"STEALTH 2D Simulations of Teknekron's Benchmark Problems for Repository Design Models"

September, 1987

Prepared by: Krishan K. Wahi
GRAM, Incorporated
1709 Moon St. NE
Albuquerque, NM 87112

Prepared for: Teknekron Transportation Systems,
Berkeley, CA

8712140104 871015
PDR WMRES EECCORS
B-6985 PDR

SECTION 1

Introduction and Background

This report describes the set up and execution of a number of Benchmark Problems for repository design models that were completed with the STEALTH 2D computer code (Ref. 1). These problems are a subset of the Benchmark Problems described in the NUREG/CR-3636 document (Ref. 2). In September, 1985 Benchmark Problems 2.4, 2.8, 2.9, 3.2, 3.5, 5.2, 5.3, 6.1, and 6.3 were selected (by Teknekron) for analysis with the STEALTH code. Under a subcontract from Sandia National Laboratories (SNLA), Dr. K. Wahi, who was with SAIC at that time, was asked by the NRC to assist Teknekron in setting up and partially completing some of these problems. The plan was to provide sufficient guidance to Teknekron such that Teknekron personnel could carry out each problem to completion. In the spring of 1986, results of the above effort were transmitted to Teknekron. Specifically, Benchmark Problems 2.4, 2.8, 3.2, and 6.1 had been run to completion, Problem 2.9 was partially completed, and Problem 5.3 had been set up to be started. In a three-day meeting with Dr. D. Vogt and Mr. R. Chapman, Dr. Wahi discussed the code modifications, problem set-up and unique input requirements of each problem. At the conclusion of that meeting all the data files, printout, microfiche output and hardcopy plots were handed over to Mr. Chapman. In addition, handwritten notes and helpful hints on STEALTH application were provided.

In July, 1986 at the request of Dr. Rosselle, GRAM, Inc. submitted a proposal to Teknekron to complete the remaining Benchmark Problems with STEALTH. This proposal was finally accepted and authorization given in April, 1987 to initiate the work. The information and discussions that follow pertain to Benchmark Problems 2.9, 3.5, 5.2, 5.3 and 6.3 only. The SNLA computing facility was used under an arrangement between the NRC and SNLA. As a result, any computer costs incurred have been or will be paid by the NRC.

General Discussion

Calculations previous to the current effort had been carried out on the SNLA CRAY-1 machine which operated on the Cray Operating System (COS) until January, 1987. At that time a new operating system (CTSS) was installed which necessitated a conversion of the STEALTH source files and generation of new binary files. Known "bugs" in STEALTH were fixed in the process of generating CTSS source and binary files. This is an important distinction between the previous sets of Fortran updates and the new updates. Note that Fortran updates before generally consisted of two parts: one to effect problem-specific modeling changes and the other to fix known generic "bugs" or errors in the code. However, certain updates in the present set of calculations are still common to more than one problem to obtain certain types of non-standard output. Aside from that, Fortran updates associated with a given problem are specific to that problem in the present exercise.

Problems 5.2, 5.3, and 6.3 have been run in more than one step. There are two reasons for this multistep approach; one or both may apply to a given problem. For problems in which an underground opening exists (e.g., Problem 5.2), it is necessary to first obtain an equilibrium state of stress after the perturbation of the in-situ stress field created by the excavation. For problems requiring a large number of computational cycles (i.e., a relatively large amount of CPU time) it is a good practice to examine the solution at intermediate stages to ensure an error-free progress with minimal waste of computer resources. Due to the explicit numerical scheme employed in STEALTH, it is necessary to increment time with each computational cycle (or iteration) even if time is a dummy parameter. Therefore, a reference time may have to be subtracted from the STEALTH time to establish the proper simulation time. For example, in Problem 6.3 a heater test is to be simulated for 500 days. In the STEALTH simulation, a run was first made to establish the equilibrium state of stress around the tunnel for the heater test. This run consisted of 200 computational cycles which advanced the STEALTH time to 8.1588×10^6 seconds. The heater test was started in a subsequent run from cycle 201 with time advancing from 8.1588×10^6 seconds. This time value is the reference time at which the simulation time is zero. Problems for which equilibration was not necessary (e.g., Problem 5.3) the simulation began at cycle 1 and the STEALTH time is equal to the simulation time; i.e., the reference time is zero. An examination of the Fortran updates demonstrates how time is properly calculated for transient source description. SI units have been used in defining the STEALTH input. The output is, likewise, in SI units. For convenience of interpretation, the time scale on certain plots has been relabeled. STEALTH output was obtained in hardcopy as well as on microfiche. Plots were obtained in hardcopy. A listing of Fortran updates and STEALTH input data is included for each problem in an appropriate section of this report. Copies of data files (updates and input data) have also been stored on floppy disks and will be transmitted to Teknekron.

The discussion and results for each problem are presented in a separate section of this report. In general, each section presents the necessary Fortran updates, the STEALTH input data set, and the desired results. Note that the start run for each problem requires seven phases of input data. The first phase, PRB phase contains global data for the problem. The information in this phase defines the problem dimensionality, type of physical behavior to be modelled (i.e., thermal, mechanical, or thermomechanical), symmetry, overall mesh limits in the I-J (column-row) space, and magnitude of acceleration due to gravity when appropriate. The number of nodes is I x J and the number of zones or elements is (I - 1) x (J - 1) in a two-dimensional formulation. The MAT phase (Card Type 1xx) is used to select model types for material(s) and internal source(s) as well as to define thermal/mechanical material property data and source strength. The GPT phase (Card Type 2xx) contains input data for mesh generation and for defining the coordinates of geometric constraints. The ZON phase (Card Type 3xx) defines the sub-regions of the mesh and the initial conditions in each sub-region. The BDY phase (Card Type 4xx) defines boundary segments, boundary conditions for each segment, and boundary interactions with geometric constraints. The TIM phase (Card Type 5xx)

includes data to define initial, minimum, and maximum time-steps. The overall limits on number of computational cycles and problem time, and the dynamic relaxation frequency (i.e., damping) are also defined in this input phase. The relaxation frequency or damping can be defined on Card Type 514 in two ways. If a positive number is entered, it is a measure of the lowest frequency mode that needs to be critically damped. If a negative number is entered, it is interpreted as the number of cycles (or iterations) in which equilibrium is to be achieved. A determination of this input parameter is sometimes difficult even for experienced users. The EDT phase (Card Type 6xx) contains any and all information regarding the type and frequency of desired output and plot requests. In a restart run (i.e., the second or higher steps in a multi-stage problem) only the PRB, TIM, and EDT phases are required as input. However, certain input data may be redefined in the MAT, GPT, ZON, and BDY phases at restart time. The User's Manual clearly describes which card types are required at start time, which card types are required at restart time, and which card types are forbidden at restart time. Restart edits may be specified at selected times (or cycles) and saved such that it is possible to restart the problem from any of those edit times by using the edit data (saved on file) as the "initial" conditions at that time.

SECTION 2

Benchmark Problem 2.9

This problem is concerning the transient thermal response of a slab exposed to a uniform radiative environment. The slab has infinite length and width and a finite thickness (L = 0.25m). The rear surface is insulated, and the front surface is exposed to a uniform radiative environment.

The STEALTH 2D Code does not have a standard external radiation boundary condition option. Furthermore, the code calculates "zone-center" temperatures that are associated with the mass of a zone (element). The calculated temperature is, thus, the average temperature over the volume of a zone, and not a nodal temperature. The cross-section area of a zone is bounded by four straight line segments between nodes (i.e., the four corners) of that zone. Fortran updates were developed that permit: a calculation of the nodal temperature at the front surface, and a thermal radiation boundary simulation. These updates are listed in Table 1. The updates to Subroutine MYBDY calculate the equilibrium surface temperature by balancing the surface heat flux. To work within the framework of standard STEALTH variables, a new zonal temperature is inferred from this surface temperature for the zone adjacent to the surface. The usual STEALTH boundary flux calculation is then carried out, with appropriate heat added or removed from the boundary zone. The time step, Δt is controlled by a stability criterion as follows:

$$\Delta t \leq \frac{\Delta x^2 \rho C_p}{2K}$$

where Δx is the characteristic zone length, ρ is the mass density, C_p is the specific heat, and K is the thermal conductivity. The quantity "$K/\rho C_p$" is also known as the thermal diffusivity.

By appropriately choosing the boundary conditions, a two-dimensional model was made to behave as a one-dimensional slab. The finite-difference mesh was generated such that there were 21 nodes along the slab thickness and 3 nodes along its width for a total of 63 nodes. This mesh is shown schematically in Figure 1 along with the thermal boundary conditions. As may be seen in Figure 1, there are 20 equal zones (or elements) along the slab thickness and two elements along the width. At a given distance from the slab surface the two elements along the width should have identical thermal response. For this mesh, Δx was 0.0125m, which resulted in a stable time step of 144 seconds for the given set of constant thermal properties. Using the input specifications given in NUREG/CR-3636 and the mesh configuration discussed above, a STEALTH input data set was prepared. These data are listed in Table 2. It was necessary to run the model a total of 2404 computational cycles to simulate 96 hours of the transient response. The data on CPU time, I/O time, and memory are summarized for all the problems at the end of this report. The output specifications are for surface temperature of both sides of the slab at 4, 24, and 96 hours. These results are tabulated below.

Time (hrs)	Temperature (K)	
	Front Surface	Near Rear Surface
4	372.88	533.96
24	317.92	382.21
96	276.15	279.65

Note that the temperatures are provided near the rear surface (instead of at the rear surface) because STEALTH does not calculate nodal temperatures. In any event, the true location at which the "near rear surface" temperature is provided is 6.25×10^{-3}m from the rear surface. For the boundary conditions of this problem, the nodal temperature at the rear surface would be slightly higher. To facilitate comparison with the analytical solution presented graphically in Figure 2.9-2 of NUREG/CR-3636 (Ref. 2), the results are presented in dimensionless parameter form as follows:

Cooling Radiation Number, $M_o = 2.006$ and τ is the Fourier Modulus.

Time (hrs)	τ	$\left[\frac{T - T_o}{T_* - T_o}\right]$	$\left[\frac{T - T_o}{T_* - T_o}\right]$
		Front Surface	Near Rear Surface
4	0.1247	0.6341	0.0441
24	0.7484	0.8355	0.6000
96	2.9936	0.9885	0.9756

Temperature time histories at distances of 6.25×10^{-3}m, 0.118m, and 0.2438m from the front surface of slab are shown in Figures 2, 3, and 4, respectively. Profiles of temperature across the slab at 4 hours, 24 hours and 96 hours are given in Figures 5, 6, and 7.

TABLE 1

Fortran Updates to STEALTH 2D for Problem 2.9

```
*ID PRB29
*C STEALTH
*I MYBDY2.14
*CALL GPTARY2
*CALL ZONARY2
*CALL TIMVAR
C
      DATA SIGMA, T2 / 5.67E-8, 273.0 /
*D MYBDY2.21,22
      LNOR = NOR(IX,JX)
      GO TO (31,990,990,31,990,990,31,990,990) , LNOR
   31 JXT = JC
      IF(LNOR .EQ. 1) JXT = JT
      TMPZ = TMP(IX+1,JXT)
      COND = CON(IX+1,JXT)
      DELX = XPN(IX+1,JX) - XPN(IX,JX)
      GM = 2.*COND/(DELX * SIGMA * T2**3)
      TZ = TMPZ / T2
      BT = GM*TZ + 1.
      TS = (1.+TZ) / 2.
      DO 11 IWAH = 1,4
      FT = TS**4 + GM*TS - BT
      FP = 4. * TS**3 + GM
      TS = TS - FT/FP
   11 CONTINUE
      TSURF = T2 * TS
      TMPZON = 2.*TSURF - TMPZ
C       ** PRINT SURFACE TEMPERATURE AT SELECTED TIMES **
C
      IF(NSPRT .EQ. 2) GO TO 99
      GO TO 990
   99 WRITE(NFMSG,1111) QDOT, TSURF
 1111 FORMAT(/1H ,10X,7HQDOT = ,F12.4,10X,8HTSURF = ,F12.4)
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0,0.18,0.98,HGT,WID,0.0,CDN)
```

TABLE 2

STEALTH 2D Input Data Set for Problem 2.9

```
ITL     PROBLEM 2.9, SLAB RADIATION
PRB                                                 2.
PRO     2.0
DTS     3.0
GRD     1.0       1.0       21.0      3.0
END
MAT                                                 2.
114     1.0       2.0       2.0
121     1.0       2930.0
152     1.0       1.15
154     1.0       2.12425E+6
END
GPT                                                 2.
211     1.0       1.0       1.0       0.0       0.0
221     1.0       1.0       21.0      1.0       3.
247     1.        0.        0.250     0.        0.0250
END
ZON                                                 2.
311     1.0       1.0       21.       1.        3.
321     1.0       1.0
322     1.0       1.0       5.79920 E8 546.0    5.79920 E8
END
BDY                                                 2.
411     1.        1.        1.        21.       1.
411     2.        21.       1.        21.       3.
411     3.        21.       3.        1.        3.
411     4.        1.        3.        1.        1.
412     1.        1.        5.        5.
412     2.        1.        5.        5.
412     3.        1.        5.        5.
412     4.        1.        5.        8.
END
TIM                                                 2.
511     36.
512     30.         144.
513     1.2       1.0
521     3.4560  E5 2500.
END
EDT                                                 2.
611     1.
613     1.
621     1.        0.        1.440 E+04 3.60 E+03
621     2.        0.        3.456   e5  8.64  e4
622     1.0       21.0      1.        3.
623     11.0      14.0      61.       53.
624     3.
641     1.        0.        3.456   E5   8.640E4
671     1.         0.        3.456E+05 3.60 E+03
674     1.        1.        61.       1.        2002.
674     2.        1.        61.       1.        21002.
674     3.        2.        61.                            1.440  E04 2.
674     4.        2.        61.                            8.640  E04 2.
674     5.        2.        61.                            3.456  E05 2.
```

continued

TABLE 2 concluded

674	6.	1.	61.	1.	11002.
END					
END					

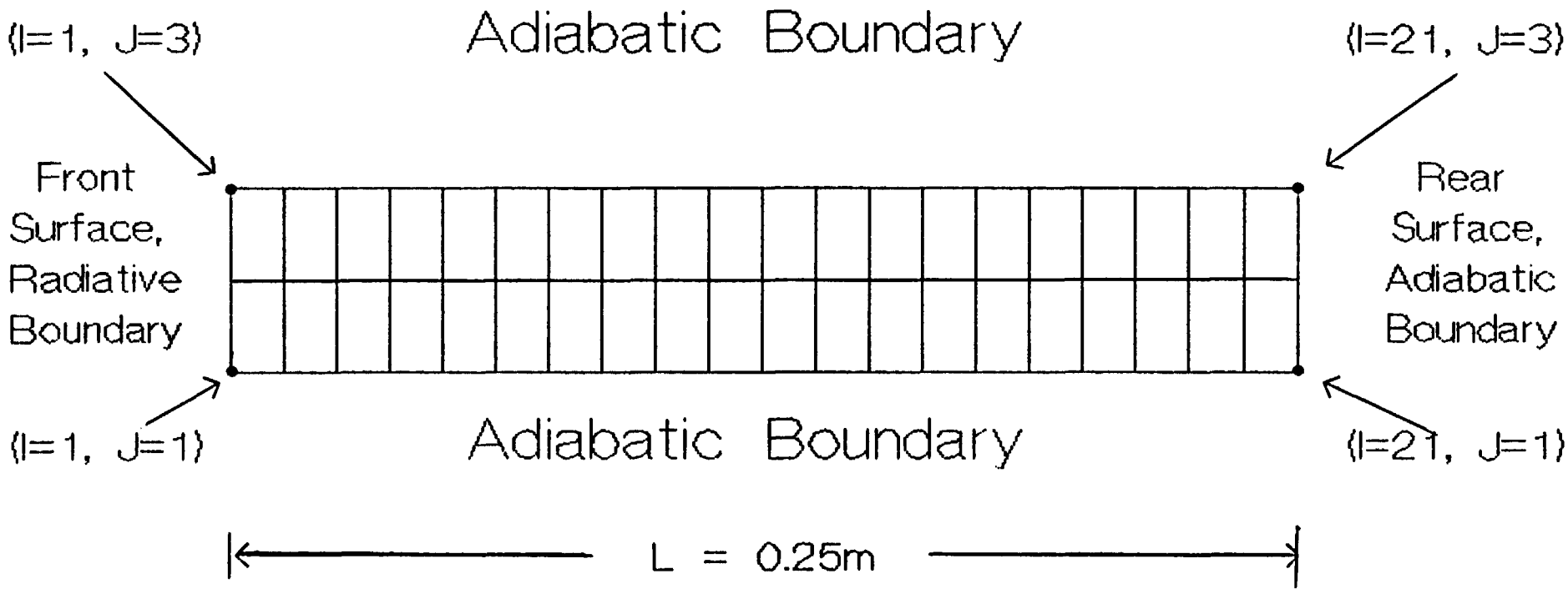


Figure 1. Finite-difference Mesh and Boundary Conditions for Benchmark Problem 2.9 (not to scale).

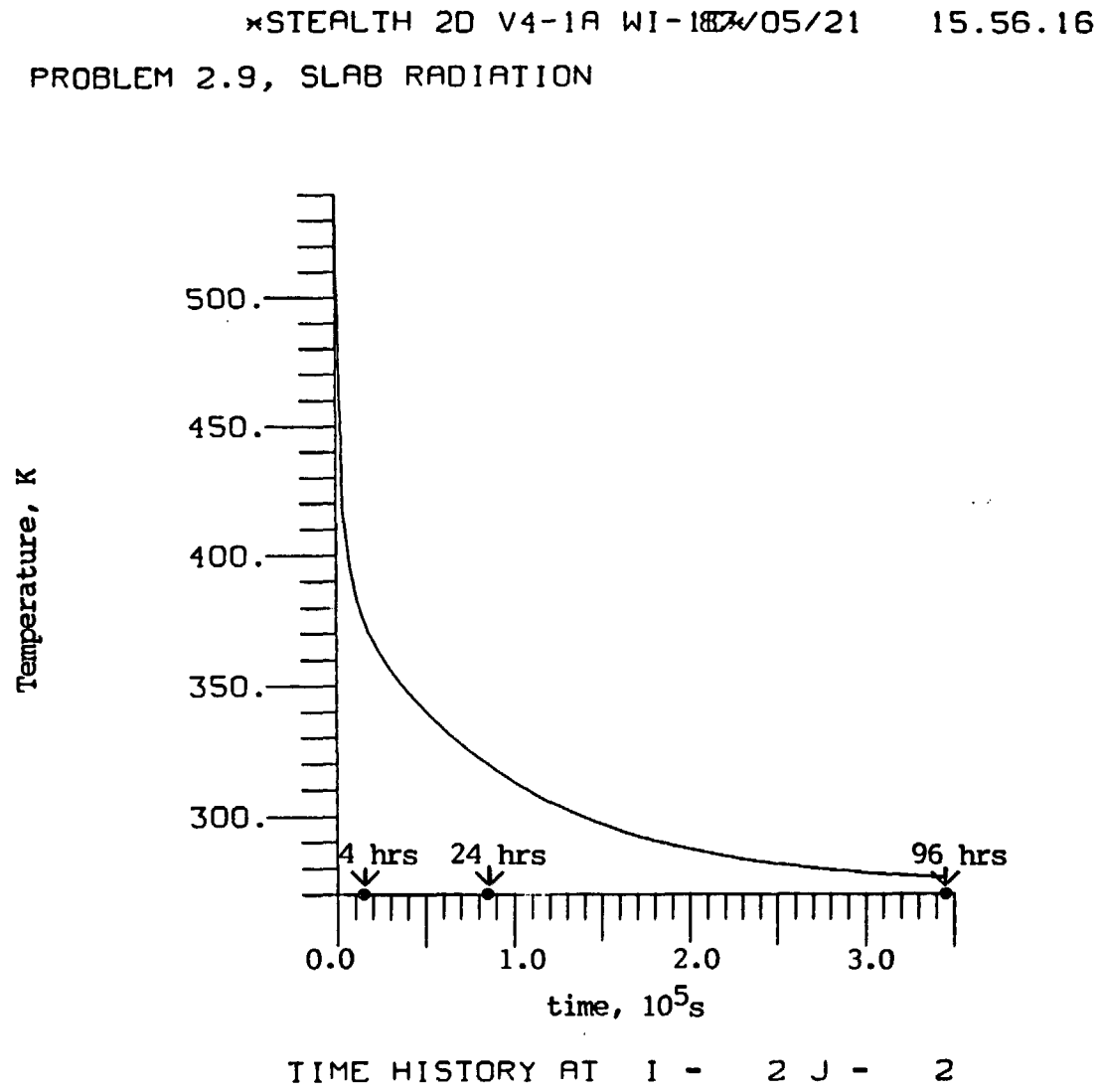


Figure 2. Temperature time history near the front surface of slab, Benchmark Problem 2.9.

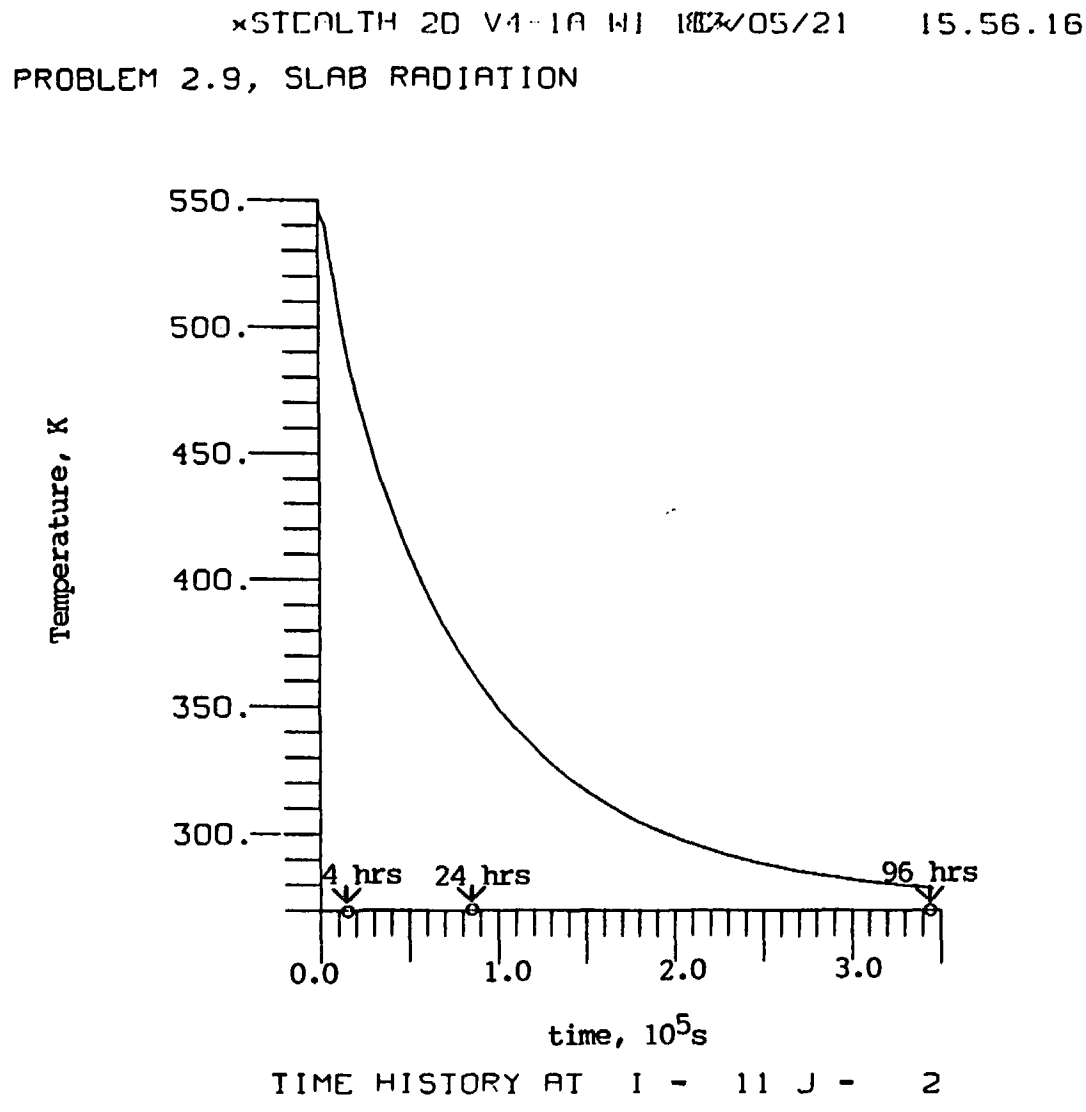


Figure 3. Temperature time history near the middle of slab, Benchmark Problem 2.9.

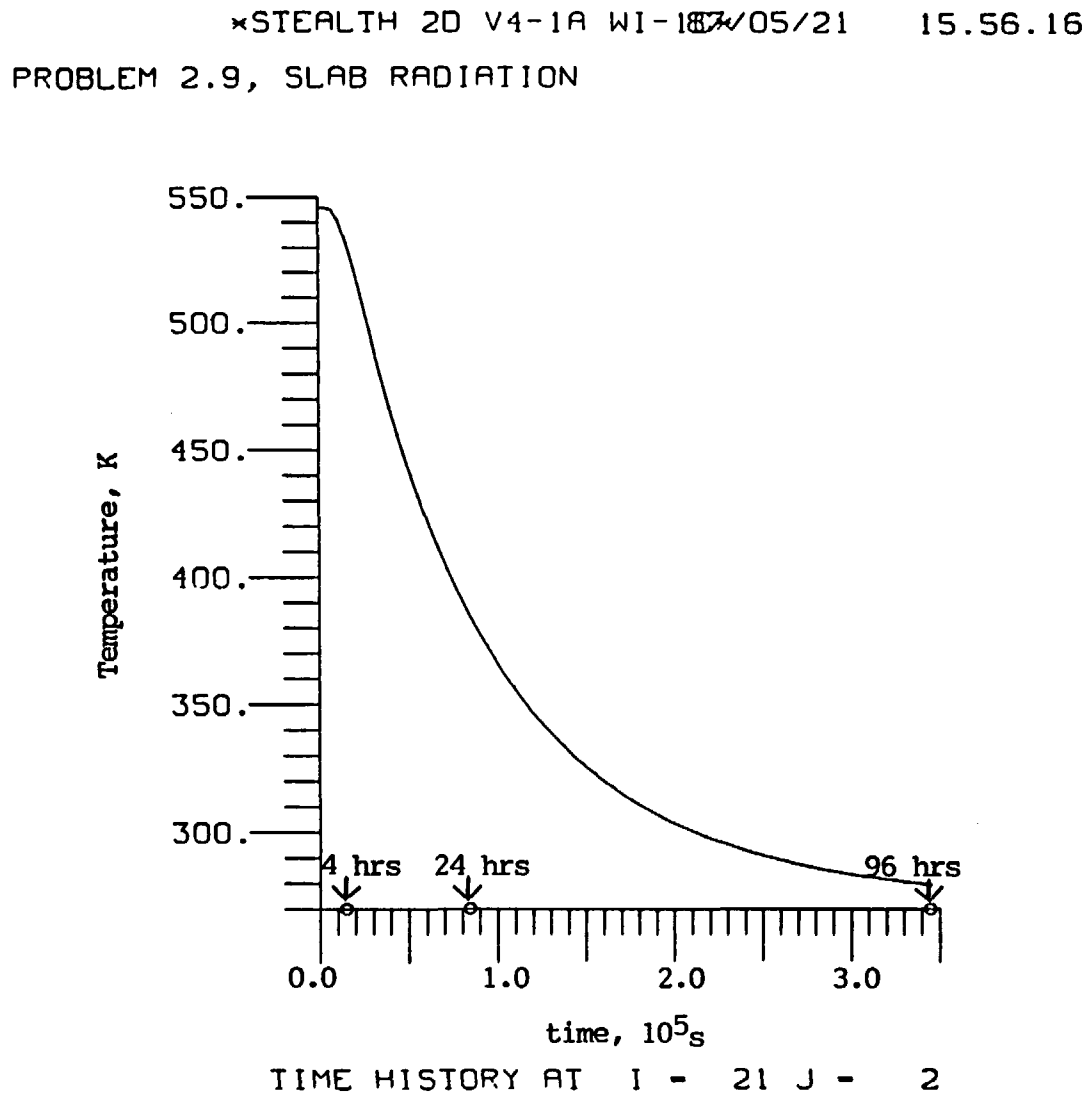


Figure 4. Temperature time history near the rear surface of slab, Benchmark Problem 2.9.

