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PRELIMINARY HEAT TRANSFER STUDIES FOR THE DST TRANSFER PIPING

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for CH2M Hill Hanford Group, Inc.
Richland, WA 99352

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Abstract: Heat transfer studies were made to determine the thermal characteristics of double-shell tank transfer piping under both transient and steady-state conditions. A number of design and operation options were evaluated for this piping system which is in its early design phase.

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PRELIMINARY HEAT TRANSFER STUDIES FOR THE DOUBLE-SHELL TANK TRANSFER PIPING

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CONTENTS

APPENDICES

LIST OF FIGURES

NOTE: Use the following conversions for the English units of measure in Figures 1-17.

To Convert From	To	Multiply By
Inch	meter	2.540×10^{-2}
Inch (piping)	meter	2.500×10^{-2}
Foot (piping)	meter	3.000×10^{-1}
Ft/s	m/s	3.048×10^{-1}
Btu/h-ft	W/m	0.961
To Convert From	To	Calculate
°F	°C	$t_{°C} = (t_{°F} - 32)/1.8$

LIST OF TABLES

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1.0 INTRODUCTION

Some of the Double-Shell Tank (DST) Transfer Piping Subsystem is being designed to support the first phase of waste feed delivery. This system includes piping which will transfer waste between double-shell tanks, and from the double-shell tank waste feed staging tanks to the River Protection Project Privatization Contractor facility where it will be processed into an immobilized waste form. Some of this piping is currently in the conceptual design phase; therefore, engineering heat transfer studies are required to provided engineering information that will have a direct bearing on design options, design features, and the design of auxiliary systems. This study will potentially aid in establishing specifications for the design.

1.1 PIPING DESIGN DESCRIPTION

The DST Transfer Piping Subsystem consists of a number of piping runs. The longest run currently identified is approximately 2070 m (6,800 ft) with 1680 m (5,500 ft) of new piping. The longest new piping section is approximately 1770 m (5,800 ft) long. Currently, the piping is envisioned to be similar to the cross-site pipeline (project W-058). The DST Transfer Piping System comprises double-walled, underground piping that establishes the primary and secondary confinement of the waste. This concentric pipe-in-pipe design consists of an 80 mm (3-in.) Schedule 40 stainless steel (type 304) primary confinement pipe within a 150 mm (6-in.) Schedule 40 carbon steel secondary confinement pipe. Air (at 1 atm) fills the annular region between these pipes. The secondary confinement pipe is encased in 5.08 cm (2-in.-) thick polyurethane foam insulation. This piping system is buried below 0.914 m (36 in.) of soil (controlled density backfill). Variations on this base design were investigated including designs without insulation and with 2.5 cm (1 in.) of insulation.

It is expected that the tank waste will be mixed with diluent (water) so that waste thermophysical properties are the same as given in the *Double-Shell Tank Transfer Piping Subsystem*, HNF-4161 (also see Sections 3.1.2 and 3.2.2 of this document). The temperature of the diluted waste ranges from just above freezing to 93.3 °C (200 °F).

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2.0 SCOPE

Two sets of heat transfer analyses were performed to investigate thermal characteristics.

The first set of analyses determined the steady-state temperature drop of the waste as it traverses the full length of the pipe. The design goal is to limit this temperature drop, when considering bounding conditions and properties, to 11.1 °C (20 °F). This temperature drop limit was used for the piping design of the DST Cross-Site Transfer System. It is postulated that larger temperature drops will cause particles to precipitate from the waste slurry and potentially lead to line plugging.

The second set of analyses determined the transient response of the "cold" empty piping system to the introduction of preheated water. It is desired to determine the time and the amount of heated water required to bring the inner primary confinement pipe to near steady-state temperature, so that the waste will not lose significant heat during the subsequent transfer.

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3.0 ANALYSIS AND RESULTS

3.1 STEADY-STATE TEMPERATURE DROP ANALYSIS

Sixteen cases were investigated, which included a matrix of conditions related to combination of pipe inlet temperatures, insulation thickness, and uncertainties in material properties. Analyses covered the range of waste inlet temperatures from 31.8 °C (50 °F) to 93.3 °C (200 °F). Pipe insulation thickness ranged from no insulation to 5.08 cm (2 in.).

Analyses were based on a bounding pipe length of 2133 m (7,000 ft). Results for lengths shorter than 2133 m (7,000 ft) can be interpolated from detail results presented in Appendix A. All analyses assumed a constant waste flow velocity of 1.83 m/s (6 ft/s) (530 L/min [~140 gal/min]) in the primary containment pipe. All analyses assumed that the soil surrounding the pipe is an infinite thermal sink at 0.8 °C (33.5 °F) (*Natural Phenomena Hazards, Hanford Site, Washington*, HNF-SD-GN-ER-501), the minimum winter temperature at 91 cm (36 in.) below grade at the Hanford Site.

3.1.1 Steady-State Heat Transfer Model

Steady-state heat transfer calculations were preformed by the FORTRAN program DPIPEHT, which was developed for this analysis. The listing of the program DPIPEHT can be found in Appendix B. DPIPEHT is based on the model described in this section. References to this program given herein are indicated by the use of double brackets, [[ ]].

The model is a pseudo two-dimensional (R-Z) heat flow, consists of a number of one-dimensional axial (Z-direction) segments that transfer heat to the ambient soil in the radial (R) direction only. Heat is transferred between axial segment only by way of the enthalpy of the flowing waste (there is no heat transfer in the axial (Z) direction by conduction).

The following modeling assumptions were made.

1. Steady-state conditions exist (conservative, assumes a constant minimum soil temperature).
2. Convective coefficient between the pipe and fluid is infinite, i.e., $T_{fluid} = T_{pipe}$.
3. Thermal conductivity across the pipe wall is infinite; i.e., the temperature at the inside and outsides of a given pipe are equal.
4. Neglect any internal heat generation in the waste from radioactive decay.
5. Neglect any minor heat loss from the support system for the inner pipe.

The model for radial heat transfer from a given axial segment is shown schematically in Figure 1a. This model is based on thermal circuit treatment. Thermal resistances are across the air gap (R_gap), and through the insulation (R3). The temperature drop across the air gap is from resistances of the resistances caused by combined convection/conduction (R1), and thermal radiation (R2). For a given axial segment length of dl, the following resistances are computed.

$$R1 = [1/(2\cdot\pi\cdot Keff\cdot dl)]\cdot \ln(D2i/D1o)$$

Where Keff = equal the effective thermal conductivity for natural convection between 2 concentric horizontal cylinders, as determined from the empirical correlation of Bayazitoglu and Guyer (WHC-SD-TP-RPT-005, Appendix A) [[DPIPEHT – Subroutine Keff]],

$$Keff = 0.386\cdot K\cdot [Pr/(0.861 + Pr)]^{1/4}\cdot(Ra_{cyl})^{1/4}$$

and

$$(Ra_{cyl})^{1/4} = [\ln(Do/Di)\cdot (Ra_{\delta})^{1/4}]/ [\delta^{3/4}\cdot(Di^{-3/5} + Do^{-3/5})^{5/4}]$$

where:

K = thermal conductivity of the gas at the mean temperature
Gr = Grashof No. based on the radial gap size
Pr = Prandtl No. of the gas
Ra = Rayleigh No. = Gr· Pr
δ = radial gap between cylinders.

The resistance across the gap from thermal radiation (R2) is:

$$R2 = 1./(h_r\cdot\pi\cdot D1o\cdot dl).$$

The Radiant Heat Transfer Coefficient, h_r, is defined as [[see DPIPEHT – Subroutine hrad]]:

$$h_r = \varepsilon\cdot\sigma\cdot(T1^4 - T2^4)/(T1-T2)$$

where:

σ = the Stefan-Boltzmann Constant
T is absolute temperature
and the ε is the effective emissivity and shape factor product. For the concentric cylinders:

$$\varepsilon = [(1-\varepsilon_c) /\varepsilon_c + 1 + A_c\cdot(1-\varepsilon_e)/(A_e\cdot\varepsilon_e)]^{-1}$$

where the subscripts c and e refer to the carrier (primary) and enclosure (secondary) pipes, respectively.

Both resistances, R1 and R2, are nonlinear and require an iterative solution [[DPIPEHT – main program]]. Here, the assumed gap temperatures made before temperature drop calculations, generally based on the previous axial segment analyzed, are adjusted until they are adequately close to the final calculated temperature.

The total gap resistance, R_gap, from the parallel combination of resistance R1 and R2 is:

$$R\_gap = 1/(1/R1 + 1/R2).$$

The thermal resistance through the insulation is:

$$R3 = (1/[2\cdot\pi\cdot Kins\cdot dl])\cdot \ln(D3/D2o).$$

Then the total thermal resistance, R_total, can be calculated from the series combinations of R_gap and R3, or:

$$R\_total = R\_gap + R3.$$

The radial heat loss in the i^{th} axial segment can then be calculated:

$$q(i) = (T3-T1(i)) / R\_total(i).$$

The temperature T1(1) is the pipe inlet temperature. Once the radial heat flow outward, q(i), is calculated, the temperature at the outer pipe wall, T2, can be calculated to use in the iterative process to converge on a solution in the given axial segment.

The waste (fluid) in the pipe will now be cooled by the loss of the heat (q) within the segment. The temperature drop in the flowing fluid in the axial segment is:

$$\Delta T(i) = q(i)/(mdot\cdot C_p)$$

where:

mdot is the mass flow rate of the waste in the pipe, and
C_p is the heat capacity of the waste.

Therefore, the temperature in the i+1 segment is:

$$T1(i+1) = T1(i) - \Delta T(i).$$

The calculation is incremented for all segments until the total length is traversed. The schematic for this axial model is show in Figure 1b.

The DPIPEHT model was tested (validated) by comparison with results of several hand calculations (*Inside Pit and Buried Pipeline Heat Loss Calculations – 314-200 East/West Upgrades,* W314-P-006; *Heat Loss from Buried Transfer Line: W-058/Cross-Site Transfer System, Preliminary Calculation,* W-058-008) on other Hanford Site double-encased piping. The comparison was good considering the limitations of the hand calculations and the differences in the system. These benchmark runs are on file with Samuel L. Hecht. Another comparison was made with the results from a commercial finite element program used in the follow-on transient analyses (see Section 3.1). The calculated exit temperature only differed by 0.005 °C (0.01 °F) for the base case with a 93 °C (200 °F) inlet, a very good agreement.

3.1.2 Steady-State Model Input

Model input includes the pipe inlet temperature, the constant soil temperature, the waste velocity, the waste density, the waste specific heat, the insulation thickness, the emissivities of the outer and inner pipes, the pipe length, and the number of calculations divisions used. A range of values exist for a number of thermophysical properties (Table 1). Nominal, best estimate, calculations used mid-range property values (if applicable), whereas extreme values were used in bounding calculations (see Section 3.1.3). Thermophysical properties used here and in the transient calculations (Section 3.2) were taken from *Double-Shell Tank Transfer Piping Subsystem Specification*, HNF-4161; CRC (1970); *Thermal Analysis Methods for Safety Analysis Report for Packaging,* WHC-SD-TP-RPT-005; Rohsenow and Hartnett (1973); Touloukian and Ho (1979); and U. C. Berkeley (1968). The properties for the insulation were taken from the specification for the cross-site transfer piping (*Project Turnover Rev 1; Technical Requirements Buried Pipeline for Replacement of the Cross-Site Transfer System,* W-058-C1) for the specific insulation with a density of 38.4 kg/m^3 (2.4 lb/ft^3).

Table 1. Thermophysical Properties used in Steady-State Analysis.

Property	Value range
Thermal conductivity of insulation, Kins	0.019 - 0.0242 W/m-°C (0.011- 0.014 Btu/h-ft-°F)
Specific gravity of diluted waste	1.0 – 1.4
Heat capacity of diluted waste, C_p	4,180 J/kg °C (1.0* Btu/lbm-°F)
Emissivity of stainless steel pipe, ε	0.21 – 0.38
Emissivity of carbon steel pipe –slight oxidation	0.78 –0.82

*See Section 3.1.4.

3.1.3 Steady-State Analysis Results

Sixteen cases were run to investigate the effects of the parameters of interest (see Table 2), with a number of parameters being held constant throughout the matrix of cases. These were waste flow velocities (1.83 m/s [6 ft/s]), pipe overall length (2133 m [7,000 ft]), temperature of the soil, heat sink (0.8 °C [33.5 °F]), and C_p of the waste (4,180 J/kg °C [1.0 Btu/lbm- °F]). Detail results and input data for each case are given in Appendix A. Data and program files for these analyses can be found in snf1.rl.gov:/home/v92627/twrs/piping. A summary of these results is given in Table 2.

These results also are shown graphically in Figures 2 and 3.[1] Figure 2 shows the total waste temperature drop as a function of inlet temperature for the various amounts of insulation. Figure 3 gives the average radial heat loss per unit length as a function of inlet temperatures and

[1] Conversion factor for Figure 2, T °C/F T[°F] – 32)/18; for Figure 3, to get W/m multiply Btu/h-ft by 0.961 or W/m = 0.961·(Btu/h-ft).

amount of insulation. For pipe length less than 2133 m (7,000 ft), refer to results given in Appendix A.

Table 2 also shows the effect of uncertainties of material properties on the results. The upper bound solutions (Cases 1U and 3U) consider the extreme combination of uncertainties given in Table 1, so as to produce a maximum temperature loss. Conversely, the lower bound solutions use material properties that will yield the minimum temperature loss. For the base case (Case 1), the upper bound temperature loss is 34.5% greater than the nominal value. The lower bound case gives temperature drops 24.9% lower than the nominal value. For the case without insulation the percentage change is slightly lower. The amount of heat loss variation is affected to a lesser extent than the temperature drop. Here, approximately ±11.5% and ± 7.9% variations can be attributed to material properties uncertainties.

Table 2. Steady-State Analysis Results.

Conditions:
Flow velocity = 1.8 m/s (6 ft/s) T (soil) = 0.8 °C (33.5 °F)
Pipe length = 2133 m (7,000 ft) C_p = 4180 J/kg-°C (1.0 Btu/lb-°F)

Case	Insulation	Inlet Temperature (°F)*	Uncertainties	Fluid Temperature Drop (°F)*	Avg. Heat Loss/ft (Btu/h)*
1	2 in.	200		1.97	23.3
1U	2 in.	200	Upper bound	2.65	26.2
1L	2 in.	200	Lower bound	1.48	20.5
2	1 in.	200		3.17	37.6
3	None	200		14.25	169.1
3U	None	200	Upper bound	18.49	182.7
3L	None	200	Lower bound	11.27	156.0
4	2 in.	150		1.35	16.0
5	None	150		9.45	112.1
6	2 in.	100		0.75	8.9
7	None	100		4.76	56.5
8	2 in.	50		0.18	2.1
9	None	50		0.89	10.6
10	1 in.	50		0.27	3.2

*T (°C) = (T °F-32)/1.8
To convert to W multiply Btu/h by 0.293.
To convert to cm multiply in. by 2.54.

