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CALC No. M-CLC-K-00622 Rev. 0

EMTD
EQUIPMENT AND MATERIALS TECHNOLOGY DEPARTMENT

High Activity Moderator
Stress Analysis
Evaporator
Thermal Shock
Retention - Permanent

STRUCTURAL INTEGRITY EVALUATION OF HIGH ACTIVITY MODERATOR SYSTEM EVAPORATOR (U)

By

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ISSUED: May 1994

Authorized Derivative Classifier

M.R. Buckner — M.R. Buckner

6-13-94 — Date

MASTER

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Westinghouse Savannah River Company

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gtD

PROJECT: STRUCTURAL INTEGRITY EVALUATION OF HIGH ACTIVITY MODERATOR SYSTEM EVAPORATOR (U)

DOCUMENT: CALCULATION NO. M-CLC-K-00622 Rev. 0

TITLE: STRUCTURAL INTEGRITY EVALUATION OF HIGH ACTIVITY MODERATOR SYSTEM EVAPORATOR (U)

Note: This evaluation is a Level 2 calculation as defined in Procedure No. 2.31 of Manual E7.

APPROVALS

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EXECUTIVE SUMMARY

The High Activity Moderator (HAM) system is operated in a batch mode in which the evaporator tank is filled with 70°F cold moderator (D_2O) every 4 hours. This operation induces thermal shock to the walls of the tank. Thermal and structural analyses are performed to evaluate the impact of this thermal shock on the 220°F hot evaporator tank walls. Conservative thermal models are analyzed. Case 1 analyzes a 4" wide strip of D_2O running down the tank walls during the filling process and Case 2 analyzes the tank being filled instantly with 70°F D_2O. It is found that Case 1 results in larger temperature gradients at the walls than Case 2. The temperature gradients are then input into the structural model for calculating the thermal stresses.

The structural analysis shows that the maximum stress intensity due to combined pressure and thermal loading is about 17240 psi which is well below the yield stress (21000 psi) of the evaporator tank wall material, stainless steel 304L.

The fatigue life is evaluated in accordance with the criteria given in ASME Code, Section VIII. It is found that at the stress level of 17240 psi plus any residual stresses that might be present at the welded attachments to the tank wall, the fatigue life is about 4×10^6 cycles. If the evaporator tank is filled every 4 hours, the tank fatigue life is well above the anticipated batch operation period of 2 years.

CALC No. M-CLC-K-00622 Rev. 0
TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Background

Process water containing high activity contaminants is processed in the High Activity Moderator (HAM) system to remove as much radioactivity as possible before sending to 400-Area for further purification. The HAM system is located in K-Area. The major component of the HAM system is the evaporator tank. It is within this vessel that the actual activity removal occurs.

Historically, the auxiliary evaporator tank has been used for processing high activity moderator (D_2O) contained in either spent deionizer vessels or 55-gallon drums (Reference 1). However, recent piping modifications have allowed the use of the system evaporator tank as an additional vessel for HAM processing.

At the present time, only the system evaporator is being used for HAM processing. The HAM system is being operated in the batch mode with D_2O being charged to the evaporator from 55-gallon drums. The D_2O is purified by boiling the evaporator's contents and condensing the vapor in a condensate tank.

The D_2O from the drums is at room temperature of 70° to 80° F while the evaporator operates at about 220°F. The Reactor Engineering Department requested that an analysis be performed to assess the impact of possible thermal shock to the system evaporator due to the cold water coming in contact with the evaporator walls.

1.2 Purpose

This calculation will analyze the impact of introducing 70°F D_2O on the structural integrity of the system evaporator. The analysis will assess the fatigue life of the evaporator tank due to thermal cycling and meet the acceptance criteria in the ASME B&PV Code, Section VIII, Division 2.

2.0 MATERIALS OF CONSTRUCTION

2.1 Mechanical Properties for Engineering Analysis

The system evaporator is constructed from stainless steel Type 304L. The attachments to the vessel are made of carbon steel A36. Mechanical properties listed in Table 1 are used in the analysis. A Poisson's ratio of 0.3 is used.

Table 1 - Mechanical Properties

Evaporator Component	Material of Construction	Temperature (°F)	Yield Strength Sy (ksi)	Young's Modulus E (ksi)	Stress Intensity Sm (ksi)
Walls	SS Type 304L	70	25	28300	16.7
		220	21	27480	16.7
Structural attachments	A36	70	36	29500	16.9
		220	See Note	28700	16.9

Note: This value is not available in the ASME Code. Structural attachments to the evaporator at 220°F are not loaded during evaporator operation and, therefore, this value is not required.

Nozzles and flanges are attached to the top of the tank. These attachment points are far away from the tank region which is susceptible to the thermal shock due to the 70°F D_2O. The effect of this thermal shock is local and will not impose large loading on the nozzle and flange connections. Therefore, to simplify the analysis, the nozzles and flanges are not included in the evaluation.

3.0 LOADING CONDITIONS

3.1 Temperature and Pressure

The design conditions of the evaporator are given in the drawing in Reference 2. The important parameters are summarized below.

Design pressure	= 5 psig
Design temperature	= 250°F
Water capacity	= 250 gallons

The following operating conditions are present in the current batch mode of operation.

Vapor pressure	= 2.5 psig
Vapor temperature	= 220°F (based on the saturation temperature of water at 17.2 psia)[1]
Evaporation time	= 4 - 5 hours[2]
D_2O fill temperature	= 70°F[2]
D_2O fill rate	= 10 - 15 gpm
Room temperature	= 80°F[2]

3.2 Applied Loads

Two loadings are considered in this analysis.

1. A design pressure of 5 psig is used in the analysis. This will envelop the operating pressure of 2.5 psig and any hydrostatic pressure due to 3' of D_2O.

2. Thermal loading due to temperature gradients induced by the cold water filling the vessel. A conservative case of cold water in contact with the hot wall will be considered. Initial vapor temperature of 220°F corresponding to 17.2 psia is assumed. This results in the wall temperature of 149.9°F (see Section 5.5.1).

4.0 ANALYSIS METHODOLOGY

4.1 Basic Assumptions

The following assumptions are made in the thermal and structural analyses.

1. D_2O used for filling the evaporator falls down the side of the vessel surface. This is a conservative assumption since it will create larger temperature gradients.
2. The top of the evaporator tank is prevented from moving during the batch operation due to the attached pipes. Structurally this is a conservative assumption since it will produce higher stresses.
3. The effect of mixing of cold water with the hot water on the vessel wall is neglected. This is a conservative assumption since it will increase the temperature gradient at the water/wall interface.

