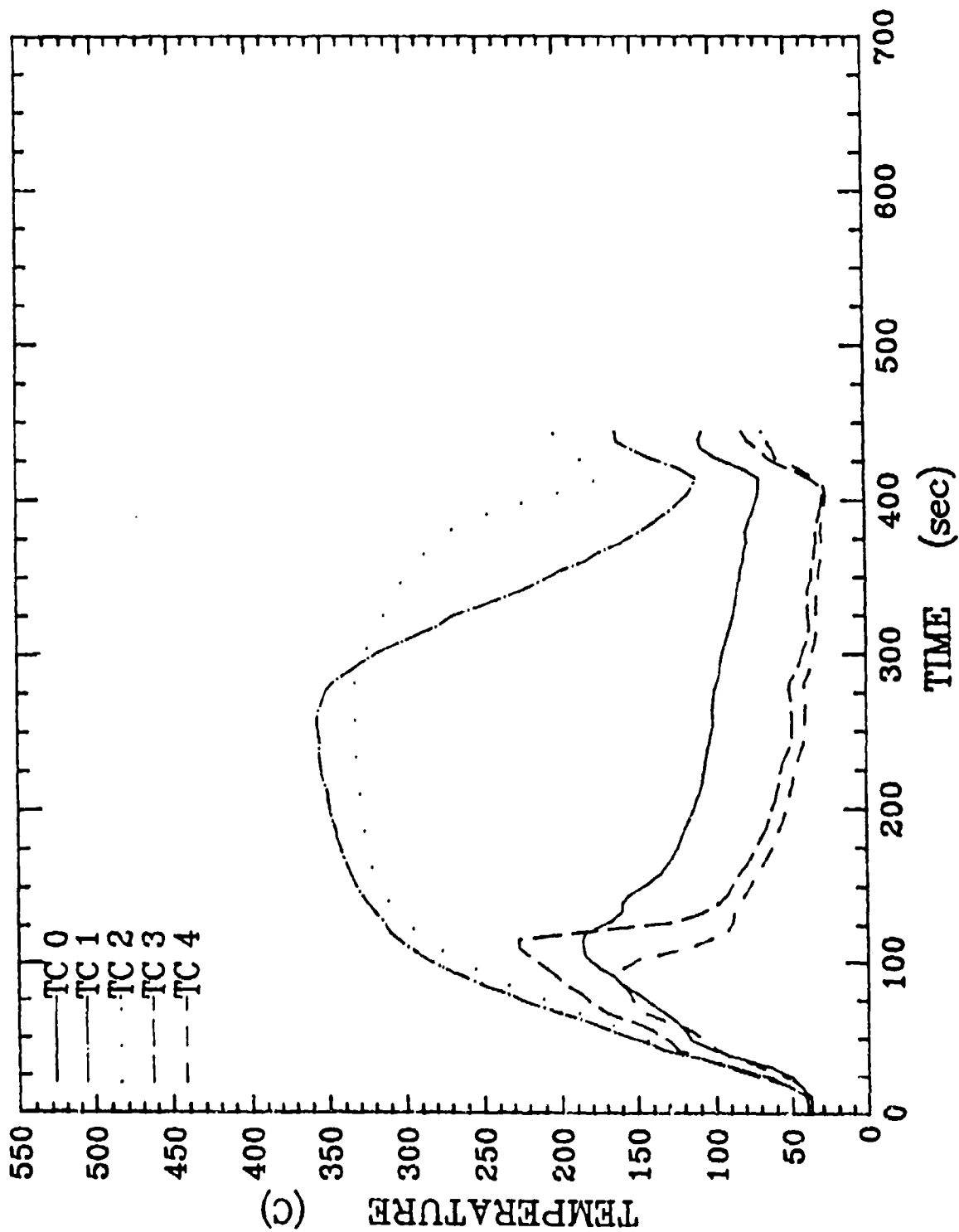
Figure D-3. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).
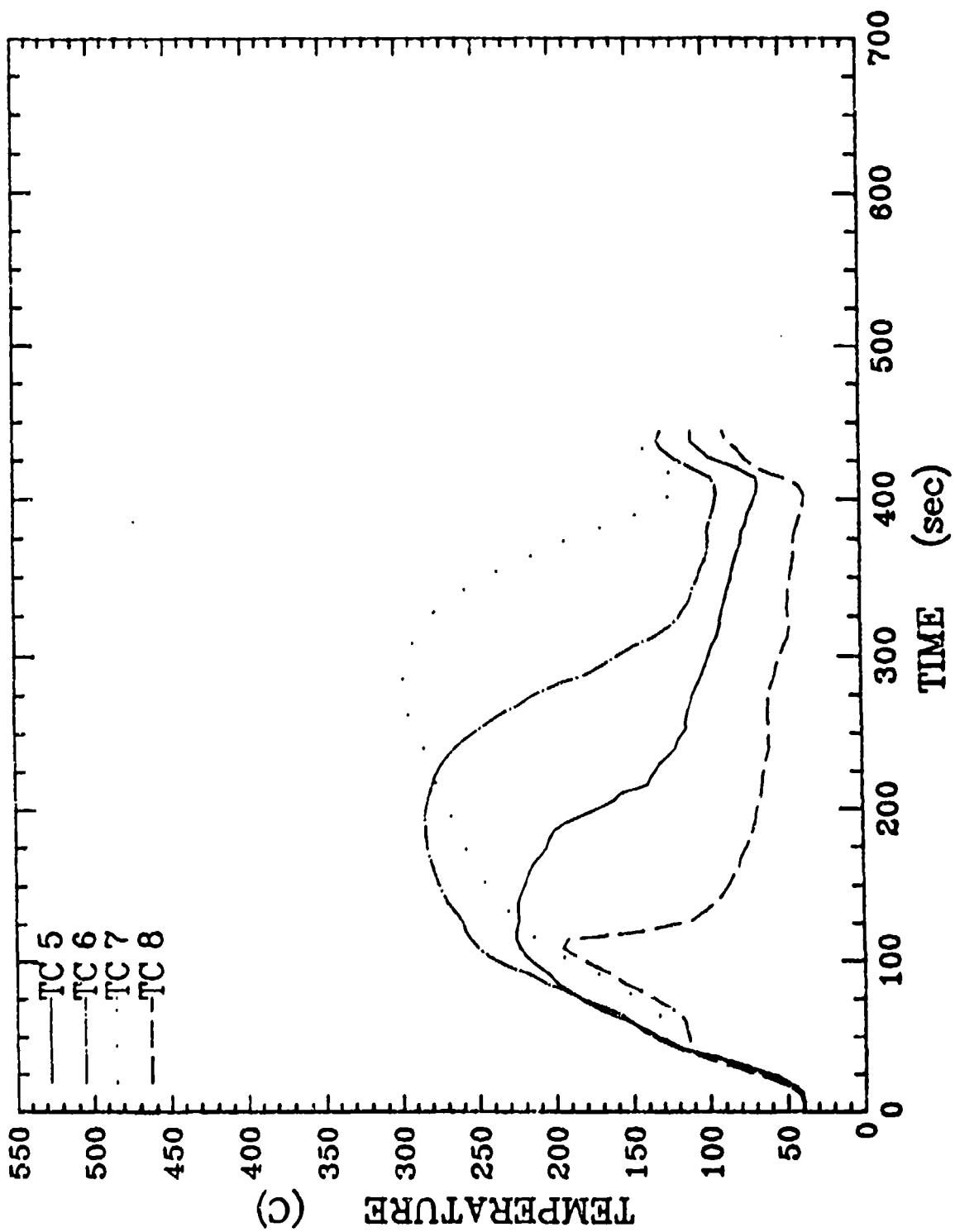
Figure D-4.   Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).