3.1.4 Discussion of Steady-State Analysis Results

The results presented in Table 2 and Figures 2 and 3 show that the insulated piping is far superior in the heat loss characteristics than the uninsulated pipe. Here, the heat loss is reduced by about a factor of seven when using 5.08 cm (2 in.) of insulation. When considering the worst-case evaluation for the 2133 m (7,000-ft) length, the 10.3 °C (18.5 °F) temperature drop is very close to the design limit of 11.1 °C (20 °F). Furthermore, when considering other uncertainties not addressed in the above calculation (see discussion below); the predicted temperature drop may be higher by up to 30%, making the uninsulated design unacceptable.

One uncertainty not addressed in the calculation is that of the specific heat, C_p, of the slurry. In the analyses it was assumed to be that of water. This was done at the recommendation of the customer, and because the value was historically used in similar analyses. However, when considering a slurry with a 30% mass ratio of solids, and the solid having specific heats as low as 20% of water, the slurry's C_p would be only 76% of that used in the analysis (some double-shell tanks have wastes with specific heat of 50% of that of water on a volumetric basis). As the temperature drop in the waste is inversely proportional to the specific heat, then the temperature drop would increase by 32% (assuming no increase in mass/unit volume of waste). Hence, worst case temperature drop values over the 2133 m (7,000 ft) length, could be as high as 12.9 °C (23.3 °F) and 1.94 °C (3.5 °F) for the uninsulated and 5.08 cm (2 in.) insulated designs, respectively (this is an ultra conservative treatment and assumes some inconsistent combinations).

The analysis also assumed that the insulation properties were that of perfect theoretical condition and did not consider effects of degradation or construction. Hence, one might consider the cases with 2.54 cm (1 in.) of insulation as a conservative representation of the actual performance for the design using 5.08 cm (2 in.) of insulation.

For the case of 5.08 cm (2 in.) of insulation and 65.6 °C (150 °F) inlet temperature, about 85% of the temperature drop occurs in the insulation (15% in air gap). Within the air gap, slightly more heat is transmitted by convection than by radiation.

3.2 TRANSIENT PIPING HEAT-UP ANALYSIS

These analyses predict the transient behavior of an initially cold and empty piping system (at Tsoil or 0.8 °C [33.5 °F]) to the introduction of flowing heated water. Because of the results of the steady-state analyses effectively eliminated the uninsulated piping from consideration, analyses will only consider the insulated pipe cases 2.54 cm (1 in.) and 5.08 cm (2 in.) thick. Although the length explicitly modeled is 2133 m (7,000 ft), lesser lengths are implicitly addressed because axial heat flow by conduction is a secondary effect. All analyses assume a constant waste flow velocity of 1.83 m/s (6 ft/s) and an infinite heat sink of the soil at 0.8 °C (33.5 °F). Hot water inlet temperatures of 10.0, 37.8, 65.6, and 93.3 °C (50, 100, 150, and 200 °F), were evaluated for both pipe geometries considered. Hence, a total of eight cases were run.

3.2.1 Transient Heat Transfer Model

Transient heat transfer analyses were made with the commercial finite element program ANSYS™ (ANSYS, 1998). The ANSYS computer program is a large-scale multi-purpose finite element program, which may be used for solving several classes of engineering analysis, including steady-state and transient heat transfer problems. ANSYS has been used at the Hanford Site since 1975 and is recognized worldwide as one of the most widely used and capable programs of its type.

Figure 4 shows the schematic of finite element model used here (model shown has 5.08 cm [2 in.] of insulation). This model is an axisymmetric model, with symmetry about the "Y" axis. The "Y" direction represents the length of the pipeline. This total length of 2133 m (7,000 ft) is divided in nine segments, each being 237 m (777 ft). The "X" direction represents the radial directions from the center of the pipe to outer diameter of the insulation. Figure 4 gives both the node numbers and the material type numbers.

Three different types of elements are used in this model: (1) a thermal-fluid pipe (FLUID116), (2) a two-dimensional thermal solid (PLANE55), and (3) a radiation link (LINK31).

The thermal-fluid pipe element was used to model the fluid within the primary confinement pipe and provides for the radial heat transfer to the inner pipe wall. This element is a three-dimensional element with the ability to conduct heat and transmit fluid between its two primary nodes. Heat flow is caused by the conduction within the fluid and the mass transport of the fluid. Convection to neighboring nodes is accounted for by the use of the film coefficient, which is related to the fluid-flow rate and material properties at the relevant temperature. This element has the ability to calculate flow rate based on pressure head and hydraulic parameters; however, for this model, a constant flow rate of 1.83 m/s (6 ft/s) was specified. Cross-sectional area and hydraulic diameter also were specified. Although this element simulates fluid within a pipe, the condition of air ahead of the fluid front needed to be modeled. This was done by the specification of a pseudo, temperature-dependent, film coefficient to simulate the water-air interface. This required a manually iterative mode to check for reasonable results; i.e., correct location of the discontinuity at given times.

The two-dimensional thermal solid elements were used as axisymmetric ring elements that represented the thermal conduction in both pipe walls, in the air gap, and in the insulation. This four-node element has the single degree of freedom (i.e., temperature) at each node. The radiation link element was used to model the radiation heat transfer across the annular gap. For this element, the emissivity, form factors and areas were specified.

The fluid (waste) within the primary confinement pipe was modeled with thermal-fluid elements, with material number = 1, located between nodes 1 and 10 (at x = 0 location) on Figure 4. Convective links are between nodes 1 through 10 with corresponding nodes 11-20 on the pipe inner surface. The primary confinement pipe is represent by two-dimensional thermal solid elements with material number = 2. These element types with material number = 3 represents

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the air gap (effective conductivity). Two-dimensional thermal solid elements with material number = 4 were used to model the secondary confinement pipe. The insulation was modeled with two-dimensional thermal solid elements with material number = 6. Thermal radiation was model with the radiation link element, material number 5.

The ANSYS input listing, for the case with 5.08 cm (2 in.) of insulation and an inlet temperature of 93.3 °C (200 °F), can be found in Appendix C. Only minor modifications to this listing were required for the other cases and, hence, their listings were not included. All input and results data are currently stored electronically in the directory: cea6.rl.gov:/tmp/slh/piping.

3.2.2 Transient Model Input

Model input include the specification of the pipe inlet temperature (time-dependent temperature boundary conditions boundary conditions on node 1 and 11), and the soil temperature on the outside of the insulation (boundary conditions on nodes 51 – 60).

Material properties used were nominal values and included those given in Table 1. Additional properties, not included in Table 1, include the thermal conductivity and viscosity of the waste, the densities, thermal conductivities and specific heat of the steel pipe materials, and the density and specific heat of insulation. These sometime temperature-dependent properties can be found in the ANSYS input listing given in Appendix C.

3.2.3 Transient Analysis Result

[Note: For the transient analysis, cases were numbered with the following convention: XtYYY; where for X specifies the insulation design as related to the steady-state case numbers 1 – 3, i.e., an X = 1 indicates 5.08 cm (2 in.) of insulation, and X = 2 indicates 2.54 cm (1 in.). YYY is the inlet temperature.]

Temperature time histories of the primary confinement pipe inner wall at various locations along its length are given in Figures 5 through 12 for the eight cases analyzed.[2] Figure 13 shows temperature contours during the transient for case 1t200, at time snapshot from 0.163 to 0.582 hour. Figures 14 through 17 give the times required to heat up to within 1.11 °C (2 °F) to 11.1 °C (20 °F) of the steady-state temperatures for the case of 5.08 cm (2 in.) of insulation (Only the case of 5.08 cm [2 in.] of insulation is given as it is the most conservative; i.e., it gives slightly longer times – see Section 3.2.4). Interpolating between these figures (for inlet temperature) and lines (for length) will provide results for any conditions within the range of the analyses. These results are approximate when used for pipelines of length less than the 2133 m (7,000 ft) analyzed.

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[2] Conversion factor for Figures 5 through 12: T(°C) = (T[°F]-32)/1.8.

3.2.4 Discussion of Transient Analysis Results

A slight error may be expected in the time and curvature of the initial temperature rise because of the method of simulating the air to water boundary and the coarseness of the finite element mesh. However, parametric studies have shown no affect on the temperature response because of these parameter choices after 50% of the temperature difference is obtained. Hence, the choices of parameters are not expected to affect the predicted heat-up durations given in Figures 14 through 17.

The results given in Figures 5 through 12 show little difference in the thermal response between cases with 2.54 cm (1 in.) or 5.08 cm (2 in.) of insulation. This is probably because the air gap provides "dynamic resistance" and for short time periods when the thermal inertia of the inner pipe is the dominate parameter in the thermal behavior. Therefore, it takes shorter times for the inner pipe temperatures to approach its steady-state values for pipes with less insulation, because their steady-state temperatures are lower.

The amount of preheated water required to heat piping to its desired temperature can be determined from Figures 14 through 17 as show in the examples given in Table 3.

Table 3. Amount of Preheated Water and Time Needed to Heat a 1830 m (6,000-ft) Section of Pipe Assuming 5.08 cm (2 in.) of Insulation and Initial Temperature of 0.8 °C (33.5 °F).

Temperature difference from steady state based on preheated water temperature °C (°F)	Preheated water temperature °C (°F)	Time required (hours)	Volume of preheated water required liters (gallons)
2.78 (5)	65.6 (150)	1.01	32,200 (8,510)
11.1 (20)	65.6 (150)	0.48	15,300 (4,030)
2.78 (5)	37.8 (100)	0.62	19,700 (5,210)
11.1 (20)	37.8 (100)	0.38	12,100 (3,190)

Although the time required to come to "near" steady-state condition may require several hours for cases of long pipelines and large temperature changes, the bulk of the temperature change (~ 90% of the ΔT) occurs, in all cases evaluated, within the first 30 minutes or so. Here, it may be beneficial to preheat the heat-up water to slightly above the desired inlet temperature, to achieve the desired preheated pipe temperature in a relatively short period of time. It may also be beneficial to use flow rates other than the 1.83 m/s (6 ft/s) analyzed.

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Figure 1. Schematic of Steady-State Heat Transfer Model;
(a) Radial Direction, (b) Axial Direction.

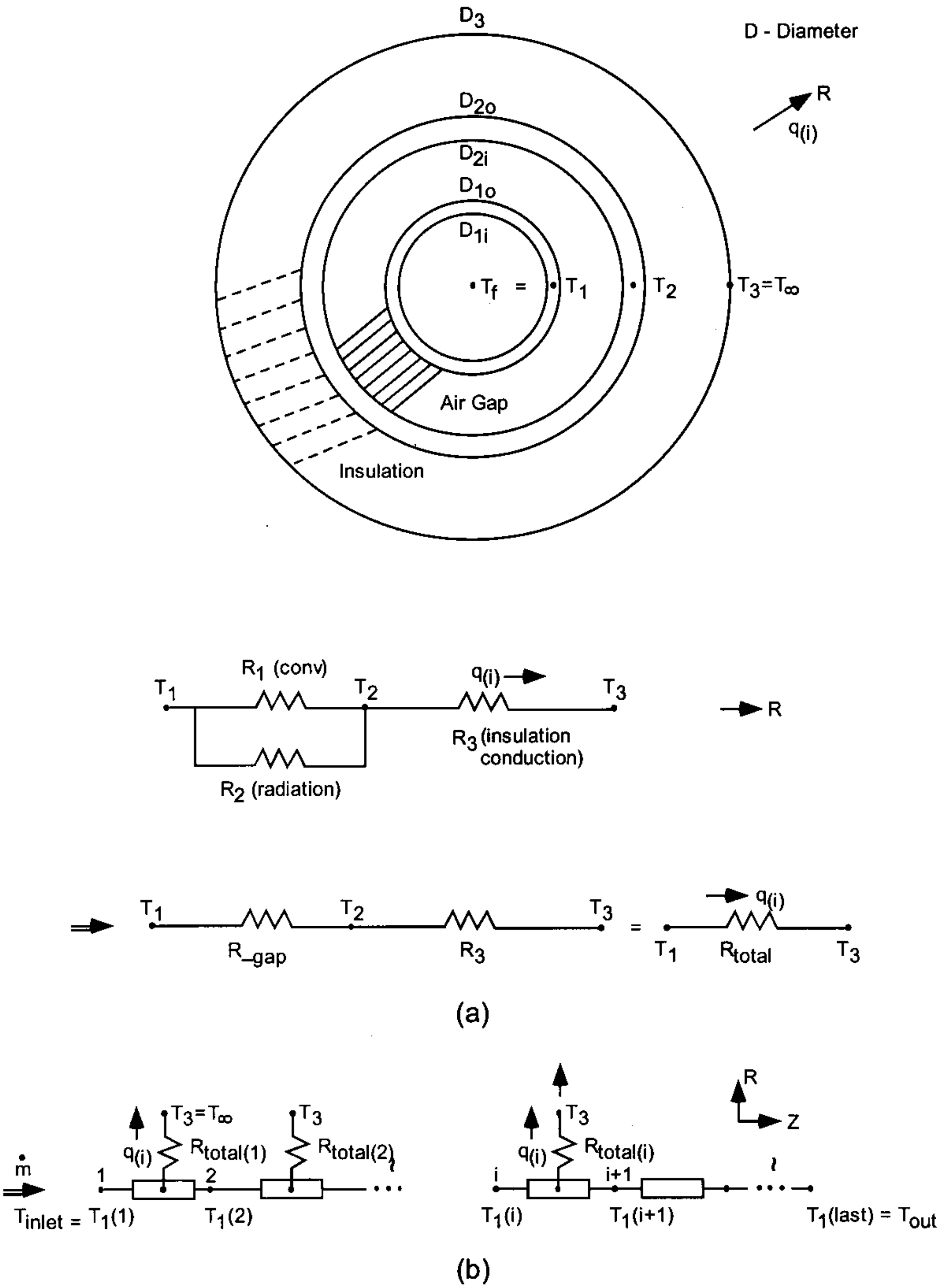


Figure 2. Waste Temperature Drop in Double-Shell Tank Transfer Piping.