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[1] Review of D_2O data (SRTC undocumented publication) shows that the difference between saturation temperatures of D_2O and water at 17.2 psia is negligible.

[2] Values are approximated and will vary slightly with building temperature and/or steam flow rate.

4.2 Design Criteria

The evaporator vessel is constructed in accordance with ASME B&PV Code, Section VIII. The acceptance criteria for analyzing cyclic loading is given in Section VIII, Division 2, Appendix 5. Primary and secondary stresses will be calculated using the finite element elastic analysis method.

5.0 FINITE ELEMENT MODEL AND ANALYSIS

5.1 Overview

Finite element models of the evaporator vessel are constructed for analyzing the vessel response to the various loadings. These loadings include pressure loads and the thermal loads due to temperature gradients induced by flowing cold water. The three dimensional finite element model can accommodate different mechanical and thermal loads. A linear elastic stress analysis is performed as required by the ASME , Section VIII, Division 2 Code.

5.2 Finite Element (FE) Models

5.5.1 Thermal Model

Thermal models to calculate the most conservative and best estimates for temperature gradients are described in Reference 5. Two different thermal cases are modeled: 1) cold water running down the tank wall in a 4" wide strip and; 2) the tank being filled instantly with cold water between water level 20" and 36". Case 1 gives the most conservative estimate and Case 2 gives the best estimate.

5.5.2 Structural Model

The basic dimensions (Fig. 1) for generating the FE model were taken from the design drawings [2]. The drum is modeled with second order shell elements (Type S8R5) in ABAQUS FE Code [3] with the wall mid surface radius as the vessel radius. A source listing of the ABAQUS input file is given in Appendix 1.

5.3 Finite Element (FE) Mesh

5.5.1 Thermal Model

The analysis in Reference 5 is based on a finite element analysis using P/Thermal computer code.

5.5.2 Structural Model

Figure 2 shows the finite element (FE) mesh of the evaporator vessel. The FE mesh contains 900 thin shell elements for the model. Only half of the drum surface was modeled to take advantage of the symmetry of the drum surface. It is realized that the loading conditions are not symmetric, however, the effect of thermal gradients induced by the cold water flow decays quickly circumferentially. The top and the bottom of the vessel are not modeled in the analysis since there is no cooling of these surfaces.

5.4 Boundary and Initial Conditions

5.5.1 Thermal Model

Boundary and initial conditions for the thermal analysis are described in Reference 5.

5.5.2 Structural Model

Conservative boundary conditions of fixed ends are used at the two ends of the vessel. The boundary condition due to symmetry about plane X = 0 (Fig. 2) is applied at the mid plane. An initial uniform temperature of 220°F for the lower 20" of the evaporator which is always full of water. The remaining surface of the tank in contact with water vapor is at 149.9°F initially.

5.5 Evaporator Vessel Analysis

5.5.1 Thermal Analysis

The thermal analysis results are given in Reference 5. It is found that for Case 1 the maximum temperature gradient along the wall in the vapor region is 35°F/in while the maximum temperature gradient below the water line is 65°F/in. The temperature gradients away from the cold water strip are less than these values. These gradients are input in the structural model to calculate the thermal stresses. For the second case where the vessel is filled instantly with 70°F water, the maximum temperature gradient is 10°F/in.

5.5.2 Structural Analysis

Primary stresses are due to pressure loading. Using a design pressure of 5 psig, the hoop stress is given as:

$$\sigma_h = \frac{P*R}{t} = \frac{5*18}{0.1875} = 480 \text{ psi}$$

Since there are no shear stresses due to pressure in the hoop direction, σ_h is also the principal stress. Furthermore, since longitudinal stresses are tensile, primary membrane stress intensity can be conservatively assumed to be equal to 480 psi.

Secondary stresses are due to thermal loading. Temperature profiles are taken from the thermal analysis and imposed on the evaporator vessel. These stresses are calculated by the finite element methods described above. The maximum stress intensity range is calculated from the principal stresses σ_1, and σ_2 for the shell elements. The σ_1, σ_2 and σ_3 are the principal stresses in the three normal directions. σ_1 and σ_2 are given in the ABAQUS computer runs listed in Appendix 2 while σ_3 in the radial direction is small and is assumed zero for computing the maximum stress intensity. The principal stresses are then combined to obtain stress intensity S [4] as follows:

$$S = \text{Max}(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|)$$

S value is listed as TRESC (Tresca equivalent stress, defined as the maximum difference between the principal stresses) in the ABAQUS printout. Maximum S value for the Case 1 is summarized in Table 2. In Table 2, S_{11} and S_{22} are the normal stress components and Q is the thermal stress intensity range (=S) required in the ASME Code stress check.

Table 2 - Calculation of Maximum Stress Intensity

Thermal Loading	Element No. †	S_{11} (psi)	S_{22} (psi)	σ_1 (psi)	σ_2 (psi)	σ_3 (psi)	TRESC (psi)	Q (psi)
Case 1	316 (I)	12320	17245	12316	17249	0	17249	17249
	316 (O)	-492	-207	-887	188	0	1075	1075

† See ABAQUS computer runs in Appendix A. (I) and (O) are the inside and outside surfaces of the elements.

Case 2 is enveloped by Case 1 and is, therefore, not analyzed for thermal stresses.

5.5.3 ASME Code Stress Check

ASME Code check will be carried out only for the loading condition with maximum stress intensity, S, which occurs for Case 1.

The evaporator vessel is a non-safety class component. Therefore, ASME Code Section VIII Appendices 4 and 5 [4] is used for the code stress check. The code stress check includes the limits on the following stress intensities.

- Primary membrane stress intensity (P_m or P_L)
- Primary bending stress intensity (P_b)
- Secondary stress intensity range (Q)
- Peak stresses - due to welds, notches, cladding, etc. (F)

The limits on the above intensities are given in Fig. 4-130.1 of the Appendix 4 of the ASME Code [4] and are as follows:

$$P_m \le S_m = 16.70 \text{ ksi (see Table 1)}$$
$$P_m+P_b \le 1.5\, S_m = 25.05 \text{ ksi}$$
$$P_m+P_b+Q \le 3.0\, S_m = 50.10 \text{ ksi}$$

P_m is calculated in Section 5.5.2, P_b due to pressure loading is zero, and Q is calculated in Table 2 above. Peak stresses (F) due to welds, notches, cladding, etc. are difficult to calculate. However, a conservative estimate can be made for an attachment welded at the vessel outer surface close to the cold flowing water. This weld is a fillet weld but does not carry any load during normal operation of the evaporator vessel. A maximum peak stress equal to the yield stress of the material is assumed to exist at the surface of the vessel due to fillet weld.