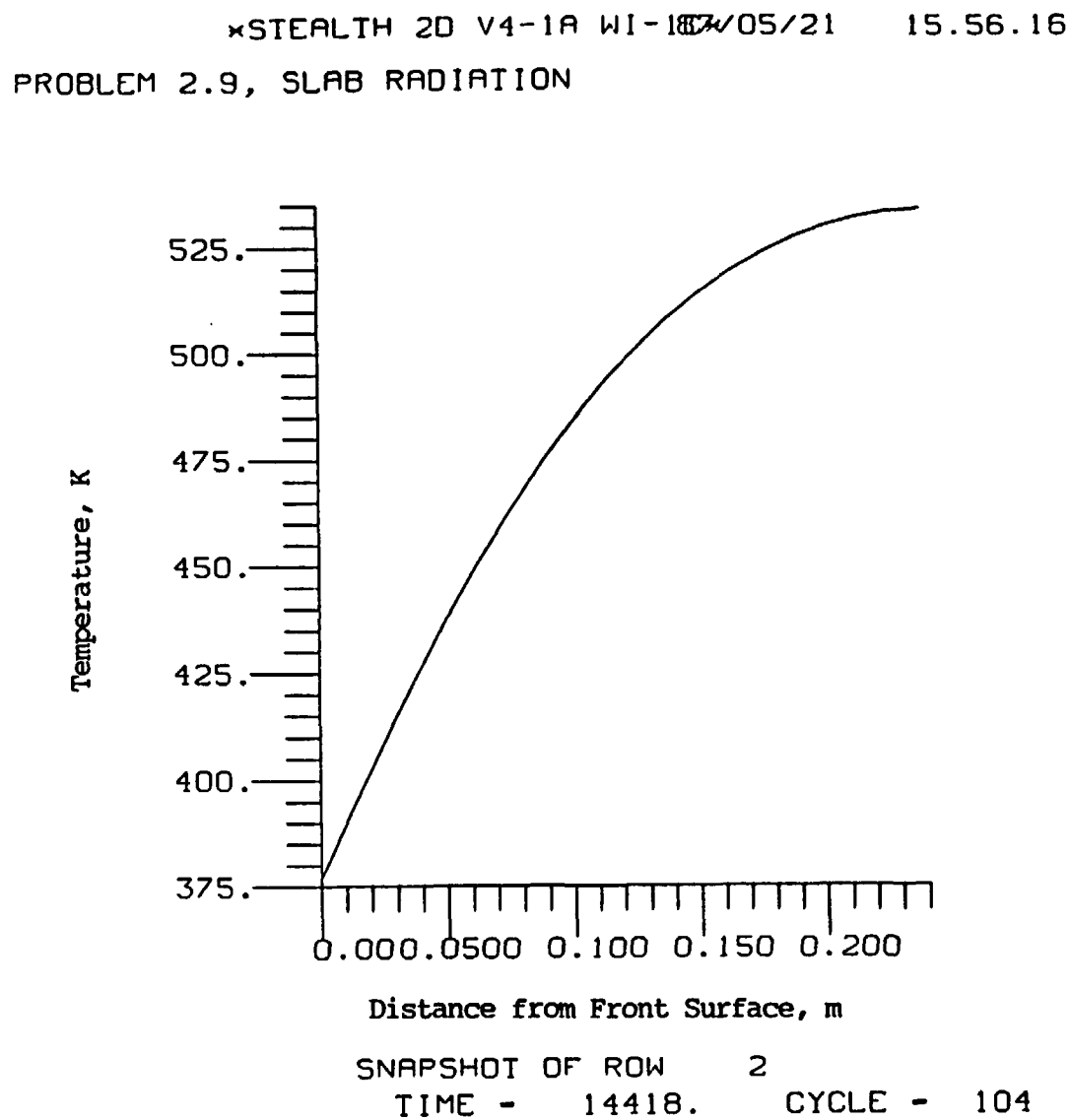


Figure 5. Temperature profile through slab thickness at 4 hours, Benchmark Problem 2.9.

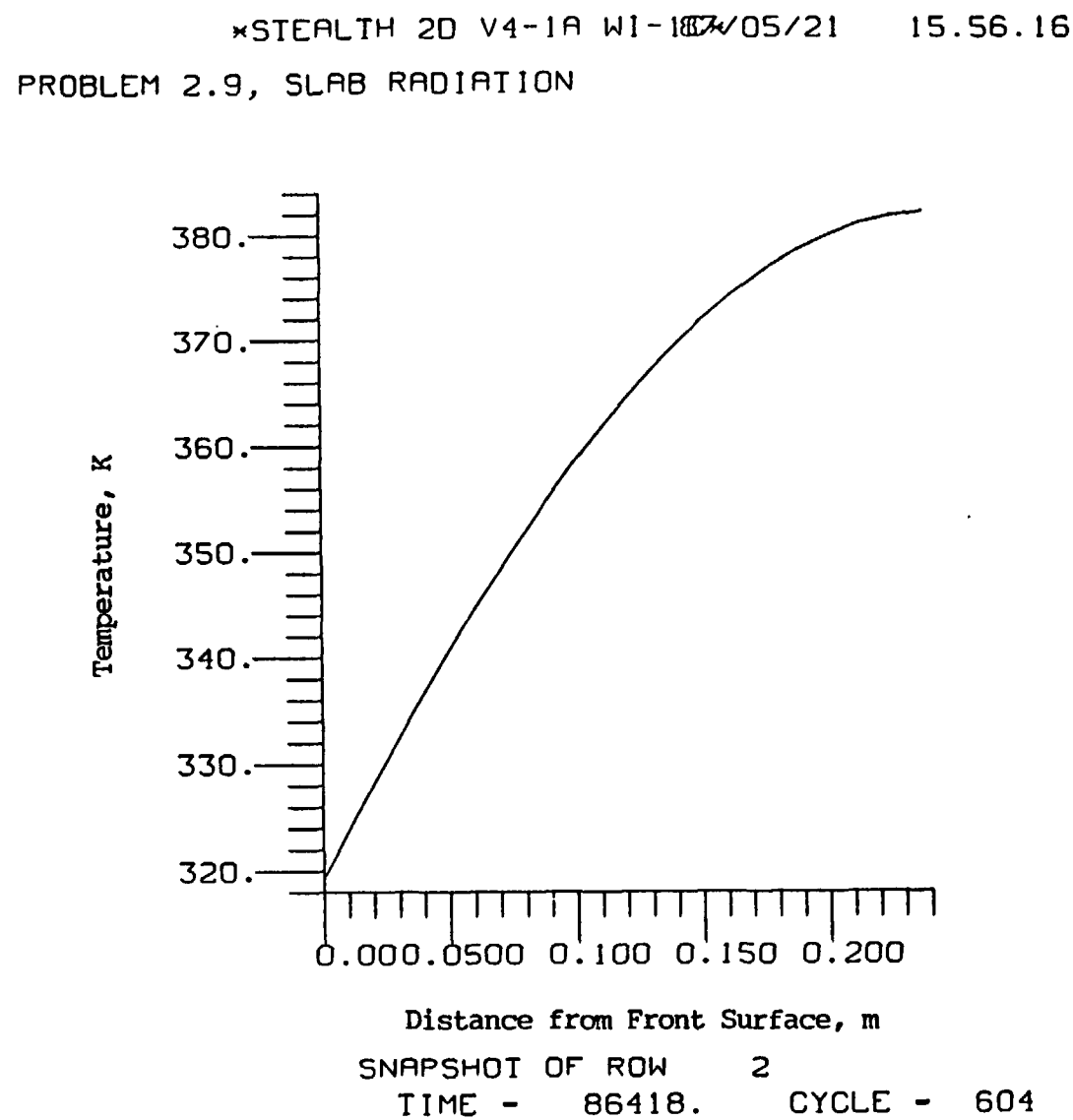


Figure 6. Temperature profile through slab thickness at 24 hours, Benchmark Problem 2.9.

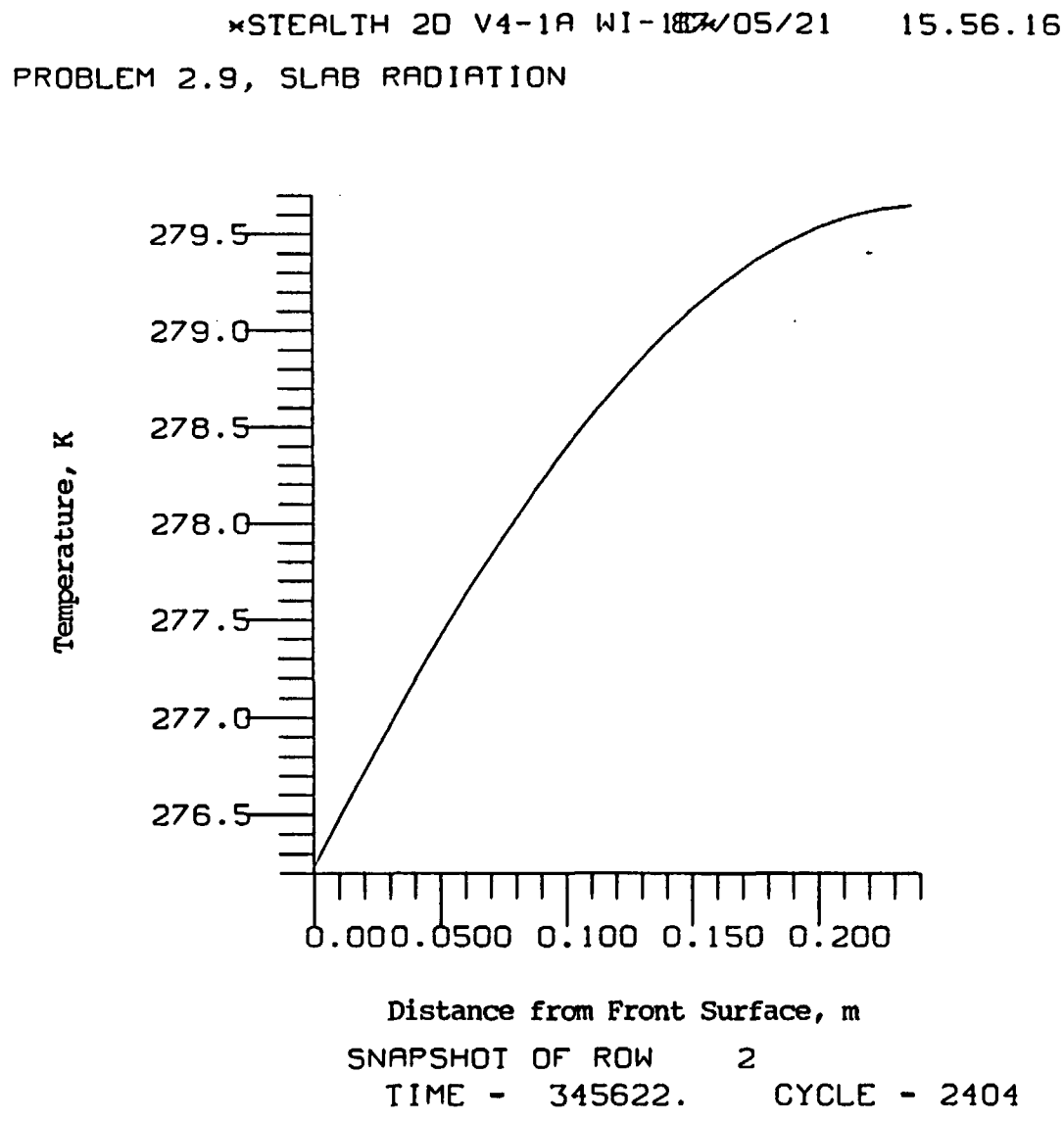


Figure 7. Temperature profile through slab thickness at 96 hours, Benchmark Problem 2.9.

SECTION 3

Benchmark Problem 3.5

This problem is designed to exercise two different yield criteria in the repository design codes. The criteria of interest are the von Mises criterion and the Drucker-Prager criterion. The plastic yielding and flow of a rectangular block loaded by a uniform pressure in one direction is to be modeled. The block is constrained in a second orthogonal direction and is free to expand in the third orthogonal direction. Two cases of this problem, one for each criterion, have been run. When using a two-dimensional code, this problem must be modeled in a plane-strain geometry. Whereas the von Mises criterion is the standard yield criterion in STEALTH, the Drucker-Prager criterion is not a standard option. The code does use the Prandtl-Reuss flow rule and allows a strain hardening yield surface. Fortran updates were developed to formulate the Drucker-Prager criterion as a user-defined yield model. Updates were also needed for each case to define the load increment function. Starting with an initial load of 300 MPa, the load is incremented by 30 MPa every 100 computational cycles. These updates to STEALTH are listed in Table 3 (von Mises case) and Table 4 (Drucker-Prager case). The boundary conditions needed for this problem are available as standard options in STEALTH. A rectangular mesh was generated that had 11 rows (J lines) and 16 columns (I lines) resulting in a total of 176 nodes and 150 zones. The mesh and the boundary conditions (same for both cases) are shown in Figure 8. The statement of the von Mises criterion in STEALTH is not identical to its statement in Equation (1) of Reference 2. Specifically, the numerical value of k_M needs to be multiplied by a factor of "$\sqrt{3}$" for the two statements to be consistent. Accordingly, the k_M value of 190 MPa is multiplied by $\sqrt{3}$ to obtain the value 329.1 MPa and entered on input card type 132 for the von Mises case data set. The entire data set is presented in Table 5. For the Drucker-Prager case the k_{DP} value of 36 MPa given in Reference 2 in incorrect. The correct value of 362 MPa was obtained by solving Equation (9) given on page 82 of the reference. The k_{DP} and α values are entered on card type 132 for the Drucker-Prager case data set. Except for the yield model parameters, all input data for the Drucker-Prager case, given in Table 6, is identical to that for the von Mises case. STEALTH does not calculate total strains; it works with strain rates and strain increments. Furthermore, it is not clear from the output specifications in Reference 2 which strain components are desired at what locations in the slab. It is possible to compute by hand the strains in a given element or global strains in the slab from the deformed mesh coordinates. Time is a dummy parameter in this problem; an arbitrary time step of 0.1 seconds has been chosen. Load is incremented every 100 cycles (i.e., every 10 seconds) starting with an initial load of 300 MPa. In other words, roughly 100 computational cycles or iterations are run to achieve equilibrium for a given external load. Printout of relevant variables is obtained every 50 cycles starting at cycle 45. Thus, the printout at cycle 95 gives the equilibrium solution at a load of 300 MPa, and the printout at cycle 195 gives the solution at a load of 330 MPa, etc. Intermediate printouts are for monitoring convergence. The maximum number of cycles

requested in each case is 1195 corresponding to a final load of 630 MPa, which is 2.1 times the initial load.

The results for the von Mises case will be presented first. In the elastic range at applied load values of 300 MPa and 330 MPa the stress components in the center of the slab and the total strains are presented in Table 7. The solution is not identical in each computational element. The element-to-element variations are relatively small in the elastic range. For comparison with the analytical solution the stress values selected are for the element (I=16, J=2) near the slab mid-height and the right edge. The ε_1 strain is hand-computed from the deformation of the node (I=1, J=11) at the top left corner of the mesh. Likewise, the ε_2 strain is hand-computed from the deformation of the node (I=16, J=1) at the bottom right corner of the mesh. The solution when the applied load is 360 MPa indicates plastic deformation nearly everywhere in the mesh. Theoretically, initial yielding should occur at 359 MPa. The slab should remain plastic as long as the load is maintained at 359 MPa or higher. This is indeed the response at higher load levels. In Table 8, values of σ_1, σ_2, σ_3, ε_1, and ε_2 from the STEALTH results are given at different applied loads in the plastic range. To provide an indication of stress variations within the mesh at a given load, the ranges of different stress components are listed in Table 9. Plots of principal components of stress versus "time" at selected locations in the slab are shown in Figures 9 through 12. Time in these figures is actually a discrete measure of load increments starting with 300 MPa. Load is increased by 30MPa every 10 units of "time." For instance, at a "time" of 110 the σ_1 value in the center of slab at an applied load of 600 MPa is 605 MPa (Figure 9), and the σ_2 value is approximately 314 MPa (Figure 10).

The results for the Drucker-Prager case are presented next. For the k_{DP} and α values assigned to the yield parameters, initial yield is expected to occur at approximately 359 MPa. The solution in the elastic range is compared with the analytical solution in Table 10. The locations of stresses and hand-computed strains from the numerical solution are the same as in the von Mises case. The solution in cycle 295 for an applied load of 360 MPa does indicate plastic failure as expected. Values of σ_1, σ_2, σ_3, ε_1 and ε_2 based on STEALTH results are given in Table 11 at applied loads of 360 MPa and higher. Stress variations within the mesh at a given load are quite large after initial yield. Not every element indicates plastic failure even at relatively high loads. The ranges of different stress components at selected loads are shown in Table 12. It is not clear whether the spatial variation of stresses within the mesh is realistic or reflects an inability of the model to converge to the proper equilibrium solution. Another possibility is that instability or "ultimate failure" occurred at a load only slightly larger than the initial yield point. In any event, a computed yield strength of zero (or less) leads to a hydrostatic state of stress. Plots of stress versus "time" at selected locations in the slab are presented in Figures 13 through 16. The parameter "time" on the abscissa is, in fact, representative of load increments every 10 units of time (100 computational cycles) as stated earlier.

TABLE 3

Fortran Updates to STEALTH 2D for Problem 3.5 (von Mises Case)

```
*ID BM35VM
*C STEALTH
*D MYFNO.27,28
      VAL = FCA(1) + FCA(2)*INT(NCCYC/FCA(3))
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0,0.18,0.98,HGT,WID,0.0,CDN)
*I DMPPRO.24
      RETURN
```

TABLE 4

Fortran Updates to STEALTH 2D for Problem 3.5 (Drucker Prager Case)

```
*ID PRB35DP
*C STEALTH
*I MYYLD.20
*CALL ZONVAR
*CALL MATVAR
*D MYYLD.25,26
C
C       ** YIELD STRESS BASED ON DRUCKER-PRAGER MODEL **
C       ** YLD0 AND YLD1 ARE KDP AND ALPHA VALUES  **
C       ** YLDN IS COMPARED WITH SQRT(J2) IN SUB. ZONSDV2 **
C
      YLDN = SQRT(3.) * (YLD0 - 3.*PRHN*YLD1)
*D MYFNO.27,28
      VAL = FCA(1) + FCA(2)*INT(NCCYC/FCA(3))
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0,0.18,0.98,HGT,WID,0.0,CDN)
*I DMPPRO.24
      RETURN
```

TABLE 5

STEALTH 2D Input Data Set for Problem 3.5 (von Mises Case)

```
TTL     ELASTIC PLASTIC BLOCK, PROB 3.5 (VON-MISES YIELD CRIT.)
PRB                                                 1.
PRO     2.0
DTS     2.0       1.
GRD     1.0       1.0       16.0      11.0
END
MAT
111     1.0       1.0
112     1.0       2.0       2.0       2.0
121     1.0       2000.0
122     1.0       1.0                 2.5    E10
132     1.0       3.2909  E8
134     1.0       1.875  E10
136     1.0          -1.0E25
END
GPT                                   2.        1.0
211     1.0       1.0       1.0
212     1.0                 5.5       2.0
212     2.0                           1.0
212     3.0       8.        0.0       3.0
221     1.0       1.0       16.0      1.0       11.0
247     1.0                 7.5                 5.0
END
ZON                                               1.0
311     1.0       1.0       16.0      1.0       11.0
321     1.0       1.0
322     1.0       1.0
END
BDY                                               1.0
411     1.0       1.0       1.0       16.0      1.0
411     2.0       16.0      1.0       16.0      11.0
411     3.0       16.0      11.0      1.0       11.0
411     4.0       1.0       11.0      1.0       1.0
412     1.0       1.0       6.0       5.0       3.0
412     2.0       1.0       3.0       5.0
412     3.0       1.0       2.0       5.0       1.0
412     4.0       1.0       6.0       5.0       2.0
422     1.0       1.0
431     1.0       9.0                    1.00E10
432     1.0       3.0     E8 0.30   E8 100.     100.
481     4.        1.        2.
481     1.        2.        3.
482     1.        1.        5.        5.        0.        0.05
482     4.        1.        5.        5.        0.        0.05
END
TIM
511     0.1
512     0.1       0.1
513     1.0       1.0
514     -95.0
521     1000.0    1195.
END
EDT                                               1.
```

continued

TABLE 5
concluded

611	2.0						
613	2.						
616	2.0						
621	1.0	45.	1100.	50.0			
622	1.0	16.0	1.0	11.0			
623	11.0	14.0	71.0	72.0	73.0	81.0	82.0
623	83.	84.	64.	42.			
624	3.						
641	1.	0.	1200.	200.			
671	1.	0.	1200.	10.			
674	1.	1.	71.	1.	2002.		
674	2.	1.	71.	1.	16002.		
674	3.	1.	73.	1.	2011.		
674	4.	1.	71.	1.	16011.		
674	5.	1.	5.	1.			
674	6.	1.	72.	1.	11005.		
674	7.	1.	72.	1.	2002.		
674	8.	1.	72.	1.	2011.		
675	9.	6.			100.		
END							
END							

TABLE 6
STEALTH 2D Input Data Set for Problem 3.5 (Drucker Prager Case)

```
TTL       ELASTIC PLASTIC BLOCK, PROB 3.5  (DRUCKER-PRAGER CRIT.)
PRB                                                   1.
PRO       2.0
DTS       2.0       1.0
GRD       1.0       1.0       16.0      11.0
END
MAT                                                   1.
111       1.0       1.0
112       1.0       6.0       2.0       2.0
121       1.0       2000.0
122       1.0       1.0                 2.5    E10
132       1.0       3.620000E8 0.40
134       1.0       1.875  E10
136       1.0          -1.0E25
END
GPT                                     2.0       1.0
211       1.0       1.0       1.0
212       1.0                 5.5       2.0
212       2.0                           1.0
212       3.0       12.       0.0       3.0
221       1.0       1.0       16.0      1.0       11.0
247       1.0                 7.5                 5.0
END
ZON                                                   1.0
311       1.0       1.0       16.0      1.0       11.0
321       1.0       1.0
322       1.0       1.0
END
BDY                                                   1.0
411       1.0       1.0       1.0       16.0      1.0
411       2.0       16.0      1.0       16.0      11.0
411       3.0       16.0      11.0      1.0       11.0
411       4.0       1.0       11.0      1.0       1.0
412       1.0       1.0       6.0       5.0       3.0
412       2.0       1.0       3.0       5.0
412       3.0       1.0       2.0       5.0       1.0
412       4.0       1.0       6.0       5.0       2.0
422       1.0       1.0
431       1.0       9.0                    1.00E10
432       1.0       3.0     E8 0.30   E8 100.     100.
481       4.        1.        2.
481       1.        2.        3.
482       1.        1.        5.        5.        0.        0.05
482       4.        1.        5.        5.        0.        0.05
END
TIM
511       0.1
512       0.1       0.1
513       1.0       1.0
514       -95.
521       1000.0    1195.
END
EDT                                                   1.
```

continued

TABLE 6
concluded

611	2.0						
613	2.						
616	2.0						
621	1.0	45.	1100.	50.0			
622	1.0	16.0	1.0	11.0			
623	11.0	14.0	71.0	72.0	73.0	81.0	82.0
623	83.	84.	64.	42.			
624	3.						
641	1.	0.	1200.	200.			
671	1.	0.	1200.	10.			
674	1.	1.	71.	1.	2002.		
674	2.	1.	71.	1.	16002.		
674	3.	1.	73.	1.	2011.		
674	4.	1.	71.	1.	16011.		
674	5.	1.	5.	1.			
674	6.	1.	72.	1.	11005.		
674	7.	1.	72.	1.	2002.		
674	8.	1.	72.	1.	2011.		
675	9.	6.			100.		
END							
END							

Table 7

Elastic Stresses and Strains in the Slab, von Mises Case

Comparison Between Analytical and Numerical Solutions

Stress or Strain Component	Applied Load, P = 300 MPa		Applied Load, P = 330 MPa	
	Analytical	Numerical Cycle 95	Analytical	Numerical Cycle 195
σ_1	-300 MPa	-299.01 MPa	-330 MPa	-329.95 MPa
σ_2	0	-0.14 MPa	0	-0.01 MPa
σ_3	-60 MPa	-60.00 MPa	-66 MPa	-66.20 MPa
ε_1	-6.40×10^{-3}	-6.344×10^{-3}	-7.04×10^{-3}	-7.008×10^{-3}
ε_2	1.60×10^{-3}	1.563×10^{-3}	1.76×10^{-3}	1.764×10^{-3}

Table 8

Post-Yielding Stresses* and Strains in the Slab, von Mises Case

Applied Load, Mpa	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)	ε_1 (%)	ε_2 (%)
360	-359.63	-0.05	-73.43	-0.765	0.194
420	-378.74	-2.68	-143.47	-1.226	0.514
480	-385.67	-5.79	-187.65	-1.994	1.269
540	-389.65	-9.65	-198.81	-3.025	2.503
600	-393.95	-13.96	-203.61	-4.275	4.176

*Refer to the text for location(s) at which stresses and strains are monitored for this table.

Table 9

Variation in Stress Components at Different Load Levels*, von Mises Case

Applied Load, MPa	σ_1, MPa		σ_2, MPa		σ_3, MPa	
	max.	min.	max.	min.	max.	min.
300	-298.22	-300.11	-0.09	-2.45	-60.00	-60.69
330	-329.85	-330.03	0.00	-0.21	-66.20	-66.25
360	-359.63	-359.99	-0.02	-0.86	-72.33	-75.15
420	-378.74	-425.43	-2.68	-53.14	-137.20	-234.06
480	-385.67	-514.71	-5.79	-150.96	-183.11	-300.23
540	-389.65	-595.30	-9.65	-268.27	-198.81	-364.40
600	-392.19	-654.91	-12.36	-374.40	-202.36	-429.03
630	-392.96	-684.98	-13.08	-349.18	-203.19	-458.9

*Spatial variation in stress across the numerical mesh at selected loads is given to caution against interpreting local stresses as representing global stresses.

Table 10

Elastic Stresses and Strains in the Slab, Drucker-Prager Case

Comparison Between Analytical and Numerical Solutions

Stress or Strain Component	Applied Load, P = 300 MPa		Applied Load, P = 330 MPa	
	Analytical	Numerical Cycle 95	Analytical	Numerical Cycle 195
σ_1	-300 MPa	-299.01 MPa	-330 MPa	-329.95 MPa
σ_2	0	-0.14 MPa	0	-0.01 MPa
σ_3	-60 MPa	-60.00 MPa	-66 MPa	-66.20 MPa
ε_1	-6.40×10^{-3}	-6.344×10^{-3}	-7.04×10^{-3}	-7.008×10^{-3}
ε_2	1.60×10^{-3}	1.563×10^{-3}	1.76×10^{-3}	1.764×10^{-3}

Table 11

Post-Yielding Stresses* and Strains in the Slab, Drucker-Prager Case

Applied Load, MPa	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)	ε_1 (%)	ε_2 (%)
360	-331.36	83.95	-49.60	-1.151	0.105
420	-330.63	-19.25	-163.36	-2.363	1.287
480	-326.83	6.88	-163.30	-4.085	4.043
540	-323.58	-77.64	-196.16	-5.669	6.174
600	-318.27	-97.94	-213.10	-7.165	8.837

*Refer to the text for location(s) at which stresses and strains are monitored for this table.

Table 12

Variation in Stress Components at Different Load Levels*, Drucker-Prager Case

Applied Load, MPa	σ_1, MPa		σ_2, MPa		σ_3, MPa	
	max.	min.	max.	min.	max.	min.
300	-298.22	-300.11	-0.09	-2.45	-60.00	-60.69
330	-329.87	-330.03	0.00	-0.21	-66.20	-66.25
360	-177.19	-392.14	310.64	-392.14	11.65	-392.14
420	-240.00	-441.45	360.37	-441.45	12.31	-441.45
480	-56.97	-477.80	135.93	-477.80	-73.27	-477.80
540	-15.34	-534.58	98.80	-534.58	-91.80	-534.58
600	9.13	-595.63	86.58	-595.63	-105.74	-595.63
630	32.36	-626.12	67.31	-626.12	-109.13	-626.1

*Spatial variation in stress across the numerical mesh at selected loads is given to caution against interpreting local stresses as representing global stresses.

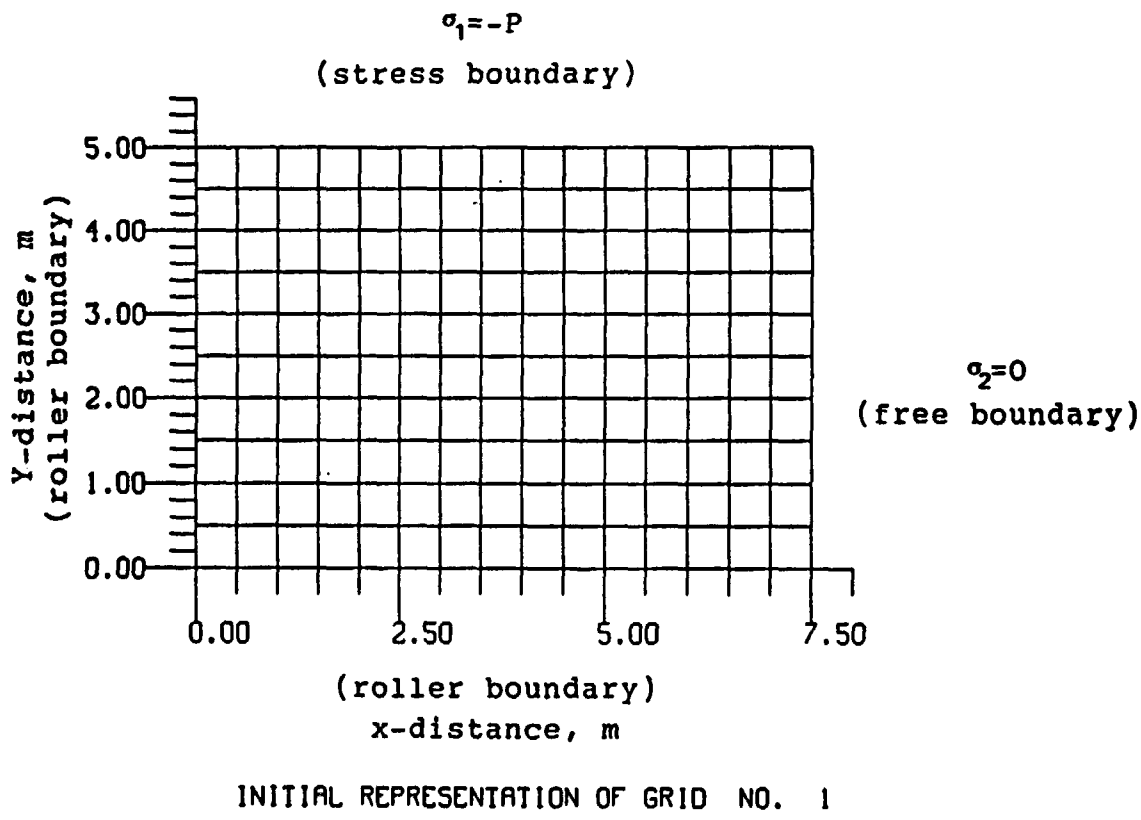


Figure 8. Undeformed mesh and boundary conditions, Benchmark Problem 3.5.