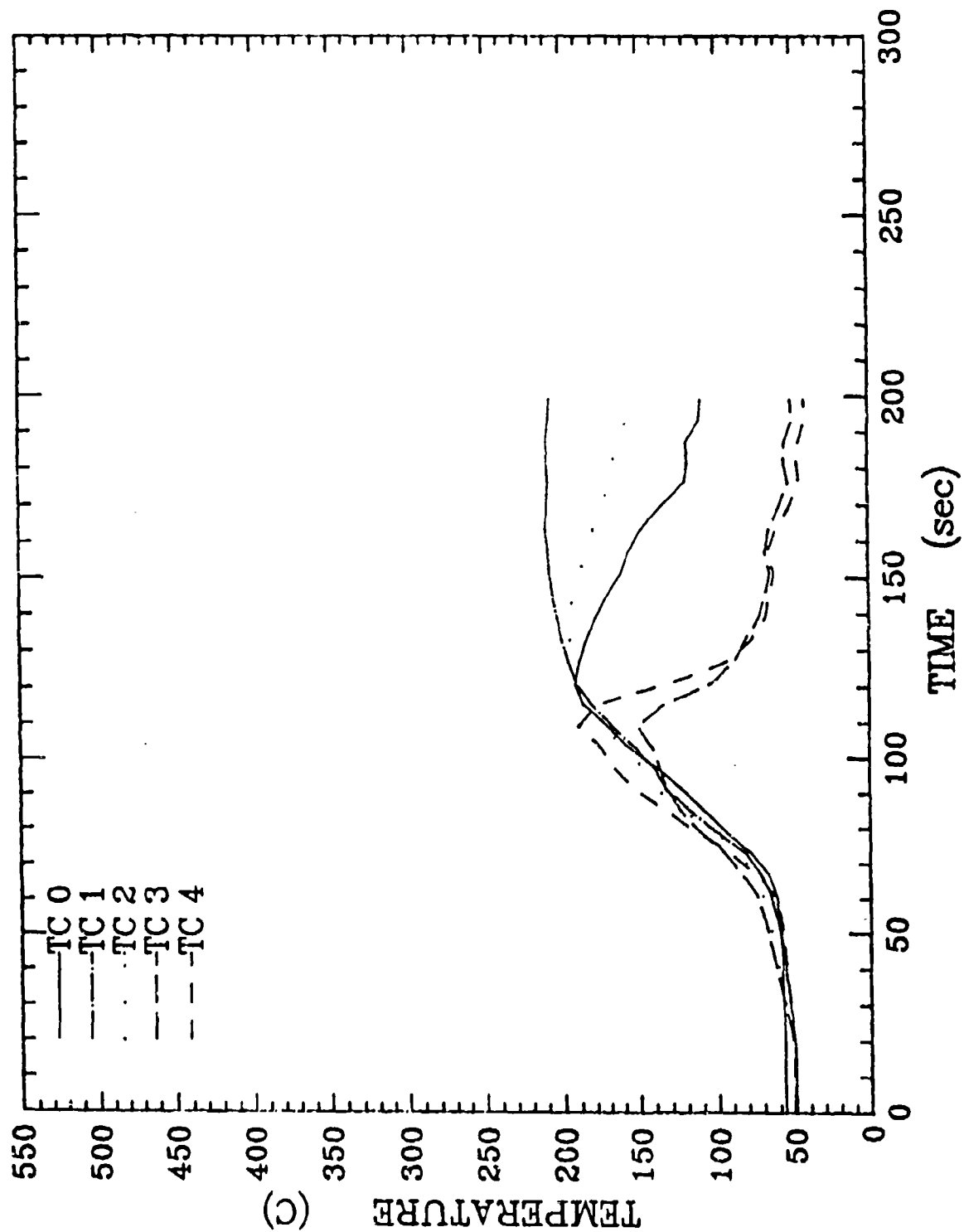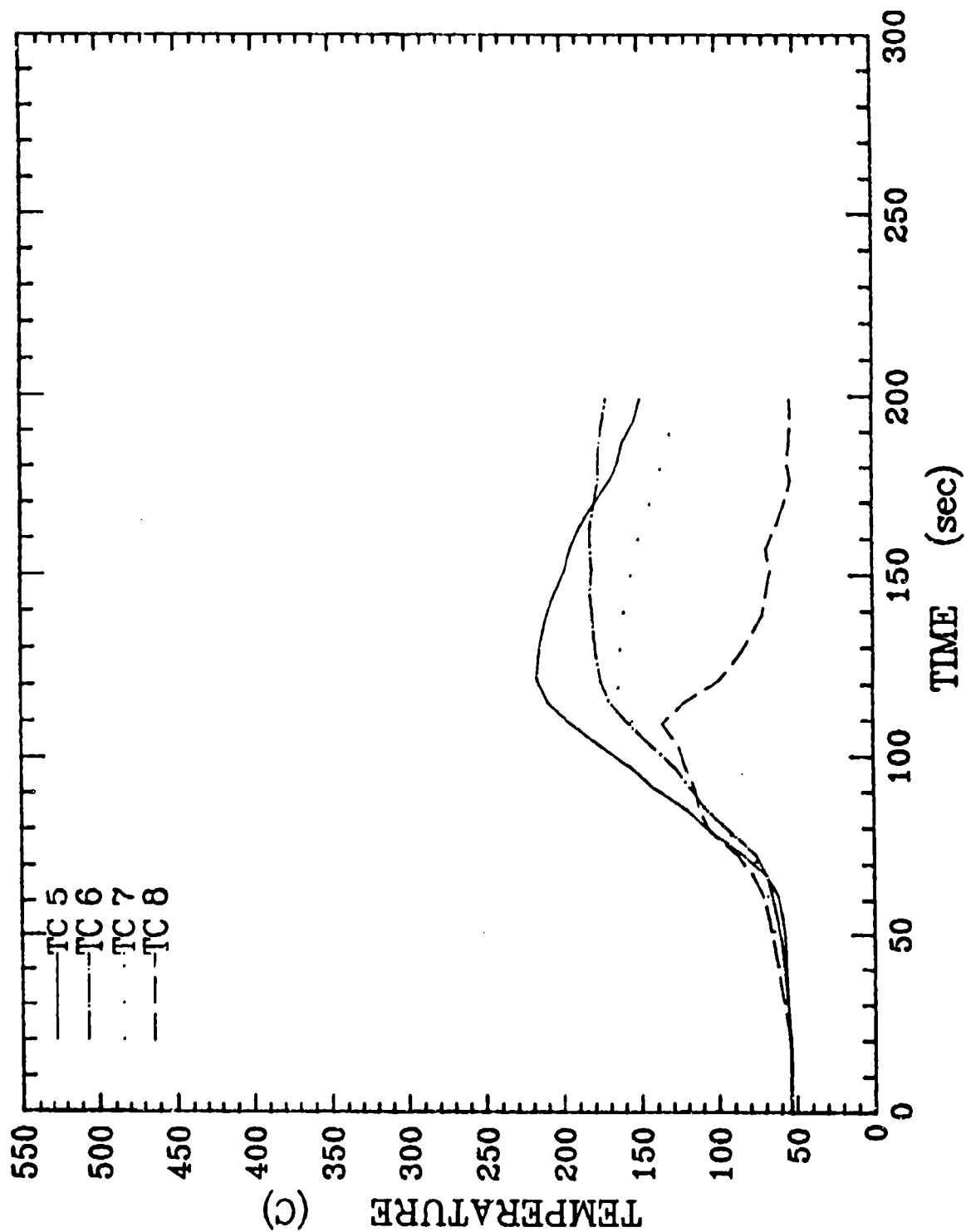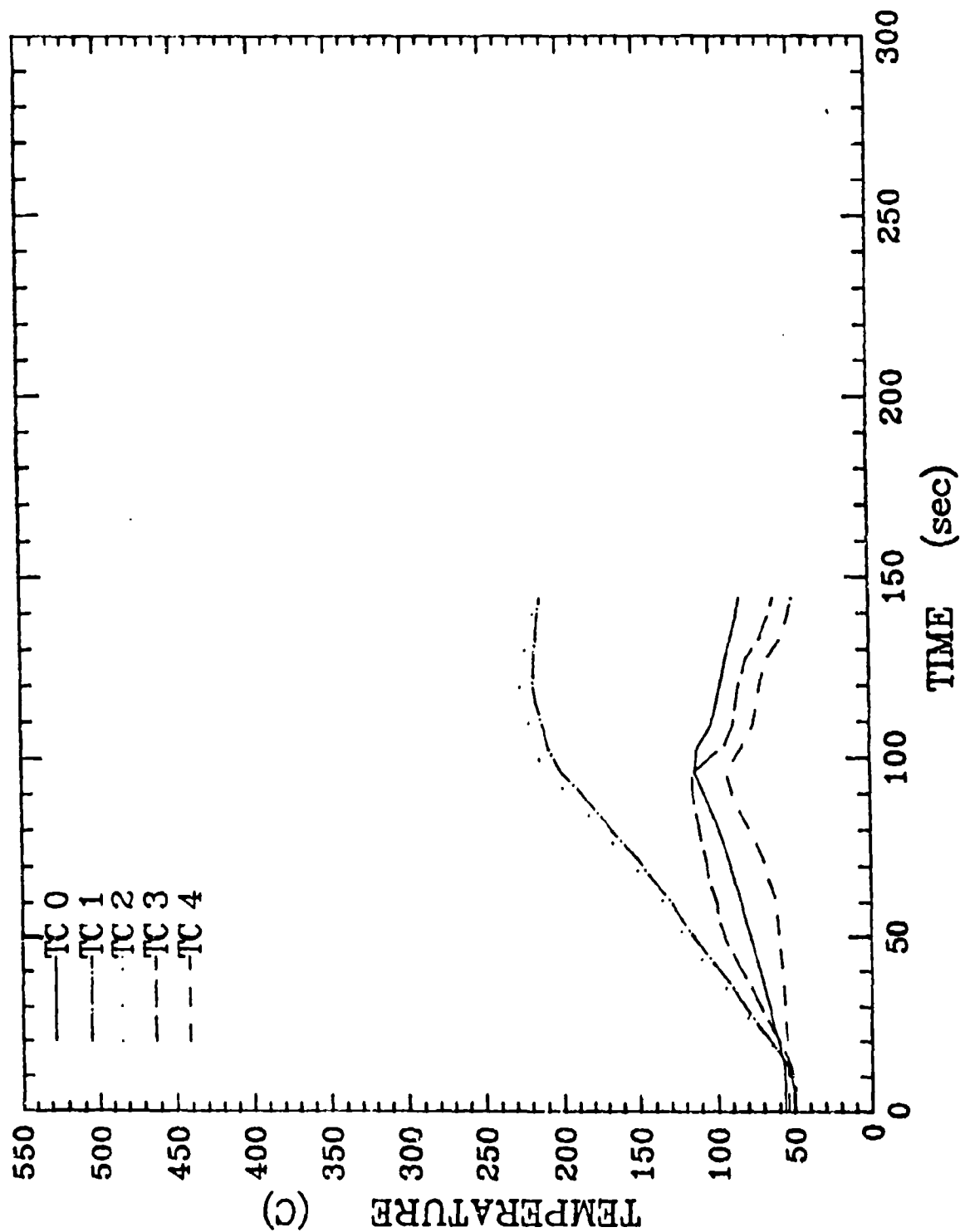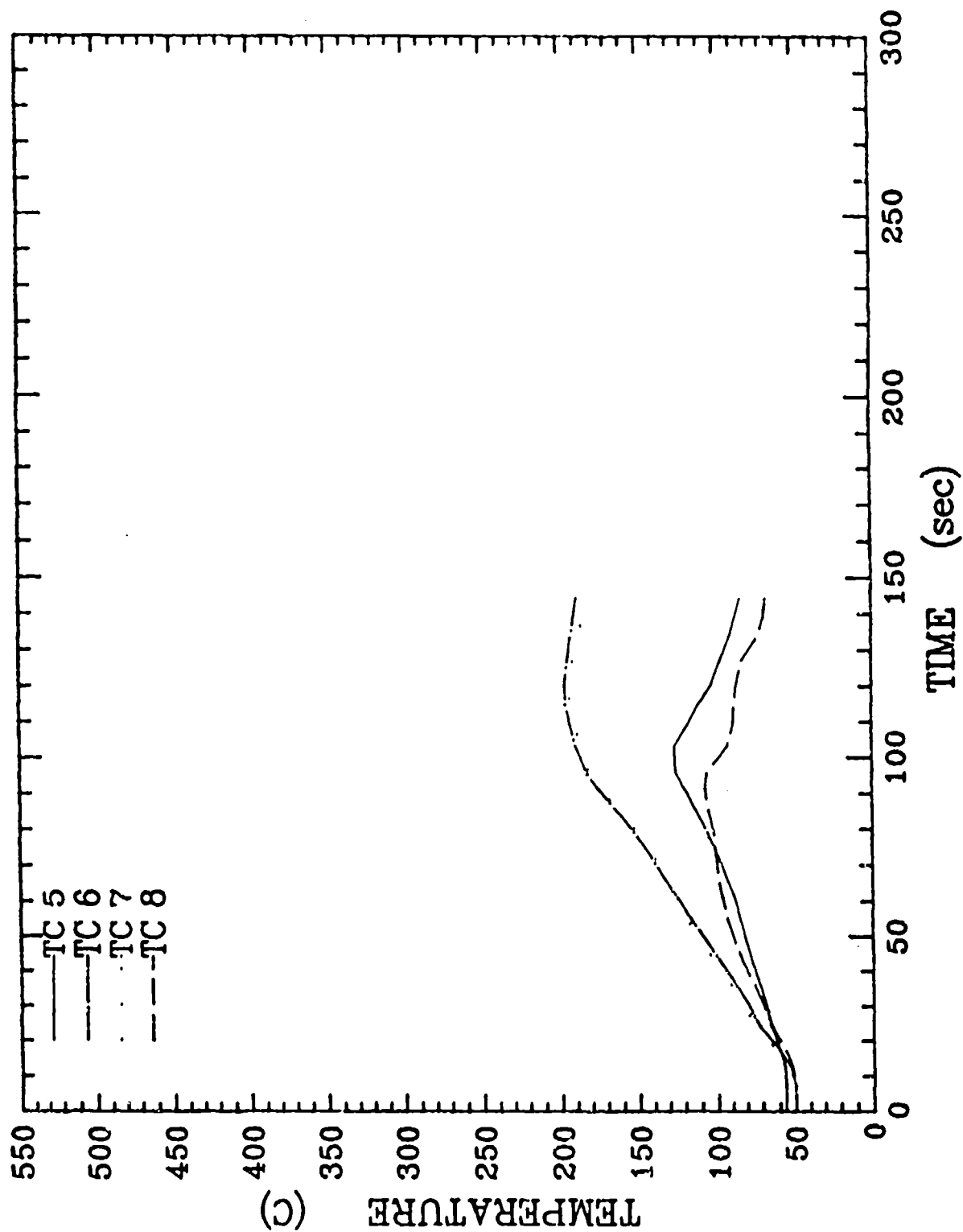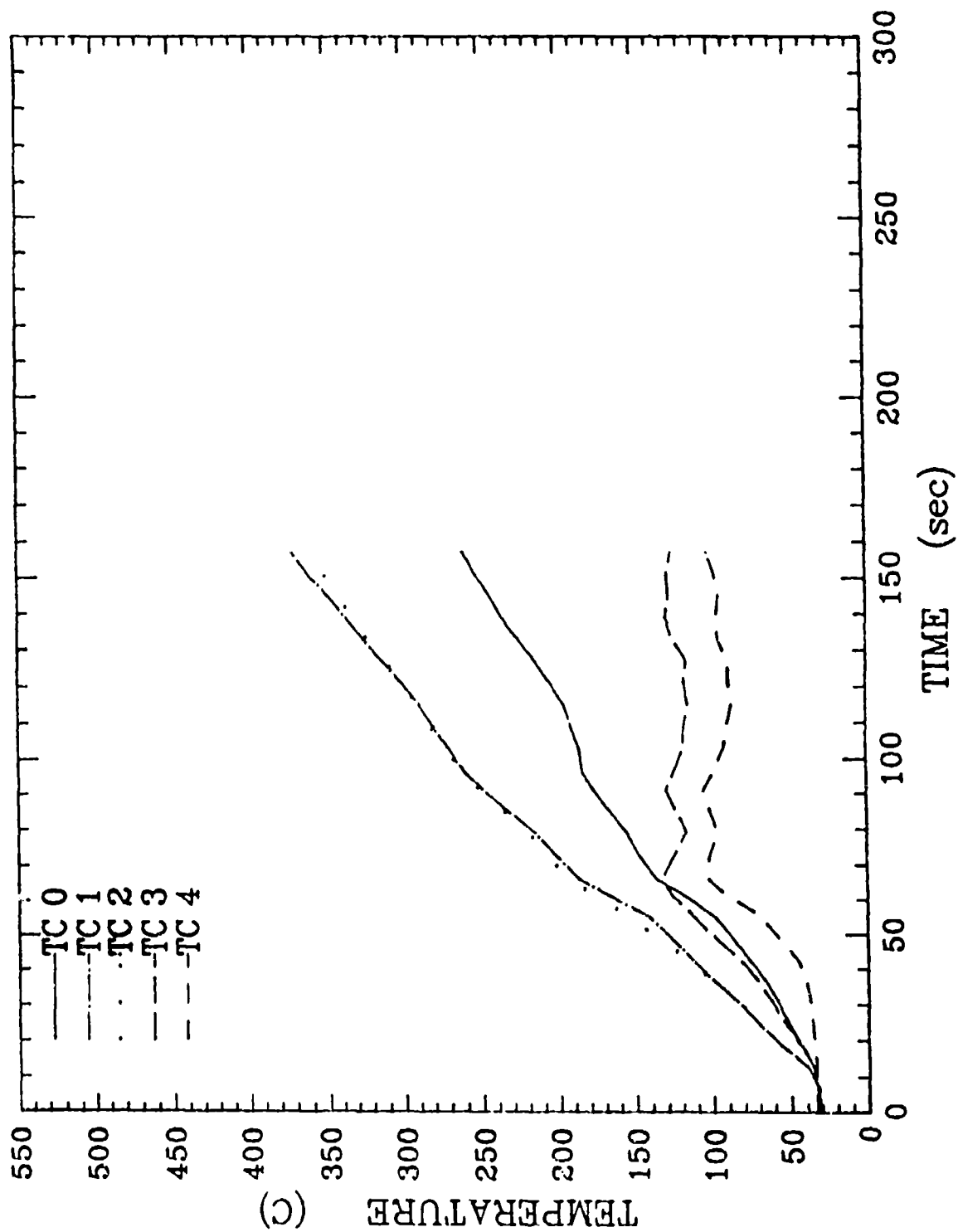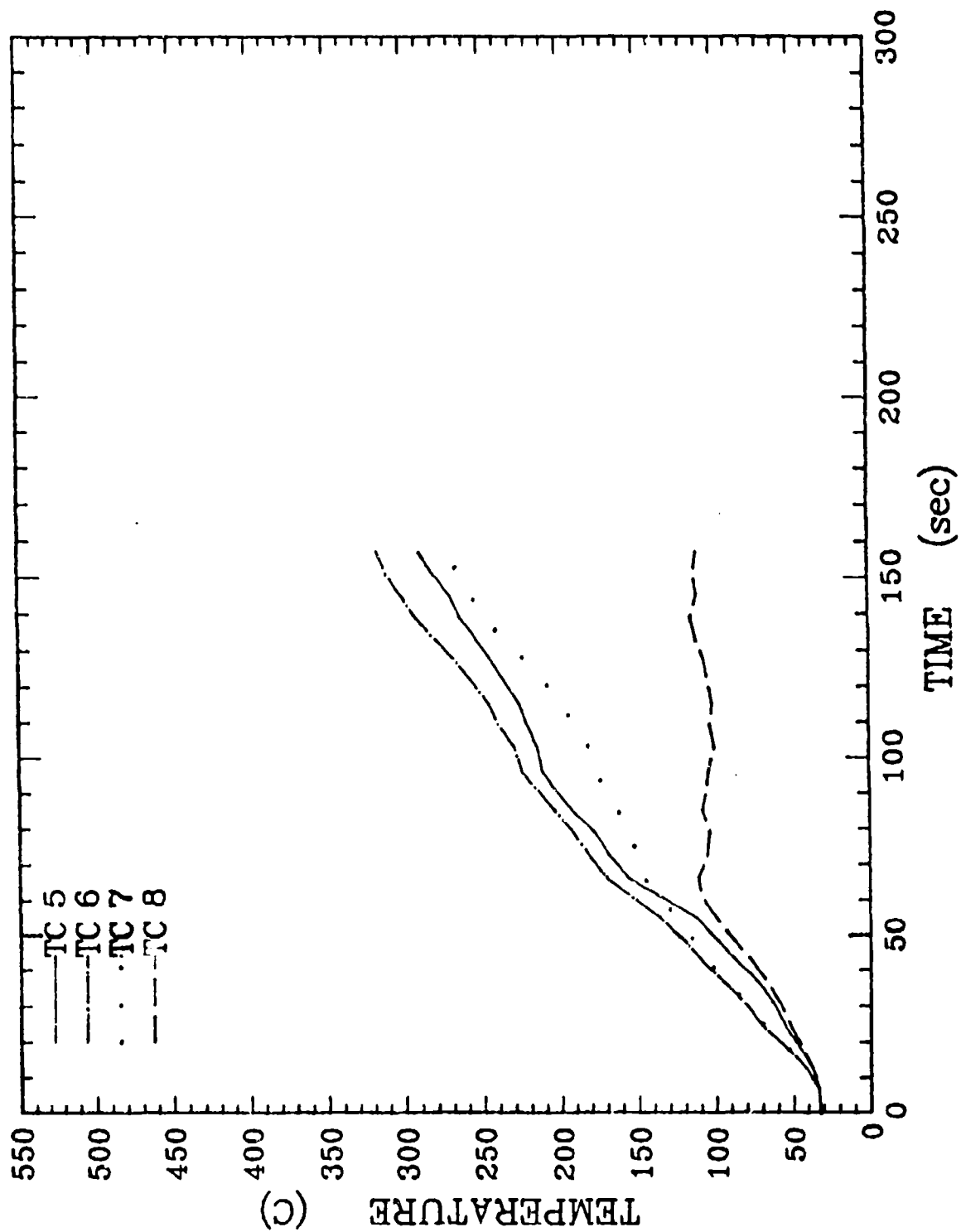