A review of the stress intensities calculated in Section 5.5.2 shows that the evaporator design meets the ASME Section VIII Code [4] requirements.

To estimate the fatigue life for thermal cyclic loading, total stress intensity range, including peak stresses, is calculated. This is designated as $2\,S_a$. The value of S_a is then used to calculate the allowable number of cycles from the design fatigue curves in Fig. 5-110.2.1 of Appendix 5 of the ASME Code [4].

$$2\,S_a = P_m+P_b+Q+F = 480 + 0 + 17249 + 21000 = 38729 \text{ psi}$$

therefore, $S_a = 19365$ psi

Using the fatigue curves in Fig. 5-110.2.1 of Appendix 5 of the ASME Code [4], we find for S_a equal to 19365 psi the maximum allowed thermal cycles is 4.3×10^6. This is well above the expected number of thermal cycles (< 5000) during the current batch operation for approximately 2 years.

6.0 CONCLUSIONS

1) The evaporator vessel design meets the ASME Code, Section VIII stress requirements.

2) The thermal cycling due to the current mode of operation will not cause fatigue failure for a period well beyond the expected 2 years of operation. This is based on the current thermal cycle period of approximately 4 hours.

7.0 REFERENCES

[1] High Activity Moderator (HAM) System, System Description, CS-GEN-IT-SYS-04-06-SD Rev. 3.

[2] Drawings: Purification Process Water Evaporator EP-271.
Assembly S5-1-2430 Rev. 6
Details S5-1-2431 Rev. 10
Details S5-1-2432 Rev. 5

[3] ABAQUS, Version 4-9, Hibbitt, Karlsson, & Sorensen, Inc., Pawtucket, Rhode Island, 1992.

[4] ASME Boiler and Pressure Vessel Code, Sections VIII, Division 2, Edition 1992.

[5] ATS-EMS-940034, Determination of Temperature Profiles in High Activity Moderator D_2O Tank, May 1994 (Attachment A to this calculation).