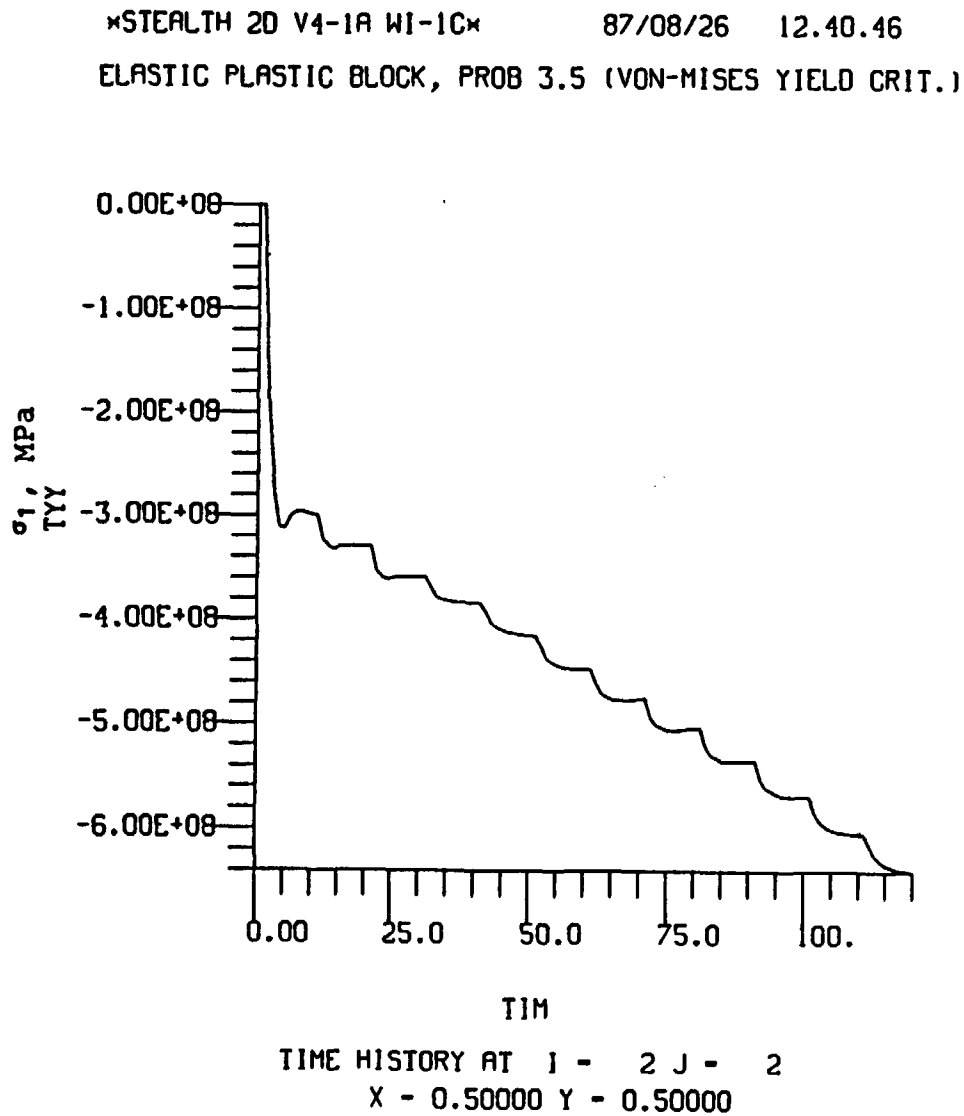


Figure 9. Principal stress σ_1 in center of slab as a function of applied load, von Mises Case.

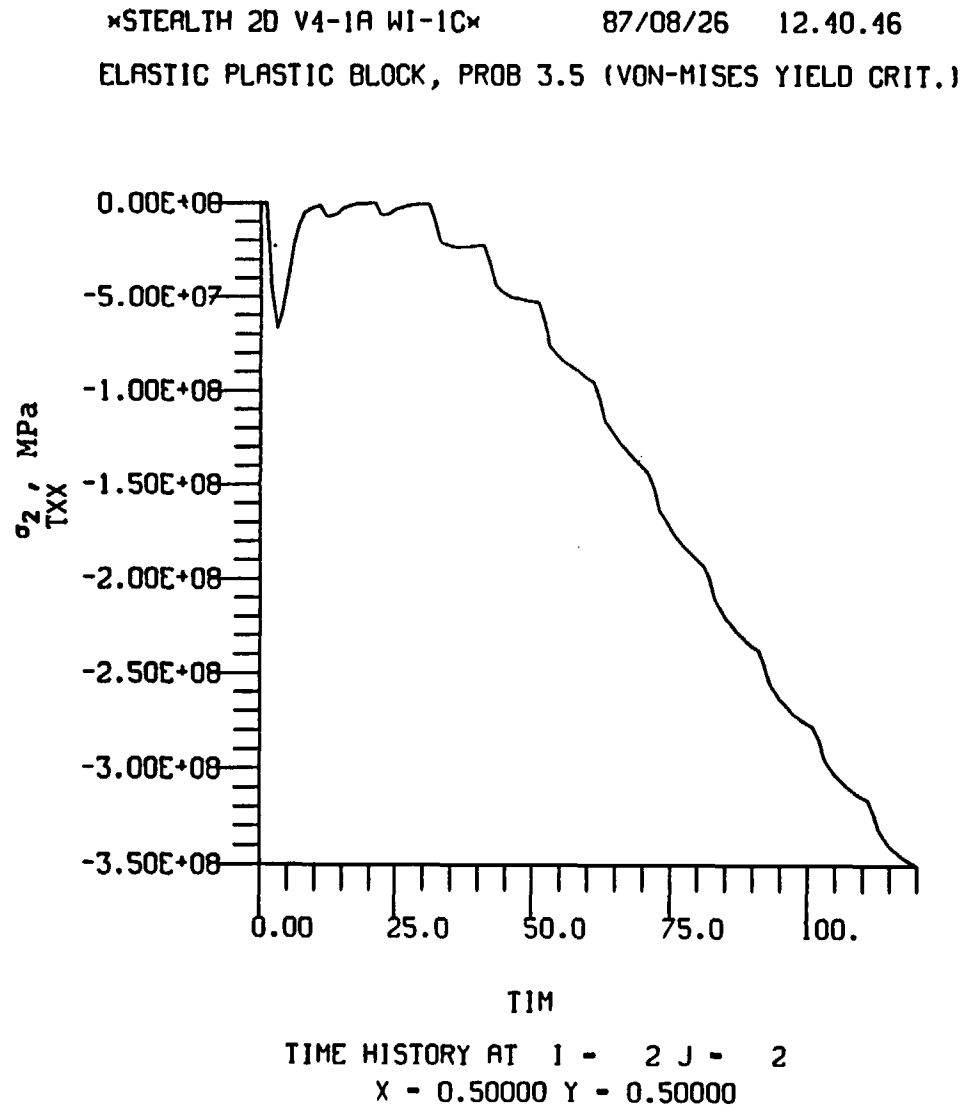


Figure 10. Principal stress σ_2 in center of slab as a function of applied load, von Mises Case.

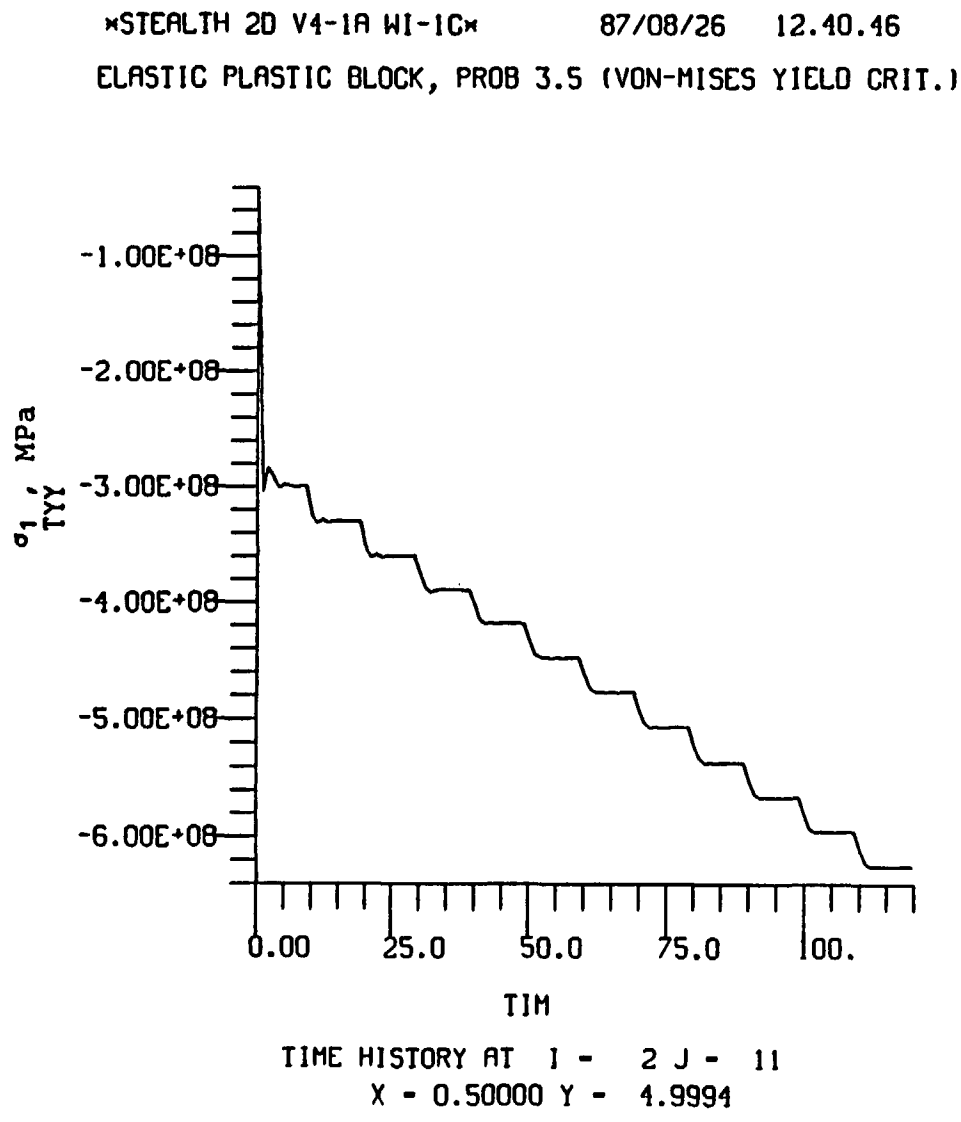


Figure 11. Principal stress σ_1 near top center of slab as a function of applied load, von Mises Case.

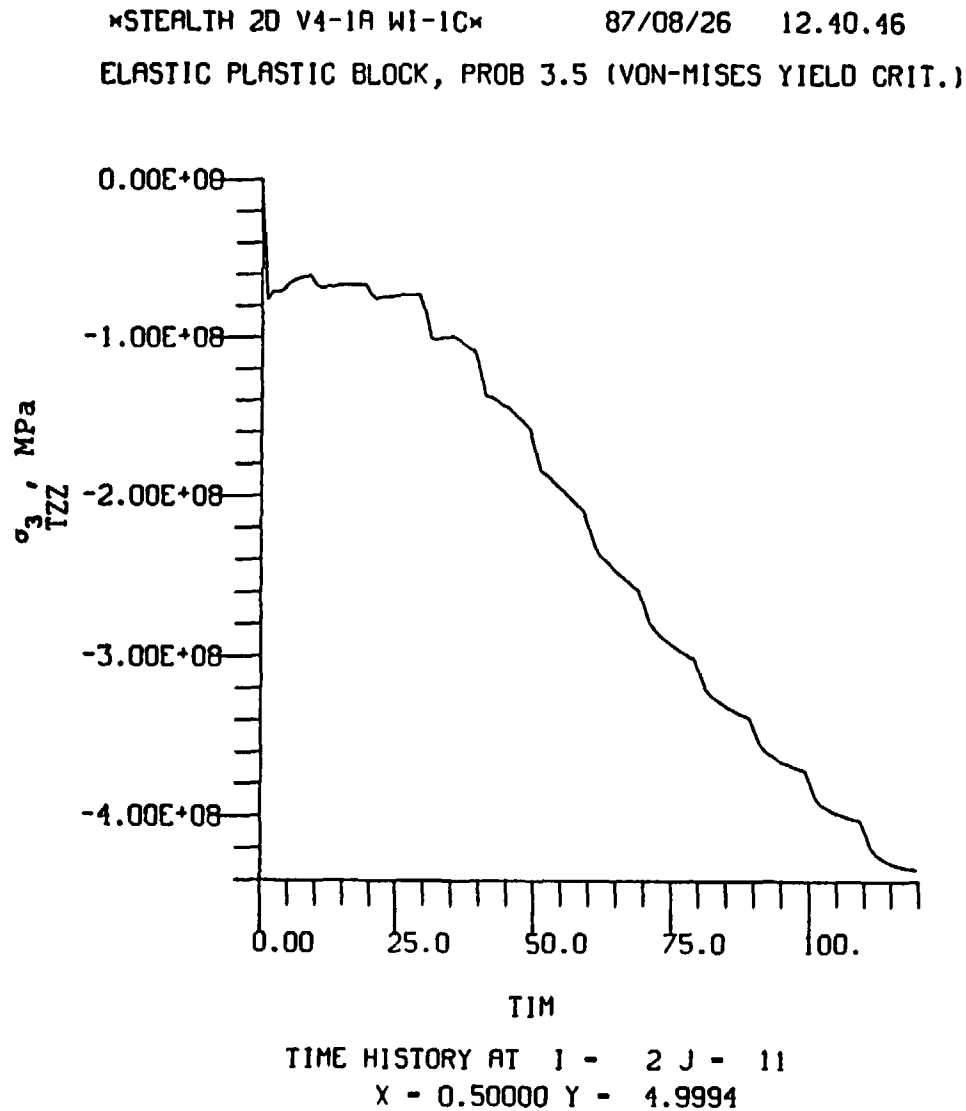


Figure 12. Principal stress σ_3 near top center of slab as a function of applied load, von Mises Case.

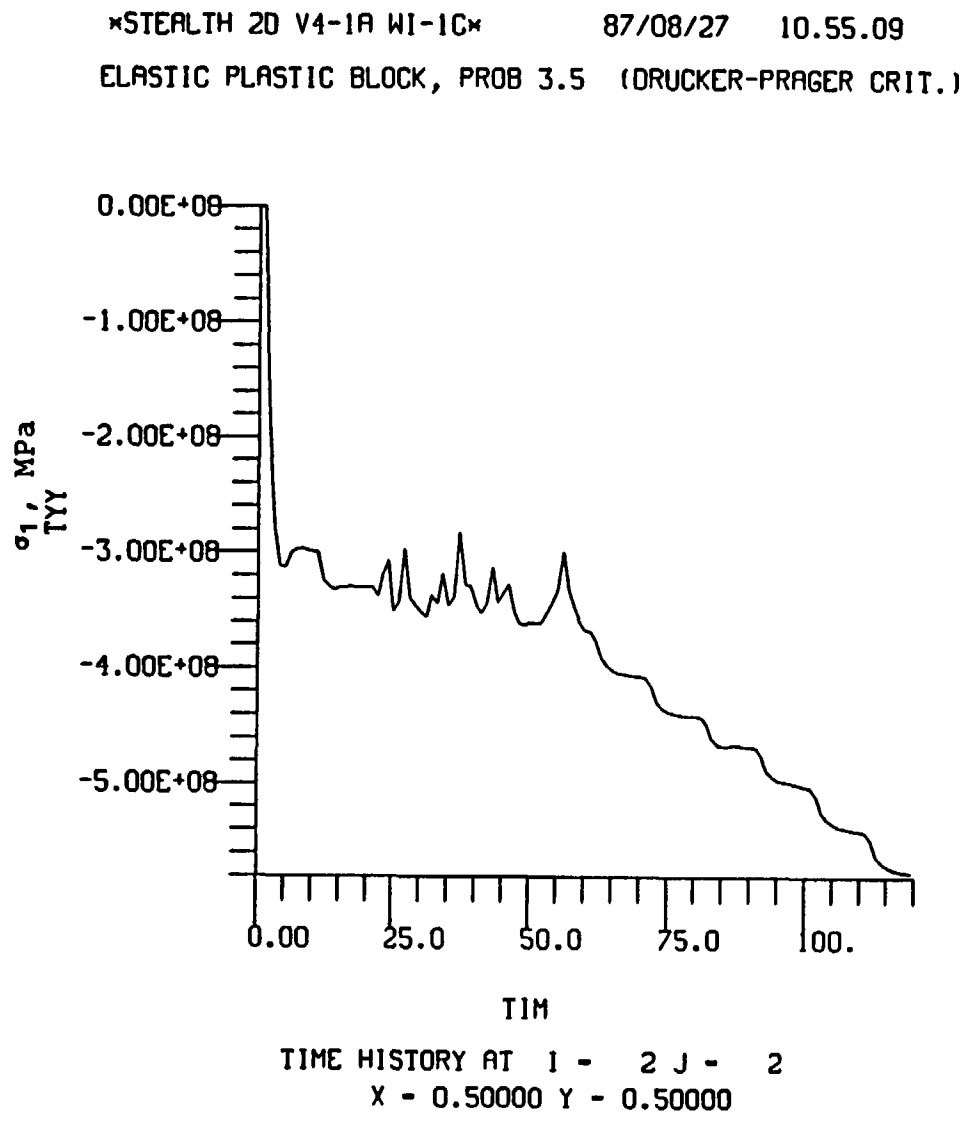


Figure 13. Principal stress σ_1 in center of slab as a function of applied load, Drucker-Prager Case.

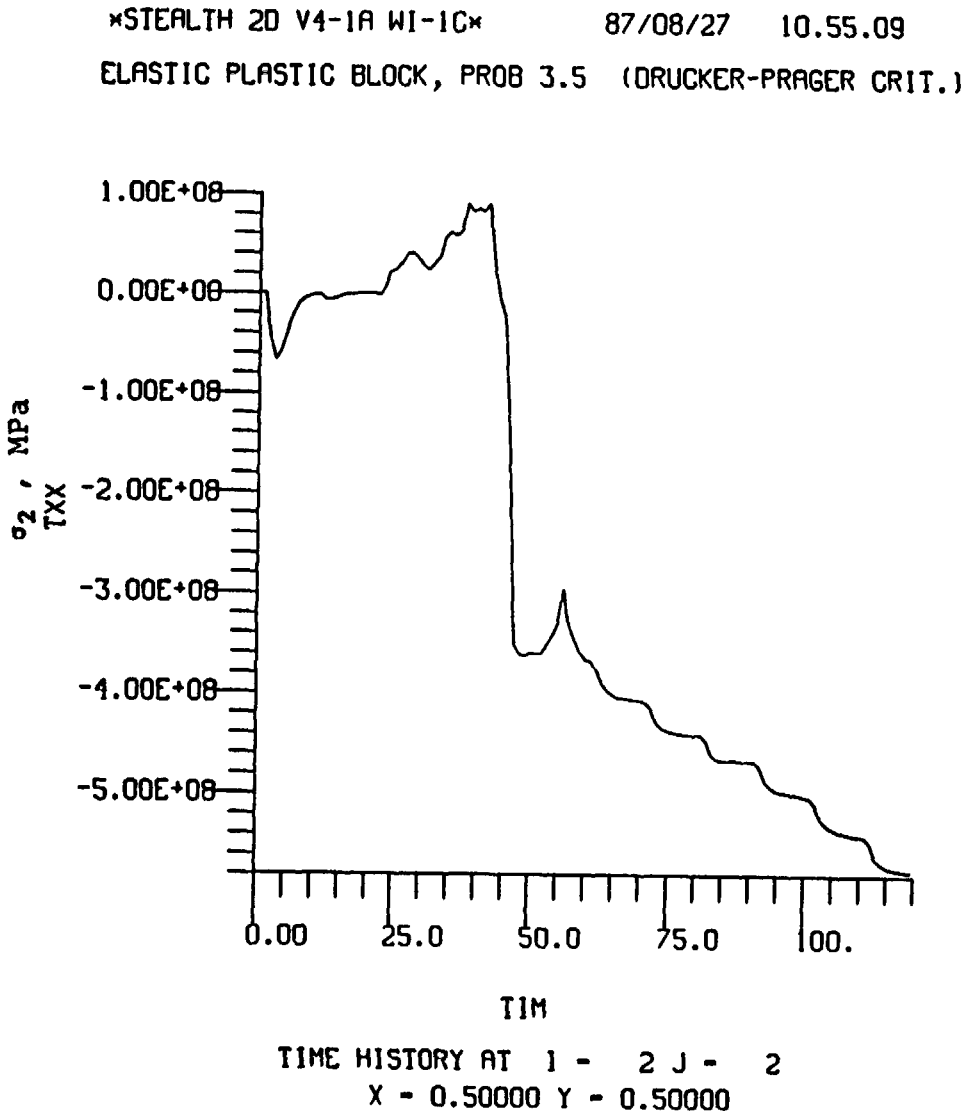


Figure 14. Principal stress σ_2 in center of slab as a function of applied load, Drucker-Prager Case.

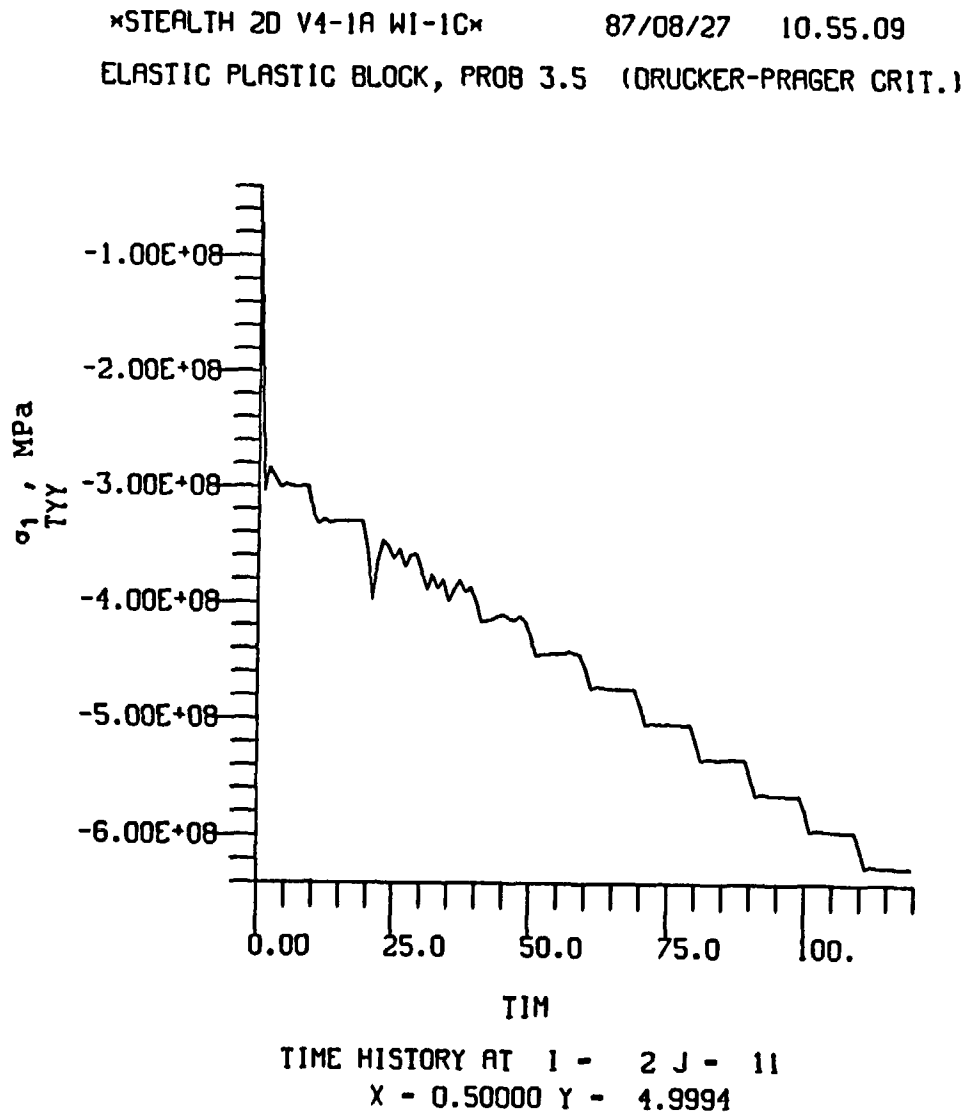


Figure 15. Principal stress σ_1 near top center of slab as a function of applied load, Drucker-Prager Case.

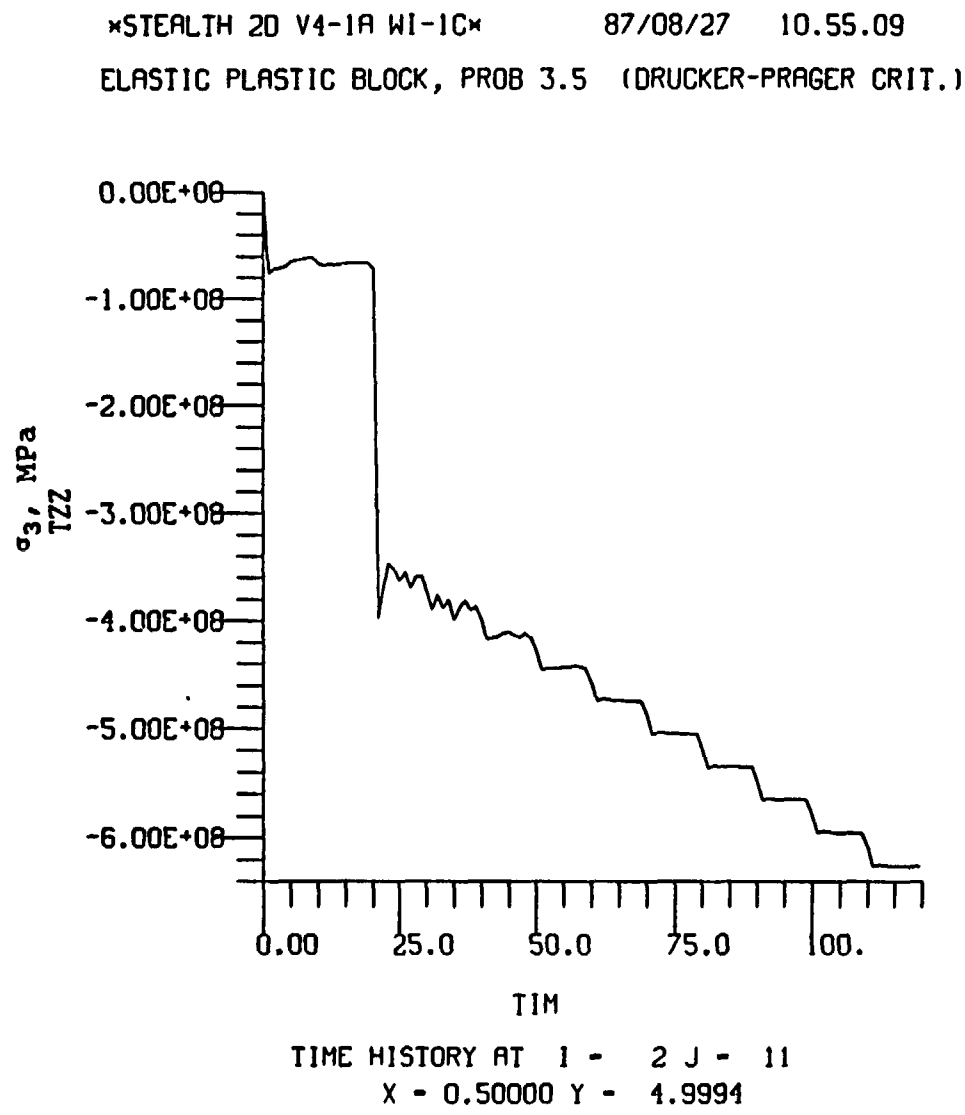


Figure 16. Principal stress σ_3 near top center of slab as a function of applied load, Drucker-Prager Case.

SECTION 4

Benchmark Problem 5.2

This problem requires a simulation of the thermomechanical response in the near field. It is designed to test the two-dimensional (plane) transient thermal and plane-strain mechanical response. The assumed medium for the STEALTH analysis is basalt.