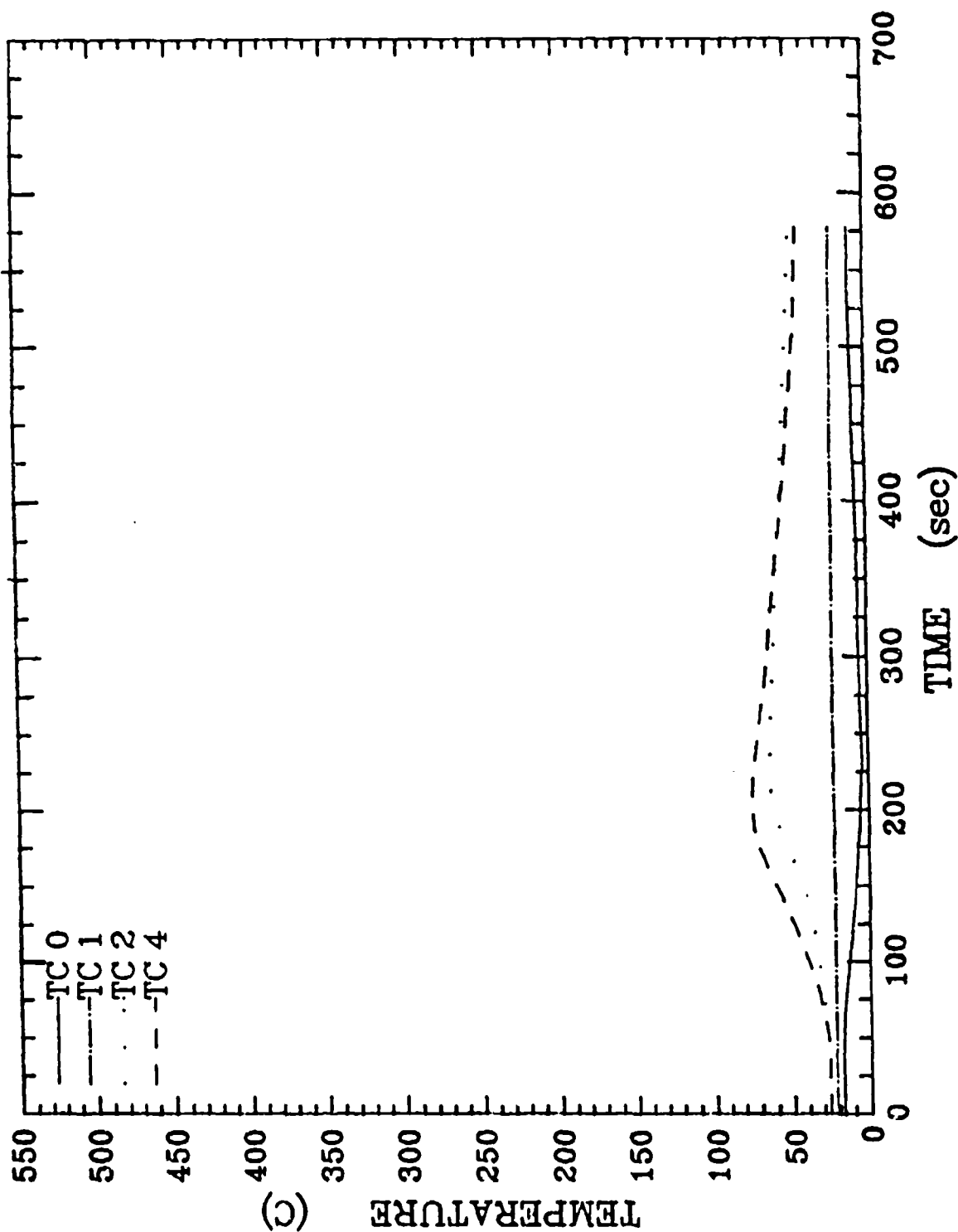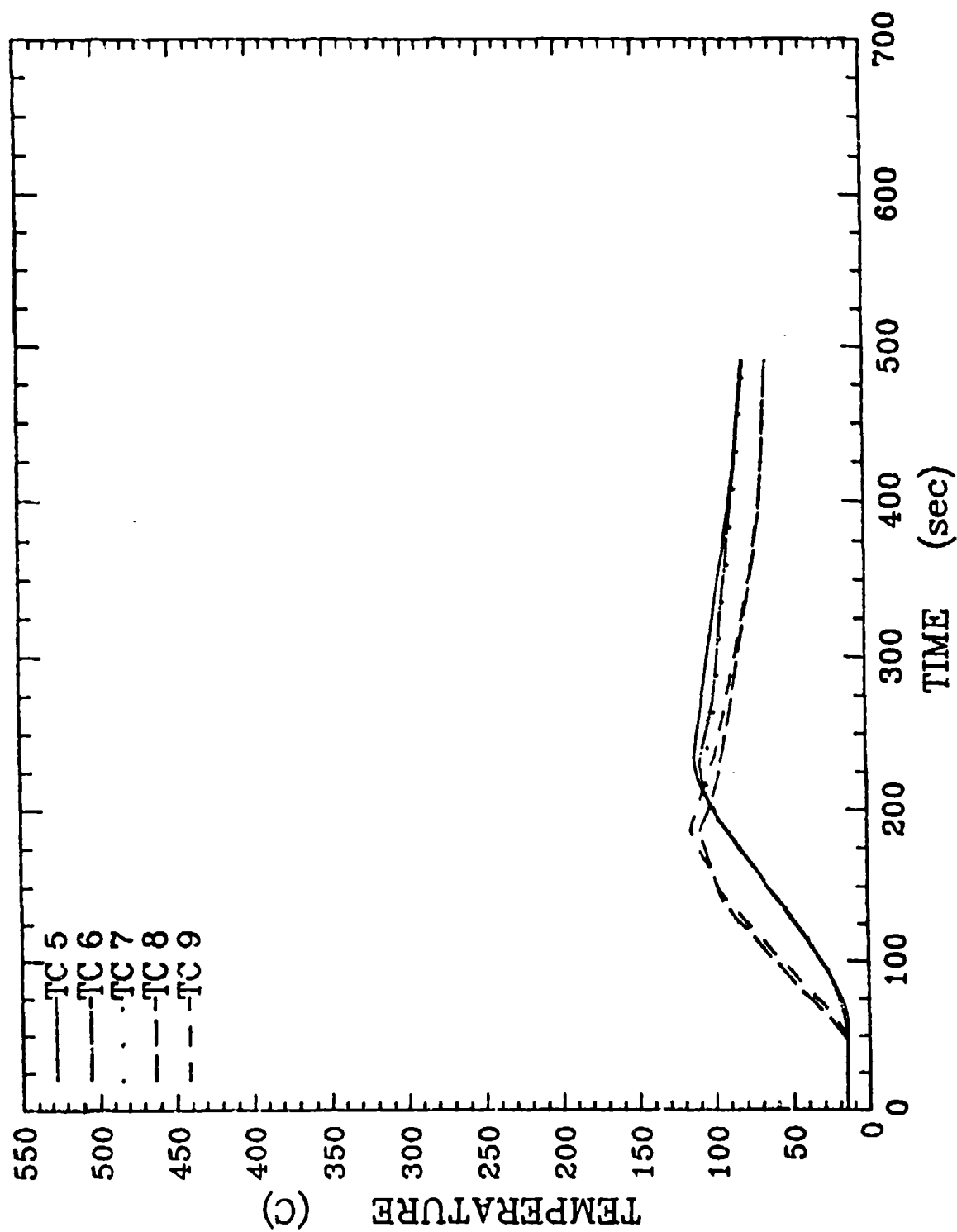
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Figure D-5. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 341 L/min).