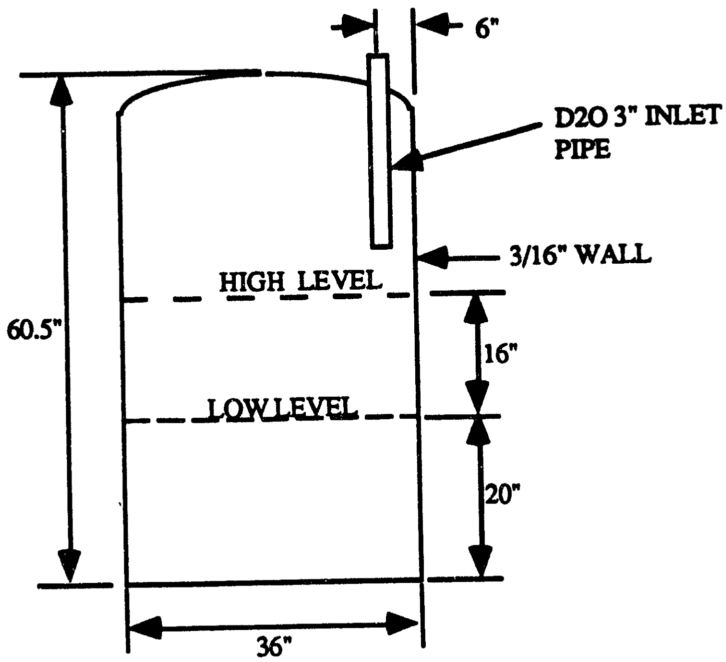

FIGURE 1 - HIGH ACTIVITY MODERATOR EVAPORATOR TANK

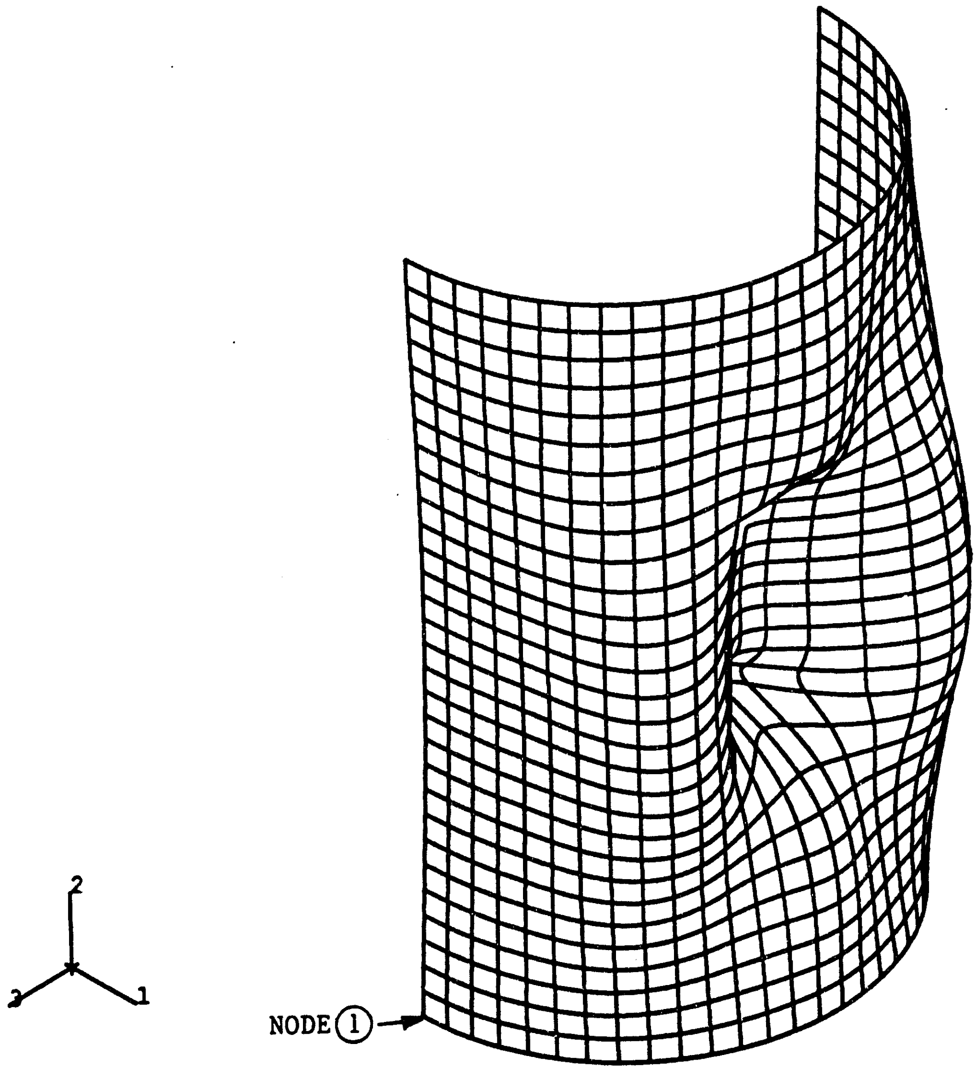

FIGURE 2 EVAPORATOR TANK FINITE ELEMENT MODEL DEFORMED SHAPE DUE TO THERMAL SHOCK - MAGNIFICATION FACTOR = 487

APPENDIX 1 - ABAQUS INPUT FILE

```
*HEADING
HIGH ACTIVITY MODERATOR TANK ANALYSIS FOR THERMAL SHOCK
*NODE
10000,0,0,0
10001,0,56,0
1,0,0,17.906
61,0,0,-17.906
*NGEN,LINE=C,NSET=L1
1,61,,10000,,,,0,1,0
*NCOPY,CHANGE NUMBER=2200,OLD SET=L1,NEW SET=L2,SHIFT
0,20,0
0,0,0,0,56,0
*NCOPY,CHANGE NUMBER=1800,OLD SET=L2,NEW SET=L3,SHIFT
0,16,0
0,0,0,0,56,0
*NCOPY,CHANGE NUMBER=2000,OLD SET=L3,NEW SET=L4,SHIFT
0,20,0
0,0,0,0,56,0
*NFILL,NSET=LOWER
L1,L2,22,100
*NFILL,NSET=MIDDLE
L2,L3,18,100
*NFILL,NSET=UPPER
L3,L4,20,100
*NSET,NSET=TANK
LOWER,MIDDLE,UPPER
*NSET,NSET=BOTTOM,GENERATE
1,61
*NSET,NSET=TOP,GENERATE
6001,6061
*NSET,NSET=EDGE,GENERATE
1,6001,100
61,6061,100
*ELEMENT,TYPE=S8R5
1,1,3,203,201,2,103,202,101
*ELGEN,ELSET=TANK
1,30,2,1,30,200,30
*ELSET,ELSET=LOWER,GENERATE
1,330
*ELSET,ELSET=MIDDLE,GENERATE
331,600
*ELSET,ELSET=UPPER,GENERATE
601,900
*SHELL SECTION,ELSET=TANK,MAT=SS304L
0.1875
*MATERIAL,NAME=SS304L
*ELASTIC
28.3E6,0.3,70.
27.48E6,0.3,220.
*EXPANSION,ZERO=70.
0.0,70.
8.834E-6,220.
```

```
*INITIAL CONDITIONS,TYPE=TEMPERATURE
LOWER,220.
MIDDLE,149.9
UPPER,149.9
*BOUNDARY
BOTTOM,ENCASTRE
TOP,ENCASTRE
EDGE,XSYMM
*RESTART,WRITE
**
**CASE1- TEMPERATURE DISTRIBUTION BY STEVE HENSEL
**
*STEP
THERMAL SHOCK DUE TO WATER FILM (ABOUT 3" WIDE) ON THE TANK WALL
*STATIC
*TEMPERATURE
2225,190.
**
2226,160.
**
2127,188.
2227,130.
2327,130.
2427,130.
2527,130.
2627,130.
2727,130.
2827,130.
2927,130.
3027,130.
3127,130.
3227,130.
3327,130.
3427,130.
3527,130.
3627,130.
3727,130.
3827,130.
3927,130.
4027,130.
**
2028,195.
2228,105.
2428,105.
2628,105.
2828,105.
3028,105.
3228,105.
3428,105.
3628,105.
3828,105.
4028,105.
**
1829,201
```

1929,188.
2029,165.
2129,128.
2229,73.
2329,70
2429,70.
2529,70.
2629,70.
2729,70.
2829,70.
2929,70.
3029,70.
3129,70.
3229,70.
3329,70.
3429,70.
3529,70.
3629,70.
3729,70.
3829,70.
3929,70.
4029,70.
4129,105.
4229,140.
**
1630,210.
1830,201.
2030,165.
2230,73.
2430,70.
2630,70.
2830,70.
3030,70.
3230,70.
3430,70.
3630,70.
3830,70.
4030,70.
4230,140.
**
1531,213.
1631,210.
1731,207.
1831,201.
1931,188.
2031,165.
2131,128.
2231,73.
2331,70.
2431,70.
2531,70.
2631,70.
2731,70.
2831,70.

2931,70.
3031,70.
3131,70.
3231,70.
3331,70.
3431,70.
3531,70.
3631,70.
3731,70.
3831,70.
3931,70.
4031,70.
4131,105.
4231,140.
**
1632,210.
1832,201.
2032,165.
2232,73.
2432,70.
2632,70.
2832,70.
3032,70.
3232,70.
3432,70.
3632,70.
3832,70.
4032,70.
4232,140.
**
1533,213.
1633,210.
1733,207.
1833,201.
1933,188.
2033,165.
2133,128.
2233,73.
2333,70.
2433,70.
2533,70.
2633,70.
2733,70.
2833,70.
2933,70.
3033,70.
3133,70.
3233,70.
3333,70.
3433,70.
3533,70.
3633,70.
3733,70.
3833,70.

```
3933,70.
4033,70.
4133,105.
4233,140.
**
2034,195.
2234,105.
2434,105.
2634,105.
2834,105.
3034,105.
3234,105.
3434,105.
3634,105.
3834,105.
4034,105.
**
2135,188.
2235,130.
2335,130.
2435,130.
2535,130.
2635,130.
2735,130.
2835,130.
2935,130.
3035,130.
3135,130.
3235,130.
3335,130.
3435,130.
3535,130.
3635,130.
3735,130.
3835,130.
3935,130.
4035,130.
**
2236,160.
**
2237,190.
**
*NODE FILE,NSET=TANK
U,RF
*EL FILE,ELSET=TANK,POSITION=CENTROIDAL
S,E
SINV,SP
*NODE PRINT,NSET=TANK
U1,U2,U3
*NODE PRINT,NSET=TOP,TOTAL=YES
RF1,RF2,RF3
*NODE PRINT,NSET=BOTTOM,TOTAL=YES
RF1,RF2,RF3
*EL PRINT,ELSET=TANK,POSITION=CENTROIDAL
```

```
S,E
SINV,SP
SF
*END STEP
```