A STEALTH 2D model was constructed according to the specifications in Section 5.2 of Reference 2 with a few exceptions as noted below. A two-dimensional plane-strain geometry was chosen which in essence provides the unit thickness as specified. Due to the fact that STEALTH performs a simultaneous thermal and mechanical solution, it is not feasible to have separate meshes with different overall model dimensions. Therefore, a mesh with a model height of 200m was selected for thermal and mechanical analyses; even though the specifications call for a 3500m high model for thermal analysis. The spatial resolution desired in the vicinity of the emplacement trench and the room puts a severe restriction on the size of thermal time step in the explicit formulation of STEALTH. This limits the length of time over which a simulation is affordable. Based on preliminary estimates of the stable thermal time step, it was decided to carry out the simulation only to a time of 30 years following emplacement. A mesh was generated in which the smallest element dimension was 0.305m and the solution carried out for a few hundred computational cycles. Due to the high anticipated cost, it was decided to make the radius of the trench twice its specified size. This caused the smallest element dimension to be 0.60m which resulted in a four-fold increase in the stable time-step. A comparison of early time thermal response was favorable for the two trial meshes. It was necessary to make Fortran updates to the code to achieve certain problem-specific capabilities. The updates, at start time, were to subroutines ZONSTR, EDTINP, DMPPRO, GENCHK, ZONMDL, ZONZHE, ZONPRH, ZONSSS, RADLOS, and PLTTTL. The update directives and statements are listed in Table 13 for the start run, and Table 14 for the restart run. Subroutine ZONSTR updates allow a definition of the in-plane principal stresses which are not standard variables in STEALTH. The EDTINP updates allow a sub-grid definition for plotting purposes thus allowing enlargement of a localized region (such as a drift region). The DMPPRO update suppresses an inappropriate error message. The GENCHK updates establish the initial stresses and temperatures as a function of depth. Updates to ZONMDL zero out the stresses in the dummy elements that comprise the cavity area. For continuity of I and J lines and for easier automatic mesh generation, dummy elements are sometimes created for convenience. The ZONZHE updates add the logic for finding the interior surface segments and for computing convection losses. A data statement defines the coefficient of convective heat transfer and the ambient temperature. The ZONPRH updates provide a correct equation-of-state for thermomechanical (TM) response. The existing TM equation-of-state in STEALTH has errors. The ZONSSS update makes a corresponding correction to the sound speed calculation for cosmetic purposes, since sound speed in a quasi-static calculation is not meaningful. The RADLOS updates

define a new cutoff to avoid accumulation of round-off error and they fix erroneous temperature definition in certain portions of the subroutine. A cosmetic fix to the top label on plots and printout is made by the update to subroutine PLTTTL. Updates listed in Table 14 include, in addition to those in Table 13, ZONZSE updates that define the reference time at which the heater is turned on. A picture of the computational mesh and the boundary conditions are given in Figure 17. There are 9 I lines and 87 J lines in the mesh giving a total of 783 nodes and 688 elements. A complete listing of the STEALTH input data set for the start run is provided in Table 15. The purpose of this first 200 cycle run is to establish the state of stress around the room cavity without the heat source. The development of excavation-induced stresses is illustrated in Figure 18. The vertical stress near the middle of the floor is shown to reach a new equilibrium value; the abscissa should be interpreted as 200 iterations each with a dummy time-increment. In two subsequent restart runs the simulation is carried from 0 to 15 years, and 15 to 30 years, respectively. A total of 2566 computational cycles were needed to reach a time of 30 years. The input data set for the second restart run is listed in Table 16. The temperature history at the mid-height of trench surface is plotted in Figure 19a (0 - 15 years) and Figure 19b (15 - 30 years). At roughly 4.4 years the temperature reaches a peak value of about 72.2°C. The temperature contours at 30 years are shown in Figure 20; only a 30m vertical and 5.5m horizontal sections of the model are included in this illustration. Contours of maximum and minimum principal stresses are presented in Figures 21 and 22 at a time of 30 years. The contours provide a qualitative measure of where stress concentrations and large gradients are; other than that they are difficult to decipher. A profile of temperature along the vertical centerline passing through the room is shown at 30 years in Figure 23. Undeformed (0 years) and deformed (at 30 years) profiles of the room surface are plotted in Figure 24. This provides a measure of the vertical and horizontal closures. The maximum vertical closure at 30 years is approximately 16.0 cm. The maximum horizontal closure at that time is 3.4 cm (twice the horizontal displacement). Some numerical noise is evident from the room surface profile shown in Figure 24. The x, y displacements of each node along the room surface are tabulated in Table 17. A general uplift due to the thermal load is seen everywhere, though it is only significant along the floor.

TABLE 13

Fortran Updates to STEALTH 2D for Problem 5.2 (Start Run)

```
*ID FRB52BS
*C STEALTH
*I ZONSTR.42
C     ** DEFINE ESTIMATED TOTAL STRESSES **
C      ** FOR PLANE STRAIN SYMMETRY ONLY **
      SIGXX = SXXN - (PRHN+AVSH)
      SIGYY = SYYN - (PRHN+AVSH)
      SSUM = SIGXX + SIGYY
      SDIF = SIGXX - SIGYY
C      ** DEFINE PRINCIPAL STRESSES **
      SIG1 = SSUM/2. + SQRT(SDIF**2/4. + SXYN**2)
      SIG2 = SSUM/2. - SQRT(SDIF**2/4. + SXYN**2)
      PANG = 0.
      IF(SDIF .EQ. 0. .AND. SXYN .EQ. 0.)GO TO 71
C     ** PANG IS THE PRINCIPAL STRESS ORIENTATION IN DEG. **
      PANG = 28.6364 * ATAN2(2.*SXYN, SDIF)
   71 CONTINUE
      EX1N = SIG1
      EX2N = SIG2
      EX3N = PANG
*D EDTINP.547
C
C      ** RECORD #664 DEFINES A SUB-GRID FOR PLOTTING **
C
  640 MINIPL = IFIX(DTAFLD(1) + .1)
      MAXIPL = IFIX(DTAFLD(2) + .1)
      IF (MINIPL .GE. 1 .AND. MINIPL .LE. MAXGPT) GO TO 641
      CALL RGEERR(INPTYP,1,1,MAXGPT,MINIPL)
  641 IF (MAXIPL .GE. 1 .AND. MAXIPL .LE. MAXGPT) GO TO 642
      CALL RGEERR(INPTYP,2,1,MAXGPT,MAXIPL)
  642 IF(MINIPL .LE. MAXIPL) GO TO 643
      CALL LIMERR(INPTYP,MINIPL,MAXIPL,1,2)
  643 LMIN = 3
      IF(NSPRO .EQ. 1 .OR. NSPRO .EQ. 11) GO TO 950
C
      MINJPL = IFIX(DTAFLD(3) + .1)
      MAXJPL = IFIX(DTAFLD(4) + .1)
      IF (MINJPL .GE. 1 .AND. MINJPL .LE. MAXROW) GO TO 644
      CALL RGEERR(INPTYP,1,1,MAXROW,MINJPL)
  644 IF (MAXJPL .GE. 1 .AND. MAXJPL .LE. MAXROW) GO TO 645
      CALL RGEERR(INPTYP,2,1,MAXROW,MAXJPL)
  645 IF(MINJPL .LE. MAXJPL) GO TO 646
      CALL LIMERR(INPTYP,MINJPL,MAXJPL,1,2)
  646 LMIN = 5
      GO TO 950
*I DMPPRO.24
      RETURN
*I GENCHK2.54
      DATA SBOT, TBOT, TGRAD / -1.57252E7, 26.878, 0.02 /
*I GENCHK2.86
      IF(JN .EQ. JLNBOT) TYINC = 0.0
      IF(JN .EQ. JLNBOT) TMPINC = 0.0
*I GENCHK2.269
```

continued

TABLE 13
continued

```
      TYINC = - ARDN(MPNO) * GRVY * (YPNNTR-YPNNBR)
      TMPINC = - TGRAD * (YPNNTR-YPNNBR)
      TYYN = SBOT + TYINC/2.
      TMPN = TBOT + TMPINC/2.
      IF(MPNO .EQ. 2) TYYN = 0.0
      TXXN = TYYN
      TZZN = TYYN
      PRHN = - (TXXN+TYYN+TZZN) / 3.
      TXX(I,JT) = TXXN
      TYY(I,JT) = TYYN
      TZZ(I,JT) = TZZN
*D GENCHK2.342,344
      TMPO = TMPN
*I GENCHK2.363
      SBOT = SBOT + TYINC
      TBOT = TBOT + TMPINC
*I ZONMDL.116
C
C       ** SET STRESSES TO ZERO IN AIR ZONES **
      IF(MPNN .NE. 2) GO TO 950
      PRHN = PRHO
      TXXN = TXXO
      TYYN = TYYO
      TZZN = TZZO
      TXYN = TXYO
      SXXN = SXXO
      SYYN = SYYO
      SZZN = SZZO
      SXYN = SXYO
  950 CONTINUE
*I ZONZHE2.57
      DATA  HCONV, TAMB / 0.40 , 24.90 /
C
*I ZONZHE2.67
      DO 5 LL = 1,NUMRM
      IF(MPNN .EQ. MPNRM(LL)) TMPO = TAMB
    5 CONTINUE
C
*D ZONZHE2.299
      IF(MPNN .EQ. MPNRM(LL) .AND. MPN(IC,JT) .NE. MPNRM(LL))
     1   GO TO 564
      IF(MPN(IC,JT) .EQ. MPNRM(LL)) GO TO 563
      GO TO 561
  563 DELY = (YPNOTL + YPNOTR)/2. - YCEN
      TSURF = (HCONV*TAMB + CONO*TMPO/DELY)/(HCONV+CONO/DELY)
      HTFHT = - HCONV * WOTOP * (TSURF-TAMB)
      GO TO 561
  564 DELY = YCENT - (YPNOTL+YPNOTR)/2.
      TSURF = (HCONV*TAMB + CONOT*TMPOT/DELY)/(HCONV+CONOT/DELY)
      HTFHT = - HCONV * WOTOP * (TAMB-TSURF)
  561 CONTINUE
C
*D ZONZHE2.348
```

continued

TABLE 13
concluded

```
      IF(MPNN .EQ. MPNRM(LL) .AND. MPN(IR,JC) .NE. MPNRM(LL))
     1  GO TO 583
      GO TO 582
  583 DELX = XCENR - (XPNOTR+XPNOBR)/2.
      TSURF = (HCONV*TAMB + CONOR*TMPOR/DELX)/(HCONV+CONOR/DELX)
      HTFHR = - HCONV * WORHT * (TAMB-TSURF)
  582 CONTINUE
*I ZONZHE2.369
      DO 769 LL = 1,NUMRM
      IF(MPNN .EQ. MPNRM(LL)) DLZHEH = ZER
  769 CONTINUE
*D ZONPRH.76,78
*D ZONPRH.84,85
      PRHRLV = EOS2 * (1./RLVN - 1./RLVO) + PRHO
      PRHZIE = THR * EOS2 * EOSB * (ZHEN-ZHEO + ZSEN-ZSEO)/SHCO
C     FROM A FUNCTION OF RELATIVE VOLUME (THERMOMECHANICAL)
*D ZONSSS.87,97
      SSSPRH = VAL
*I RADLOS.114
      IF(ABS(TMPS(II,LL)-TMPV(II,LL)).LT. 1.E-8)
     1     QAVRG(II,LL) = ZER
*I RADLOS.139
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*I RADLOS.160
      TMP(II+1,JC) = TMP(II+1,JC) + ENRDEN/SHC(II+1,JC)
*I RADLOS.180
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*I RADLOS.199
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0,0.18,0.98,HGT,WID,0.0,CDN)
```

TABLE 14

Fortran Updates to STEALTH 2D for Problem 5.2 (Restart Run)

```
*ID PRB52BS
*C STEALTH
*I ZONSTR.42
C     ** DEFINE ESTIMATED TOTAL STRESSES **
C      ** FOR PLANE STRAIN SYMMETRY ONLY **
      SIGXX = SXXN - (PRHN+AVSH)
      SIGYY = SYYN - (PRHN+AVSH)
      SSUM = SIGXX + SIGYY
      SDIF = SIGXX - SIGYY
C      ** DEFINE PRINCIPAL STRESSES **
      SIG1 = SSUM/2. + SQRT(SDIF**2/4. + SXYN**2)
      SIG2 = SSUM/2. - SQRT(SDIF**2/4. + SXYN**2)
      PANG = 0.
      IF(SDIF .EQ. 0. .AND. SXYN .EQ. 0.)GO TO 71
C     ** PANG IS THE PRINCIPAL STRESS ORIENTATION IN DEG. **
      PANG = 28.6364 * ATAN2(2.*SXYN, SDIF)
   71 CONTINUE
      EX1N = SIG1
      EX2N = SIG2
      EX3N = PANG
*I ZONZSE.45
      DATA  TREF / 8.0E7 /
*D ZONZSE.59
C       ** DEFINE REF. TIME FOR HEAT SOURCE AFTER EQL. RUN **
   30 TYEAR = (TIMH - TREF) / 3.1536E7
*D EDTINP.547
C
C      ** RECORD #664 DEFINES A SUB-GRID FOR PLOTTING **
C
  640 MINIPL = IFIX(DTAFLD(1) + .1)
      MAXIPL = IFIX(DTAFLD(2) + .1)
      IF (MINIPL .GE. 1 .AND. MINIPL .LE. MAXGPT) GO TO 641
      CALL RGEERR(INPTYP,1,1,MAXGPT,MINIPL)
  641 IF (MAXIPL .GE. 1 .AND. MAXIPL .LE. MAXGPT) GO TO 642
      CALL RGEERR(INPTYP,2,1,MAXGPT,MAXIPL)
  642 IF(MINIPL .LE. MAXIPL) GO TO 643
      CALL LIMERR(INPTYP,MINIPL,MAXIPL,1,2)
  643 LMIN = 3
      IF(NSPRO .EQ. 1 .OR. NSPRO .EQ. 11) GO TO 950
C
      MINJPL = IFIX(DTAFLD(3) + .1)
      MAXJPL = IFIX(DTAFLD(4) + .1)
      IF (MINJPL .GE. 1 .AND. MINJPL .LE. MAXROW) GO TO 644
      CALL RGEERR(INPTYP,1,1,MAXROW,MINJPL)
  644 IF (MAXJPL .GE. 1 .AND. MAXJPL .LE. MAXROW) GO TO 645
      CALL RGEERR(INPTYP,2,1,MAXROW,MAXJPL)
  645 IF(MINJPL .LE. MAXJPL) GO TO 646
      CALL LIMERR(INPTYP,MINJPL,MAXJPL,1,2)
  646 LMIN = 5
      GO TO 950
*I DMPPRO.24
      RETURN
*I GENCHK2.54
```

continued

TABLE 14
continued

```
      DATA SBOT, TBOT, TGRAD / -1.57252E7, 26.878, 0.02 /
*I GENCHK2.86
      IF(JN .EQ. JLNBOT) TYINC = 0.0
      IF(JN .EQ. JLNBOT) TMPINC = 0.0
*I GENCHK2.269
      TYINC = - ARDN(MPNO) * GRVY * (YPNNTR-YPNNBR)
      TMPINC = - TGRAD * (YPNNTR-YPNNBR)
      TYYN = SBOT + TYINC/2.
      TMPN = TBOT + TMPINC/2.
      IF(MPNO .EQ. 2) TYYN = 0.0
      TXXN = TYYN
      TZZN = TYYN
      PRHN = - (TXXN+TYYN+TZZN) / 3.
      TXX(I,JT) = TXXN
      TYY(I,JT) = TYYN
      TZZ(I,JT) = TZZN
*D GENCHK2.342,344
      TMPO = TMPN
*I GENCHK2.363
      SBOT = SBOT + TYINC
      TBOT = TBOT + TMPINC
*I ZONMDL.116
C
C       ** SET STRESSES TO ZERO IN AIR ZONES **
      IF(MPNN .NE. 2) GO TO 950
      PRHN = PRHO
      TXXN = TXXO
      TYYN = TYYO
      TZZN = TZZO
      TXYN = TXYO
      SXXN = SXXO
      SYYN = SYYO
      SZZN = SZZO
      SXYN = SXYO
  950 CONTINUE
*I ZONZHE2.57
      DATA  HCONV, TAMB / 0.40 , 15.00 /
C
*I ZONZHE2.67
      DO 5 LL = 1,NUMRM
      IF(MPNN .EQ. MPNRM(LL)) TMPO = TAMB
    5 CONTINUE
C
*D ZONZHE2.299
      IF(MPNN .EQ. MPNRM(LL) .AND. MPN(IC,JT) .NE. MPNRM(LL))
     1   GO TO 564
      IF(MPN(IC,JT) .EQ. MPNRM(LL)) GO TO 563
      GO TO 561
  563 DELY = (YPNOTL + YPNOTR)/2. - YCEN
      TSURF = (HCONV*TAMB + CONO*TMPO/DELY)/(HCONV+CONO/DELY)
      HTFHT = - HCONV * WOTOP * (TSURF-TAMB)
      GO TO 561
  564 DELY = YCENT - (YPNOTL+YPNOTR)/2.
```

continued

TABLE 14
concluded

```
      TSURF = (HCONV*TAMB + CONOT*TMPOT/DELY)/(HCONV+CONOT/DELY)
      HTFHT = - HCONV * WOTOP * (TAMB-TSURF)
  561 CONTINUE
C
*D ZONZHE2.348
      IF(MPNN .EQ. MPNRM(LL) .AND. MPN(IR,JC) .NE. MPNRM(LL))
     1  GO TO 583
      GO TO 582
  583 DELX = XCENR - (XPNOTR+XPNOBR)/2.
      TSURF = (HCONV*TAMB + CONOR*TMPOR/DELX)/(HCONV+CONOR/DELX)
      HTFHR = - HCONV * WORHT * (TAMB-TSURF)
  582 CONTINUE
*I ZONZHE2.369
      DO 769 LL = 1,NUMRM
      IF(MPNN .EQ. MPNRM(LL)) DLZHEH = ZER
  769 CONTINUE
*D ZONPRH.76,78
*D ZONPRH.84,85
      PRHRLV = EOS2 * (1./RLVN - 1./RLVO) + PRHO
      PRHZIE = THR * EOS2 * EOS8 * (ZHEN-ZHEO + ZSEN-ZSEO)/SHCO
C     FROM A FUNCTION OF RELATIVE VOLUME (THERMOMECHANICAL)
*D ZONSSS.87,97
      SSSPRH = VAL
*I RADLOS.114
      IF(ABS(TMPS(II,LL)-TMPV(II,LL)).LT. 1.E-8)
     1     QAVRG(II,LL) = ZER
*I RADLOS.139
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*I RADLOS.160
      TMP(II+1,JC) = TMP(II+1,JC) + ENRDEN/SHC(II+1,JC)
*I RADLOS.180
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*I RADLOS.199
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0,0.18,0.98,HGT,WID,0.0,CDN)
```

TABLE 15
STEALTH 2D Input Data Set for Problem 5.2 (Start Run)

```
TTL       PROBLEM 5.2 THERMAL-MECHANICAL ANALYSIS - BASALT .
PRB
PRO       2.0
DTS       4.0       1.0
SYM       1.0
GRV       0.0       -9.8066
GRD       1.0       1.0       9.0       87.0
END
MAT                                                   1.
111 BASALT1.0       3.0
112       1.0       2.0       2.0       2.0
114       1.0       2.0       2.0
121       1.0       2700.0
122       1.        1.        0.         2.4306E10
123       1.        -0.5      2.        1.             6.5E-6
132       1.0        2.7713E08
134       1.0        1.3889E10
136       1.0        -1.0 E+12
152       1.0       1.1
154       1.0         2.2545E6
111 AIR   2.0       1.0
112       2.0       1.        1.        2.
114       2.0       2.        2.
121       2.0       0.83
122       2.        1.        0.        1.0000E+06
136       2.          -1.0E+12
152       2.0       0.035
154       2.0       35.0
111 SOURC 3.0       3.0
112       3.0       2.0       2.0       2.0
114       3.0       2.0       2.0       3.0
121       3.0       2700.0
122       3.        1.        0.         2.4306E10
123       3.        -0.5      2.        1.             6.5E-6
132       3.0        2.7713E08
134       3.0        1.3889E10
136       3.0        -1.0 E+12
152       3.0       1.1
154       3.0         2.2545E6
156       3.0       0.0
END
GPT                                     1.        1.
211           1.0       1.0       1.0       0.0   -593.9
212           1.0       0.0    -390.0       2.0
212           2.0       0.0    -600.0       3.0
212           3.0       7.5    -600.0       2.0
212           4.0       7.5    -390.0       3.0
221           1.0       1.0       2.0       1.0      36.0
221           2.0       1.0       4.0      42.0      52.0
221           3.0       2.0       4.0       1.0      36.0
221           4.0       4.0       9.0       1.0      36.0
221           5.0       1.0       2.0      36.0      41.0
221           6.0       2.0       4.0      36.0      41.0
```

continued

TABLE 15
continued

221	7.0	4.0	9.0	36.0	41.0		
221	8.0	4.0	9.0	41.0	42.0		
221	9.0	4.0	9.0	42.0	47.0		
221	10.0	4.0	9.0	47.0	52.0		
221	11.0	1.0	2.0	52.0	87.0		
221	12.0	2.0	4.0	52.0	87.0		
221	13.0	4.0	9.0	52.0	87.0		
247	1.	0.	0.610	-593.9	90.15	1.0	0.98
247	3.	0.610	1.890	-593.9	90.15	1.0	0.98
247	4.	2.50	5.00	-593.9	90.15	1.0	0.98
247	5.	0.	0.610	-503.75	6.25	1.0	1.0
247	6.	0.610	1.890	-503.75	6.25	1.0	1.0
247	7.	2.50	5.00	-503.75	6.25	1.0	1.0
247	8.	2.50	5.00	-497.5	0.6	1.0	1.0
247	9.	2.50	5.00	-496.9	4.75	1.0	1.0
247	10.	2.50	5.00	-492.15	8.25	1.0	1.0
247	11.	0.	0.610	-483.9	90.0	1.0	1.02
247	12.	0.610	1.890	-483.9	90.0	1.0	1.02
247	13.	2.50	5.00	-483.9	90.0	1.0	1.02
232	2.0	1.0	42.0	0.0	-496.90		
232	2.0	1.0	43.0	0.0	-495.95		
232	2.0	1.0	44.0	0.0	-495.00		
232	2.0	1.0	45.0	0.0	-494.05		
232	2.0	1.0	46.0	0.0	-493.10		
232	2.0	1.0	47.0	0.0	-490.90		
232	2.0	1.0	48.0	0.0	-489.50		
232	2.0	1.0	49.0	0.0	-488.10		
232	2.0	1.0	50.0	0.0	-486.70		
232	2.0	1.0	51.0	0.0	-485.30		
232	2.0	1.0	52.0	0.0	-483.90		
232	2.0	2.0	42.0	0.610	-496.90		
232	2.0	2.0	43.0	0.610	-495.95		
232	2.0	2.0	44.0	0.610	-495.00		
232	2.0	2.0	45.0	0.610	-494.05		
232	2.0	2.0	46.0	0.610	-493.10		
232	2.0	2.0	47.0	0.610	-490.95		
232	2.0	2.0	48.0	0.610	-489.60		
232	2.0	2.0	49.0	0.610	-488.20		
232	2.0	2.0	50.0	0.610	-486.80		
232	2.0	2.0	51.0	0.610	-485.35		
232	2.0	2.0	52.0	0.610	-483.90		
232	2.0	3.0	42.0	1.5550	-496.90		
232	2.0	3.0	43.0	1.5550	-495.95		
232	2.0	3.0	44.0	1.5550	-495.00		
232	2.0	3.0	45.0	1.5550	-494.05		
232	2.0	3.0	46.0	1.5550	-493.10		
232	2.0	3.0	47.0	1.5550	-491.25		
232	2.0	3.0	48.0	1.5550	-490.05		
232	2.0	3.0	49.0	1.5550	-488.50		
232	2.0	3.0	50.0	1.5550	-486.95		
232	2.0	3.0	51.0	1.5550	-485.40		
232	2.0	3.0	52.0	1.5550	-483.90		
232	2.0	4.0	42.0	2.5	-496.90		

continued

TABLE 15
continued

```
232          2.0        4.0        43.0        2.5    -495.95
232          2.0        4.0        44.0        2.5    -495.00
232          2.0        4.0        45.0        2.5    -494.05
232          2.0        4.0        46.0        2.5    -493.10
232          2.0        4.0        47.0        2.5    -492.15
232          2.0        4.0        48.0        2.5    -490.50
232          2.0        4.0        49.0        2.5    -488.85
232          2.0        4.0        50.0        2.5    -487.20
232          2.0        4.0        51.0        2.5    -485.55
232          2.0        4.0        52.0        2.5    -483.90
END
ZON                                                       1.
311            1.0        1.0        9.0        1.0      87.0
311            2.0        1.0        4.0       42.0      47.0
311            3.0        1.0        2.0       37.0      41.0
321            1.0        1.0
321            2.0        2.0
321            3.0        3.0
322            1.0        1.0
322            2.0        1.0
322            3.0        1.0
341            1.0
341            2.0
341            3.0
371      1.            5.67E-8 273.15
372      1.        1.        4.        42.        47.        2.0
373      1.        3.        0.9       0.9        0.9
END
BDY                                                 1.
411      1.0       1.0       1.0       9.0        1.0
411      2.0       9.0       1.0       9.0        87.0
411      3.0       9.0       87.0      1.0        87.0
411      4.0       1.0       87.0      1.0        1.0
412      1.0       1.0       2.0       2.0        1.0
412      2.0       1.0       6.0       5.0        4.0
412      3.0       1.0       2.0       2.0        3.0
412      4.0       1.0       6.0       5.0        2.0
422      1.0       1.0
422      3.0       3.0
423      1.0       1.0
423      3.0       3.0
431      1.0       1.0       0.0           1.0E+49
432      1.        +1.57252E7
431      3.0       1.0       0.0           1.0E+49
432      3.0       +1.04296E6
451      1.0       1.0       0.0           1.0E+49
452      1.0       26.878
451      3.0       1.0       0.0           1.0E+49
452      3.0       22.878
481      4.        1.        2.
481      2.        3.        4.
482      4.        1.        5.        5.         0.         0.05
482      2.        1.        5.        5.         0.         0.05
```

continued

TABLE 15
concluded

```
END
TIM
511          4.0E+05
512          1.0E+05   4.0E+05
513      1.1        0.95
514      -200.
521      2.84018E12   200.
END
EDT                                                    1.
611      2.
613      2.
616      2.
621      1.0        0.         300.       100.
622      1.0        9.0        38.0       49.0
623      11.        14.        53.        54.        61.        62.        71.
623      72.
624      3.
641      1.         0.         200.       100.
671      1.         0.         200.       2.
674      1.         1.         71.        1.         5044.
674      2.         1.         72.        1.         3042.
674      3.         1.         71.        1.         6035.
674      4.         1.         72.        1.         4048.
674      5.         1.         5.         1.
END
END
```

TABLE 16

STEALTH 2D Input Data Set for Problem 5.2 (Restart Run)

```
TTL     PROBLEM 5.2 T-M ANALYSIS - BASALT, 15 - 30 yr
PRB
SOR     2.          5.53200E8
END
TIM
521     1.02610E09   2600.
END
EDT                                                 1.
611     1.
613     1.
616     2.
621     1.            5.5320E8  4.7304E8  2.3652E8
622     1.0         9.0         35.0        54.0
623     11.         14.         53.         54.         61.         62.         71.
623     72.         91.         92.         93.         73.
624     3.
641     1.            5.5320E8  4.7304E8  2.3652E8
671     1.          1383.       1200.       10.
674     1.          1.          71.         1.          5044.
674     2.          1.          72.         1.          3042.
674     3.          1.          71.         1.          6035.
674     4.          1.          72.         1.          4048.
674     5.          1.          61.         1.          2042.
674     6.          2.          61.                                   1.0261E9 2000.
674     7.          2.          14.                                   1.0261E9 42.
674     8.          2.          71.                                   1.0261E9 5000.
674     9.          2.          72.                                   1.0261E9 5000.
674     10.         1.          61.         1.          2039.
674     11.         1.          61.         1.          2041.
674     12.         1.          61.         1.          2048.
674     13.         1.          61.         1.          5045.
END
END
```

TABLE 17

Nodal Displacements Along Room Surface at 30 Years

Node #	I, J indices	Initial Coordinates (m) X	Y	Displacements (mm) ΔX	ΔY
1	1,42	0.000	-496.90	0.00	178.00
2	2,42	0.610	-496.90	18.39	113.00
3	3,42	1.555	-496.90	-16.78	211.00
4	4,42	2.500	-496.90	25.87	33.00
5	4,43	2.500	-495.95	2.26	22.00
6	4,44	2.500	-495.00	17.21	21.00
7	4,45	2.500	-494.05	-2.13	13.00
8	4,46	2.500	-493.10	11.98	17.00
9	4,47	2.500	-492.15	-13.68	6.00
10	3,47	1.555	-491.25	4.20	46.00
11	2,47	0.610	-490.95	-0.96	18.00
12	1,47	0.000	-490.90	0.00	43.00

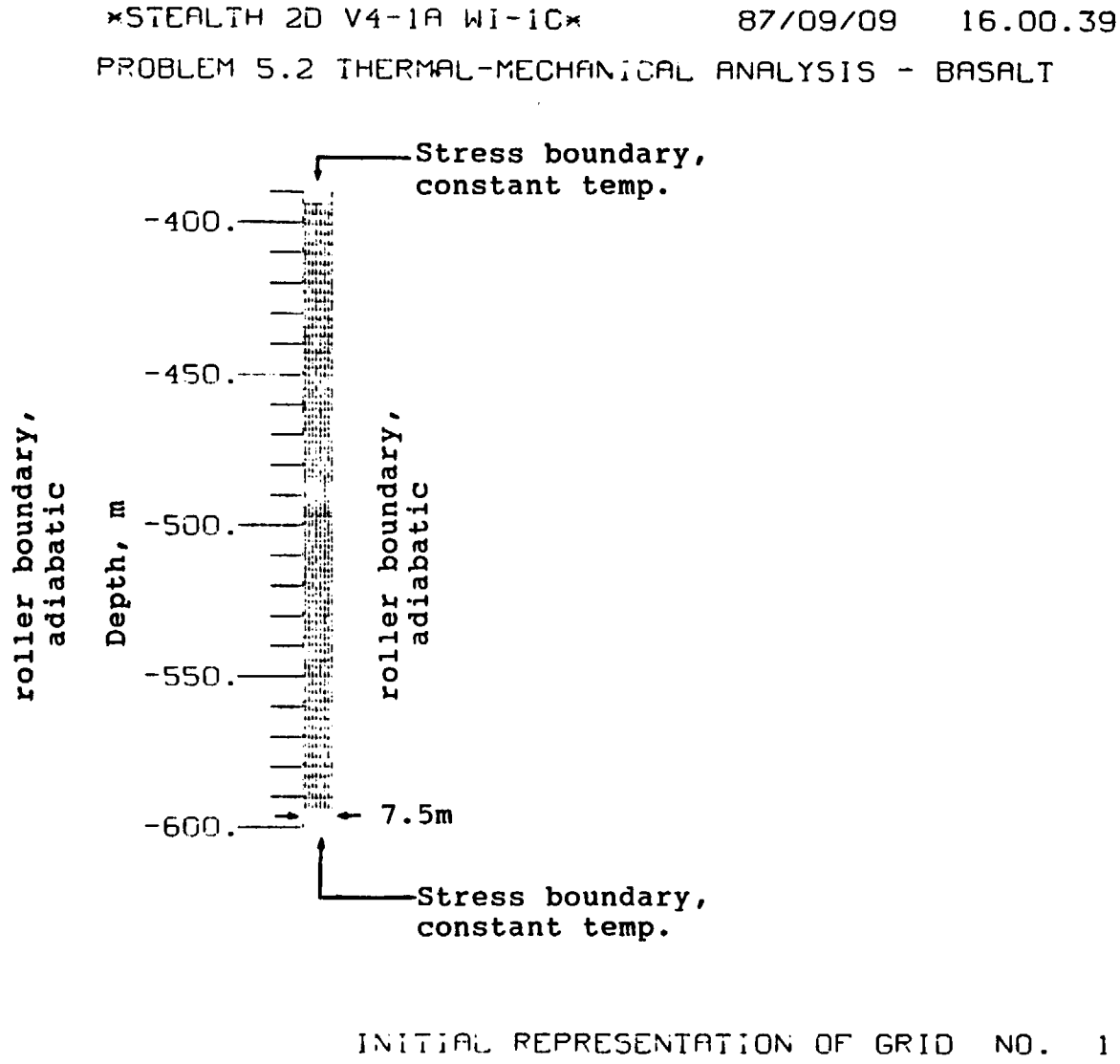


Figure 17. Initial mesh configuration and boundary conditions.