Figure D-6. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 341 L/min).

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Figure D-7. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 170 L/min).

Figure D-8. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 170 L/min).

Figure D-9. Calorimeter Temperature/Time Profile (Uncoated, Halon 2402 Coolant, 2.5 kg/s).

Figure D-10. Calorimeter Temperature/Time Profile (Uncoated, Halon 2402 Coolant, 2.5 kg/s).

Figure D-11. Calorimeter Temperature/Time Profile (FM-26 Coating, Water Coolant, 341 L/min).

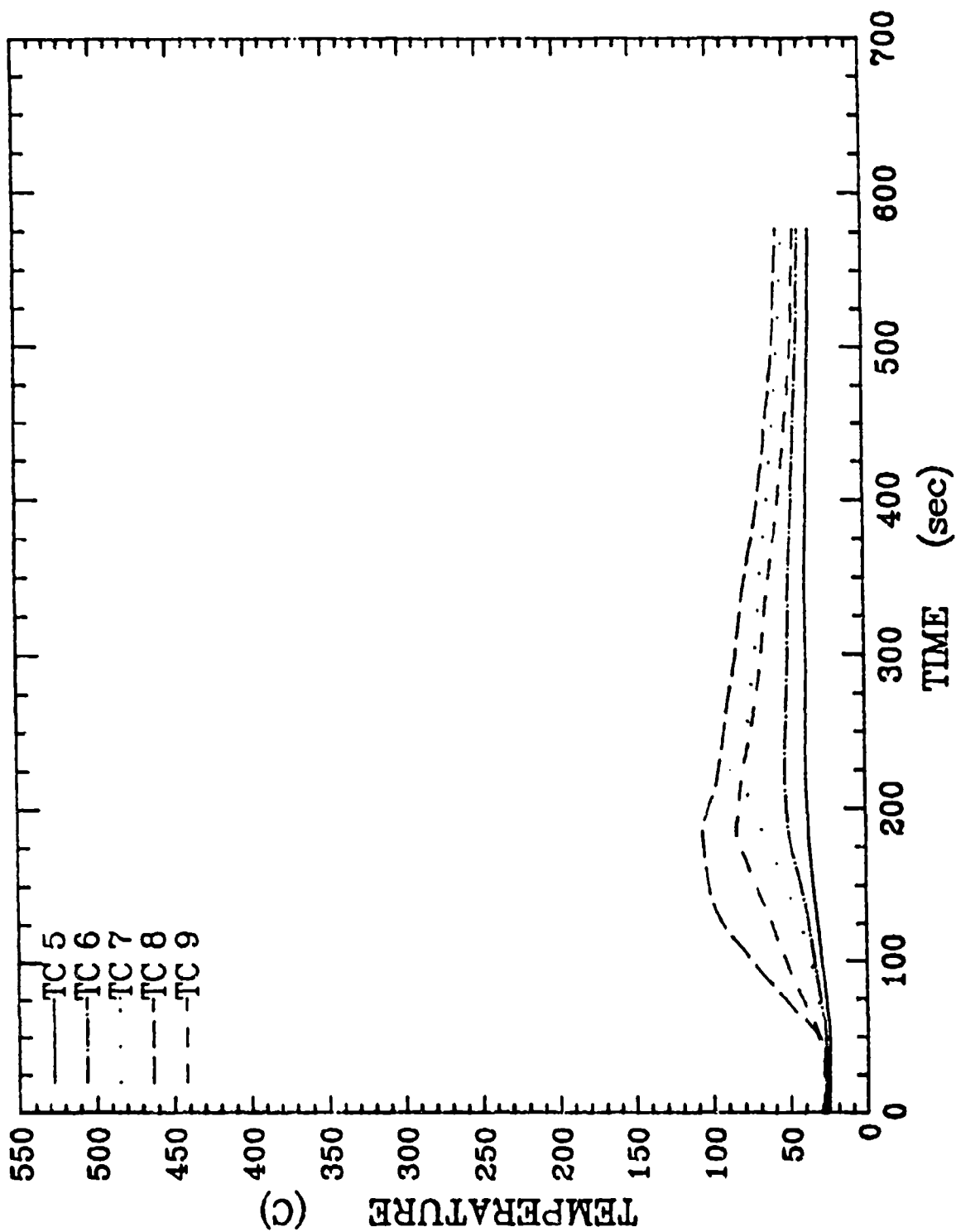Figure D-12. Calorimeter Temperature/Time Profile (FM-26 Coating, Water Coolant, 341 L/min).