APPENDIX 2 - TABLE OF ABAQUS COMPUTER RUNS

Item No.	Output (.DAT) File	Restart (.RES) File	File Description
1	HAM	HAM	High Activity Moderator (HAM) Tank Analysis for Thermal Shock

ATTACHMENT "A"

WESTINGHOUSE SAVANNAH RIVER COMPANY
INTER-OFFICE MEMORANDUM

ATS-EMS-940034
NON-CRITICAL DATA

May 13, 1994

TO: N. K. Gupta, 773-42A

FROM: S. J. Hensel, 773-42A SJH

J. W. Jerrell 6-7-94
J. W. Jerrell Technical Reviewer Date

J. R. Pelfrey 6-7-94
J. R. Pelfrey Manager Date

Determination of Temperature Profiles in High Activity Moderator D2O Tank (U)

An upper bound and a conservative best estimate calculation of the maximum thermal gradients in the heavy water tank during cold water additions were made. The upper bound analysis is based on a falling film of cold water cooling the tank wall above the pool of hot water in the tank. The maximum thermal gradient along the tank wall (top to bottom) occurs at the hot water surface and is approximately 65°F/inch. The falling film is assumed to cool a 4-inch wide vertical strip of the tank wall. A maximum temperature gradient of 35°F/inch in the circumferential direction occurs at the edge of the strip. The best estimate analysis realistically assumes cold water is added without contact with the tank wall. In this case, conduction from the cold water cools the tank wall. The cold water is assumed to remain in a layer on top of the existing hot water. The maximum temperature gradient along the tank wall from top to bottom in this case was only 10°F/inch.

Determination of Temperature Profiles in High Activity Moderator D2O Tank

Particulates and other small contaminants in heavy water are being removed by vaporization and condensing out the clean water. The water is heated to 220°F in a stainless steel 304 tank (3 ft. O.D., 5 ft. 1/2 in. high) and the vapor is removed leaving the contaminants behind. Cold heavy water at 70 °F is added to the tank periodically whenever the water level falls below 20 inches. Water addition ceases when the level reaches 36 inches. The periodic addition of cold water induces cyclic thermal stresses which may lead to tank failure via fatigue. Both upper bound and conservative best estimate tank temperature profiles have been calculated. These profiles are to be used as input to a thermal stress analysis.

The addition of cold water and its cooling effects can be considered to occur in two ways. The first way, and the most conservative from a cooling perspective, consists of a cold water film falling down a portion of the tank wall. The strip of wall cooled by the falling film may be only 4 inches wide and would extend from near the tank top to the top of the hot water level. Assuming a very good convection coefficient and neglecting the rise in film temperature, this strip could ideally be at the cold water temperature, 70°F. Realistically, a falling film will not occur since the cold water exit nozzle ensures very minimal wall contact although some splashing probably occurs. The added cold water mixes with the hot water already in the tank such that localized tank wall cooling occurs during the mixing process. A conservative, and simplistic, second view of this problem is to consider an instantaneous addition of cold water which raises the water level from 20 to 36 inches, and assumes that the 16 inch cold water layer remains on top of the hot water (even though its density is greater). The tank wall is now in contact with hot water from the bottom to 20 inches, cold water from 20 to 36 inches, and hot water vapor from 36 inches to the top. The cold water layer will cool the tank wall and the hot water below.

The falling film scenario was modeled in two ways. First, the temperature profile along the tank wall (vertically) was computed transiently. A schematic of the axisymmetric model is shown in Figure 1. A second model, shown in Figure 2, was used to determine the circumferential temperature distribution in a steady-state analysis. The schematic of the model used in the second scenario, a layer of cold water, is shown in Figure 3. Again, transient temperatures were computed.

The analyses were performed using P/Thermal. Material properties for heavy water and 304 steel are contained in the P/Thermal library. In all analyses the ambient condition outside the tank is still air at 80°F. The initial condition for the falling film analysis (Figure 1) was computed assuming hot water vapor (220°F) above the hot liquid water level. A similar initial condition was used in the best estimate analysis (Figure 3). All convection coefficients for each model and analysis are presented in the Appendix.

The results of these analyses are shown in Figures 4, 5, and 6. These figures contain the temperature gradients of interest along with an idealized gradient (based on 220°F hot water temperature and 70°F cold water temperature), and the initial temperature gradients. In Figures 4 and 6 the distance is measured from the tank bottom. In Figure 5, the azimuthal distance is from the center of the falling film. Clearly, the falling film is quite conservative and results in a maximum gradient of roughly 65°F/inch at the water interface as shown in Figure 4. The circumferential gradient is 35°F/inch as shown in Figure 5. The temperature gradient through the tank wall (from inside to outside) was never more than 1°F. The results in Figure 6 are interesting since the temperature profile is a minimum in the middle o[illegible] where it is in contact with the cold water. The gradient in this case, 10°F/inch, is not very large because the heat from the tank wall can't be absorbed by the cold water between 20 and 36 inches very well. The convection of the falling film is a much better cooling mechanism, as shown in Figure 4, than contact conduction.

A thermal analysis of the heavy water tank during refill has been performed to provide input to a thermal stress analysis. The results indicate that an upper bound temperature gradient is 65°F/inch along the tank wall, and the gradient through the wall is less than 1°F. The circumferential gradient due to a localized falling film would be 35°F/inch. A conservative best estimate analysis suggests that the maximum gradient along the tank wall is closer to 10°F/inch.