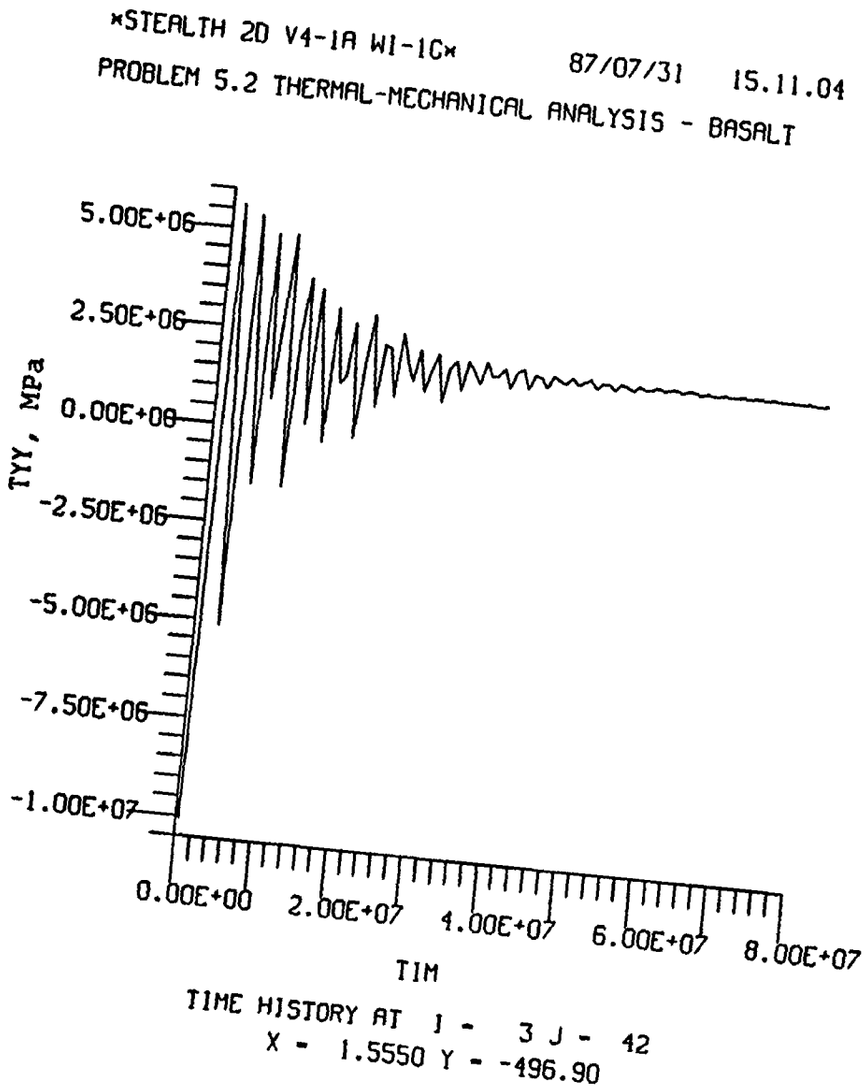


Figure 18. Excavation stress equilibration in the drift floor, initial vertical stress in middle of floor prior to heating.

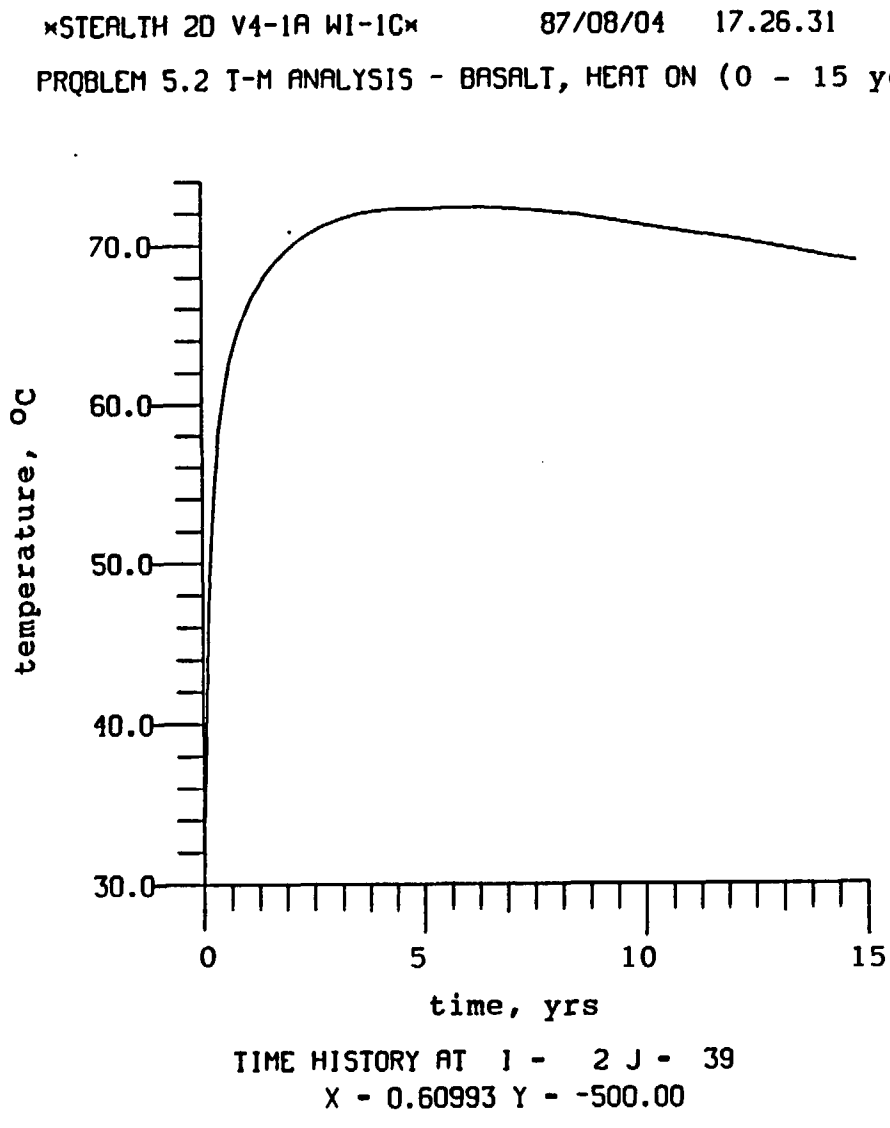


Figure 19a. Temperature history at trench surface (mid-height), 0 - 15 years.

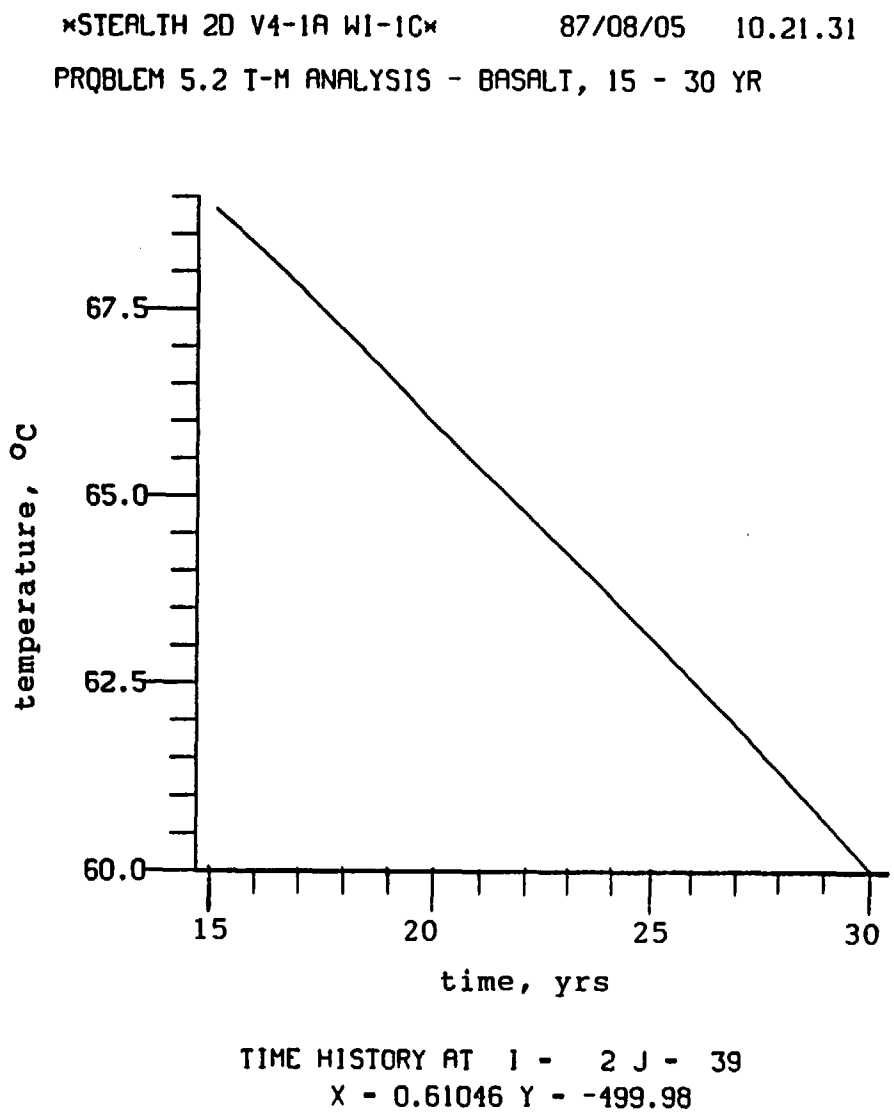


Figure 19b. Temperature history at trench surface (mid-height), 15 - 30 years.

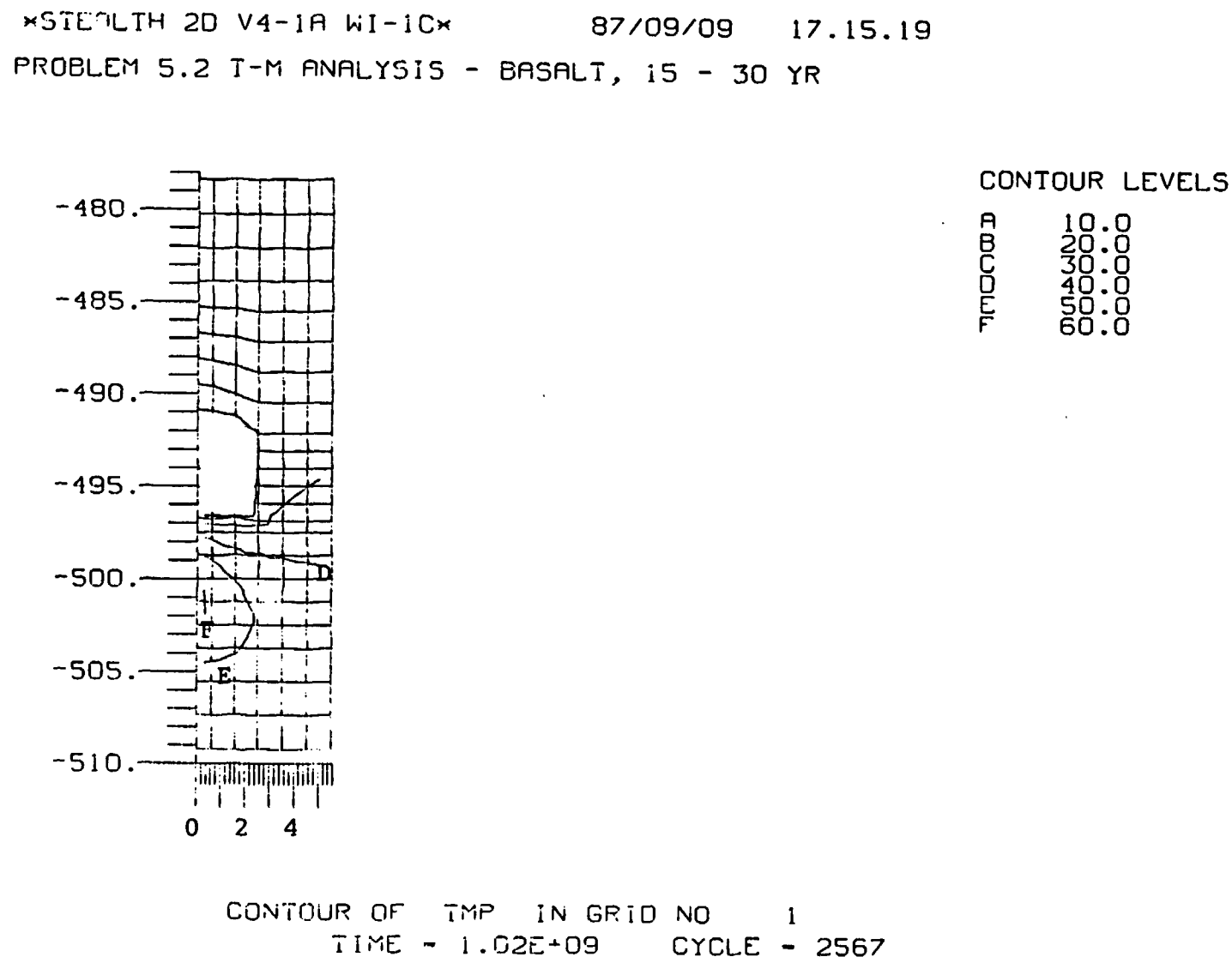


Figure 20. Temperature contours in the vicinity of the room at 30 years.

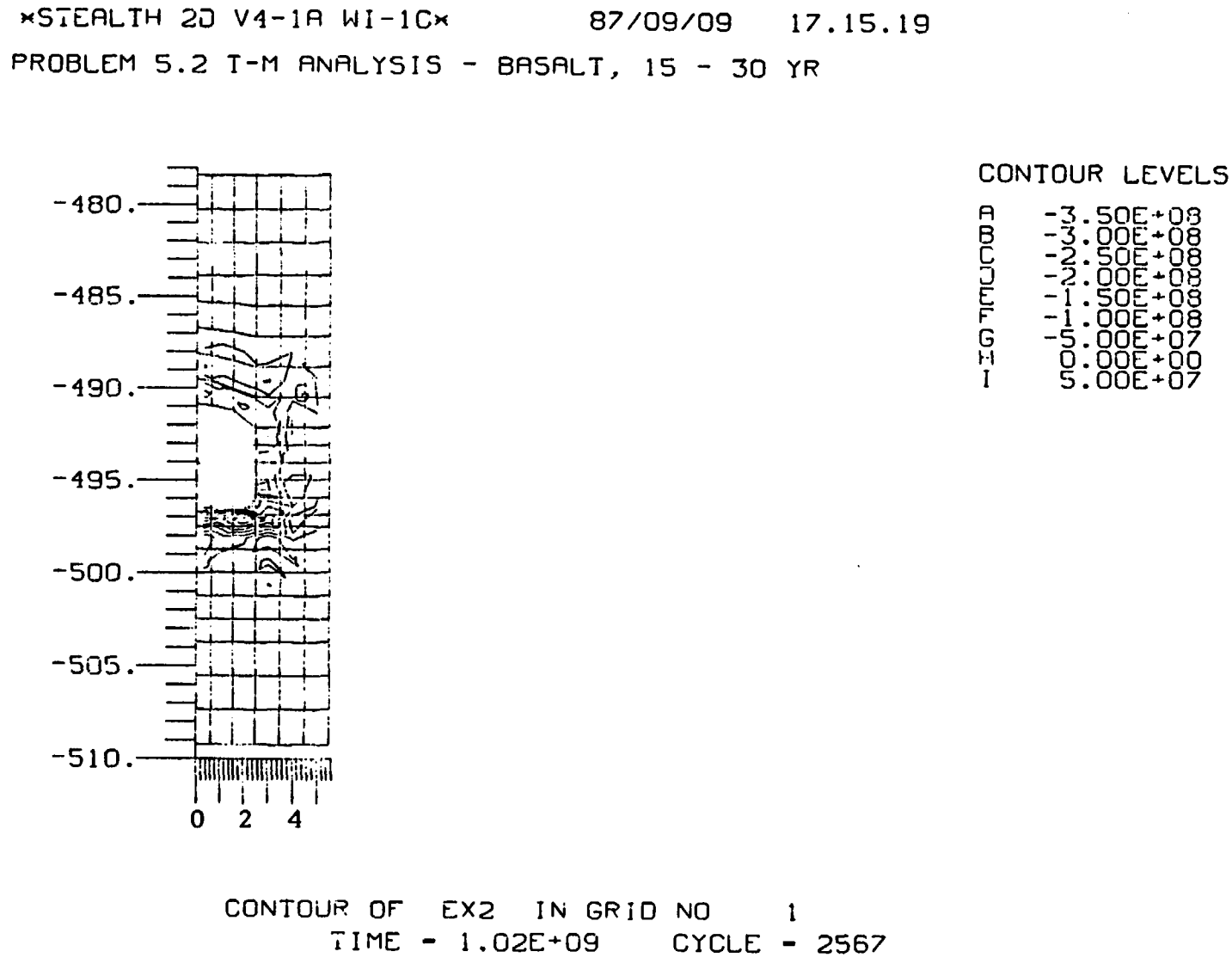


Figure 21. Contours of maximum principal stress in the vicinity of the room at 30 years.

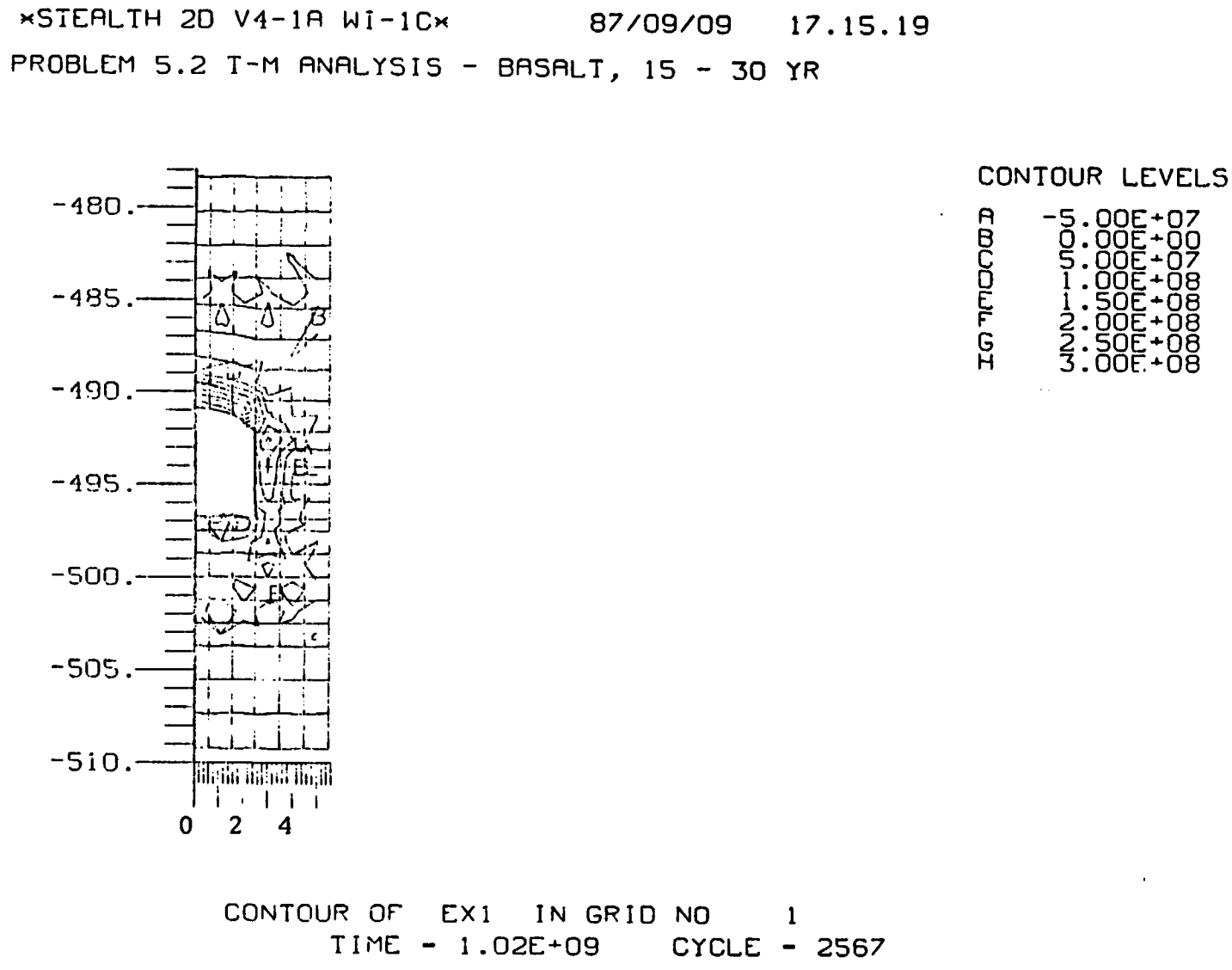


Figure 22. Contours of minimum principal stress in the vicinity of the room at 30 years.

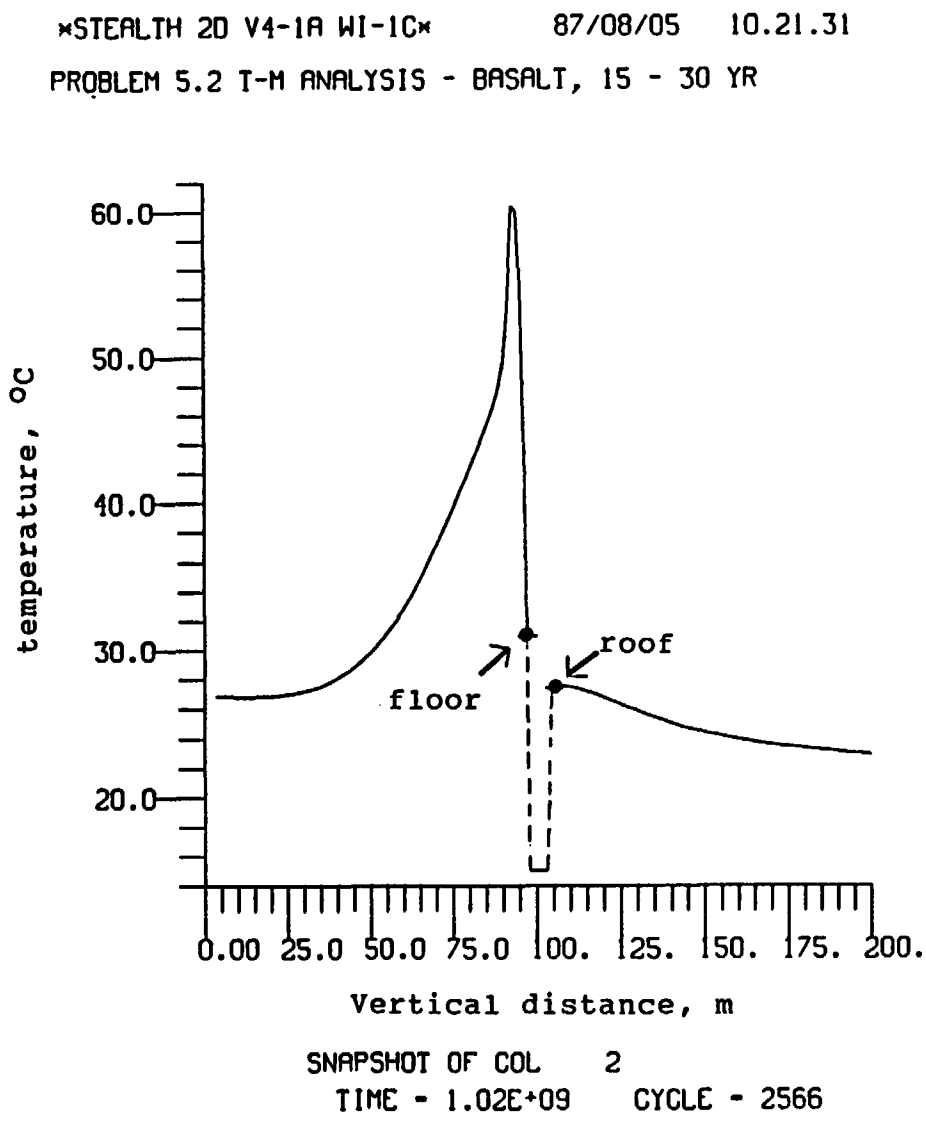


Figure 23. Temperature profile along vertical centerline (through the room) at 30 years.

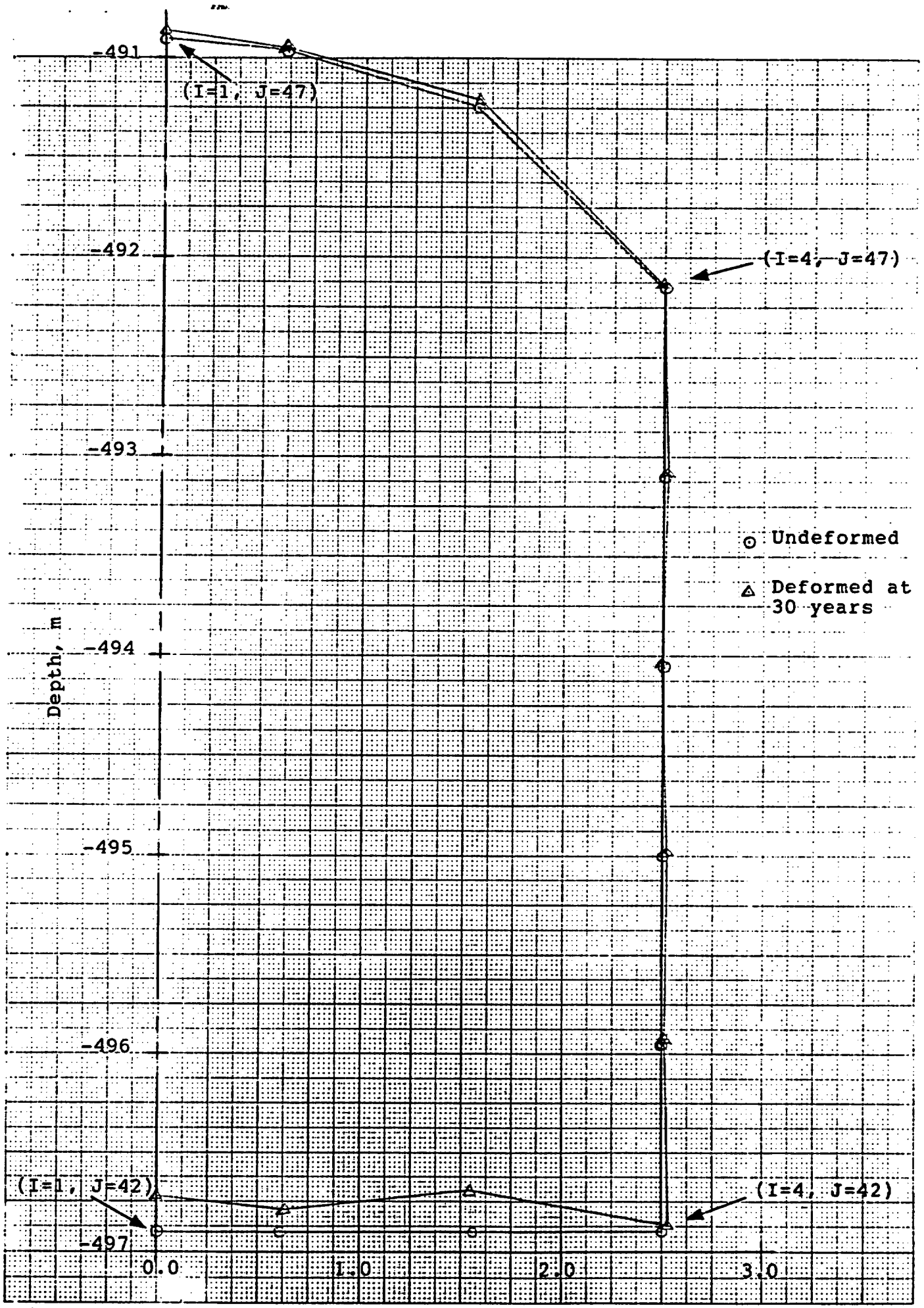


Figure 24. Undeformed and deformed nodal positions along room surface.