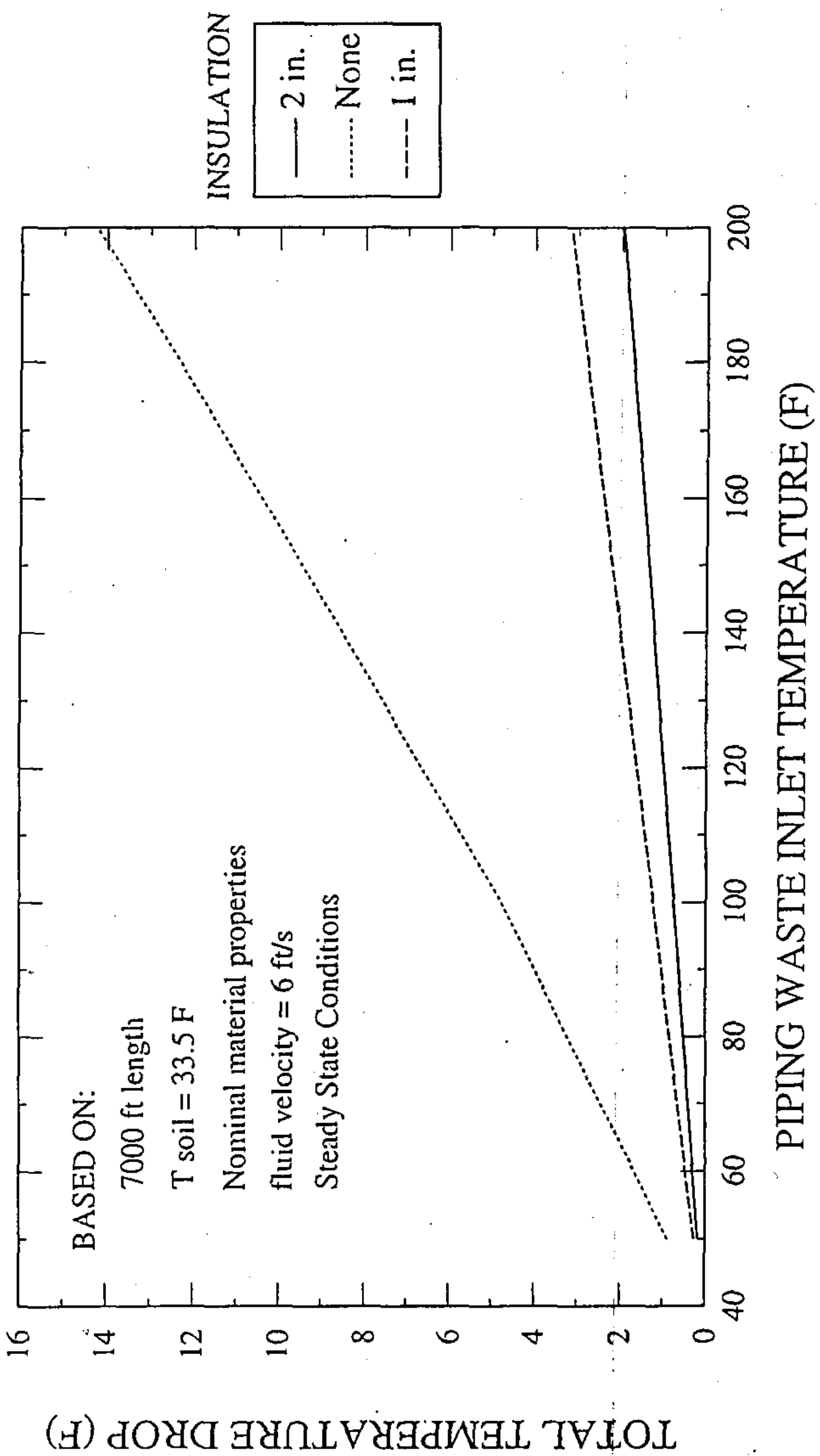


Figure 3. Double-Shell Tank Transfer Piping Heat Loss.

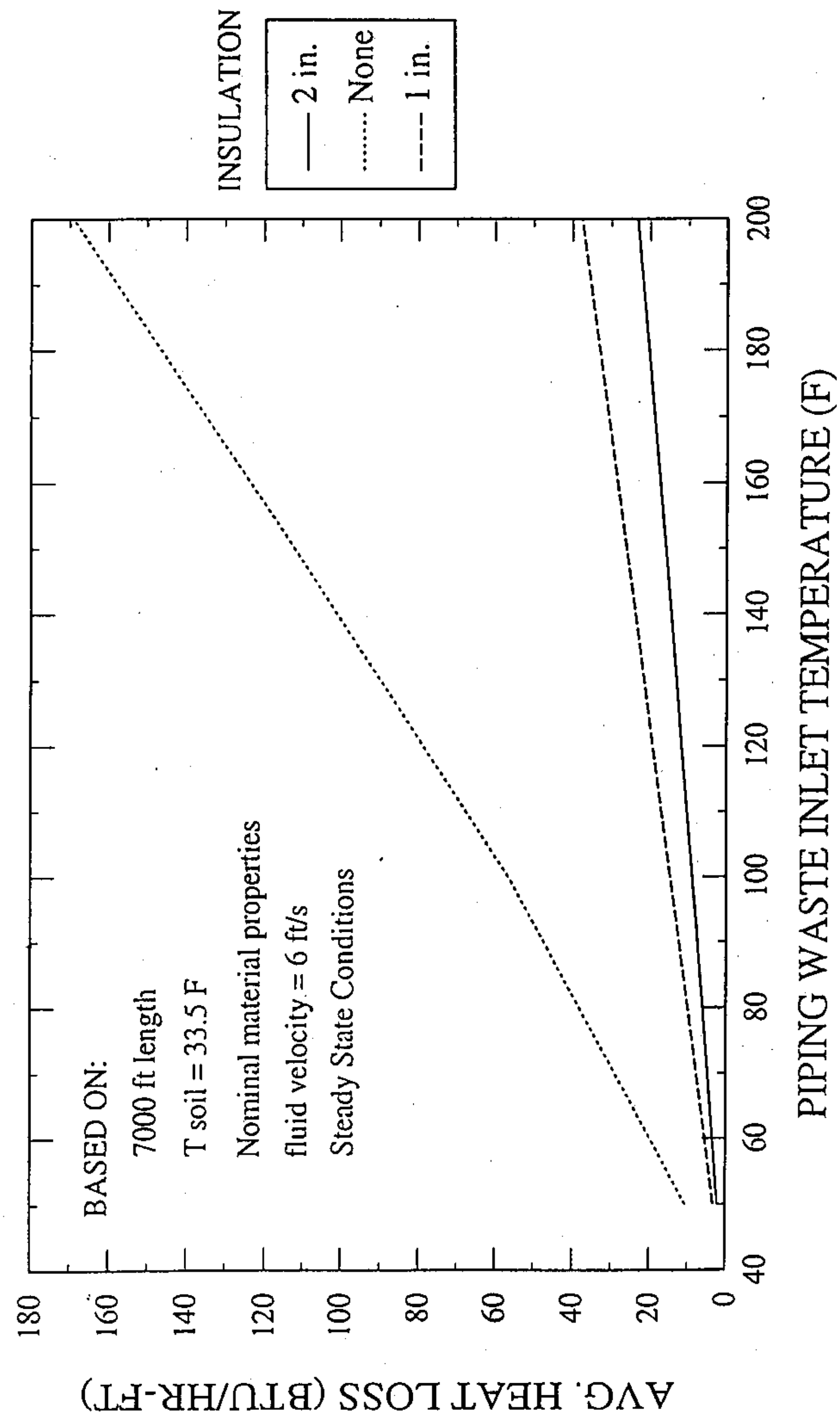
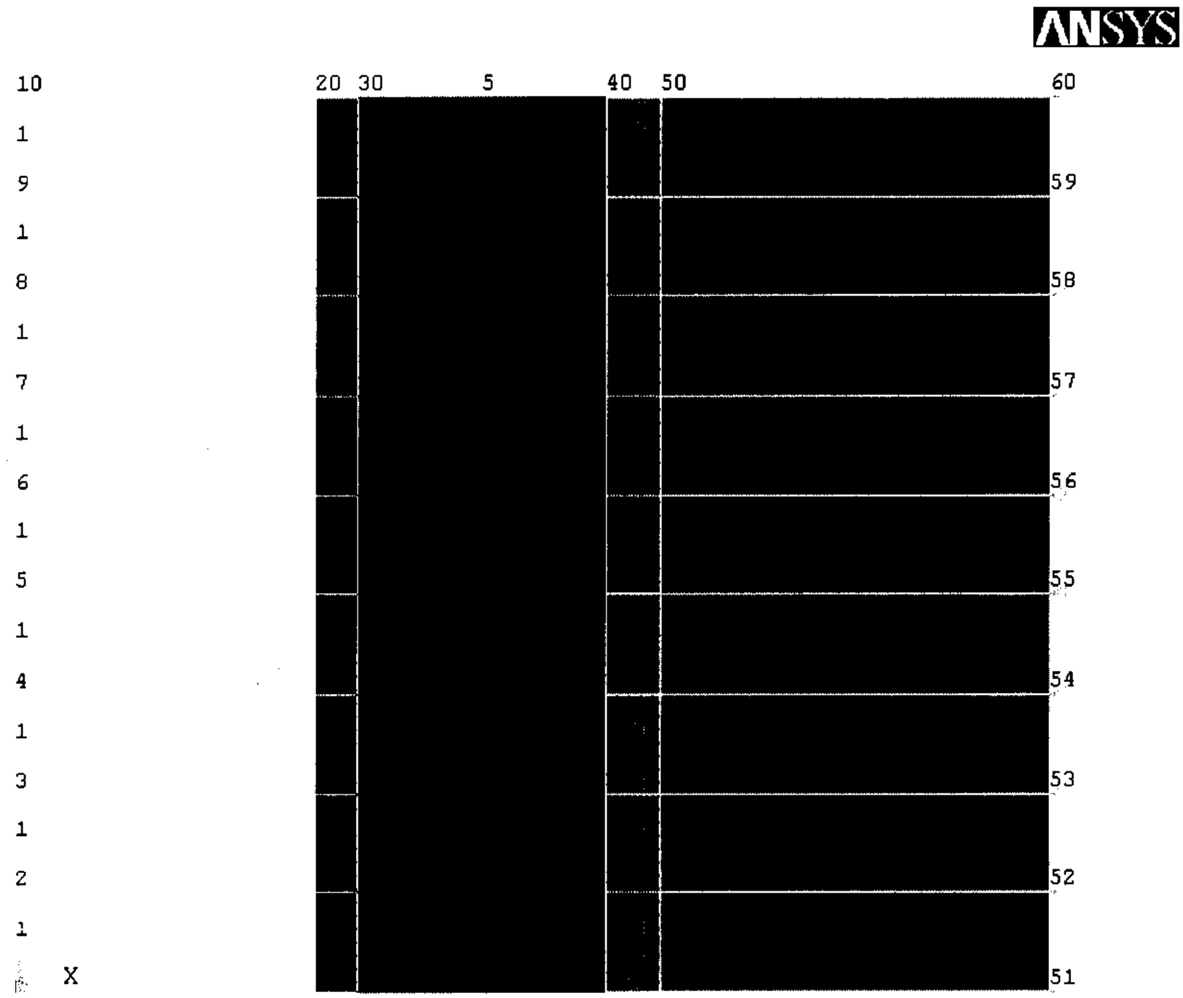


Figure 4. Mesh of Finite Element Model for Thermal Transient of Double-Shell Tank Piping.



DST TRANSFER PIPE - THERMAL TRANSIENT - case 1t200 2 in. insulation

Figure 5. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 1t50: 5.08 cm [2 in.] of insulation and 10 °C [50 °F] inlet water)

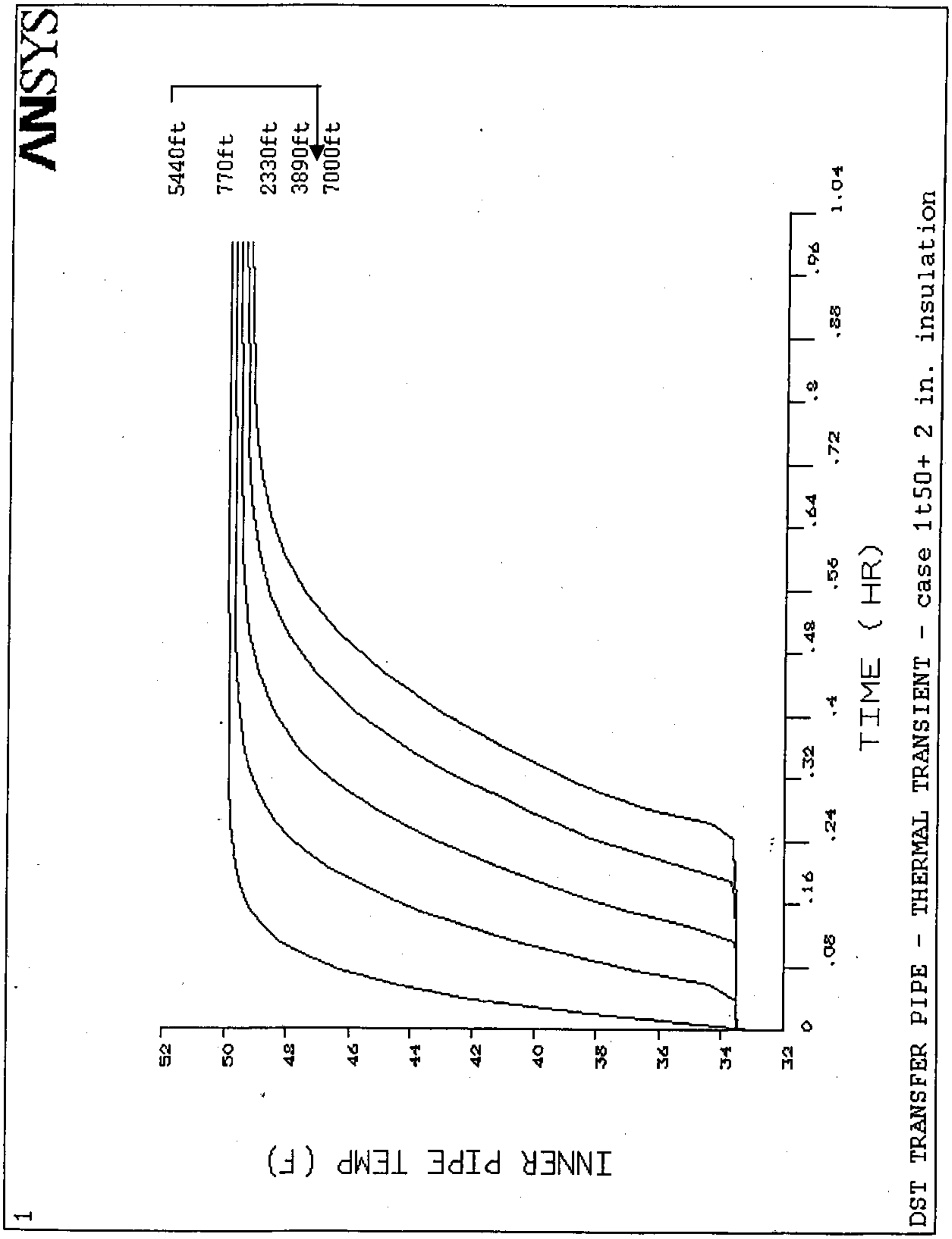


Figure 6. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 1t100: 5.08 cm [2 in.] of insulation and 37.8 °C [100 °F] inlet water)