APPENDIX

Falling Film Analysis:

h=2 Btu/ft.^{2}-hr. for natural convection to ambient air and hot water vapor
h=23 Btu/ft.^{2}-hr. for convection of hot liquid water to tank wall
h=2000 Btu/ft.^{2}-hr. for falling cold water film convection coefficient

Cold Water Layer Analysis:

h=2 Btu/ft.^{2}-hr. for natural convection to ambient air and hot water vapor

Schematic of Falling Film Model
(Not to scale)

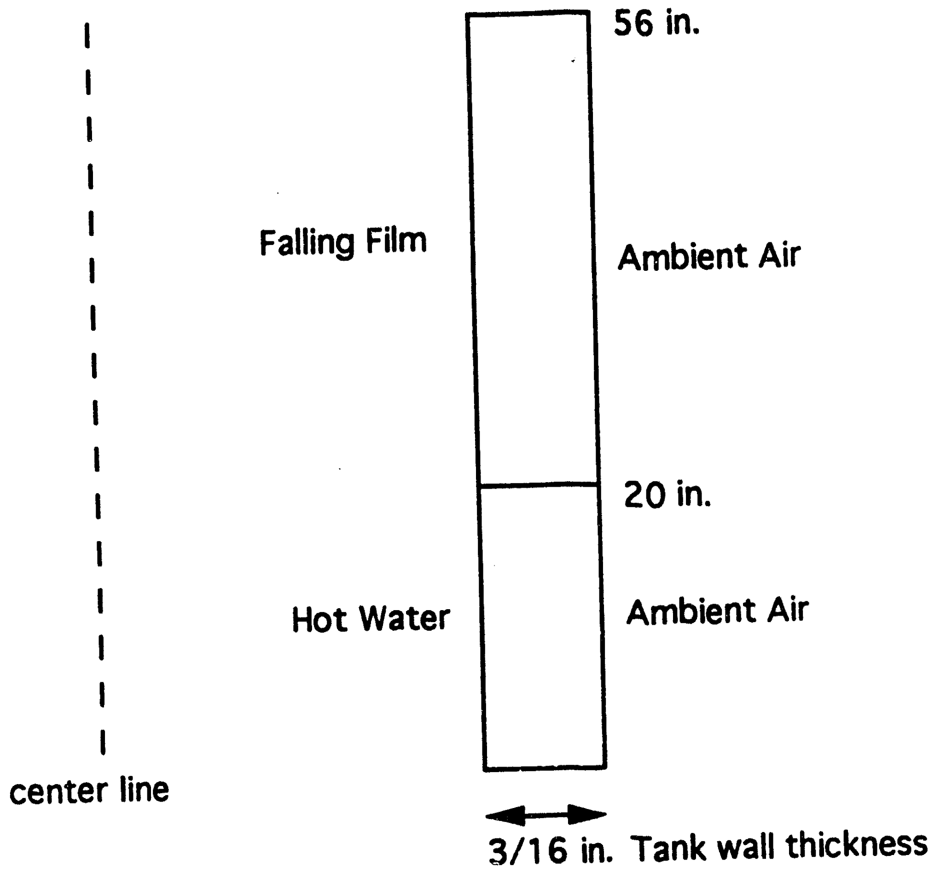

Figure 1

Schematic of Slab Model
(Not to scale)

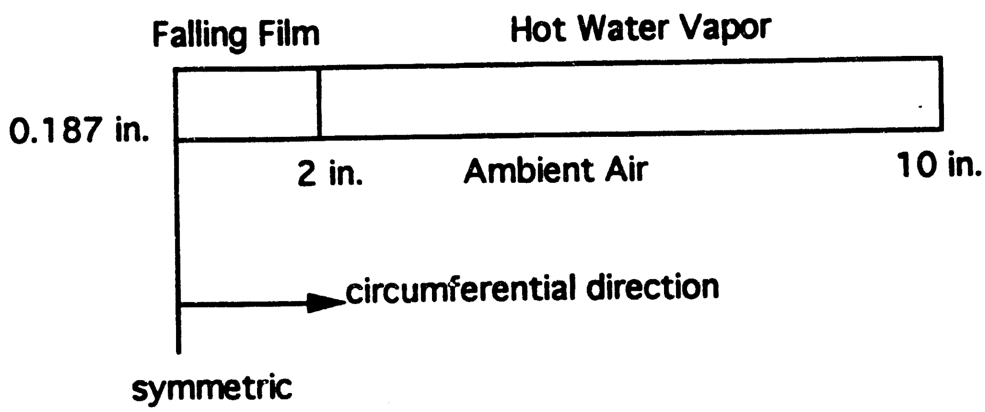

Figure 2

Schematic of Best Estimate Model
(not to scale)