SECTION 5

Benchmark Problem 5.3

This problem is designed to test the thermomechanical capability of two and three dimensional codes at the far-field scale of a repository. No openings are to be modeled at depth.

The STEALTH 2D model for this problem assumes an axisymmetric geometry and a salt medium. The entire region is given the properties of salt with the repository region generating heat at a prescribed rate. The thermal loading results from time-dependent volumetric heat generation in a cylindrical disk with a radius of 1467m and a height of 15m at a depth of 500m. In STEALTH, prescribing ventilation at interior nodes when no cavity exists would require extensive and careful modification. Ventilation was, therefore, ignored in this model. The initial and boundary conditions as well as the material property data specified in Reference 2 have been used, except as noted.

Fortran updates to STEALTH were necessary to properly simulate this problem. Table 18 lists the updates that were made to subroutines ZONSTR, GENCHK, ZONCRP, ZONPRH, ZONSSS, PLTTTL, DMPPRO, and EDTINP. The nature of these updates (except in ZONCRP) is the same as that of updates for Problem 5.2; however, the specific statements are, in general, different. Although viable creep models are available in STEALTH, an improved creep algorithm for the "Exponential - Time Law" was obtained from SAIC and is included in the updates. Note that it was not necessary to update ZONZHE or RADLOS for this problem since cavity radiation and convection were absent. An equilibrium run was not needed for this problem because initial stresses were lithostatic and there were no excavations to alter the in-situ stress field. Also, the source description was possible through standard input cards. The updates at start and restart times were identical. It should be pointed out that GENCHK updates, which establish the initial stresses and temperatures, are not really needed at restart time. On the other hand, they do not impact the computation in any way when included at restart time, and yet provide a record of what was done at start time.

This problem could have been completed in a single run. But for reasons given in the introduction, we chose to run it from 0 to 300 years in the start run. Restart edits were saved at 30, 100, 200, and 300 years. A listing of the STEALTH 2D input deck is provided in Table 19. Note that the relaxation frequency parameter is set to zero on card type 514. This is due to the fact that creep provides its own relaxation that, according to experience, provides sufficient damping for the purpose of obtaining pseudo-equilibrium. Previous experience shows that in problems involving creep if a non-zero damping factor is included, overdamping results which tends to underestimate creep deformation. The finite-difference mesh and the boundary conditions are shown on Figure 25. There are 41 I lines, 34 J lines, 1,394 nodes and 1,320 elements in the problem. The source region is bounded by columns 1 to 15 and rows 23 to 24. The x coordinate of column 15 is 1,467m and the y coordinates of rows 23 and 24 are -507.5m and -492.5m, respectively. The results for the first 300 years seemed reasonable

except that a kink in the temperature history appeared at a time of 100 years. For instance, the temperature history for the centermost source element is shown in Figure 26a. The response beyond 100 years has an abrupt, pronounced convex-upward shape that is contrary to intuition. It was suspected that the piecewise-linear source strength data that is "hard-wired" in STEALTH might be in error. A check of the data pairs of normalized strength and associated time revealed that the resolution in the time domain between 100 and 300 years was rather poor. It was decided to rerun the problem from 100 years with a better source strength description. Updates were made to subroutine ZONZSE that included additional data points to capture the curvature of the decay curve. The update listing for this run is given in Table 20; aside from the ZONZSE updates it is identical to Table 18. The corresponding STEALTH input data at a restart time of 100 years is given in Table 21. This run took the simulation from 100 to 1,000 years. It is possible to carry the calculation to 10,000 years or to any other time; however, the computer cost would be beyond the resources available in this sub-project. All the output specified in Reference 2 was obtained up to a simulation time of 1,000 years. Figure 26 (a and b) shows the temperature history at the repository mid-point for 0 - 1,000 years. Temperature contours over the modeled region at 30, 100, 300, and 1,000 years are shown in Figures 27, 28, 29, and 30. Contours of maximum and minimum principal stresses at time values of 30, 100, 300, and 1,000 years are given in Figures 31 through 38. Ground surface displacement profiles at 30, 100, 300, and 1,000 years are plotted in Figures 39 through 42. A displacement history for the surface mid-point between 100 to 1,000 years is shown in Figure 43. Temperature profiles close to the vertical certerline at 100 and 300 years are given in Figures 44 and 45. No provision was made in the model for fissure development. The only failure potential was for an element to undergo plastic deformation. An inspection of the results (printout) at 30, 100, 300, and 1,000 years indicated no instance of plastic yielding. Tensile stress did develop in certain regions that could be construed as tensile failure. The locations, extent, and times at which tensile stresses are seen to occur are summarized in Table 22.

TABLE 18
Fortran updates to STEALTH 2D for Problem 5.3

```
*ID PRB53SL
*C STEALTH
*I ZONSTR.42
C     ** DEFINE TOTAL STRESSES **
      SIGXX = SXXN - (PRHN+AVSH)
      SIGYY = SYYN - (PRHN+AVSH)
      SIGZZ = SZZN - (PRHN+AVSH)
      SSUM = SIGXX + SIGYY
      SDIF = SIGXX - SIGYY
C      ** DEFINE PRINCIPAL STRESSES IN THE X-Y PLANE **
      SIG1 = SSUM/2. + SQRT(SDIF**2/4. + SXYN**2)
      SIG2 = SSUM/2. - SQRT(SDIF**2/4. + SXYN**2)
      SIG3 = SIGZZ
      PANG = 0.
      IF(SDIF .EQ. 0. .AND. SXYN .EQ. 0.)GO TO 71
C     ** PANG IS THE PRINCIPAL STRESS ORIENTATION IN DEG. **
      PANG = 28.6364 * ATAN2(2.*SXYN, SDIF)
   71 CONTINUE
      EX1N = AMAX1(SIG1,SIG2,SIG3)
      EX2N = AMIN1(SIG1,SIG2,SIG3)
      EX3N = PANG
*I GENCHK2.54
      DATA SBOT, TBOT, TGRAD / -7.37953E7, 85., 0.02 /
*I GENCHK2.86
      IF(JN .EQ. JLNBOT) TYINC = 0.0
      IF(JN .EQ. JLNBOT) TMPINC = 0.0
*I GENCHK2.269
      TYINC = - ARDN(MPNO) * GRVY * (YPNNTR-YPNNBR)
      TMPINC = - TGRAD * (YPNNTR-YPNNBR)
      TYYN = SBOT + TYINC/2.
      TMPN = TBOT + TMPINC/2.
      TXXN = TYYN
      TZZN = TYYN
      PRHN = - (TXXN+TYYN+TZZN) / 3.
      TXX(I,JT) = TXXN
      TYY(I,JT) = TYYN
      TZZ(I,JT) = TZZN
*D GENCHK2.342,344
      TMPO = TMPN
*I GENCHK2.363
      SBOT = SBOT + TYINC
      TBOT = TBOT + TMPINC
*D ZONCRP2.34
C      ** IMPROVED CREEP ALGORITHM -- MODEL#3 -- MAY 1,86(FROM SAIC) **
      REAL*8 N, L
      DIMENSION BETA(3),CT(3),Q1(3)
      DATA BETA /0.95D0, 0.975D0, 0.99D0/
      DATA MAXSUB /256/
*I ZONCRP2.71
C         MODEL INPUT PARAMETERS
*I ZONCRP2.77
C         EXR7   = OPTIONAL SWITCH TO NOT ALLOW NEGATIVE
C                  PRIMARY CREEP RATES (DEFAULT = 0 = OFF)
```

continued

TABLE 18
continued

```
C          EXR8    = YJ2N CUTOFF (DEFAULT = 1.0D-5)
C          EXR9    = MAXIMUM TIME-STEP TEMPERATURE RISE FOR
C                    CREEP MODEL (DEFAULT = 30 DEG C)
C
C          CR1     = PRIMARY CREEP STRAIN (EP)
C          CR2     = STEADY-STATE CREEP STRAIN (ES)
C          CR3     = TOTAL CREEP STRAIN = EP + ES
C          CR4     = YJ2 AT START OF MODEL
C          CR5     = YJ2 AFTER CREEP ADJUSTMENT
C
*D ZONCRP2.79
*D ZONCRP2.81,336
C
C          SET UP MATERIAL PROPERTIES IF CURRENT MATERIAL
C          IS DIFFERENT THAN PREVIOUS MATERIAL
C
   30 IF(MPNN.EQ.MPNLST) GO TO 33
      MPNLST = MPNN
      A      = AEXR1(MPNN)
      N      = AEXR2(MPNN)
      L      = AEXR3(MPNN)
      EA     = AEXR4(MPNN)
      B      = AEXR5(MPNN)
      Y      = AEXR6(MPNN)
      IOPT   = IFIX(AEXR7(MPNN) + 0.1)
      IF(AEXR8(MPNN).LE.SMLNUM) AEXR8(MPNN) = 1.0D-5
      IF(AEXR9(MPNN).LE.SMLNUM) AEXR9(MPNN) = 30.0D0
      G      = SHRN
      AA     =  A / (1.0D6)**N
      DO 31 II=1,3
      CT(II) = (BETA(II)**(ONE - N) - ONE)
     *       * (ONE - BETA(II)**(N + ONE))
     *       / (ONE - BETA(II))**2 / (N**2 - ONE)
      Q1(II) = (ONE - BETA(II)**(N + ONE))
     *       / (N + 1) / (ONE - BETA(II))
   31 CONTINUE
C
C          START OF MODEL
   33 DTMP   = TMPN - TMPO
C
C          CHECK FOR LARGE TEMPERATURE RISE
      IF(DTMP.LE.AEXR9(MPNN)) GO TO 34
      WRITE(6,1000) I, J, AEXR9(MPNN), DTMP
 1000 FORMAT(
     *      /10X,10H**********,
     *      /10X,10HE R R O R ,
     *      /10X,27HTHE TEMPERATURE RISE DURING,
     *      /10X,24HTHE TIME-STEP IS GREATER,
     *      /10X,13HFOR ZONE I = ,I10, 6H, J = ,I10,
     *      /10X, 5HTHAN ,1PE12.5,
     *      /10X,19HTEMPERATURE RISE = ,1PE12.5
     *      )
      NSERR  = 3
```

continued

TABLE 18
continued

```
      NSEXT  = 2
      GO TO 990
C
C         TEMPERATURES IN DEGREES KELVIN
   34 TMPH   = (TMPN + TMPO) * 0.5D0 + 273.0D0
      GAM    = L * DTMP / TWO / TMPH**2
      AF     = 1.5D0 * AA * (ONE + GAM**2 / 6.0D0) * EXP(-L / TMPH)
      YJ2N   = SQRT(THR / TWO * (SXXN**2 + SYYN**2 + SZZN**2)
     *       + THR * SXYN**2)
C
C         YJ2O IS CURRENT YJ2N AT BEGINING OF CREEP MODEL
      YJ2O   = YJ2N
C
C         FIRST UPDATE STEALTH CREEP STRAINS
      CR1N   = CR1O
      CR2N   = CR2O
      CR3N   = CR3O
C
C         TRANSFER STEALTH CREEP STRAINS INTO LOCAL MODEL
C         CREEP STRAINS
      EP     = CR1N
      ES     = CR2N
      ET     = CR3N
C
C         IF YJ2N IS LESS THAN CUTOFF SKIP CREEP MODEL
      IF(YJ2N.LT.AEXR8(MPNN)) GO TO 990
      NSUB   = 0
      HH     = ZER
C
C          BEGIN SUBSTEP LOOP
  300 ZD     = AF * YJ2N**N
      NSUB   = NSUB + 1
      II     = 1
      IF(EP.LT.1.0D-4) II = 2
      IF(EP.LT.1.0D-5) II = 3
      IF(NSUB.EQ.1)    II = 3
      IF(ZD.LT.1.5D0*Y) GO TO 325
C
C          FAST BRANCH
      IF(EP.LT.1.5D0*EA) GO TO 301
      EP   = 1.5D0 * EA
      GO TO 350
  301 Q2     = YJ2N * (ONE - BETA(II)) / TWO / G
      XX     = 1.5D0 * EA - EP
      W      = Q2 / TWO - 1.5D0 / B - XX
      DS     = W + SQRT(W**2 + THR * Q2 / B)
      DP     = XX
      YY     = B * DS * TWO / THR
      IF(YY.LT.50.0) DP = XX * (ONE - EXP(-YY))
      H      = DS / ZD / Q1(II)
      GO TO 380
C
C          SLOW BRANCH
```

continued

TABLE 18
continued

```
  325 IF(IOPT.EQ.1) GO TO 360
      IF(EP.LT.EA*ZD/Y) GO TO 360
C
C           EP IS SATURATED
  350 SIGMAB = YJ2N * (ONE + (N - ONE) * TWO * G * ZD
     *        / YJ2N * (DLTH - HH))**(ONE/(ONE-N))
      ES   = ES + (YJ2N - SIGMAB) / TWO / G
      ET   = EP + ES
      GO TO 399
  360 Q2      = YJ2N * (ONE - BETA(II)) / TWO / G
      W       = (Q2 / TWO + EP) / Q1(II) / ZD
     *        - (B * EA + ONE) / B / Y
      H       = W + SQRT(W**2 + TWO * Q2 / Q1(II) / ZD / B / Y)
      DS      = ZD * Q1(II) * H
      XX      = EA * Q1(II) * ZD / Y / CT(II) - EP
      IF(IOPT.EQ.0) XX = AMAX1(XX,ZER)
      DP      = XX
      YY      = B * Y * H
      IF(YY.LT.50.0) DP = XX * (ONE - EXP(-YY))
      IF(DP+EP.LT.ZER) DP = ZER
C
C           COMPATABILITY FACTOR
  380 CF      = Q2 / (DS + DP)
      DS      = DS * CF
      DP      = DP * CF
      H       = H  * CF
C
C           SUBSTEP UPDATE
      ES   = ES + DS
      EP   = EP + DP
      HH      = HH + H * CT(II)
      SIGMAB = YJ2N * BETA(II)
C
C          DEBUG PRINTOUT
C
C     IF(I.EQ.3.AND.J.EQ.3)
C    *WRITE(6,3800) NSUB,ES,EP,YJ2N,SIGMAB,HH,BETA(II)
C3800 FORMAT(2X,'NSUB,ES,EP,YJ2N,SIGMAB,HH',I3,1X,6(1PE12.5,5X))
      IF(HH.GT.DLTH) GO TO 389
C
C           CONTINUE SUBSTEPS
      YJ2N = SIGMAB
      IF(NSUB.LT.MAXSUB) GO TO 300
      WRITE(6,3900) I, J
 3900 FORMAT(
     *        /10X,10H**********,
     *        /10X,10HE R R O R ,
     *        /10X,29HMAXIMUM NUMBER OF CREEP MODEL
     *        /10X,29HSUBSTEPS HAS BEEN EXCEEDED BY
     *        /10X, 9HZONE I = ,I10, 6H, J = ,I10
     *       )
      NSERR  = 3
      NSEXT  = 4
```

continued

TABLE 18
continued

```
      GO TO 990
  389 IF(NSUB.GT.1.OR.II.EQ.3) GO TO 390
      YJ2N   = YJ20
      NSUB   = 0
      HH     = ZER
      II     = 3
      GO TO 300
C
C          INTERPOLATE FOR SIGMAB AT DLTH
  390 DT1    = DLTH - (HH - H * CT(II))
      DT2    = HH - DLTH
      SIGMA1 = YJ2N / (ONE + (YJ2N**(N-ONE))
     *       * (N - ONE) * TWO * G * AF * DT1)**(ONE/(N-ONE))
      DUM    =  ONE - SIGMAB**(N-ONE) * (N - ONE) * TWO * G * AF * DT2
      IF(DUM.LT.ZER) DUM = 1.0D-50
      SIGMA2 = SIGMAB / DUM**(ONE / (N - ONE))
      IF(SIGMA1.LT.SIGMAB) SIGMA1 = SIGMAB + (YJ2N - SIGMAB) * DT2
     *                             / (DT1 + DT2)
      IF(SIGMA2.GT.YJ2N)   SIGMA2 = YJ2N - (YJ2N - SIGMAB) * DT1
     *                             / (DT1 + DT2)
      SIGMAB = (SIGMA1 * DT2 + SIGMA2 * DT1) / (DT1 + DT2)
C
C          CORRECT FOR STRAINS AT DLTH
      DD     = (YJ2N - SIGMAB) / TWO / G / (DS + DP)
      ES     = ES - DS * (ONE - DD)
      EP     = EP - DP * (ONE - DD)
      ET     = ES + EP
C
C          ADJUST STRESS DEVIATORS
  399 SXXN   = SXXN * SIGMAB / YJ20
      SYYN   = SYYN * SIGMAB / YJ20
      SZZN   = SZZN * SIGMAB / YJ20
      SXYN   = SXYN * SIGMAB / YJ20
C
C         UPDATE STEALTH CREEP VARIABLES
      CR1N   = EP
      CR2N   = ES
      CR3N   = ET
      CR4N   = YJ20
      CR5N   = SIGMAB
*D ZONPRH.76,78
*D ZONPRH.84,85
      PRHRLV = EOS2 * (1./RLVN - 1./RLVO) + PRHO
      PRHZIE = THR * EOS2 * EOSB * (ZHEN-ZHEO + ZSEN-ZSEO)/SHCO
C     FROM A FUNCTION OF RELATIVE VOLUME (THERMOMECHANICAL)
*D ZONSSS.87,97
      SSSPRH = VAL
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1.0,0.18,0.98,HGT,WID,0.0,CDN)
*I DMPPRO.24
      RETURN
*D EDTINP.547
C
```

continued

TABLE 18
concluded

```
C       ** RECORD #664 DEFINES A SUB-GRID FOR PLOTTING **
C
  640 MINIPL = IFIX(DTAFLD(1) + .1)
      MAXIPL = IFIX(DTAFLD(2) + .1)
      IF (MINIPL .GE. 1 .AND. MINIPL .LE. MAXGPT) GO TO 641
      CALL RGEERR(INPTYP,1,1,MAXGPT,MINIPL)
  641 IF (MAXIPL .GE. 1 .AND. MAXIPL .LE. MAXGPT) GO TO 642
      CALL RGEERR(INPTYP,2,1,MAXGPT,MAXIPL)
  642 IF(MINIPL .LE. MAXIPL) GO TO 643
      CALL LIMERR(INPTYP,MINIPL,MAXIPL,1,2)
  643 LMIN = 3
      IF(NSPRO .EQ. 1 .OR. NSPRO .EQ. 11) GO TO 950
C
      MINJPL = IFIX(DTAFLD(3) + .1)
      MAXJPL = IFIX(DTAFLD(4) + .1)
      IF (MINJPL .GE. 1 .AND. MINJPL .LE. MAXROW) GO TO 644
      CALL RGEERR(INPTYP,1,1,MAXROW,MINJPL)
  644 IF (MAXJPL .GE. 1 .AND. MAXJPL .LE. MAXROW) GO TO 645
      CALL RGEERR(INPTYP,2,1,MAXROW,MAXJPL)
  645 IF(MINJPL .LE. MAXJPL) GO TO 646
      CALL LIMERR(INPTYP,MINJPL,MAXJPL,1,2)
  646 LMIN = 5
      GO TO 950
```

TABLE 19
STEALTH 2D Input Data Set for Problem 5.3 (Start Run)

```
TTL       PROBLEM 5.3 THERMAL-MECHANICAL ANALYSIS - SALT
PRB
PRO       2.0
DTS       4.0       1.0
SYM       2.0
GRV       0.0       -9.8066
GRD       1.0       1.0       41.0      34.0
END
MAT                                                   1.
111 SALT  1.0       3.0
112       1.0       2.0       2.0       2.0       3.0
114       1.0       2.0       2.0
121       1.0       2150.0
122       1.        1.        0.         1.4706E10
123       1.        -0.5      2.        1.          4.0E-5
132       1.0       5.7158E+07
134       1.0        5.6390e09
136       1.0        -1.0 E+12
152       1.0       4.5
154       1.0         1.7845E6
182       1.        0.            5.76E-8 4.10     4042.0       3.98E-8
183       1.           7.20E-2 158.0
111 SOURC 2.0       3.0
112       2.0       2.0       2.0       2.0       3.0
114       2.0       2.0       2.0       3.0
121       2.0       2150.0
122       2.        1.        0.         1.4706E10
123       2.        -0.5      2.0         1.          4.0E-5
132       2.0       5.7158E+07
134       2.0        5.6390e09
136       2.0        -1.0 E+12
152       2.0       4.5
154       2.0         1.7845E6
156       2.        0.88744
182       2.        0.            5.76E-8 4.10     4042.0       3.98E-8
183       2.           7.20E-2 158.0
END
GPT                                       1.        1.
211       1.0       1.0       1.0       0.0       -3500.
212       1.0       0.0       15.0      2.0
212       2.0       0.0       -3500.    1.0
212       3.0       5642.     -3500.    1.0
212       4.0       5642.     15.       3.0
221       1.0       1.0       15.       1.0       23.0
221       2.0       15.       41.       1.0       23.0
221       3.0       1.0       15.       23.0      24.0
221       4.0       15.       41.       23.0      24.0
221       5.0       1.0       15.       24.0      34.0
221       6.0       15.       41.       24.0      34.0
247       1.        0.        1467.     -3500.    2992.5    1.02      0.94
247       2.        1467.     4175.     -3500.    2992.5    1.02      0.94
247       3.        0.        1467.     -507.5    15.       1.02      1.00
247       4.        1467.     4175.     -507.5    15.       1.02      1.00
```

continued

TABLE 19
continued

```
247     5.      0.      1467.   -492.5  492.5   1.02    1.10
247     6.      1467.   4175.   -492.5  492.5   1.02    1.10
END
ZON                                     1.
311     1.0     1.0     41.0    1.0     34.0
311     2.0     1.0     15.     23.0    24.0
321     1.0     1.0
321     2.0     2.0
322     1.0     1.0
322     2.0     1.0
341     1.0
341     2.0
END
BDY                                     1.
411     1.0     1.0     1.0     41.0    1.0
411     2.0     41.     1.0     41.0    34.0
411     3.0     41.     34.0    1.0     34.0
411     4.0     1.0     34.0    1.0     1.0
412     1.0     1.0     6.0     2.0     3.0
412     2.0     1.0     6.0     5.0     4.0
412     3.0     1.0     3.0     2.0     1.0
412     4.0     1.0     6.0     5.0     2.0
423     1.0     1.0
423     3.0     3.0
451     1.0     1.0     0.0         1.0E+49
452     1.0     15.0
451     3.0     1.0     0.0         1.0E+49
452     3.0     85.0
481     1.      2.      3.
481     2.      3.      4.
481     4.      1.      2.
482     1.      1.      5.      5.      0.      1.0
482     2.      1.      5.      5.      0.      1.0
482     4.      1.      5.      5.      0.      1.0
END
TIM
511     3.1536E+07
512        2.0E+07 3.1536E07
513     1.1     0.95
514     0.
521      9.4608E09   350.
END
EDT                                     1.
611     1.
613     1.
616     1.
621     1.      0.          9.4608E8  9.4608E8
621     2.      0.          9.4608E9  3.1536E9
622     1.0     41.0    1.      34.0
623     11.     14.     53.     54.     61.     71.     72.
623     73.     74.     91.     92.     93.
624     3.
641     1.      0.          9.4608E8  9.4608E8
```

continued

TABLE 19
concluded

```
641     2.      0.        9.4608E9  3.1536E9
671     1.      0.        9.4608E9  9.4608e7
674     1.      1.      61.       1.       15024.
674     2.      1.      61.       1.       15025.
674     3.      1.      61.       1.       2024.
674     4.      1.      61.       1.       2025.
674     5.      1.      71.       1.       15024.
674     6.      1.      72.       1.       8024.
674     7.      1.      5.        1.
674     8.      2.      61.                100.                24.
674     9.      2.      61.                100.                2000.
674     10.     2.      14.                            9.4608E8 34.
674     11.     2.      72.                100.                15000.
674     12.     1.      14.       1.       1034.
674     13.     2.      14.                            3.1536E9 34.
674     14.     2.      14.                            9.4608E9 34.
675     15.     4.      61.                            9.4608E8
675     16.     4.      61.                            3.1536E9
675     17.     4.      61.                            9.4608E9
675     18.     4.      91.                            9.4608E8
675     19.     4.      91.                            3.1536E9
675     20.     4.      91.                            9.4608E9
675     21.     4.      92.                            9.4608E8
675     22.     4.      92.                            3.1536E9
675     23.     4.      92.                            9.4608E9
END
END
```