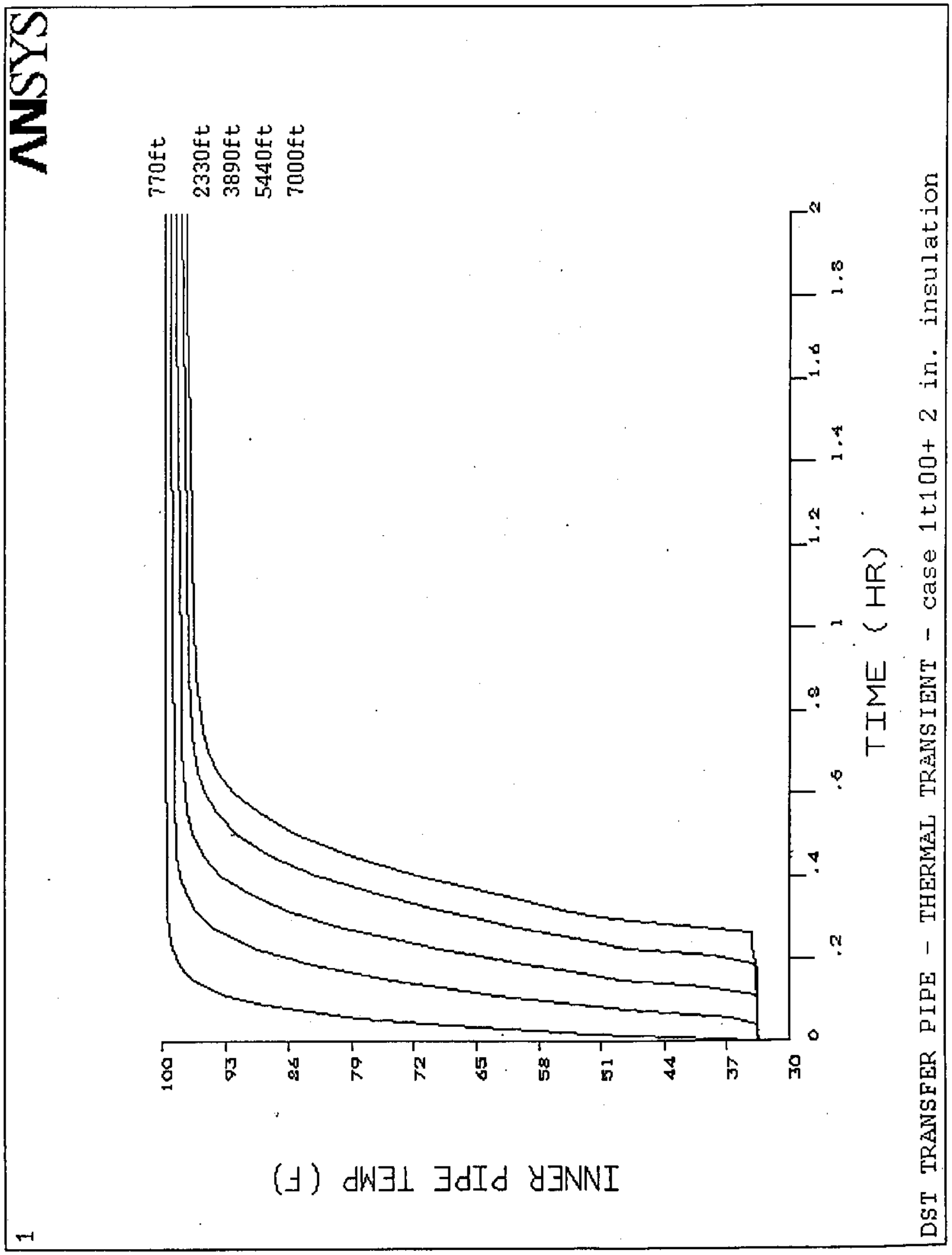


Figure 7. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 1t150: 5.08 cm [2 in.] of insulation and 65.6 °C [150 °F] inlet water)

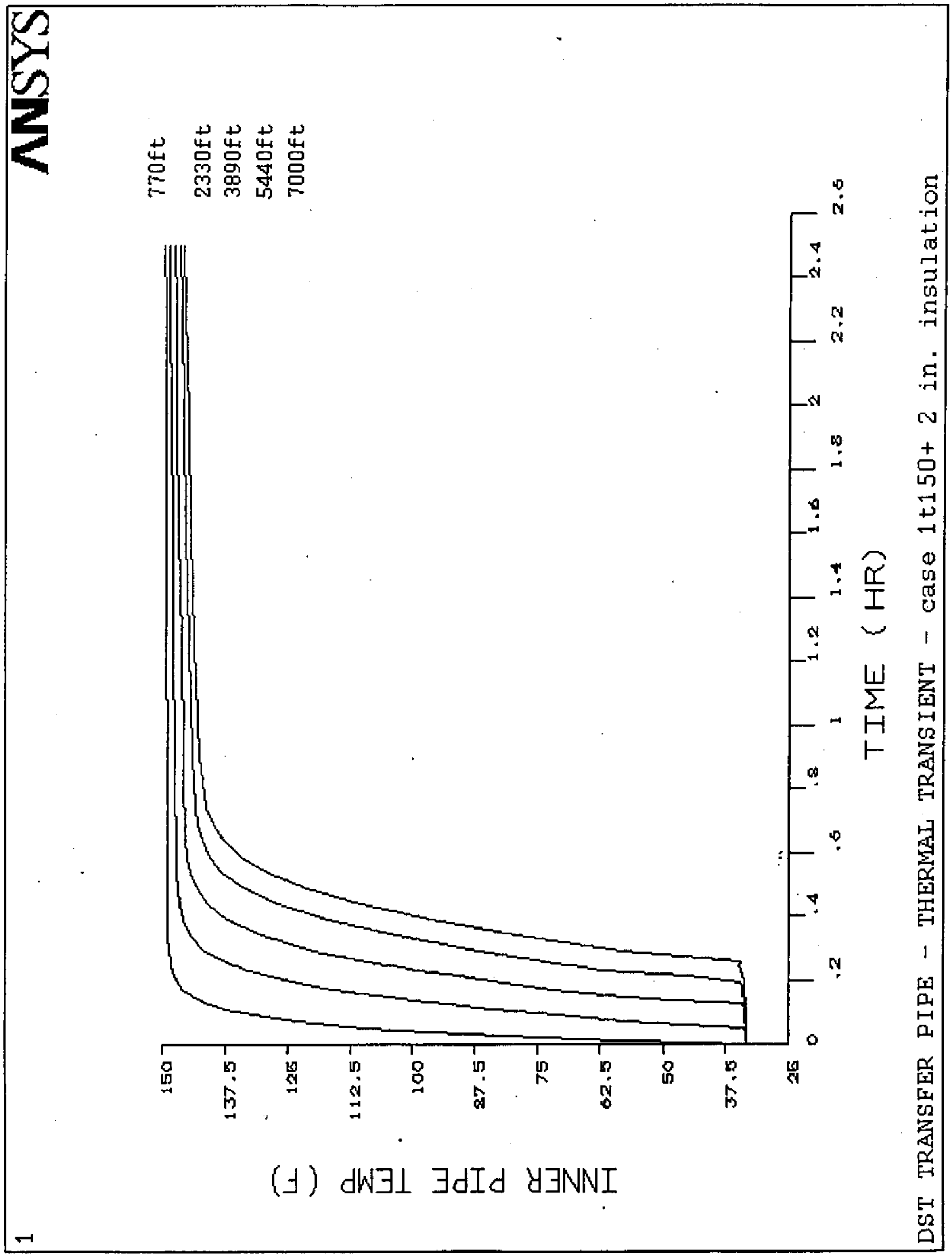


Figure 8. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 1t200: 5.08 cm [2 in.] of insulation and 93.3 °C [200 °F] inlet water)

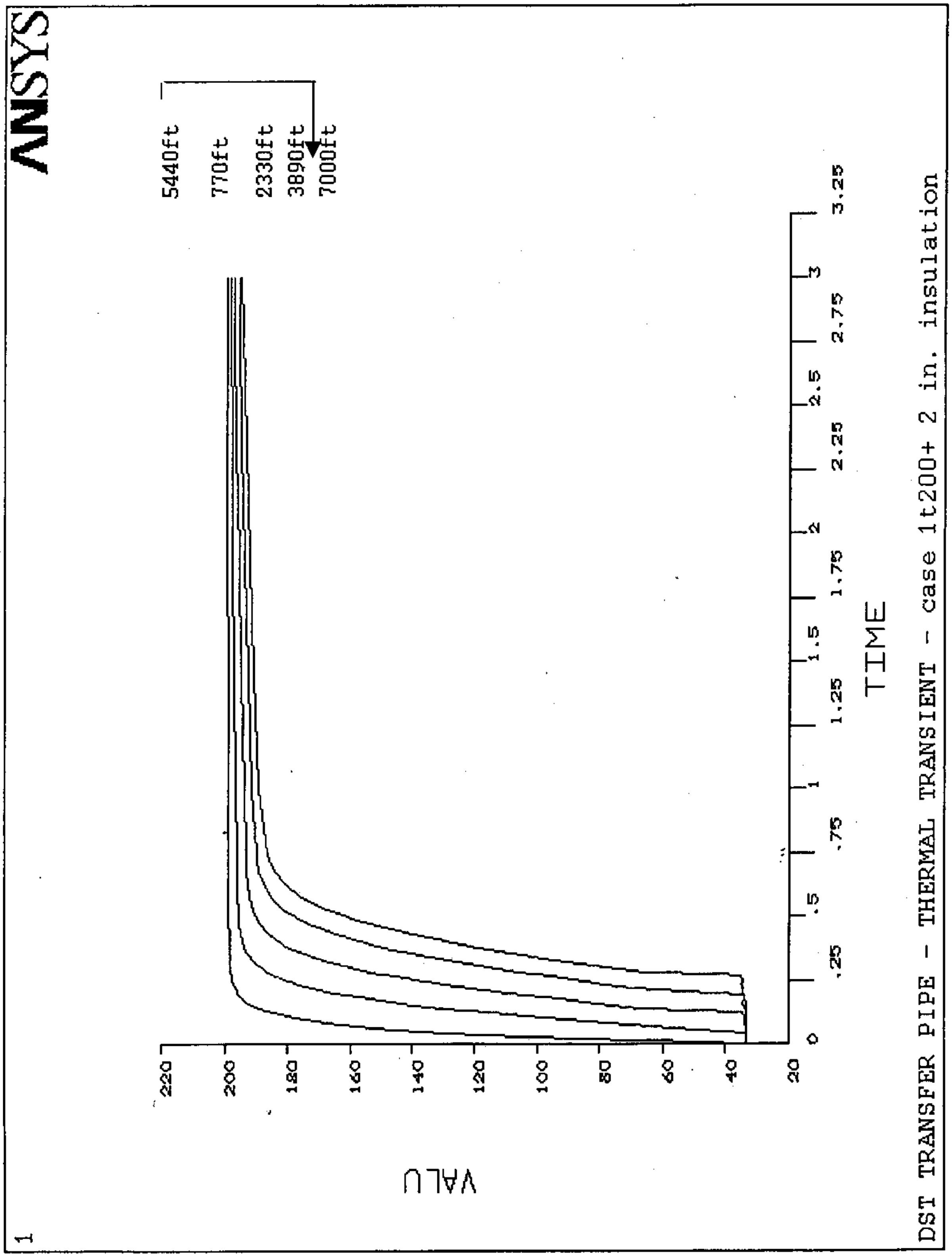


Figure 9. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 2t50: 2.54 cm [1 in.] of insulation and 10 °C [50 °F] inlet water)

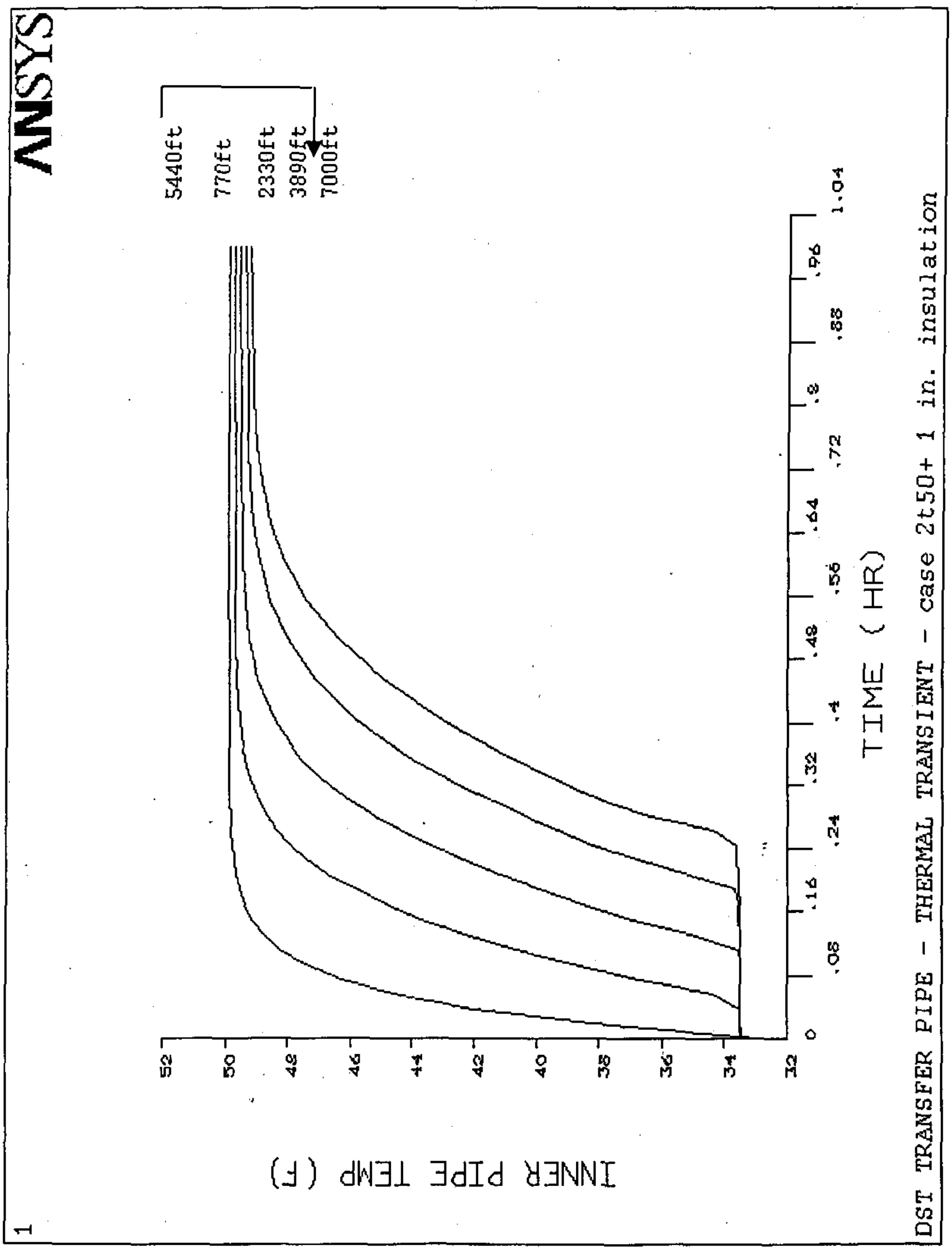


Figure 10. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 2t100: 2.54 cm [1 in.] of insulation and 37.8 °C [100 °F] inlet water)