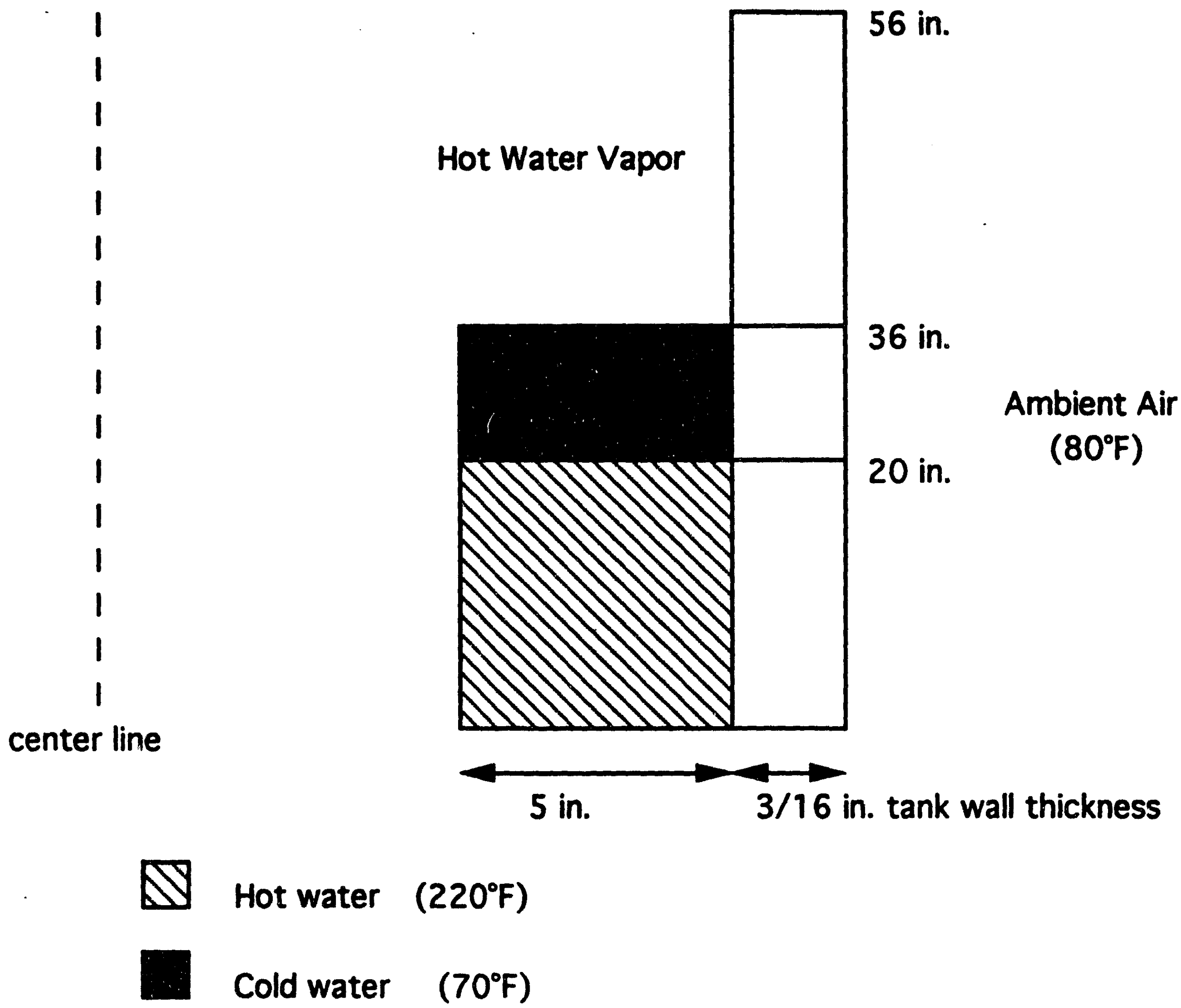

Figure 3

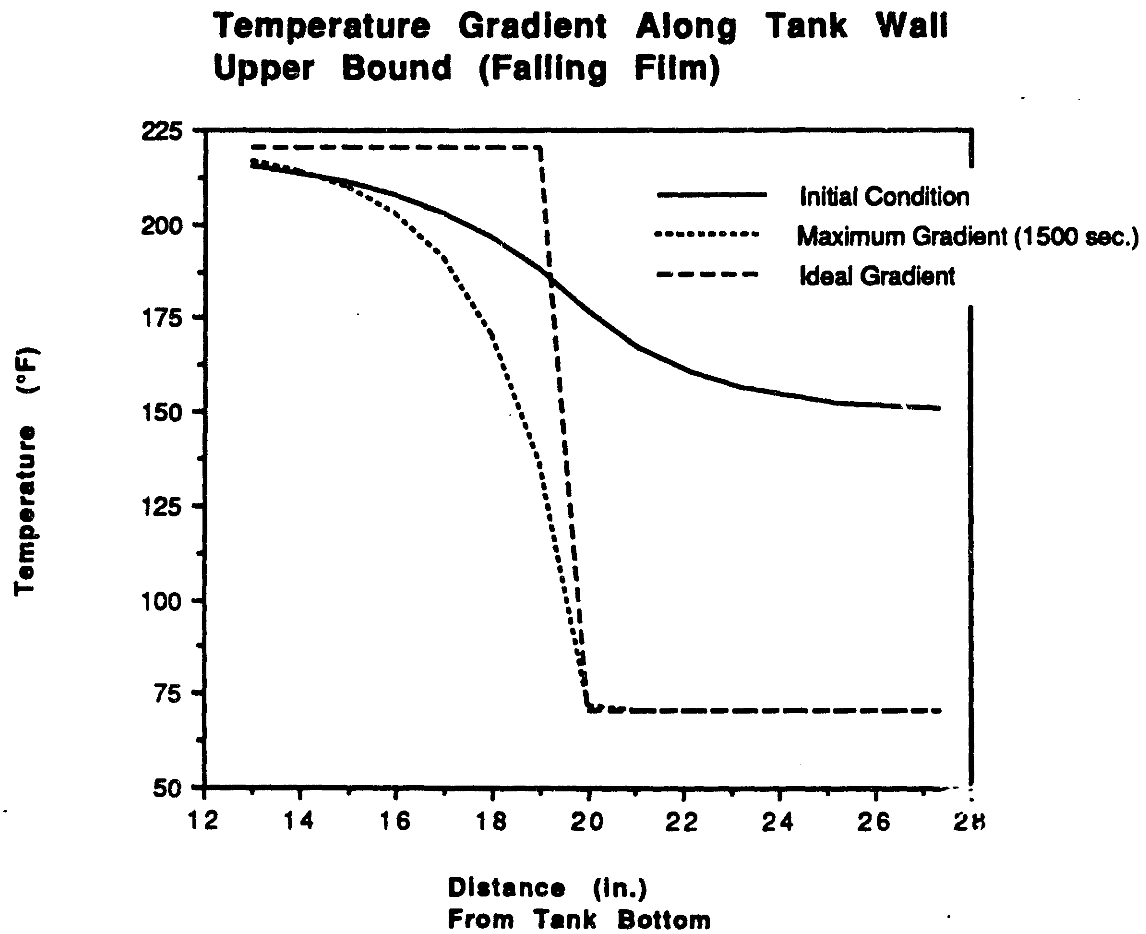
Temperature Gradient Along Tank Wall
Upper Bound (Falling Film)
225
200
175
150
125
100
75
50
12
14
16
18
20
22
24
26
28
Initial Condition
Maximum Gradient (1500 sec.)
Ideal Gradient
Temperature (°F)
Distance (in.)
From Tank Bottom