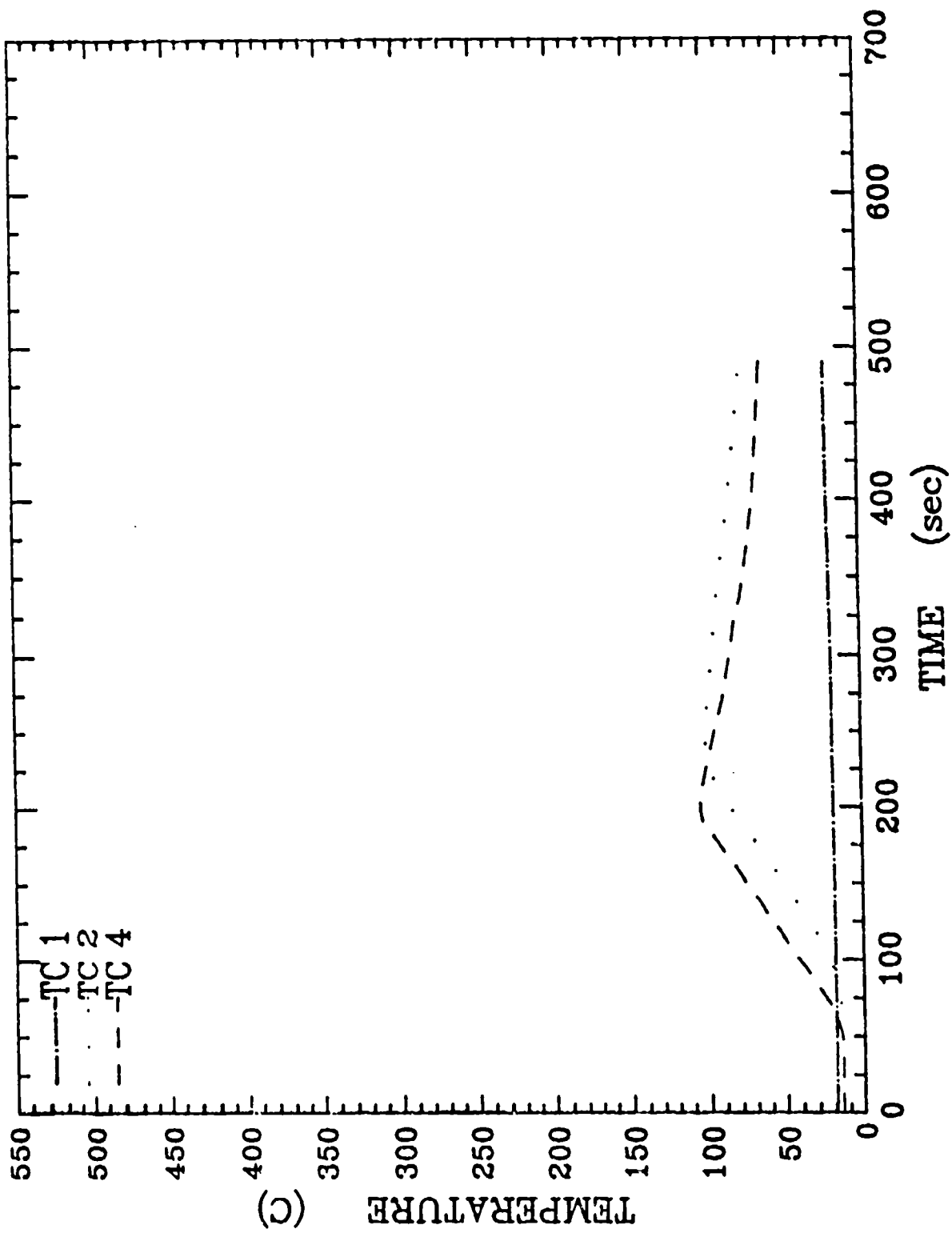
Figure D-13. Calorimeter Temperature/Time Profile (FM-26 Coating, AFFF Coolant, 341 L/min of water).