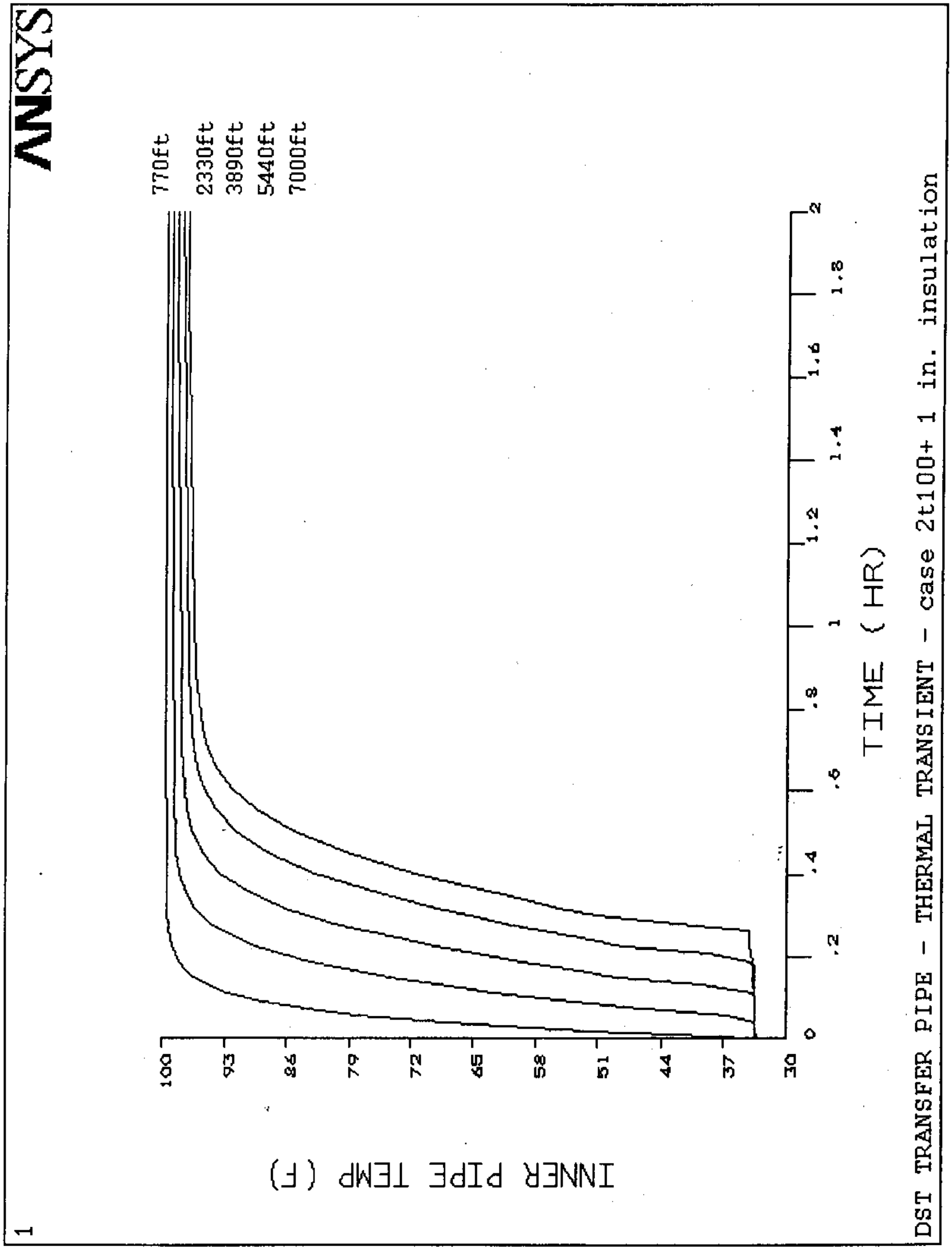


Figure 11. Transient Thermal Response of the Primary Confinement Pipe Inner Wall.
(Case 2t150: 2.54 cm [1 in.] of insulation and 65.6 °C [150 °F] inlet water)

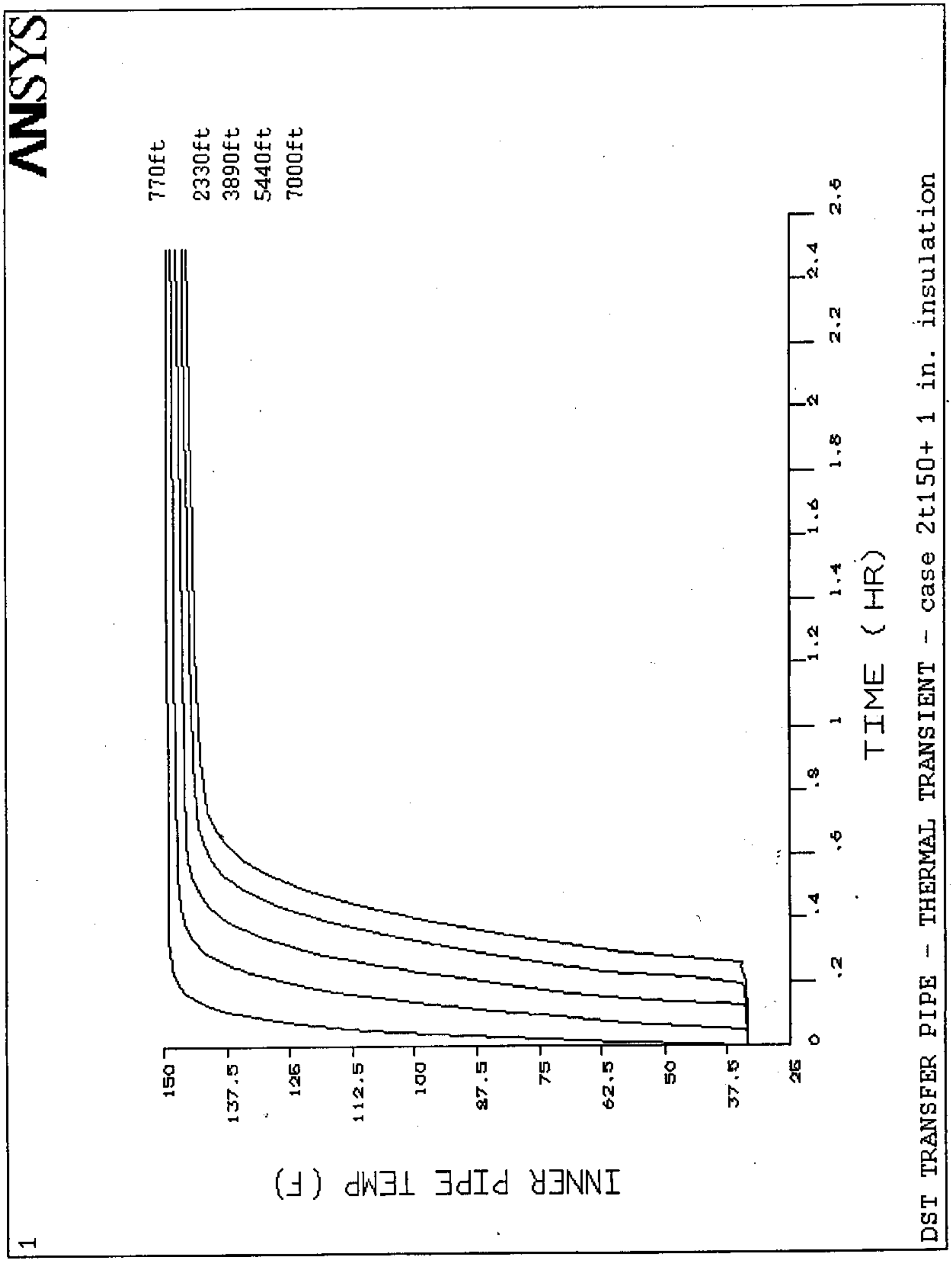


Figure 12. Transient Thermal Response of the Primary Confinement Pipe Inner Wall. (Case 2t200: 2.54 cm [1 in.] of insulation and 93.3 °C [200 °F] inlet water)

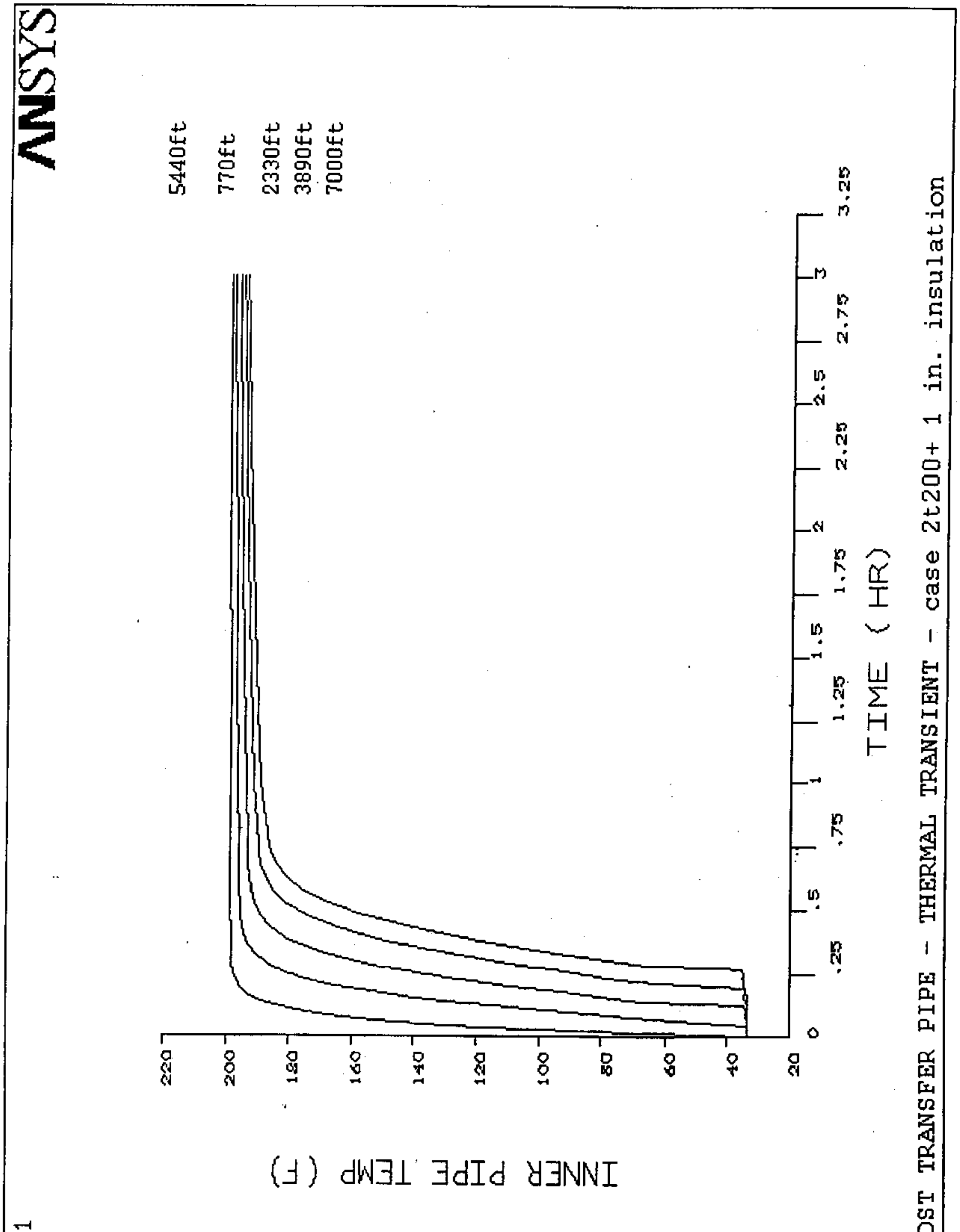
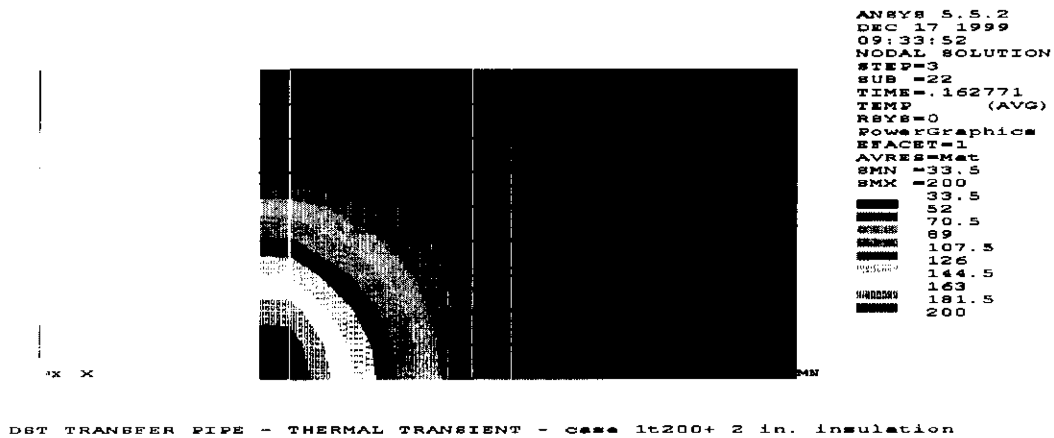
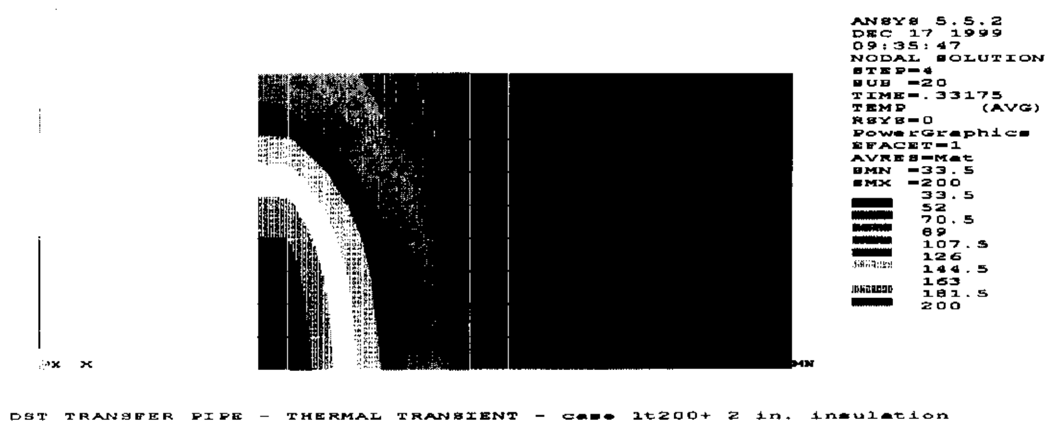


Figure 13. Temperature Profile During Heat-Up Transient: 5.08 cm (2-in.) Insulation, 93.3 °C (200 °F) Inlet Top: time = 0.162 h; Middle: time = 0.332 h; Bottom: time = 0.582 h.