TABLE 20
Fortran Updates to STEALTH 2D for Problem 5.3 (Restart)

```
*ID PRB53SL
*C STEALTH
*D ZONZSE.29,30
C          ** BETTER RESOLUTION BETWEEN 100 AND 300 YEARS **
     * 15.,  20.,  30.,  50.,  70.,  100.,  150.,
     * 200.,  250.,  300.,  500.,  800.,  1000.,  3000. /
*D ZONZSE.35,36
     * .6847, .6250, .5240, .3890, .3030, .2400, .1900,
     * .1500, .1200, .1000, .0700, .0500, .0450, .0260 /
*I ZONSTR.42
C    ** DEFINE TOTAL STRESSES **
      SIGXX = SXXN - (PRHN+AVSH)
      SIGYY = SYYN - (PRHN+AVSH)
      SIGZZ = SZZN - (PRHN+AVSH)
      SSUM = SIGXX + SIGYY
      SDIF = SIGXX - SIGYY
C      ** DEFINE PRINCIPAL STRESSES IN THE X-Y PLANE **
      SIG1 = SSUM/2. + SQRT(SDIF**2/4. + SXYN**2)
      SIG2 = SSUM/2. - SQRT(SDIF**2/4. + SXYN**2)
      SIG3 = SIGZZ
      PANG = 0.
      IF(SDIF .EQ. 0. .AND. SXYN .EQ. 0.)GO TO 71
C     ** PANG IS THE PRINCIPAL STRESS ORIENTATION IN DEG. **
      PANG = 28.6364 * ATAN2(2.*SXYN, SDIF)
   71 CONTINUE
      EX1N = AMAX1(SIG1,SIG2,SIG3)
      EX2N = AMIN1(SIG1,SIG2,SIG3)
      EX3N = PANG
*I GENCHK2.54
      DATA SBOT, TBOT, TGRAD / -7.37953E7, 85., 0.02 /
*I GENCHK2.86
      IF(JN .EQ. JLNBOT) TYINC = 0.0
      IF(JN .EQ. JLNBOT) TMPINC = 0.0
*I GENCHK2.269
      TYINC = - ARDN(MPNO) * GRVY * (YPNNTR-YPNNBR)
      TMPINC = - TGRAD * (YPNNTR-YPNNBR)
      TYYN = SBOT + TYINC/2.
      TMPN = TBOT + TMPINC/2.
      TXXN = TYYN
      TZZN = TYYN
      PRHN = - (TXXN+TYYN+TZZN) / 3.
      TXX(I,JT) = TXXN
      TYY(I,JT) = TYYN
      TZZ(I,JT) = TZZN
*D GENCHK2.342,344
      TMPO = TMPN
*I GENCHK2.363
      SBOT = SBOT + TYINC
      TBOT = TBOT + TMPINC
*D ZONCRP2.34
C      ** IMPROVED CREEP ALGORITHM -- MODEL#3 -- MAY 1,86(FROM SAIC) **
      REAL*8 N, L
      DIMENSION BETA(3),CT(3),Q1(3)
```

continued

TABLE 20
continued

```
      DATA BETA /0.95D0, 0.975D0, 0.99D0/
      DATA MAXSUB /256/
*I ZONCRP2.71
C         MODEL INPUT PARAMETERS
*I ZONCRP2.77
C         EXR7    = OPTIONAL SWITCH TO NOT ALLOW NEGATIVE
C                   PRIMARY CREEP RATES (DEFAULT = 0 = OFF)
C         EXR8    = YJ2N CUTOFF (DEFAULT = 1.0D-5)
C         EXR9    = MAXIMUM TIME-STEP TEMPERATURE RISE FOR
C                   CREEP MODEL (DEFAULT = 30 DEG C)
C
C         CR1     = PRIMARY CREEP STRAIN (EP)
C         CR2     = STEADY-STATE CREEP STRAIN (ES)
C         CR3     = TOTAL CREEP STRAIN = EP + ES
C         CR4     = YJ2 AT START OF MODEL
C         CR5     = YJ2 AFTER CREEP ADJUSTMENT
C
*D ZONCRP2.79
*D ZONCRP2.81,336
C
C         SET UP MATERIAL PROPERTIES IF CURRENT MATERIAL
C         IS DIFFERENT THAN PREVIOUS MATERIAL
C
   30 IF(MPNN.EQ.MPNLST) GO TO 33
      MPNLST = MPNN
      A      = AEXR1(MPNN)
      N      = AEXR2(MPNN)
      L      = AEXR3(MPNN)
      EA     = AEXR4(MPNN)
      B      = AEXR5(MPNN)
      Y      = AEXR6(MPNN)
      IOPT   = IFIX(AEXR7(MPNN) + 0.1)
      IF(AEXR8(MPNN).LE.SMLNUM) AEXR8(MPNN) = 1.0D-5
      IF(AEXR9(MPNN).LE.SMLNUM) AEXR9(MPNN) = 30.0D0
      G      = SHRN
      AA     =  A / (1.0D6)**N
      DO 31 II=1,3
      CT(II) = (BETA(II)**(ONE - N) - ONE)
     *       * (ONE - BETA(II)**(N + ONE))
     *       / (ONE - BETA(II))**2 / (N**2 - ONE)
      Q1(II) = (ONE - BETA(II)**(N + ONE))
     *       / (N + 1) / (ONE - BETA(II))
   31 CONTINUE
C
C          START OF MODEL
   33 DTMP   = TMPN - TMPO
C
C          CHECK FOR LARGE TEMPERATURE RISE
      IF(DTMP.LE.AEXR9(MPNN)) GO TO 34
      WRITE(6,1000) I, J, AEXR9(MPNN), DTMP
 1000 FORMAT(
     *      /10X,10H**********,
     *      /10X,10HE R R O R ,
```

continued

TABLE 20
continued

```
     *       /10X,27HTHE TEMPERATURE RISE DURING,
     *       /10X,24HTHE TIME-STEP IS GREATER,
     *       /10X,13HFOR ZONE I = ,I10, 6H, J = ,I10,
     *       /10X, 5HTHAN ,1PE12.5,
     *       /10X,19HTEMPERATURE RISE = ,1PE12.5
     *       )
      NSERR  = 3
      NSEXT  = 2
      GO TO 990
C
C          TEMPERATURES IN DEGREES KELVIN
   34 TMPH    = (TMPN + TMPO) * 0.5D0 + 273.0D0
      GAM     = L * DTMP / TWO / TMPH**2
      AF      = 1.5D0 * AA * (ONE + GAM**2 / 6.0D0) * EXP(-L / TMPH)
      YJ2N    = SQRT(THR / TWO * (SXXN**2 + SYYN**2 + SZZN**2)
     *        + THR * SXYN**2)
C
C          YJ2O IS CURRENT YJ2N AT BEGINING OF CREEP MODEL
      YJ2O    = YJ2N
C
C          FIRST UPDATE STEALTH CREEP STRAINS
      CR1N    = CR1O
      CR2N    = CR2O
      CR3N    = CR3O
C
C          TRANSFER STEALTH CREEP STRAINS INTO LOCAL MODEL
C          CREEP STRAINS
      EP      = CR1N
      ES      = CR2N
      ET      = CR3N
C
C          IF YJ2N IS LESS THAN CUTOFF SKIP CREEP MODEL
      IF(YJ2N.LT.AEXR8(MPNN)) GO TO 990
      NSUB    = 0
      HH      = ZER
C
C           BEGIN SUBSTEP LOOP
  300 ZD      = AF * YJ2N**N
      NSUB    = NSUB + 1
      II      = 1
      IF(EP.LT.1.0D-4) II = 2
      IF(EP.LT.1.0D-5) II = 3
      IF(NSUB.EQ.1)    II = 3
      IF(ZD.LT.1.5D0*Y) GO TO 325
C
C           FAST BRANCH
      IF(EP.LT.1.5D0*EA) GO TO 301
      EP    = 1.5D0 * EA
      GO TO 350
  301 Q2      = YJ2N * (ONE - BETA(II)) / TWO / G
      XX      = 1.5D0 * EA - EP
      W       = Q2 / TWO - 1.5D0 / B - XX
      DS      = W + SQRT(W**2 + THR * Q2 / B)
```

continued

TABLE 20
continued

```
      DP      = XX
      YY      = B * DS * TWO / THR
      IF(YY.LT.50.0) DP = XX * (ONE - EXP(-YY))
      H       = DS / ZD / Q1(II)
      GO TO 380
C
C           SLOW BRANCH
  325 IF(IOPT.EQ.1) GO TO 360
      IF(EP.LT.EA*ZD/Y) GO TO 360
C
C           EP IS SATURATED
  350 SIGMAB = YJ2N * (ONE + (N - ONE) * TWO * G * ZD
     *        / YJ2N * (DLTH - HH))**(ONE/(ONE-N))
      ES    = ES + (YJ2N - SIGMAB) / TWO / G
      ET    = EP + ES
      GO TO 399
  360 Q2      = YJ2N * (ONE - BETA(II)) / TWO / G
      W       = (Q2 / TWO + EP) / Q1(II) / ZD
     *        - (B * EA + ONE) / B / Y
      H       = W + SQRT(W**2 + TWO * Q2 / Q1(II) / ZD / B / Y)
      DS      = ZD * Q1(II) * H
      XX      = EA * Q1(II) * ZD / Y / CT(II) - EP
      IF(IOPT.EQ.0) XX = AMAX1(XX,ZER)
      DP      = XX
      YY      = B * Y * H
      IF(YY.LT.50.0) DP = XX * (ONE - EXP(-YY))
      IF(DP+EP.LT.ZER) DP = ZER
C
C           COMPATABILITY FACTOR
  380 CF      = Q2 / (DS + DP)
      DS      = DS * CF
      DP      = DP * CF
      H       = H  * CF
C
C           SUBSTEP UPDATE
      ES    = ES + DS
      EP    = EP + DP
      HH      = HH + H * CT(II)
      SIGMAB = YJ2N * BETA(II)
C
C          DEBUG PRINTOUT
C
C     IF(I.EQ.3.AND.J.EQ.3)
C    *WRITE(6,3800) NSUB,ES,EP,YJ2N,SIGMAB,HH,BETA(II)
C3800 FORMAT(2X,'NSUB,ES,EP,YJ2N,SIGMAB,HH',I3,1X,6(1PE12.5,5X))
      IF(HH.GT.DLTH) GO TO 389
C
C           CONTINUE SUBSTEPS
      YJ2N = SIGMAB
      IF(NSUB.LT.MAXSUB) GO TO 300
      WRITE(6,3900) I, J
 3900 FORMAT(
     *        /10X,10H**********,
```

continued

TABLE 20
continued

```
     *        /10X,10HE R R 0 R ,
     *        /10X,29HMAXIMUM NUMBER OF CREEP MODEL
     *        /10X,29HSUBSTEPS HAS BEEN EXCEEDED BY
     *        /10X, 9HZONE I = ,I10, 6H, J = ,I10
     *       )
      NSERR  = 3
      NSEXT  = 4
      GO TO 990
  389 IF(NSUB.GT.1.OR.II.EQ.3) GO TO 390
      YJ2N   = YJ2O
      NSUB   = 0
      HH     = ZER
      II     = 3
      GO TO 300
C
C          INTERPOLATE FOR SIGMAB AT DLTH
  390 DT1    = DLTH - (HH - H * CT(II))
      DT2    = HH - DLTH
      SIGMA1 = YJ2N / (ONE + (YJ2N**(N-ONE))
     *       * (N - ONE) * TWO * G * AF * DT1)**(ONE/(N-ONE))
      DUM    =  ONE - SIGMAB**(N-ONE) * (N - ONE) * TWO * G * AF * DT2
      IF(DUM.LT.ZER) DUM = 1.0D-50
      SIGMA2 = SIGMAB / DUM**(ONE / (N - ONE))
      IF(SIGMA1.LT.SIGMAB) SIGMA1 = SIGMAB + (YJ2N - SIGMAB) * DT2
     *                            / (DT1 + DT2)
      IF(SIGMA2.GT.YJ2N)   SIGMA2 = YJ2N - (YJ2N - SIGMAB) * DT1
     *                            / (DT1 + DT2)
      SIGMAB = (SIGMA1 * DT2 + SIGMA2 * DT1) / (DT1 + DT2)
C
C          CORRECT FOR STRAINS AT DLTH
      DD     = (YJ2N - SIGMAB) / TWO / G / (DS + DP)
      ES     = ES - DS * (ONE - DD)
      EP     = EP - DP * (ONE - DD)
      ET     = ES + EP
C
C          ADJUST STRESS DEVIATORS
  399 SXXN   = SXXN * SIGMAB / YJ2O
      SYYN   = SYYN * SIGMAB / YJ2O
      SZZN   = SZZN * SIGMAB / YJ2O
      SXYN   = SXYN * SIGMAB / YJ2O
C
C         UPDATE STEALTH CREEP VARIABLES
      CR1N   = EP
      CR2N   = ES
      CR3N   = ET
      CR4N   = YJ2O
      CR5N   = SIGMAB
*D ZONPRH.76,78
*D ZONPRH.84,85
      PRHRLV = EOS2 * (1./RLVN - 1./RLVO) + PRHO
      PRHZIE = THR * EOS2 * EOSB * (ZHEN-ZHEO + ZSEN-ZSEO)/SHCO
C     FROM A FUNCTION OF RELATIVE VOLUME (THERMOMECHANICAL)
*D ZONSSS.87,97
```

continued

TABLE 20
concluded

```
      SSSPRH = VAL
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0,0.18,0.98,HGT,WID,0.0,CDN)
*I DMPPRO.24
      RETURN
*D EDTINP.547
C
C       ** RECORD #664 DEFINES A SUB-GRID FOR PLOTTING **
C
  640 MINIPL = IFIX(DTAFLD(1) + .1)
      MAXIPL = IFIX(DTAFLD(2) + .1)
      IF (MINIPL .GE. 1 .AND. MINIPL .LE. MAXGPT) GO TO 641
      CALL RGEERR(INPTYP,1,1,MAXGPT,MINIPL)
  641 IF (MAXIPL .GE. 1 .AND. MAXIPL .LE. MAXGPT) GO TO 642
      CALL RGEERR(INPTYP,2,1,MAXGPT,MAXIPL)
  642 IF(MINIPL .LE. MAXIPL) GO TO 643
      CALL LIMERR(INPTYP,MINIPL,MAXIPL,1,2)
  643 LMIN = 3
      IF(NSPRO .EQ. 1 .OR. NSPRO .EQ. 11) GO TO 950
C
      MINJPL = IFIX(DTAFLD(3) + .1)
      MAXJPL = IFIX(DTAFLD(4) + .1)
      IF (MINJPL .GE. 1 .AND. MINJPL .LE. MAXROW) GO TO 644
      CALL RGEERR(INPTYP,1,1,MAXROW,MINJPL)
  644 IF (MAXJPL .GE. 1 .AND. MAXJPL .LE. MAXROW) GO TO 645
      CALL RGEERR(INPTYP,2,1,MAXROW,MAXJPL)
  645 IF(MINJPL .LE. MAXJPL) GO TO 646
      CALL LIMERR(INPTYP,MINJPL,MAXJPL,1,2)
  646 LMIN = 5
      GO TO 950
```

TABLE 21
STEALTH 2D Input Data Set for Problem 5.3 (Restart Run)

```
TTL     PROBLEM 5.3 THERMAL-MECHANICAL ANALYSIS - SALT
PRB
SOR     2.          3.1536E9
END
TIM
511     3.1536E+07
512        2.0E+07 3.1536E07
513     1.1       0.95
514     0.
521      3.1536E10   1050.
END
EDT                                                 1.
611     1.
613     1.
616     1.
621     1.        3.1536  E9  6.3072E9  6.3072E9
621     2.        0.          3.1536E10 3.1536E10
622     1.0       41.0      1.        34.0
623     11.       14.       53.       54.       61.       71.       72.
623     73.       74.       91.       92.       93.
624     3.
641     1.          3.1536E9  6.3072E9  6.3072E9
641     2.         1.5768E10 1.5768E10 1.5768E10
671     1.          3.1536E9 3.1536E10  3.1536E8
674     1.        1.        61.       1.        15024.
674     2.        1.        61.       1.        15025.
674     3.        1.        61.       1.        2024.
674     4.        1.        61.       1.        2025.
674     5.        1.        71.       1.        15024.
674     6.        1.        72.       1.        8024.
674     7.        1.        5.        1.
674     8.        2.        61.                 300.                24.
674     9.        2.        61.                 300.                2000.
674     10.       2.        61.                 1000.               24.
674     11.       2.        72.                 300.                15000.
674     12.       1.        14.       1.        1034.
674     13.       2.        14.                             3.1536E10 34.
674     14.       2.        14.                              9.4608E9 34.
END
END
```

TABLE 22

Development of Tensile Stresses at Various Times, Problem 5.3

Time (yrs)	Max. Radial Extent (m)	Max. Depth (m)	Max. Tensile Stress (MPa)	Location of Max. Tensile Stress Depth (m)	Radius (m)
30	~1175	~325	5.30	~225	~950
100	~1400	~35	0.63	~35	~530
300	~1290	~35	0.33	~35	~45
1,000	0	0	0	-	-

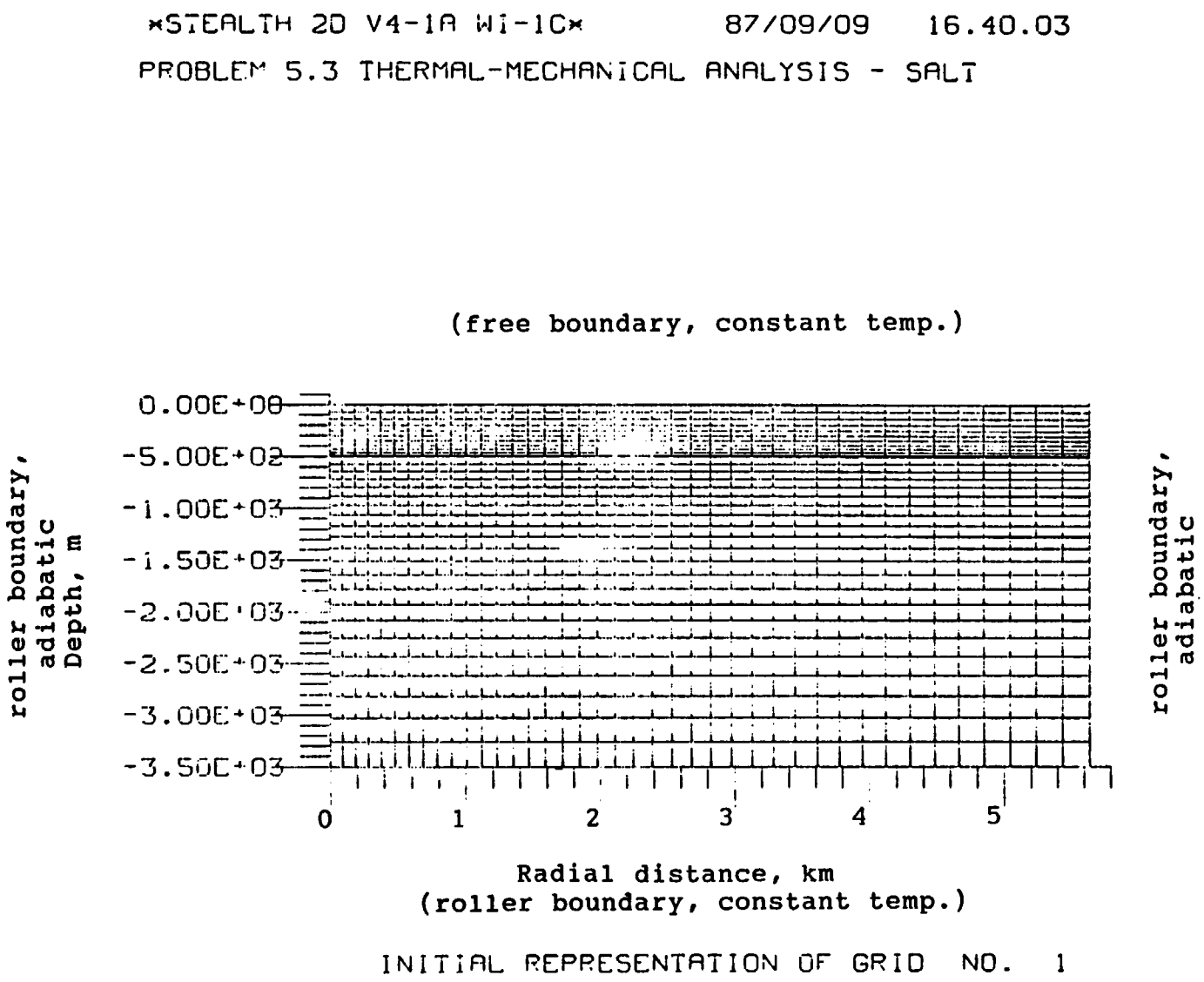


Figure 25. Initial mesh configuration and boundary conditions; axisymmetric geometry.

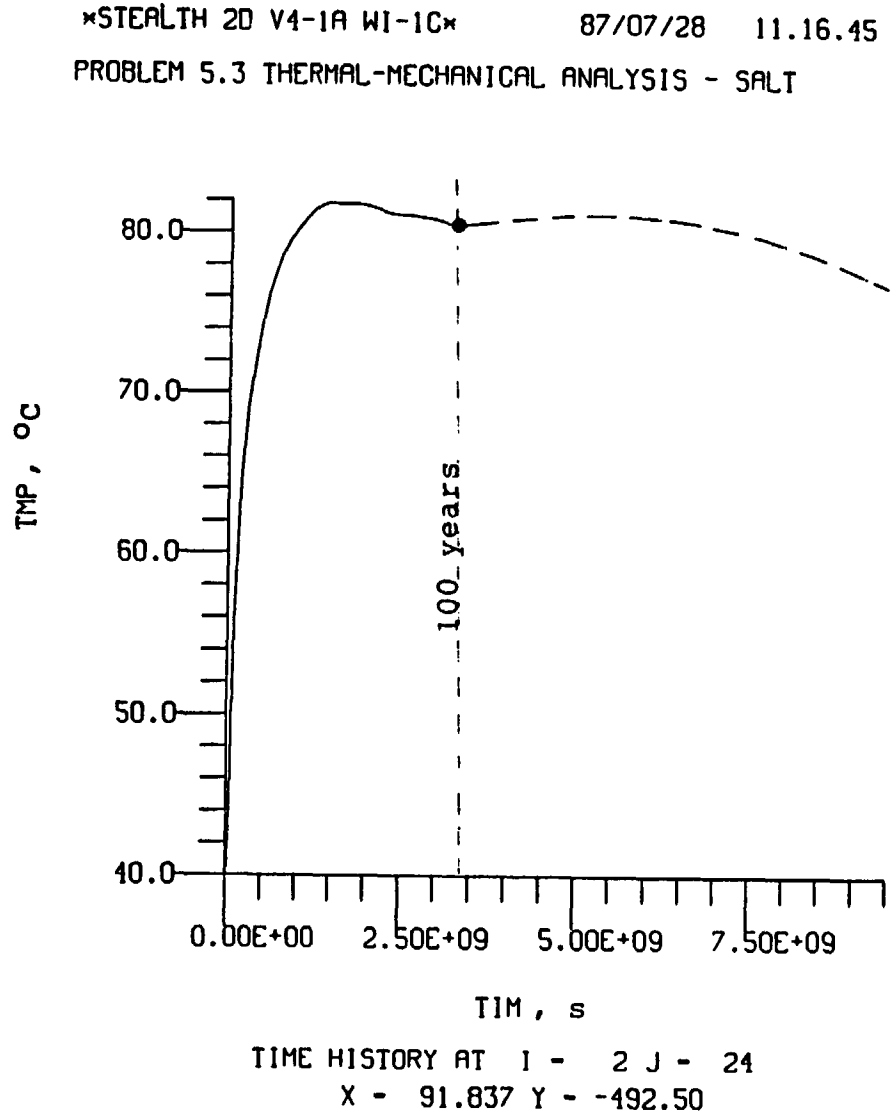


Figure 26a. Temperature history at repository midpoint (0 - 300 years).

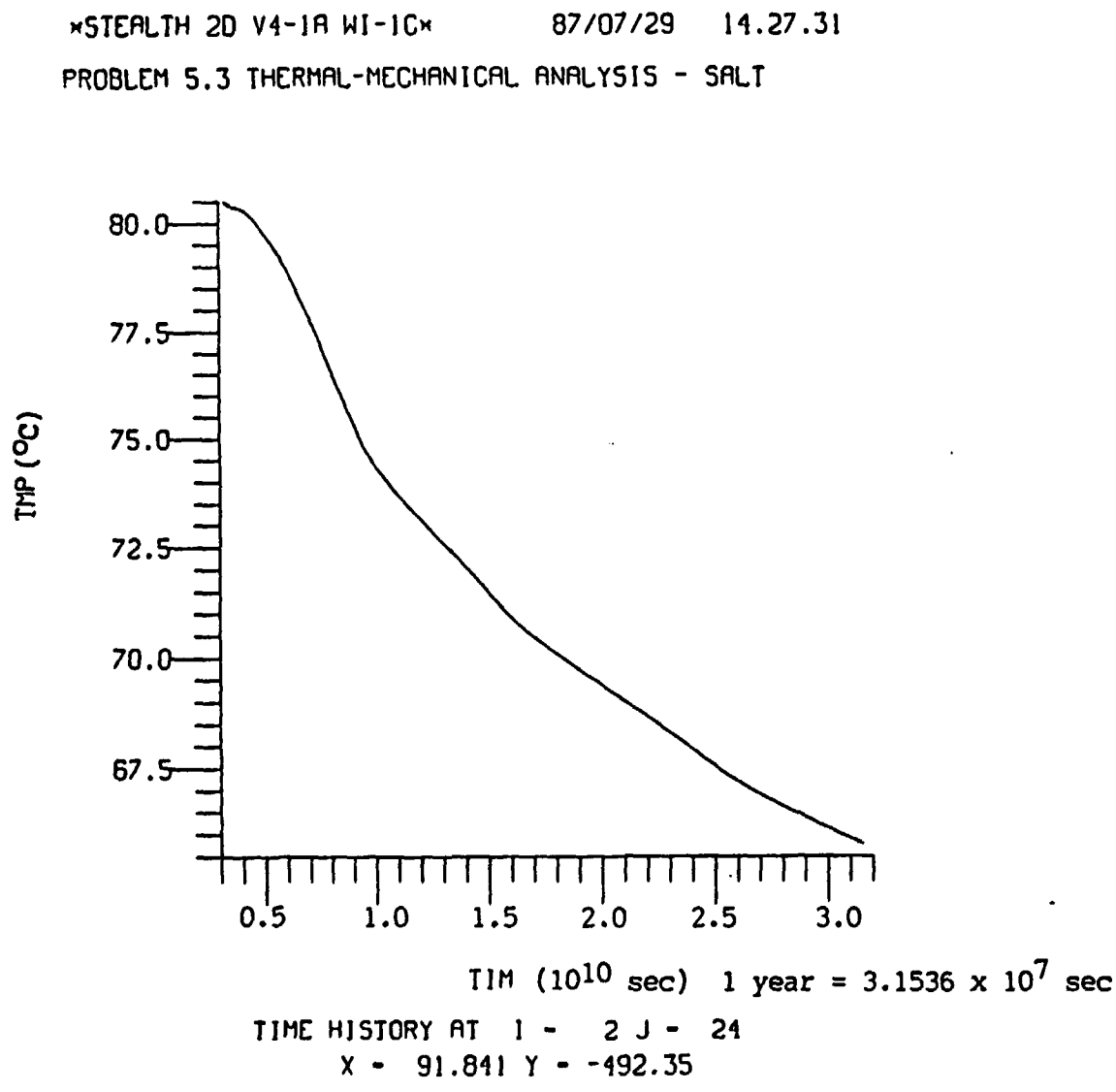


Figure 26b. Temperature History at Repository Midpoint (100 - 1,000 years)

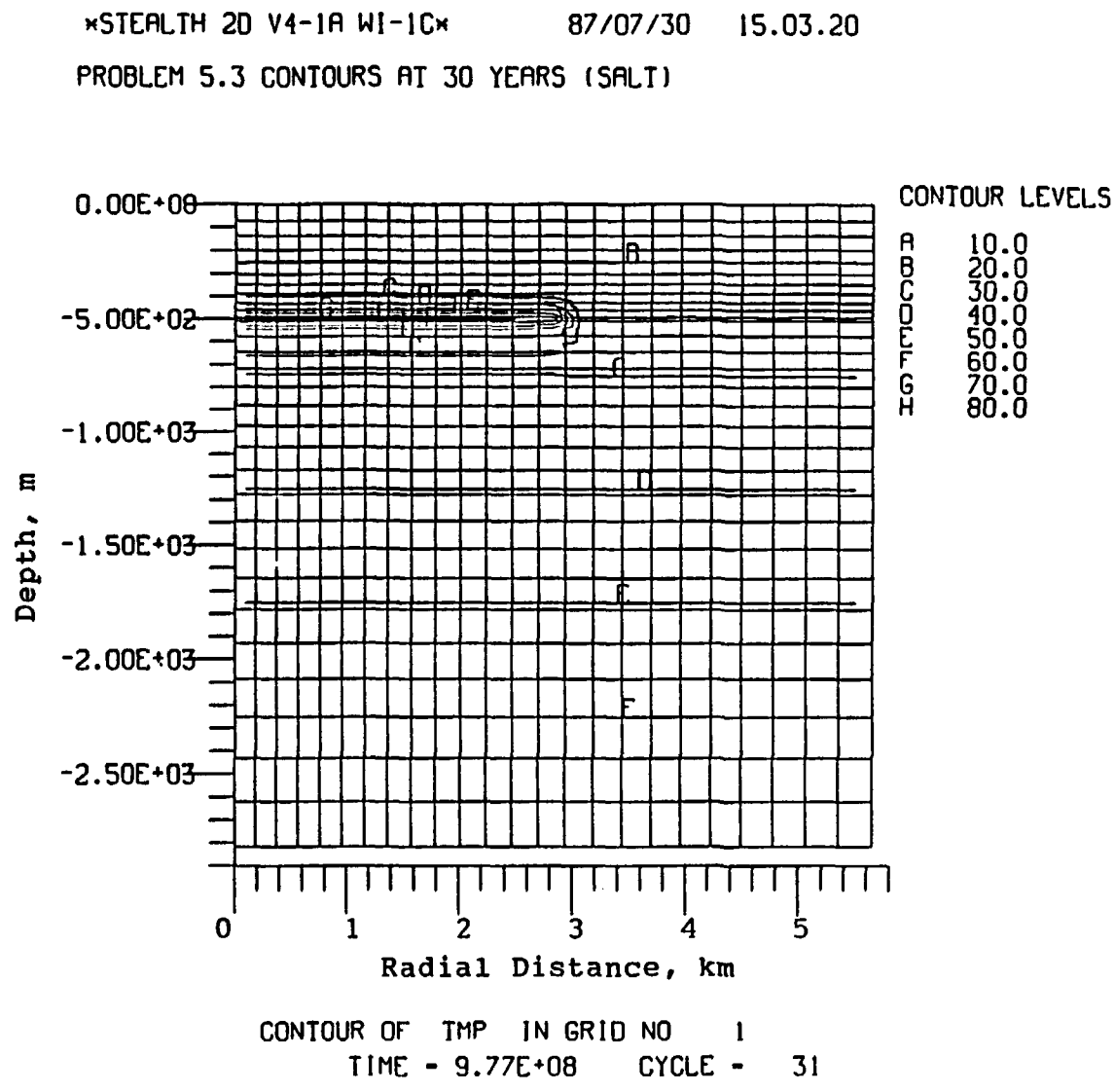


Figure 27. Temperature contours in the modeled region at 30 years.