FIGURE 4

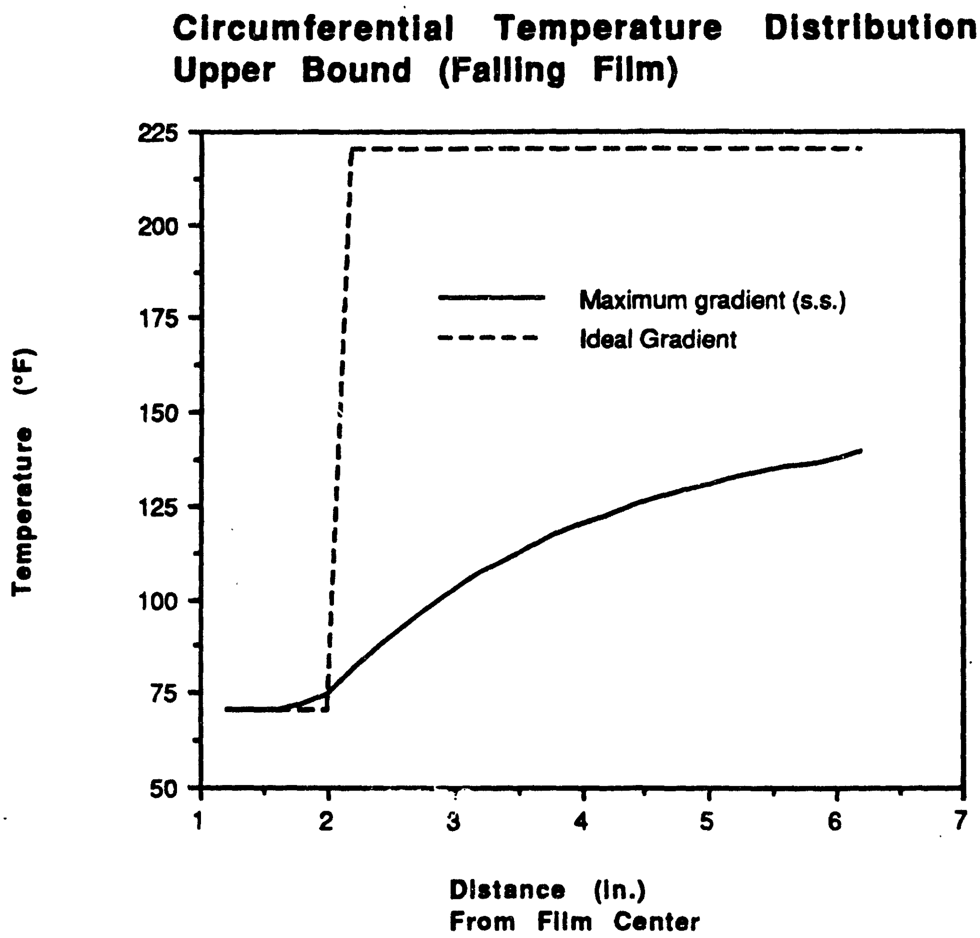
Circumferential Temperature Distribution
Upper Bound (Falling Film)
225
200
175
150
125
100
75
50
1
2
3
4
5
6
7
Maximum gradient (s.s.)
Ideal Gradient
Temperature (°F)
Distance (In.)
From Film Center

FIGURE 5

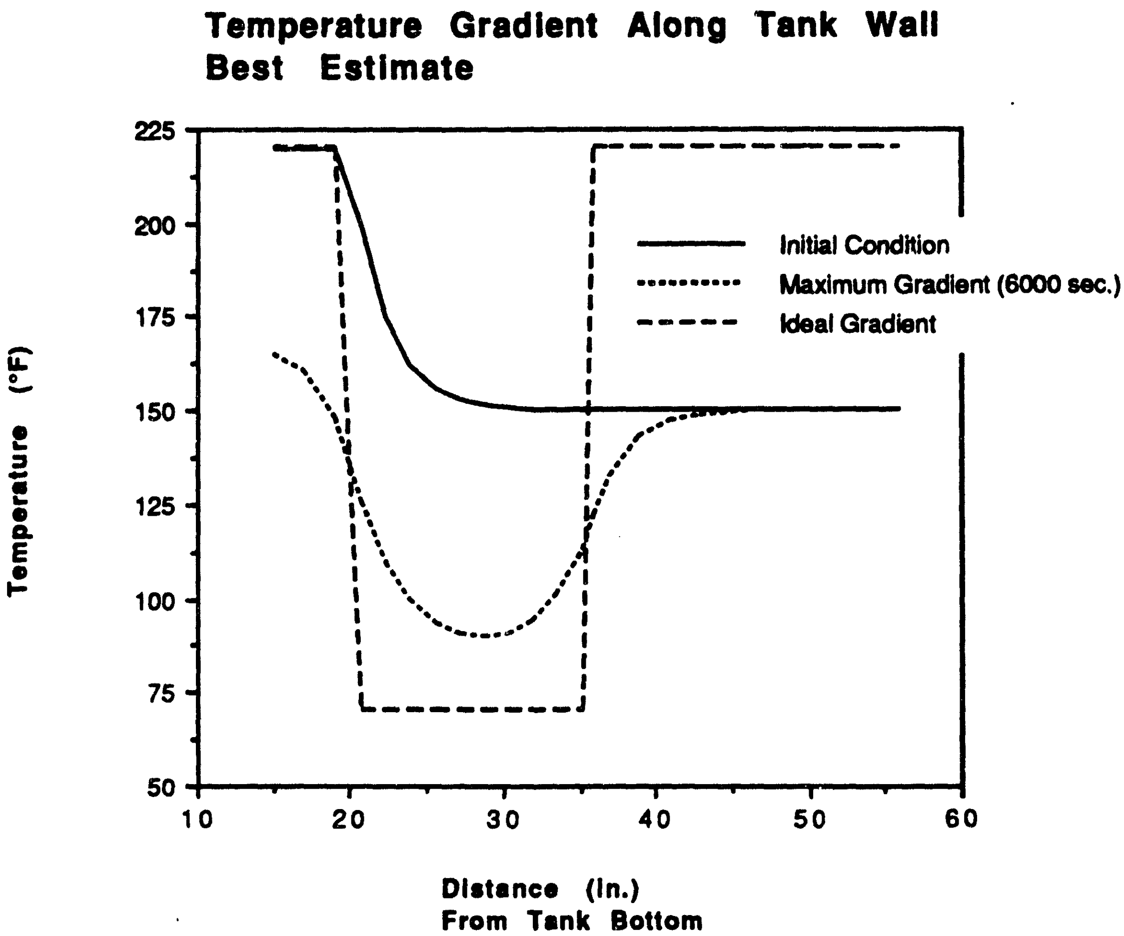
Temperature Gradient Along Tank Wall
Best Estimate
Temperature (°F)
225
200
175
150
125
100
75
50
10
20
30
40
50
60
Initial Condition
Maximum Gradient (6000 sec.)
Ideal Gradient
Distance (In.)
From Tank Bottom

FIGURE 6

END

DATE
FILMED
10/12/94