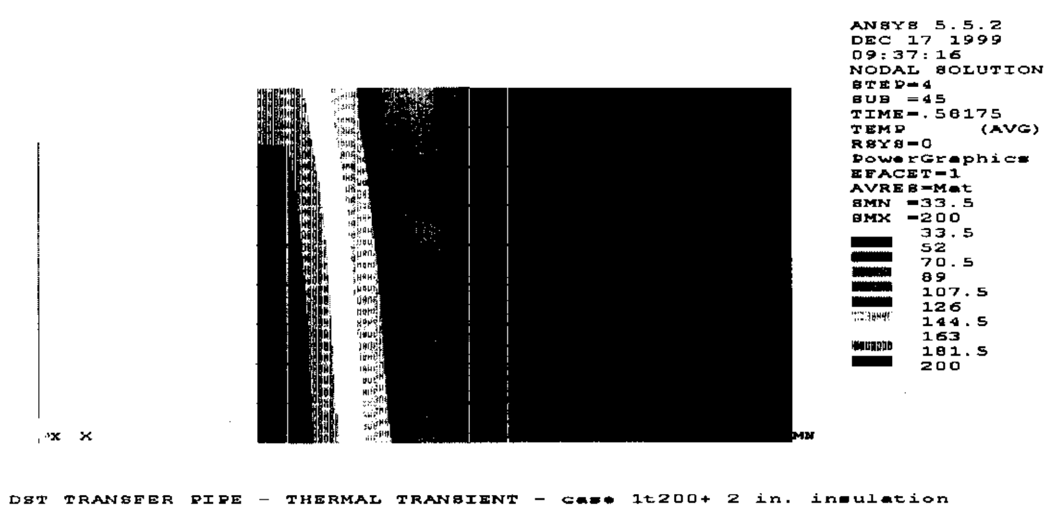


Figure 14. Double-Shell Tank Piping -- Inner Pipe Heat-Up Times: 93.3 °C (200 °F) Inlet Temperature.

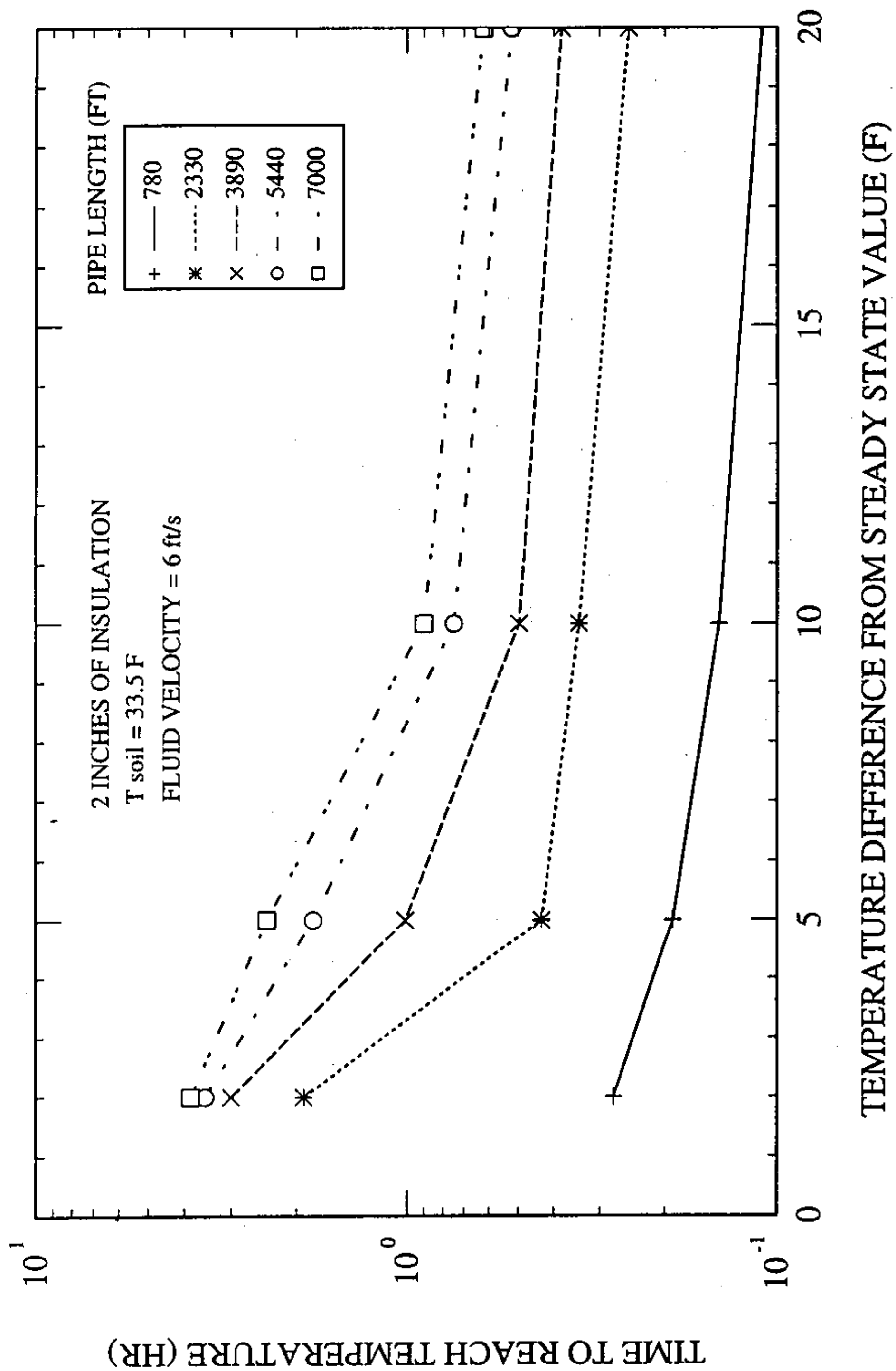


Figure 15. Double-Shell Tank Piping – Inner Pipe Heat-Up Times:
65.6 °C (150 °F) Inlet Temperature.

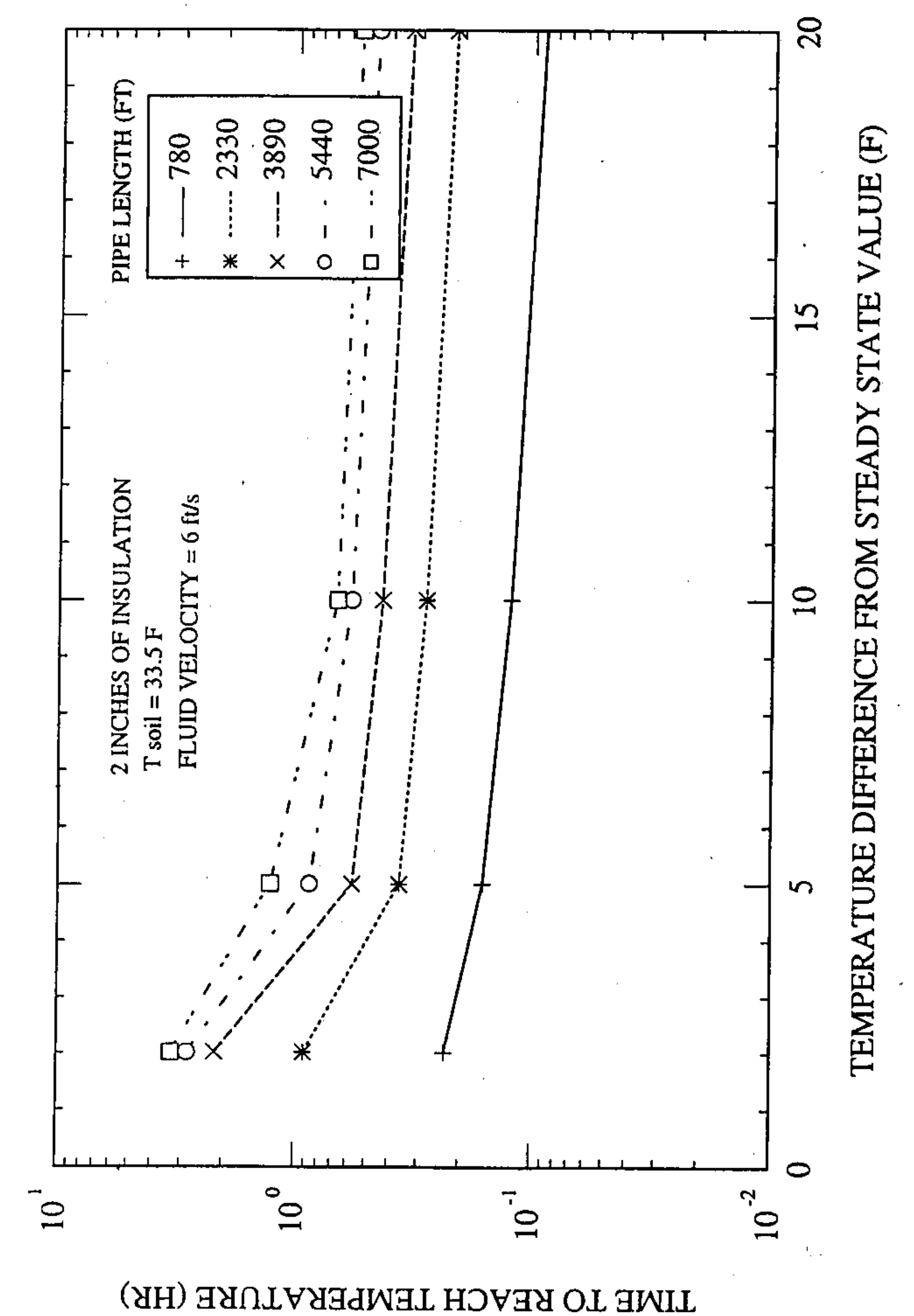


Figure 16. Double-Shell Tank Piping – Inner Pipe Heat-Up Times: 37.8 °C (100 °F) Inlet Temperature.

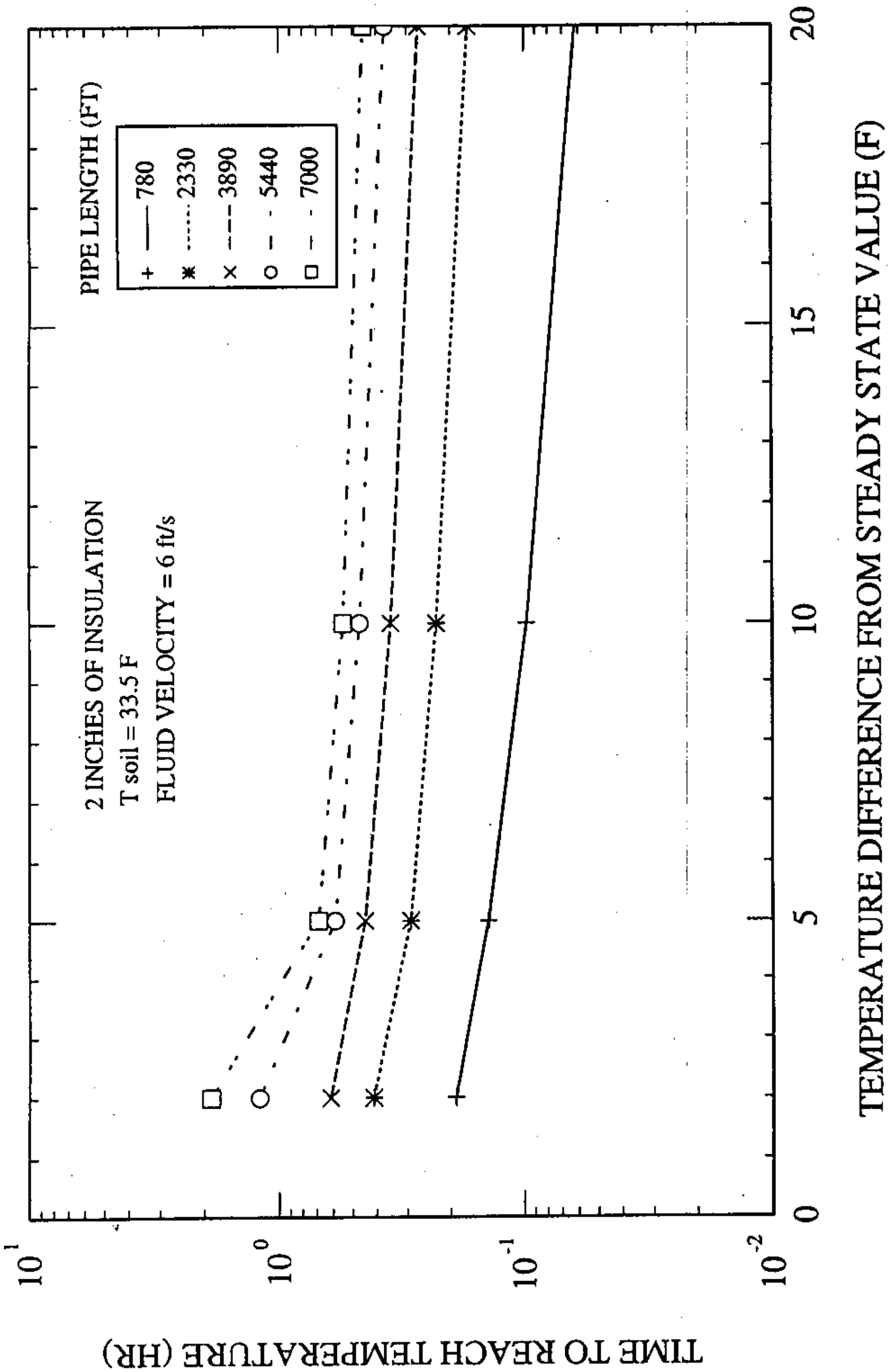
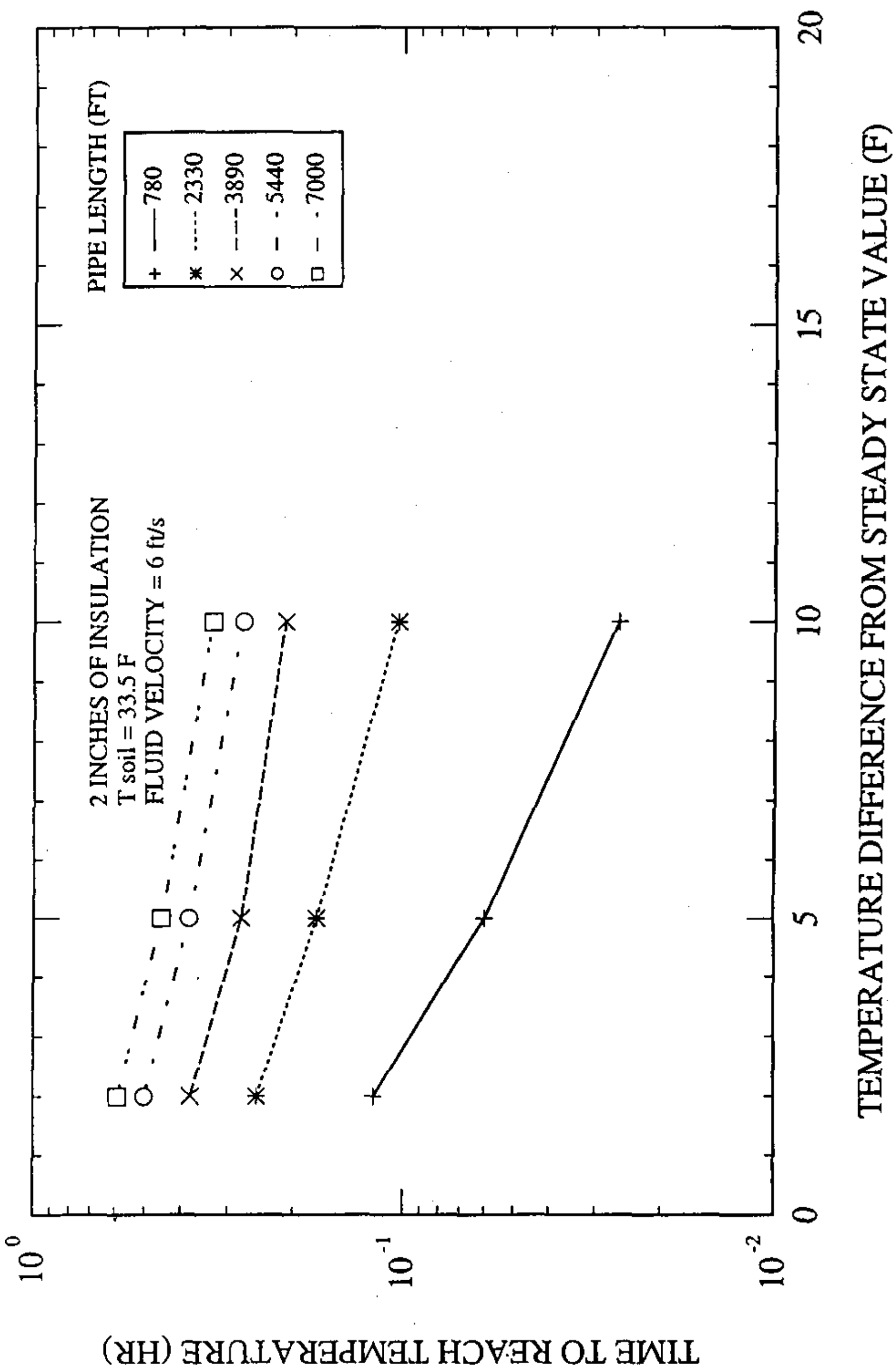


Figure 17. Double-Shell Tank Piping – Inner Pipe Heat-Up Times:
10.0 °C (50 °F) Inlet Temperature.