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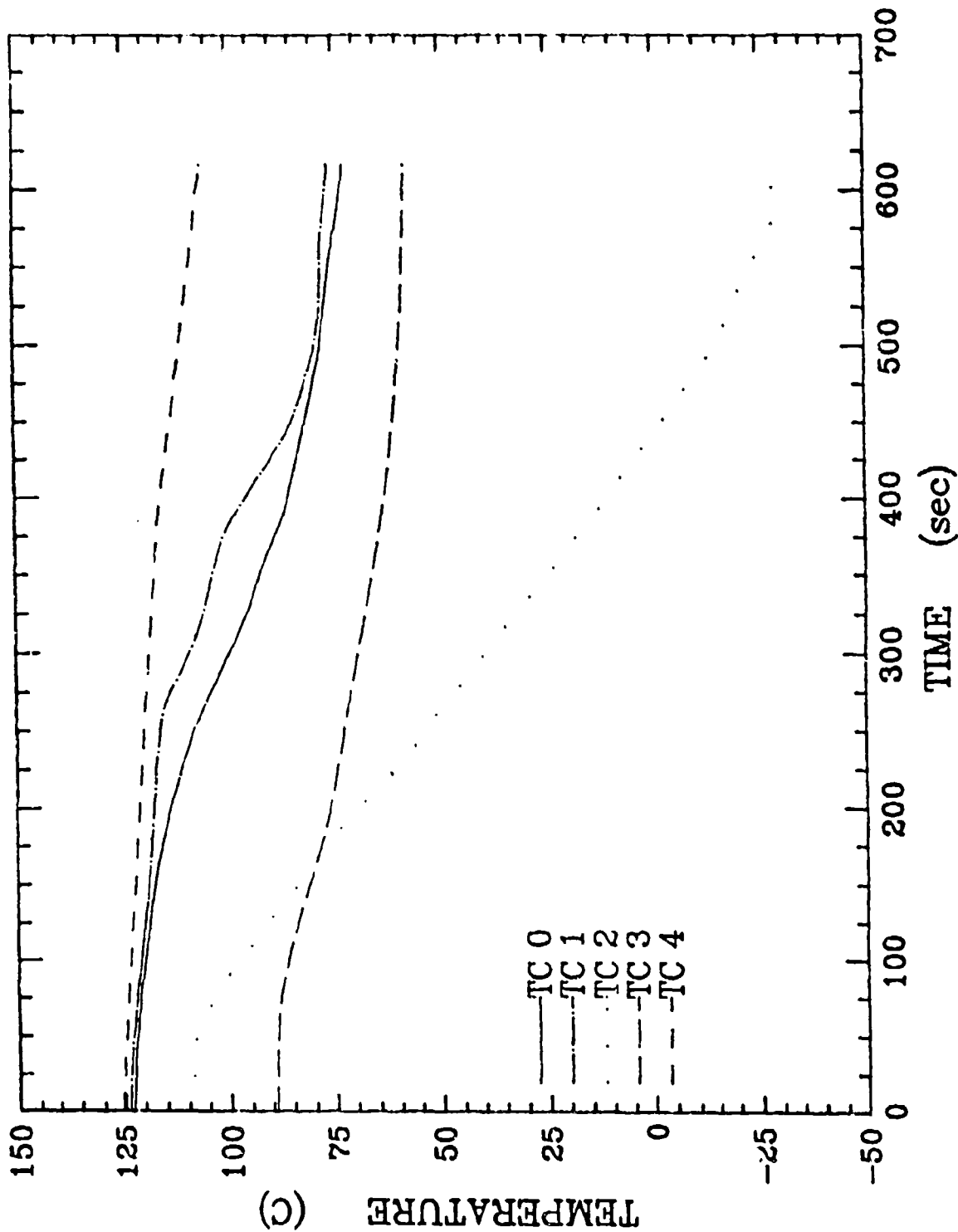Figure D-14. Calorimeter Temperature/Time Profile (FM-26 Coating, AFFF Coolant, 341 L/min of water).

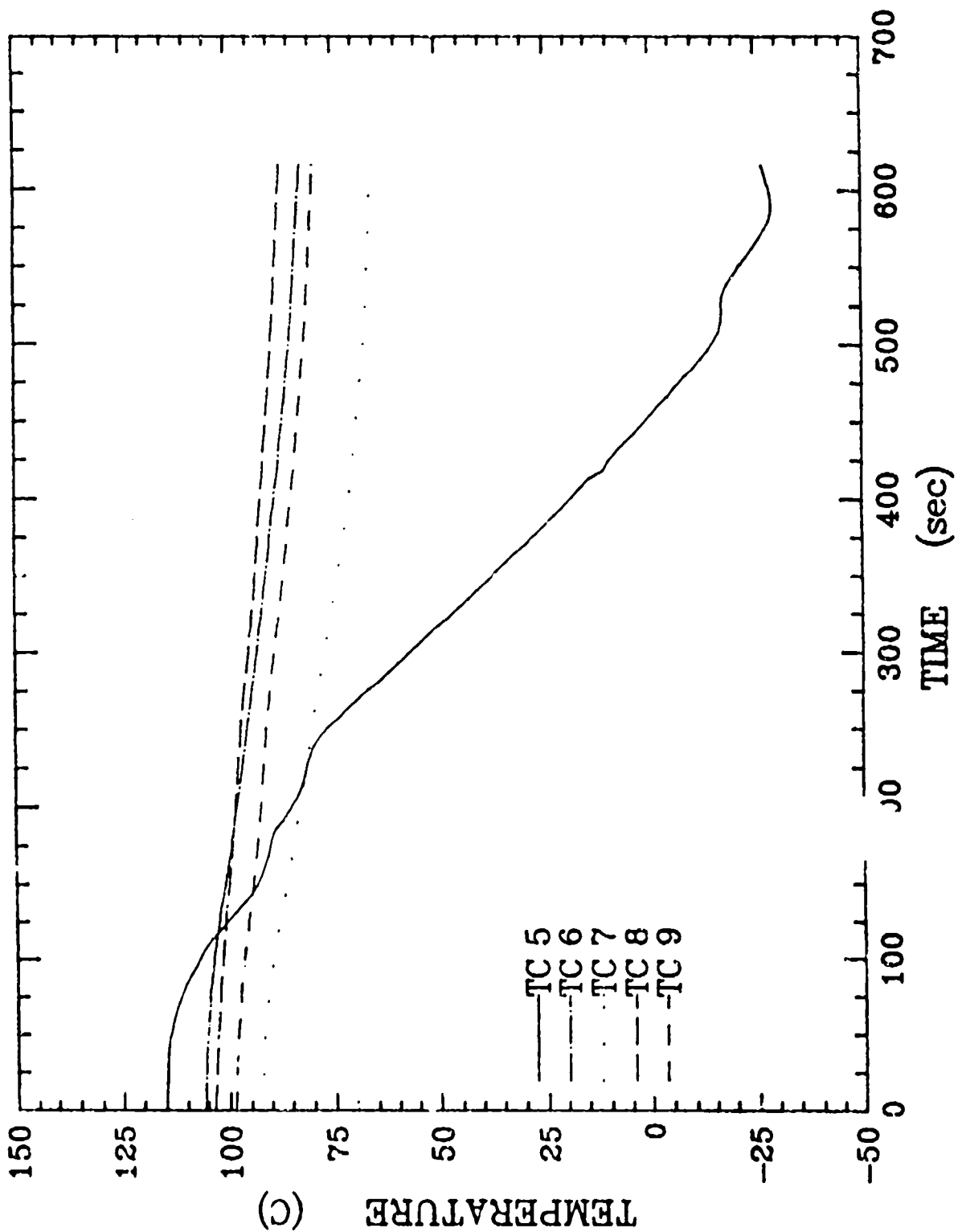Figure D-15. Calorimeter Temperature/Time Profile (FM-26 Coating, Liquid Nitrogen Coolant).

Figure D-16. Calorimeter Temperature/Time Profile (FM -26 Coating, Liquid Nitrogen Coolant).

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