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APPENDIX A

RESULTS OF STEADY-STATE ANALYSIS (DPIPEHT OUTPUT)

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```
1       TEMPERATURE DROP IN TRANSFER PIPE
      3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

      Case 1; Base case 2 in. insulation - nominal properties



      Pipe length =7000.0 ft
         10 calculational nodes are used

      Pipe inlet temperature is  200.0 F
      Soil temperature is  33.5 F

      Fluid velocity = 21600.0 ft/hr

      Fluid properties
           specific heat =  1.00 Btu/lbm-F
           wt. density = 74.9 lb/ft^3

      Emmisivities: outer, inner =0.800 and 0.290 respectively

      Outer insulation properties:
           thickness = 0.167 ft
           thermal conductivty=   0.013 Btu/hr-ft-F


 *****  RESULTS  *****

      location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

            700.00      199.80         -0.164E+05
           1400.00      199.60         -0.164E+05
           2100.00      199.41         -0.164E+05
           2800.00      199.21         -0.164E+05
           3500.00      199.01         -0.163E+05
           4200.00      198.82         -0.163E+05
           4900.00      198.62         -0.163E+05
           5600.00      198.42         -0.163E+05
           6300.00      198.23         -0.163E+05
           7000.00      198.03         -0.162E+05


      The total heat loss is -0.163E+06 Btu/hr

      The average heat loss per foot is  -23.3 Btu/hr
```

```
1      TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 2; 1 in. insulation - nominal properties



     Pipe length =7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is  200.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 74.9 lb/ft^3

     Emmisivities: outer, inner =0.800 and 0.290 respectively

     Outer insulation properties:
          thickness = 0.083 ft
          thermal conductivty=   0.013 Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

          700.00       199.68         -0.265E+05
         1400.00       199.36         -0.265E+05
         2100.00       199.04         -0.264E+05
         2800.00       198.73         -0.264E+05
         3500.00       198.41         -0.263E+05
         4200.00       198.09         -0.263E+05
         4900.00       197.78         -0.262E+05
         5600.00       197.46         -0.262E+05
         6300.00       197.15         -0.261E+05
         7000.00       196.83         -0.261E+05


     The total heat loss is -0.263E+06 Btu/hr

     The average heat loss per foot is  -37.6 Btu/hr
```

```
1      TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 3; no insulation - nominal properties



     Pipe length = 7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is 200.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 74.9 lb/ft^3

     Emmisivities: outer, inner =0.800 and 0.290 respectively

     Outer insulation properties:
          thickness = 0.0000 ft
          thermal conductivty=******** Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

           700.00       198.50          -0.125E+06
          1400.00       197.01          -0.123E+06
          2100.00       195.55          -0.122E+06
          2800.00       194.10          -0.120E+06
          3500.00       192.66          -0.119E+06
          4200.00       191.25          -0.118E+06
          4900.00       189.85          -0.116E+06
          5600.00       188.47          -0.115E+06
          6300.00       187.10          -0.114E+06
          7000.00       185.75          -0.112E+06


     The total heat loss is -0.118E+07 Btu/hr

     The average heat loss per foot is -169.1 Btu/hr
```

1 TEMPERATURE DROP IN TRANSFER PIPE
3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

Case 4; Base case design 2 in. insulation - nominal properties

Pipe length = 7000.0 ft
10 calculational nodes are used

Pipe inlet temperature is 150.0 F
Soil temperature is 33.5 F

Fluid velocity = 21600.0 ft/hr

Fluid properties
specific heat = 1.00 Btu/lbm-F
wt. density = 74.9 lb/ft^3

Emmisivities: outer, inner =0.800 and 0.290 respectively

Outer insulation properties:
thickness = 0.1670 ft
thermal conductivty= 0.0125 Btu/hr-ft-F

***** RESULTS *****

location (ft)	fluid temp (F)	heat loss-section (Btu/hr)
700.00	149.86	-0.113E+05
1400.00	149.73	-0.113E+05
2100.00	149.59	-0.113E+05
2800.00	149.46	-0.113E+05
3500.00	149.32	-0.112E+05
4200.00	149.19	-0.112E+05
4900.00	149.05	-0.112E+05
5600.00	148.92	-0.112E+05
6300.00	148.78	-0.112E+05
7000.00	148.65	-0.112E+05

The total heat loss is -0.112E+06 Btu/hr

The average heat loss per foot is -16.0 Btu/hr

```
1      TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 5; no insulation - nominal properties



     Pipe length = 7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is 150.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 74.9 lb/ft^3

     Emmisivities: outer, inner =0.800 and 0.290 respectively

     Outer insulation properties:
          thickness = 0.0000 ft
          thermal conductivty=******** Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

          700.00       149.01          -0.823E+05
         1400.00       148.03          -0.814E+05
         2100.00       147.06          -0.806E+05
         2800.00       146.10          -0.797E+05
         3500.00       145.15          -0.788E+05
         4200.00       144.21          -0.780E+05
         4900.00       143.28          -0.772E+05
         5600.00       142.36          -0.763E+05
         6300.00       141.45          -0.755E+05
         7000.00       140.55          -0.747E+05


     The total heat loss is -0.785E+06 Btu/hr

     The average heat loss per foot is -112.1 Btu/hr
```

```
1       TEMPERATURE DROP IN TRANSFER PIPE
      3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

      Case 6; Base case design: 2 in. insulation - nominal properties



      Pipe length = 7000.0 ft
         10 calculational nodes are used

      Pipe inlet temperature is 100.0 F
      Soil temperature is  33.5 F

      Fluid velocity = 21600.0 ft/hr

      Fluid properties
           specific heat =  1.00 Btu/lbm-F
           wt. density = 74.9 lb/ft^3

      Emmisivities: outer, inner =0.800 and 0.290 respectively

      Outer insulation properties:
           thickness = 0.1670 ft
           thermal conductivty=  0.0125 Btu/hr-ft-F


 *****  RESULTS  *****

      location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

            700.00       99.92         -0.627E+04
           1400.00       99.85         -0.626E+04
           2100.00       99.77         -0.625E+04
           2800.00       99.70         -0.625E+04
           3500.00       99.62         -0.624E+04
           4200.00       99.55         -0.623E+04
           4900.00       99.47         -0.622E+04
           5600.00       99.40         -0.622E+04
           6300.00       99.32         -0.621E+04
           7000.00       99.25         -0.620E+04


      The total heat loss is -0.624E+05 Btu/hr

      The average heat loss per foot is   -8.9 Btu/hr
```

```
1      TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 7; no insulation - nominal properties



     Pipe length = 7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is 100.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 74.9 lb/ft^3

     Emmisivities: outer, inner =0.800 and 0.290 respectively

     Outer insulation properties:
          thickness = 0.0000 ft
          thermal conductivty=******** Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

          700.00        99.50          -0.412E+05
         1400.00        99.01          -0.408E+05
         2100.00        98.53          -0.405E+05
         2800.00        98.04          -0.401E+05
         3500.00        97.56          -0.397E+05
         4200.00        97.09          -0.394E+05
         4900.00        96.62          -0.390E+05
         5600.00        96.15          -0.387E+05
         6300.00        95.69          -0.383E+05
         7000.00        95.24          -0.380E+05


     The total heat loss is -0.396E+06 Btu/hr

     The average heat loss per foot is  -56.5 Btu/hr
```

1 TEMPERATURE DROP IN TRANSFER PIPE
3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

Case 8; Base case design: 2 in. insulation - nominal properties

Pipe length = 7000.0 ft
10 calculational nodes are used

Pipe inlet temperature is 50.0 F
Soil temperature is 33.5 F

Fluid velocity = 21600.0 ft/hr

Fluid properties
specific heat = 1.00 Btu/lbm-F
wt. density = 74.9 lb/ft^3

Emmisivities: outer, inner =0.800 and 0.290 respectively

Outer insulation properties:
thickness = 0.1670 ft
thermal conductivty= 0.0125 Btu/hr-ft-F

***** RESULTS *****

location (ft)	fluid temp (F)	heat loss-section (Btu/hr)
700.00	49.98	-0.146E+04
1400.00	49.96	-0.146E+04
2100.00	49.95	-0.146E+04
2800.00	49.93	-0.146E+04
3500.00	49.91	-0.146E+04
4200.00	49.89	-0.146E+04
4900.00	49.88	-0.145E+04
5600.00	49.86	-0.145E+04
6300.00	49.84	-0.145E+04
7000.00	49.82	-0.145E+04

The total heat loss is -0.146E+05 Btu/hr

The average heat loss per foot is -2.1 Btu/hr

```
1       TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 9; no insulation - nominal properties



     Pipe length = 7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is  50.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 74.9 lb/ft^3

     Emmisivities: outer, inner =0.800 and 0.290 respectively

     Outer insulation properties:
          thickness = 0.0000 ft
          thermal conductivty=******** Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

           700.00        49.91          -0.761E+04
          1400.00        49.82          -0.757E+04
          2100.00        49.73          -0.752E+04
          2800.00        49.64          -0.747E+04
          3500.00        49.55          -0.742E+04
          4200.00        49.46          -0.737E+04
          4900.00        49.37          -0.732E+04
          5600.00        49.28          -0.728E+04
          6300.00        49.20          -0.723E+04
          7000.00        49.11          -0.718E+04


     The total heat loss is -0.740E+05 Btu/hr

     The average heat loss per foot is  -10.6 Btu/hr
```

```
1      TEMPERATURE DROP IN TRANSFER PIPE
      3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

      Case 10; 1 in. insulation - nominal properties



      Pipe length = 7000.0 ft
         10 calculational nodes are used

      Pipe inlet temperature is  50.0 F
      Soil temperature is  33.5 F

      Fluid velocity = 21600.0 ft/hr

      Fluid properties
           specific heat =  1.00 Btu/lbm-F
           wt. density = 74.9 lb/ft^3

      Emmisivities: outer, inner =0.800 and 0.290 respectively

      Outer insulation properties:
           thickness = 0.0833 ft
           thermal conductivty=  0.0125 Btu/hr-ft-F


 *****  RESULTS  *****

      location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

            700.00       49.97         -0.225E+04
           1400.00       49.95         -0.225E+04
           2100.00       49.92         -0.224E+04
           2800.00       49.89         -0.224E+04
           3500.00       49.86         -0.224E+04
           4200.00       49.84         -0.223E+04
           4900.00       49.81         -0.223E+04
           5600.00       49.78         -0.223E+04
           6300.00       49.76         -0.222E+04
           7000.00       49.73         -0.222E+04


      The total heat loss is -0.223E+05 Btu/hr

      The average heat loss per foot is   -3.2 Btu/hr
```

1 TEMPERATURE DROP IN TRANSFER PIPE
3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

Case 1L; Base case 2 in. insulation - lower bound properties

Pipe length = 7000.0 ft
10 calculational nodes are used

Pipe inlet temperature is 200.0 F
Soil temperature is 33.5 F

Fluid velocity = 21600.0 ft/hr

Fluid properties
specific heat = 1.00 Btu/lbm-F
wt. density = 87.4 lb/ft^3

Emmisivities: outer, inner =0.780 and 0.210 respectively

Outer insulation properties:
thickness = 0.1670 ft
thermal conductivty= 0.0110 Btu/hr-ft-F

***** RESULTS *****

location (ft)	fluid temp (F)	heat loss-section (Btu/hr)
700.00	199.85	-0.144E+05
1400.00	199.70	-0.144E+05
2100.00	199.55	-0.144E+05
2800.00	199.41	-0.144E+05
3500.00	199.26	-0.144E+05
4200.00	199.11	-0.143E+05
4900.00	198.96	-0.143E+05
5600.00	198.81	-0.143E+05
6300.00	198.67	-0.143E+05
7000.00	198.52	-0.143E+05

The total heat loss is -0.143E+06 Btu/hr

The average heat loss per foot is -20.5 Btu/hr

```
1     TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 3L; no  insulation - lower bound properties



     Pipe length = 7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is 200.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 87.4 lb/ft^3

     Emmisivities: outer, inner =0.780 and 0.210 respectively

     Outer insulation properties:
          thickness = 0.0000 ft
          thermal conductivty=******** Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

         700.00       198.83         -0.114E+06
        1400.00       197.66         -0.113E+06
        2100.00       196.51         -0.112E+06
        2800.00       195.37         -0.111E+06
        3500.00       194.24         -0.110E+06
        4200.00       193.12         -0.109E+06
        4900.00       192.00         -0.108E+06
        5600.00       190.90         -0.107E+06
        6300.00       189.81         -0.106E+06
        7000.00       188.73         -0.105E+06


     The total heat loss is -0.109E+07 Btu/hr

     The average heat loss per foot is -156.0 Btu/hr
```

```
1      TEMPERATURE DROP IN TRANSFER PIPE
     3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

     Case 1U; Base case 2 in. insulation - upper bound properties



     Pipe length = 7000.0 ft
        10 calculational nodes are used

     Pipe inlet temperature is 200.0 F
     Soil temperature is  33.5 F

     Fluid velocity = 21600.0 ft/hr

     Fluid properties
          specific heat =  1.00 Btu/lbm-F
          wt. density = 62.4 lb/ft^3

     Emmisivities: outer, inner =0.820 and 0.380 respectively

     Outer insulation properties:
          thickness = 0.1670 ft
          thermal conductivty=  0.0140 Btu/hr-ft-F


 *****  RESULTS  *****

     location (ft)  fluid temp (F)  heat loss-section (Btu/hr)

           700.00       199.73        -0.185E+05
          1400.00       199.47        -0.185E+05
          2100.00       199.20        -0.184E+05
          2800.00       198.93        -0.184E+05
          3500.00       198.67        -0.184E+05
          4200.00       198.40        -0.183E+05
          4900.00       198.14        -0.183E+05
          5600.00       197.88        -0.183E+05
          6300.00       197.61        -0.182E+05
          7000.00       197.35        -0.182E+05


     The total heat loss is -0.183E+06 Btu/hr

     The average heat loss per foot is  -26.2 Btu/hr
```

1 TEMPERATURE DROP IN TRANSFER PIPE
3 inch SHD 40 flow pipe inclosed in a 6 inch SHD40 pipe

Case 3U; no insulation - upper bound properties

Pipe length = 7000.0 ft
10 calculational nodes are used

Pipe inlet temperature is 200.0 F
Soil temperature is 33.5 F

Fluid velocity = 21600.0 ft/hr

Fluid properties
specific heat = 1.00 Btu/lbm-F
wt. density = 62.4 lb/ft^3

Emmisivities: outer, inner =0.820 and 0.380 respectively

Outer insulation properties:
thickness = 0.0000 ft
thermal conductivty=******** Btu/hr-ft-F

***** RESULTS *****

location (ft)	fluid temp (F)	heat loss-section (Btu/hr)
700.00	198.02	-0.137E+06
1400.00	196.07	-0.135E+06
2100.00	194.15	-0.133E+06
2800.00	192.26	-0.131E+06
3500.00	190.40	-0.129E+06
4200.00	188.56	-0.127E+06
4900.00	186.76	-0.125E+06
5600.00	184.98	-0.123E+06
6300.00	183.24	-0.121E+06
7000.00	181.51	-0.119E+06

The total heat loss is -0.128E+07 Btu/hr

The average heat loss per foot is -182.7 Btu/hr

APPENDIX B

LISTING OF PROGRAM DPIPEHT

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```
      program dpipeht
c
c
**************************************************************************
*
c program for the steady-state heat tranfer of DST piping system
c 3 in shd 40 pipe in a 6 in shd 40 pipe insulated
c
c  units are in ft, hr, btu, deg F and R
c
**************************************************************************
*

      real kins, mdot,len,kef
      dimension temp (100), q(100)

      open(8)           ! misc info on fort.8

c *** constants

      pi = 3.1416
      g  = 32.2                 ! ft/sec^2

      d1i = 3.068/12.
      d1o = 3.5/12.
      d2i = 6.065/12.
      d2o = 6.625/12.
c
      aflow = (pi/4.)*d1i**2
c
      write (6,900)

      call input(tin,tamb,vel,cp,den,kins,tkins,ee,ec,len,ndiv)
c
      mdot = vel*den*aflow          ! mass flow lbs/hr
      dl  = len/ndiv                      ! cal lenght div
      d3  = d2o+2*tkins
c
c *** print out inital conditions ***
      write (6,901) len,ndiv
      write (6,902) tin,tamb
      write (6,903) vel
      write (6,904) cp,den
      write (6,905) ee,ec
      write (6,906) tkins,kins
c
c *** calculated resistances
c *** only consider the gap (radiation and cond/convec) and insulation

c *** asummed tmean and delta t gap -inital guess
      deltx = tin-tamb
      delt = deltx/2.
      tmean = tin - delt/2.
c *** initialize and constant parameters
      temp(1) = tin
```

```
c *** effective emissivity
      ece = (((1.-ec)/ec)+1.+(d1o**2*(1.-ee))/(d2i**2*ee))**-1
      r3 = ALOG(d3/d2o)*(1./(2.*pi*kins*dl))    ! resistance insulation
100   continue
c
      write(8,*) ' i  Keff     r1-r2-r3      r_gap    r_total'
c
      do 500 i=1,ndiv
      ncount =0
c
200   continue

      call Keff (d2i,d1o,delt,kef,tin)          ! get Keff air gap
      r1 = ALOG(d2i/d1o)*(1./(2.*pi*kef*dl))    ! air gap cond/conv
resistance
      call hrad (ece,delt,temp(i),hr,t2est)
      r2 = 1./(hr*pi*d1o*dl)                    ! radiation resistance air
gap
c
c *** combination of resistance and heat flow out

      r_gap = 1./(1./r1 +1./r2)
      r_total = r_gap + r3

      q(i) = (tamb - temp(i))/r_total

c *** iteration control for radiation estimates

      delt = -q(i)*r_gap
      deltcal = temp(i)-t2est
      diff = delt-deltcal
      pd = ABS(diff/delt)

c     write(8,*) delt, deltcal, pd,i, ncount
      write(8,910) i,kef,r1,r2,r3,r_gap,r_total
      ncount = ncount +1
      if(ncount.gt.20) stop
      if (pd.gt.0.05) go to 200

c *** temperature change in fluid in pipe

      deltf = q(i)/(mdot*cp)
      temp(i+1) = temp(i) + deltf

500   continue
c
      qtot = 0.
      write(6,950)

      do 600 i=1,ndiv

      xl = i*dl
      qtot = qtot + q(i)
      write(6,951) xl,temp(i+1), q(i)
600   continue

      qavg = qtot/len
```

```
      write(6,960) qtot
      write(6,961) qavg

c *** print formats
900   format(1h1,5x,'TEMPERATURE DROP IN TRANSFER PIPE',/,
     15x,'3 inch SHD 40 flow pipe inclosed in a 6 inch SHD'
     2,'40 pipe',/)

901   format(///,5x,'Pipe length =',f7.1,' ft',/,
     15x,i5,' calculational nodes are used',/)
902   format(5x,'Pipe inlet temperature is',f6.1,' F',/
     1,5x,'Soil temperature is',f6.1,' F',/)
903   format(5x,'Fluid velocity =',f8.1,' ft/hr',/)
904   format(5x,'Fluid properties',/,10x,'specific heat = '
     1,f5.2,' Btu/lbm-F',/,10x,'wt. density =',f5.1,
     2' lb/ft^3',/)
905   format(5x,'Emmisivities: outer, inner =',f5.3,' and ',
     1f5.3,' respectively',/)
906   format(5x,'Outer insulation properties:',/,10x,
     1'thickness =',f7.4,' ft',/,10x,'thermal conductivty='
     2,f8.4,' Btu/hr-ft-F',///)
910   format(i5,6e11.3)

950   format(' *****  RESULTS  *****',//,5x,'location (ft)',
     1'  fluid temp (F)  heat loss-section (Btu/hr)',/)
951   format(10x,f7.2,5x,f7.2,8x,e10.3)
960   format(///,5x,'The total heat loss is ',e10.3,' Btu/hr')
961   format(/,5x,'The average heat loss per foot is ',f6.1,
     1' Btu/hr')

      stop
      end


      subroutine hrad (ece,delt,t1,hr,t2est)
c *** calculates and return the radiant heat tranfer coef. (hr)
c
      sbc = .1714e-8           ! Stefan-Boltzmann const
c
      t2est = t1 - delt
c *** convert temp to deg R
      t1r = t1 + 460.
      t2r = t2est +460.

      hr = ece*sbc*(t1r**4-t2r**4)/(t1r-t2r)

      return
      end


      subroutine input(tin,tamb,vel,cp,den,kins,tkins,ee,ec,len,ndiv)
c
c
*****************************************************************************
c input parameter are:
```

```
c   tin = pipe inlet temp
c   tamb = soil temperature - const along length
c   vel = fluid velocity
c   cp = fluid specific heat
c   den = fluid weight density
c   kins = thermal conductivity of outer insulation
c   tkins = insulation thickness
c   ee,ec = emissivities of enclosure and carrier pipes, respectively
c   len = pipe length
c   ndiv = number of calculational divisions (nodes)
c
c
****************************************************************************
c
      real kins, len
      character*80 title

      read(5,98) title
      write(6,99) title

      read(5,*) len,ndiv
      read(5,*) tin,tamb,vel
      read(5,*) cp,den
      read(5,*) kins,tkins
      read(5,*) ee,ec
c
      return

98    format(a80)
99    format(5x,a80)

      end


      subroutine Keff (do,di,delt,kef,tin)
c
c *** calculates the effective conductivity from combined
c *** convection and conduction in horz concentric cyl.
c *** emperical correlation see WHC-SD-TP-RPT-005 , APDX B
c *** properties evaluated at tin
c
      real k,kef,kek
c
c *** for air at 50 to 200 F
c
c *** properties
      Pr200 = .693                      ! Prandtl No.at 200 F
      grxx200 = 0.86e6
      xk200 = .0181                     ! thermal conductivity

      Pr50 = .715
      grxx50 = 2.7e6
      xk50 = .0144

c *** interpolate to get prop. at tin
c
      xdelta = 150.
```

```
      delpr = Pr200 - Pr50
      delgrxx = grxx200 - grxx50
      delxk = xk200 - xk50
c
      if(tin.lt.50.) tin = 50.
      delta = (tin -50.)/xdelta
      Pr = Pr50 + delpr*delta
      grxx = grxx50 + delgrxx*delta
      k = xk50 + delxk*delta
c
c
      gap =(do-di)/2.
c
      Gr = grxx*delt*gap**3    ! Grashof No
      Ra = Gr*Pr                            ! Rayleigh No
c
      top = ALOG(do/di)*Ra**.25
      bot = gap**.75*(di**(-.6) + do**(-.6))**1.25
      kek = .386*top/bot*(Pr/(.861+Pr))**.25
      kef = k*kek
c
      return
      end
```

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APPENDIX C

ANSYS INPUT DATA – CASE 1T200

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****** APPENDIX C ******

ANSYS INPUT DATA FOR TRANSIENT THERMAL ANALYSIS - CASE 1T200

PART 1: PREP7 INPUT

```
/title,DST TRANSFER PIPE - THERMAL TRANSIENT - case 1t200+ 2 in. insulation
c*** model of DST Transfer Piping
c*** thermal-fluid
c***  units are in ft, hr, btu, deg F and R
c***   reduce h film in region ahead of water front
c***
****************************************************************************

/ratio,,20000.          ! aspect ratio for viewing

c*** constants

pi = 3.1416
g  = 32.2*(3600)**2     ! ft/hr^2
! acel,,g
sbc = .1714e-8          ! Stefan-Boltzmann const
toffst,460.
tin = 200.        ! pipe inlet temp

c*** gometric constant parameters

len = 7000.
ndiv = 9
d1i = 3.068/12.
d1o = 3.5/12.
d2i = 6.065/12.
d2o = 6.625/12.
tkins = 2./12.          ! thickness insulation

c*** other

den =62.4*1.2
ee = .80          ! emittance enclosure pipe
ec = .29          ! emit. carier pipe
vel = 21600.          ! ft/hr
tamb = 33.5       ! soil temp - infinite sink

c*** calculated parameters

aflow = (pi/4.)*d1i**2
mdot = vel*den*aflow          ! mass flow lbs/hr
dl = len/ndiv                 ! cal lenght div
d3 = d2o+2*tkins
arad1 = pi*d1o*dl
arad2 = arad1/2.
```

```
c*** effective emissivity
ece=((1.-ec)/ec)+1.+(d1o**2*(1.-ee))/(d2i**2*ee)
ece = 1./ece


c*** element types

et,1,FLUID116,1,2,,0      ! thermal-fluid pipe
et,2,PLANE55,,,1          ! 2-D Thermal solid - axisymmetric
et,3,LINK31         ! Radiation link

c*** real constants

r,1,d1i,aflow,1
rmore,,,0.,.664,.5,.333

r,2,arad2,1.,ece,sbc
r,3,arad1,1.,ece,sbc

c*** material properties  30<T(F) < 200

c***  note  use a weight density

mptemp,1,50.,100.,150.,200.

c*** material 1 is H2O in Fluid116 pipe element

mp,kxx,1,.36
mp,c,1,1.0
mp,dens,1,den
mpdata,visc,1,1,3.24,1.65,1.19,.73        ! lbf-hr/ft
mptemp,1,30.,75.,80.,100.,200.
mpdata,hf,1,1,1.,1.,600.,600.,700.
mptemp
mptemp,1,50.,100.,150.,200.

c*** material 2 = stainless steel

mp,dens,2,494.
mp,c,2,0.11
mp,kxx,2,8.6              ! Btu/(ft-hr-F)

c*** material 3 = air,  effective kxx from ss solution tin =33, delta t equiv
c*** kxx is effective conduction from convection/conduct in hora nested cyl.

mpdata,kxx,3,1,.038,.054,.061,.063
mpdata,dens,3,1,.078,.071,.065,.060
mp,c,3,0.24

c*** material 4 = carbon steel
mp,dens,4,484.
mp,c,4,.12
mp,kxx,4,26.

c*** material 6 = polyurethene foam insulation 2.4 dens
mp,kxx,6,.0125
mp,dens,6,2.4
```

```
mp,c,6,.2

c*** generate nodes

n,1,0
n,10,0.,len
fill
ngen,2,10,1,10,,d1i/2.
ngen,2,10,11,20,,(d1o-d1i)/2.
ngen,2,10,21,30,,(d2i-d1o)/2.
ngen,2,10,31,40,,(d2o-d2i)/2.
ngen,2,10,41,50,,(d3-d2o)/2.

c*** generate elements

c*** thermal-fluid pipe for flow channel
e,1,2,11,12
egen,9,1,-1

type,2     ! conduction
c*** inner pipe wall
real,2
mat,2
e,11,21,22,12
egen,9,1,-1

c*** air gap effective k
mat,3
egen,2,10,-9,,,1

c*** outer pipe
mat,4
egen,2,10,-9,,,1

c*** insulation
mat,6
egen,2,10,-9,,,2

c*** radiation links in gap

mat,5
type,3
real,2
e,21,31
e,30,40
real,3
e,22,32
egen,8,1,-1

c*** constant boundray conditions. and flow rate

c*** flow rate
esel,,type,,1
sfe,all,,hflux,,mdot     ! test
esel,all
```

```
d,51,temp,tamb,,60             ! set insulation outer temp to soil temp
```

PART 2: SOLUTION RUN INPUT

```
c*** solution inp file for case p1t200

antype,trans

kbc,0
tunif,tamb
outres,all,last

! ls = 1, pseudo step -fast ramp to loading conditions.
time,.001
nsubst,10
d,1,temp,tamb+1.
d,11,temp,tamb+1.
solve

! ls = 2, pseudo step -fast ramp to loading conditons.
time,.002
nsubst,10
d,1,temp,tin
d,11,temp,tin
solve

!ls = 3, contine
time,.25
autots,on
nsubst,250
outres,all,2
solve

!ls = 4, contine
time,.75
autots,on
outres,all,5
deltim,.001,.0001,.01
solve

!ls = 5, contine to final time
time,3.0
nsubst,300
outres,all,6
solve
```

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