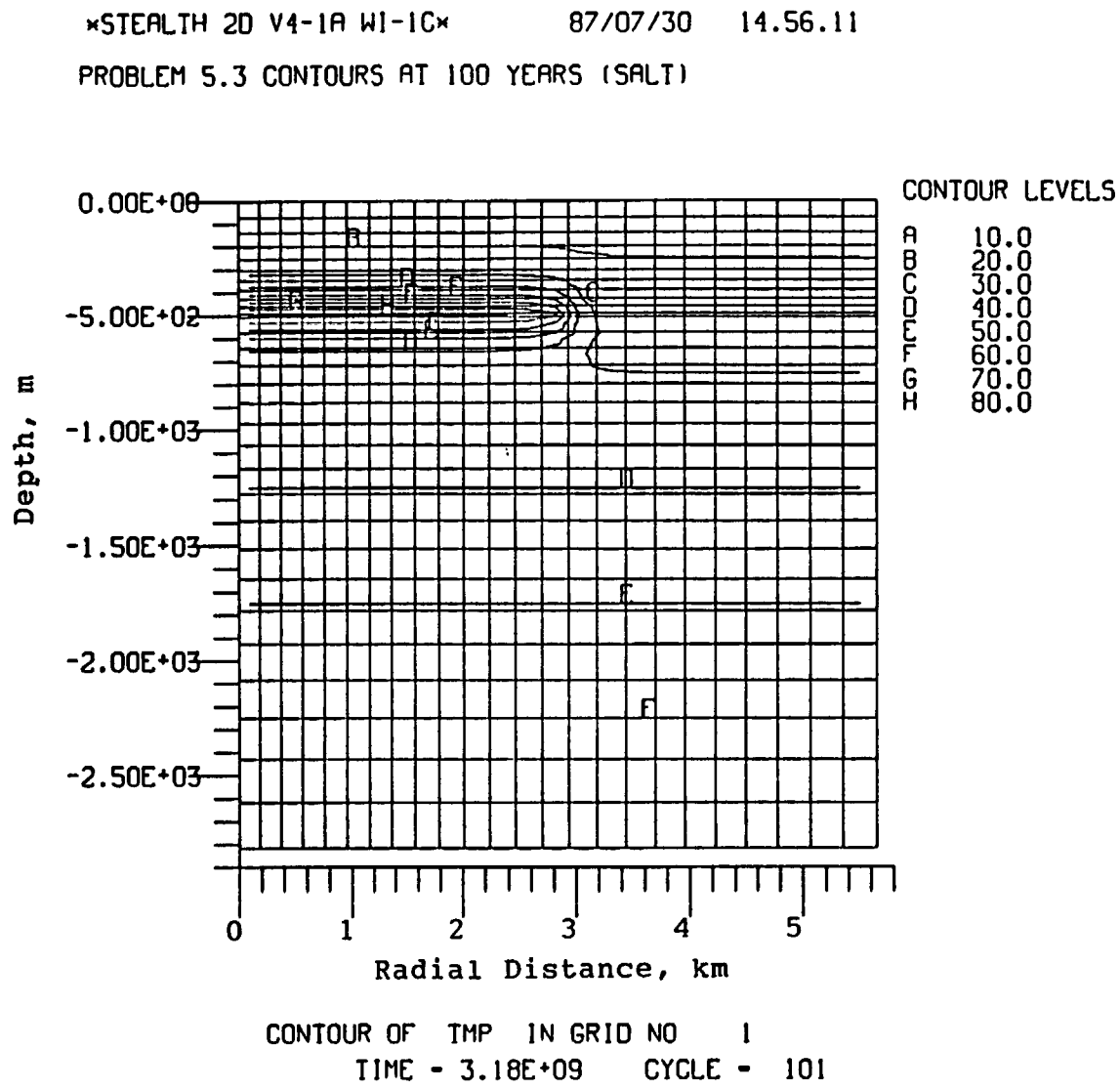


Figure 28. Temperature contours in the modeled region at 100 years.

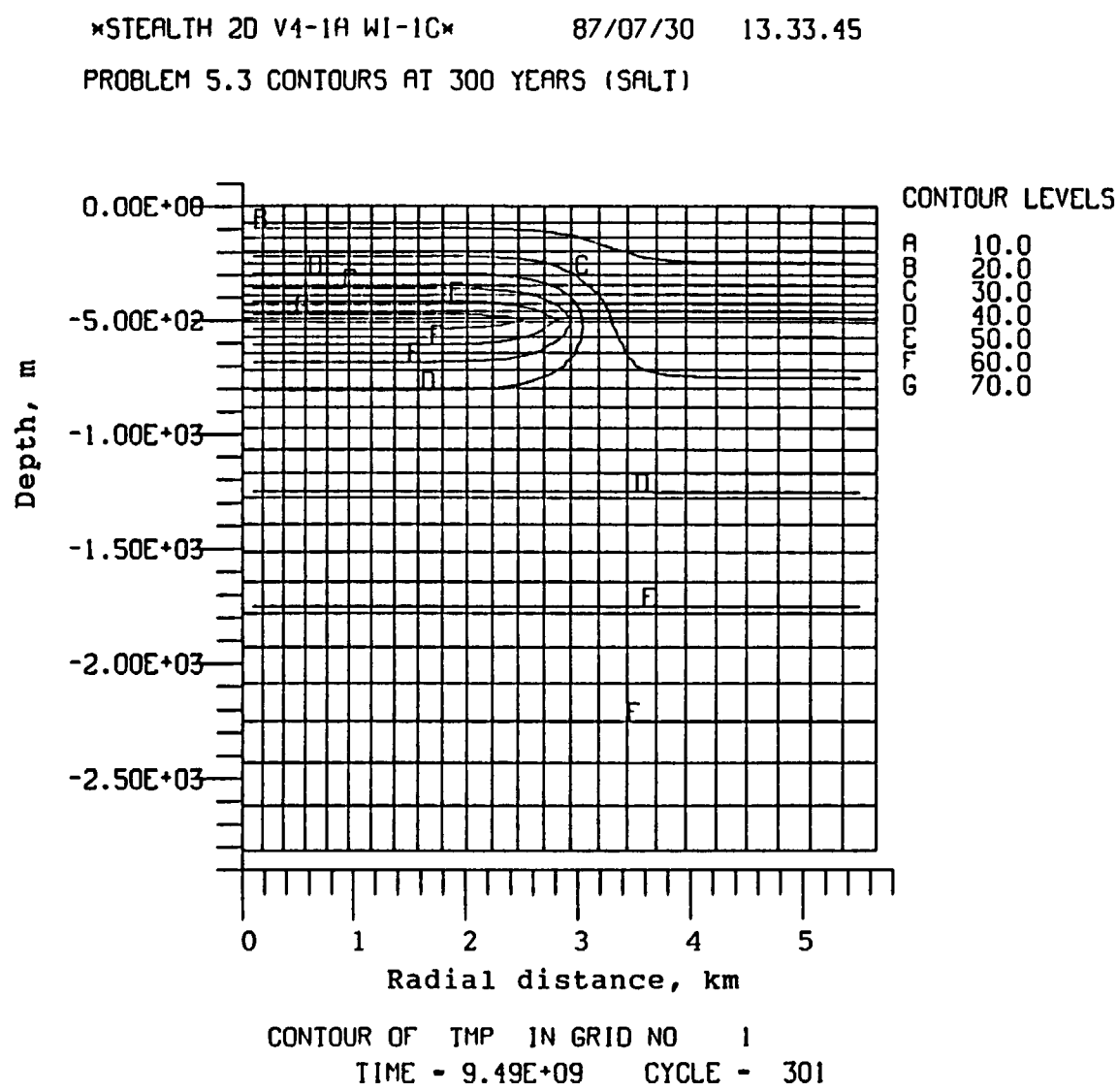


Figure 29. Temperature contours in the modeled region at 300 years.

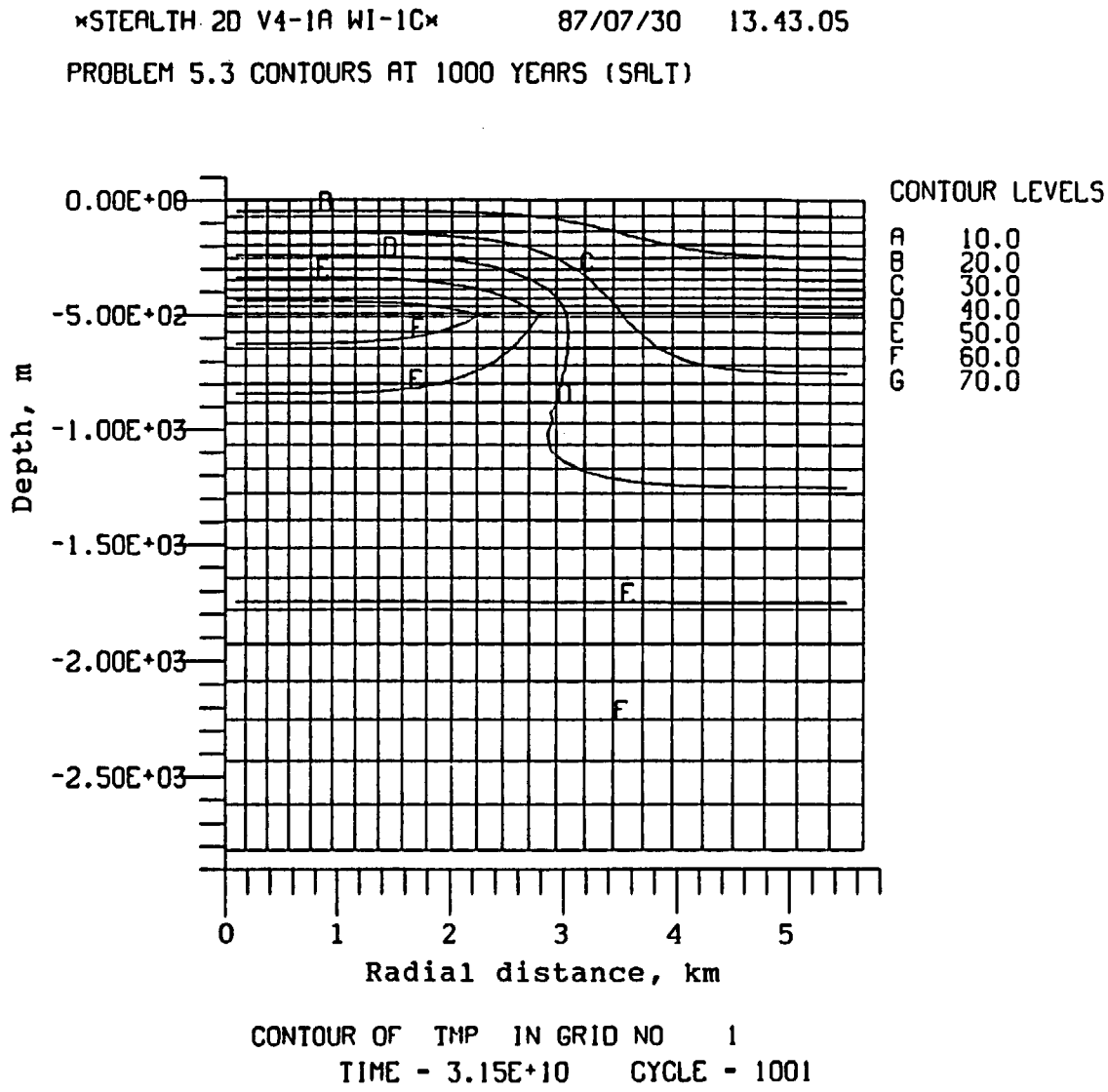


Figure 30. Temperature contours in the modeled region at 1,000 years.

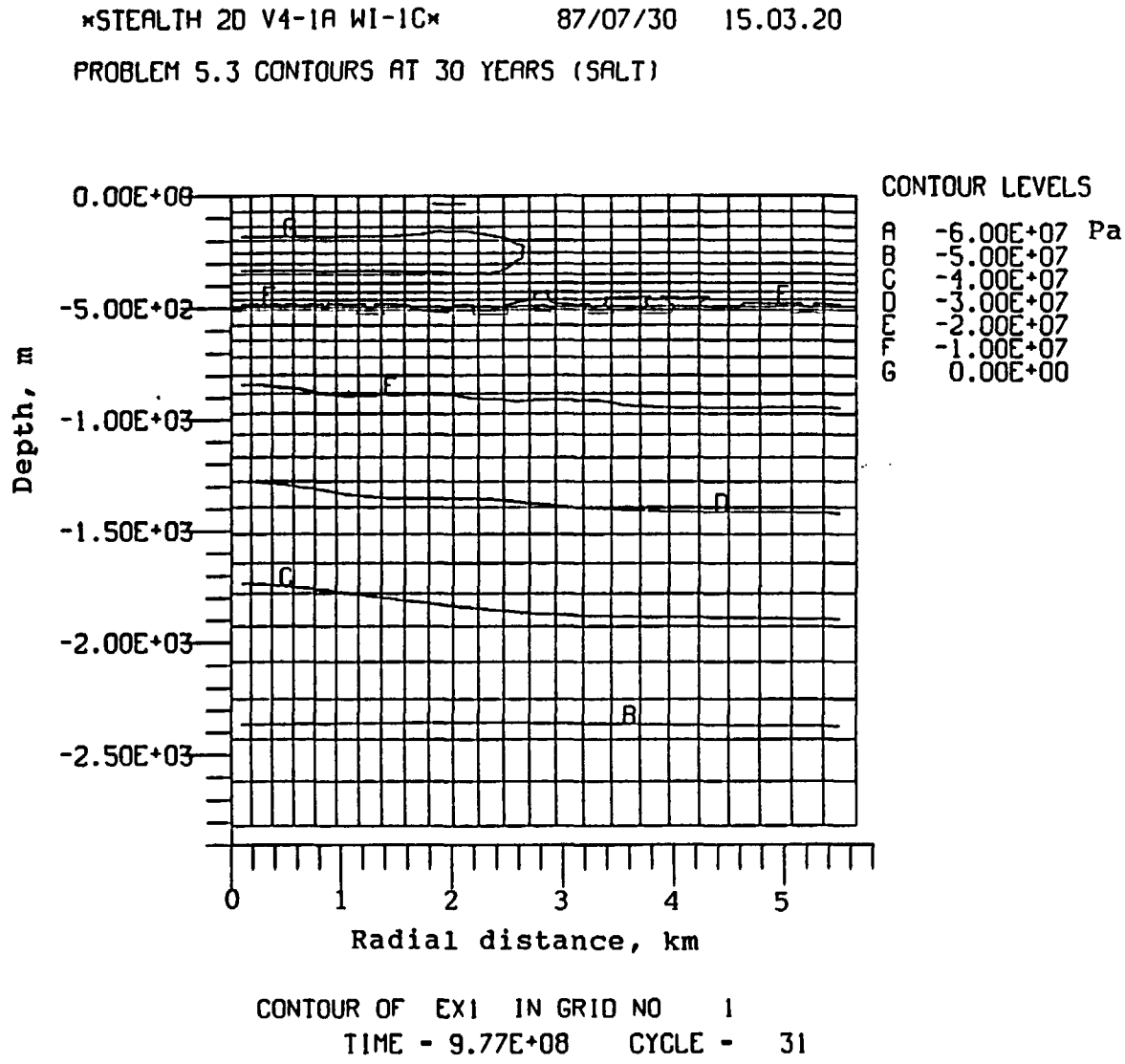


Figure 31. Contours of minimum principal stress at 30 years.

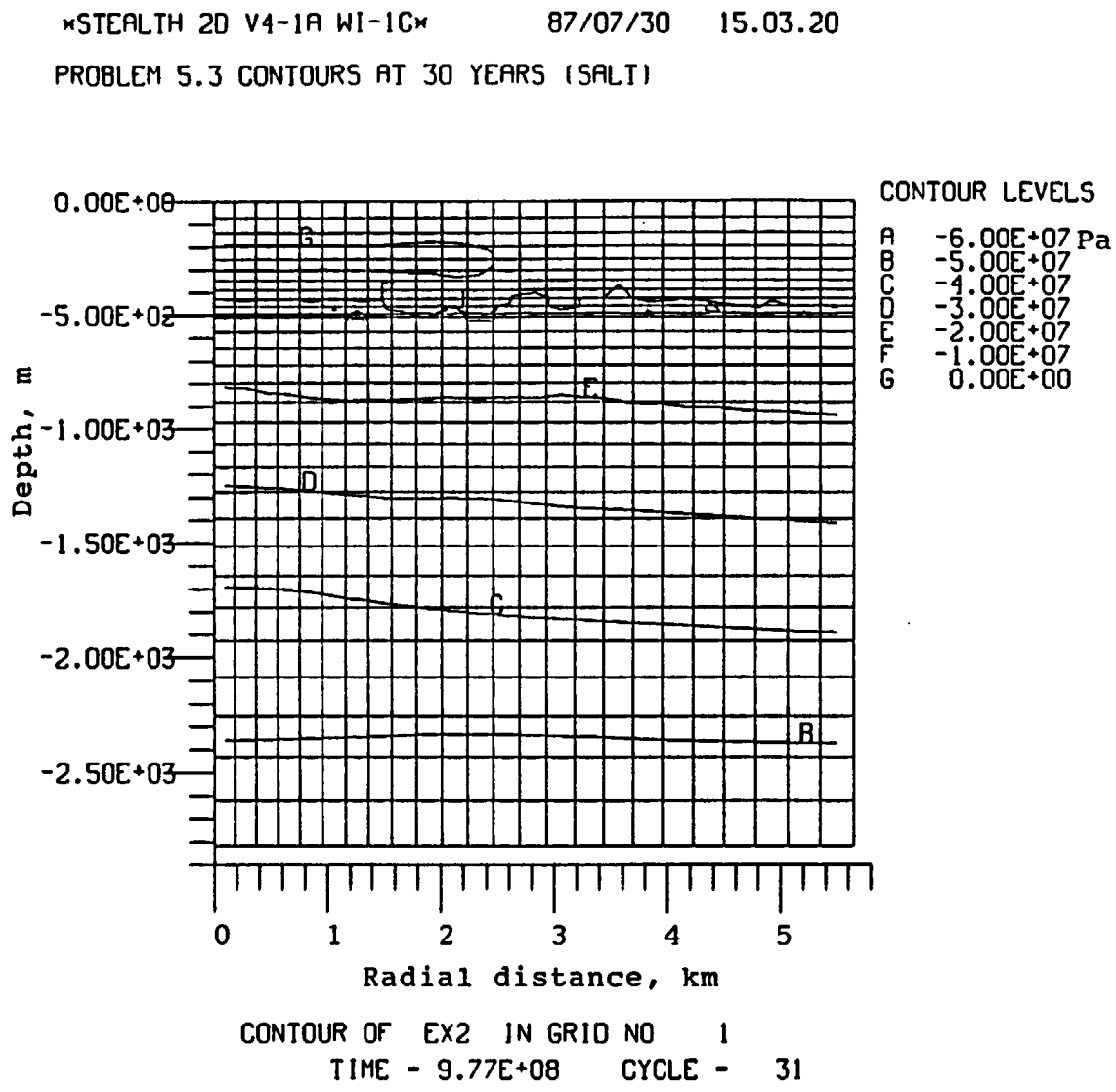


Figure 32. Contours of maximum principal stress at 30 years.

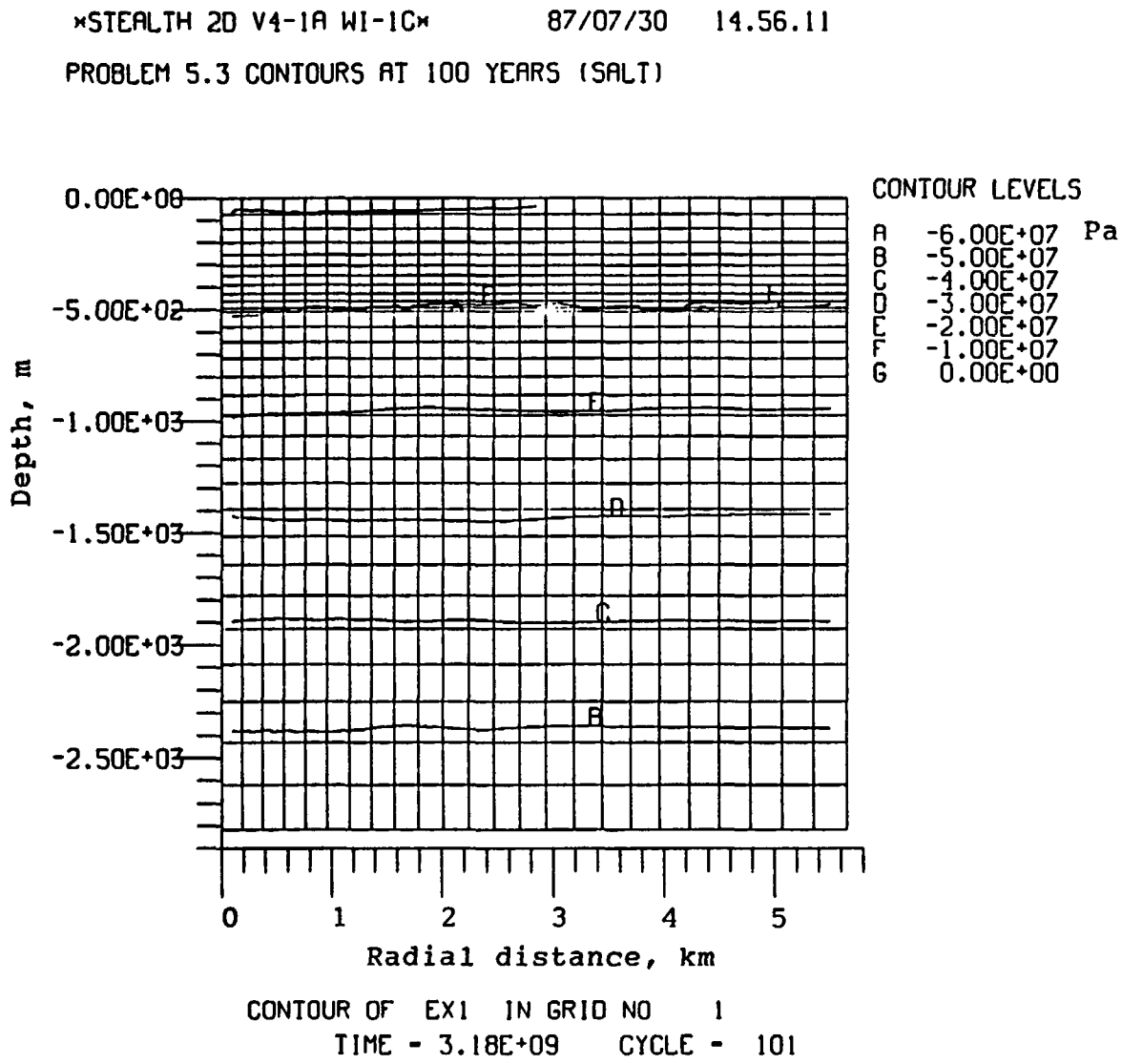


Figure 33. Contours of minimum principal stress at 100 years.

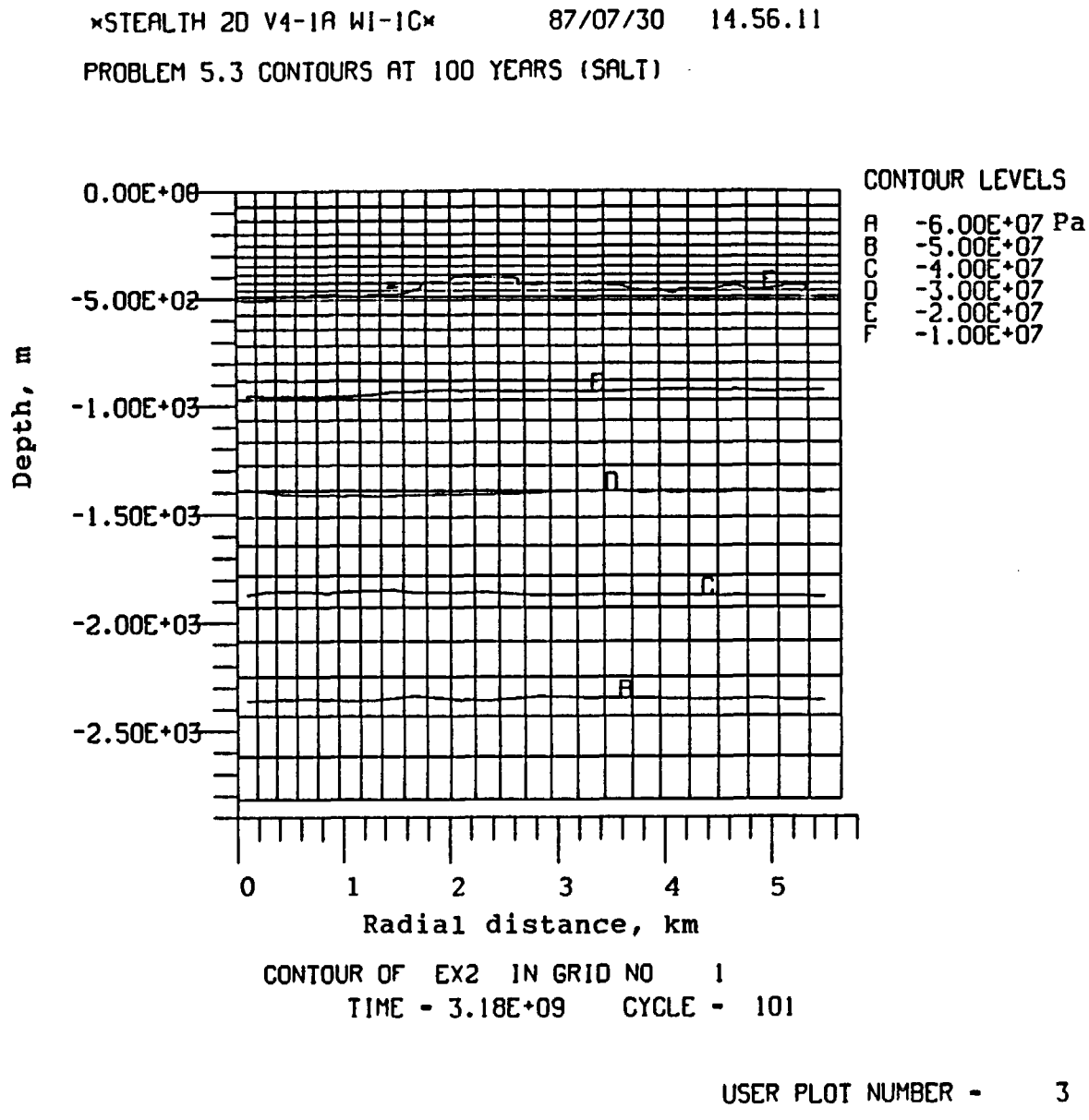


Figure 34. Contours of maximum principal stress at 100 years.

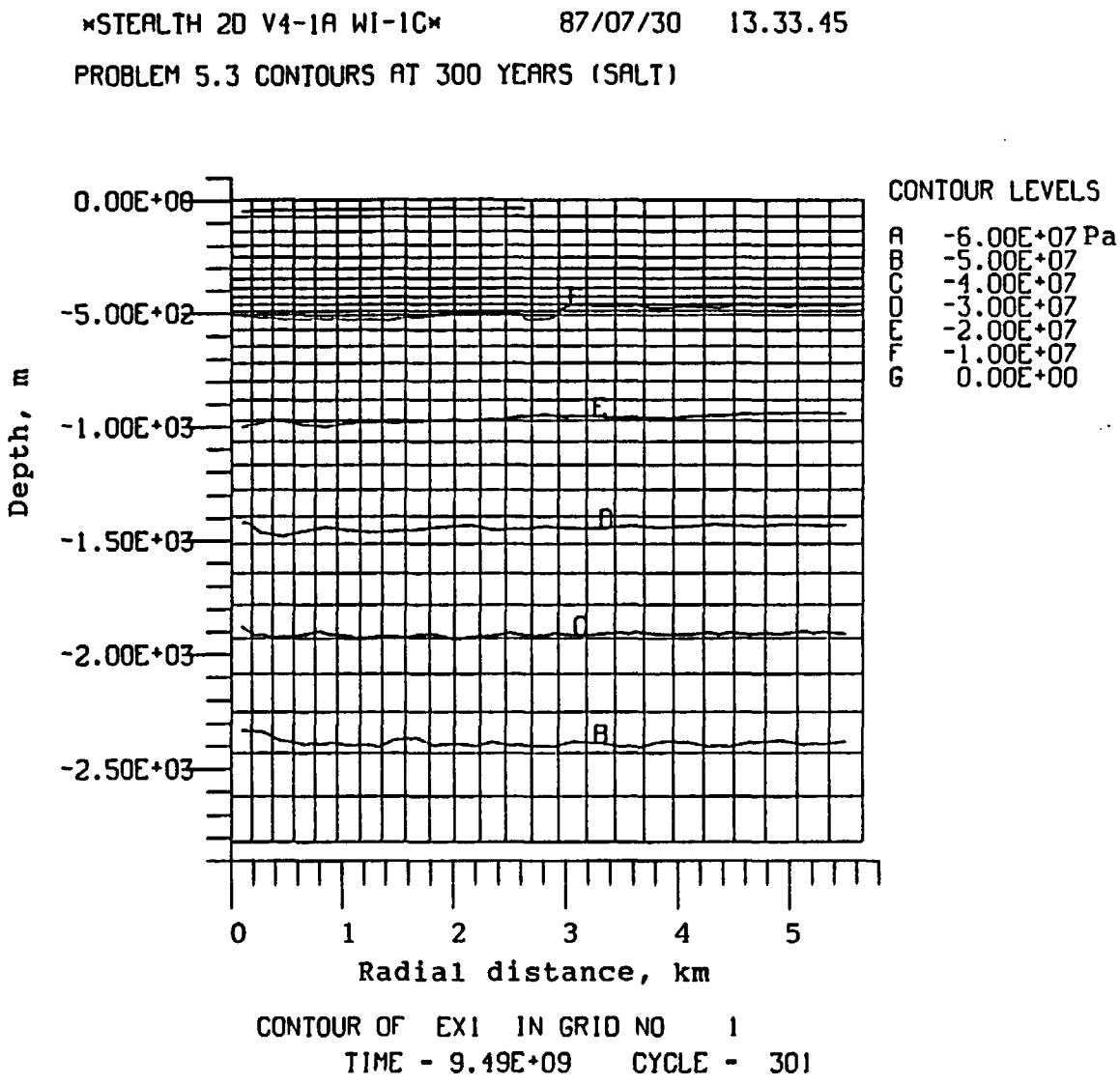


Figure 35. Contours of minimum principal stress at 300 years.

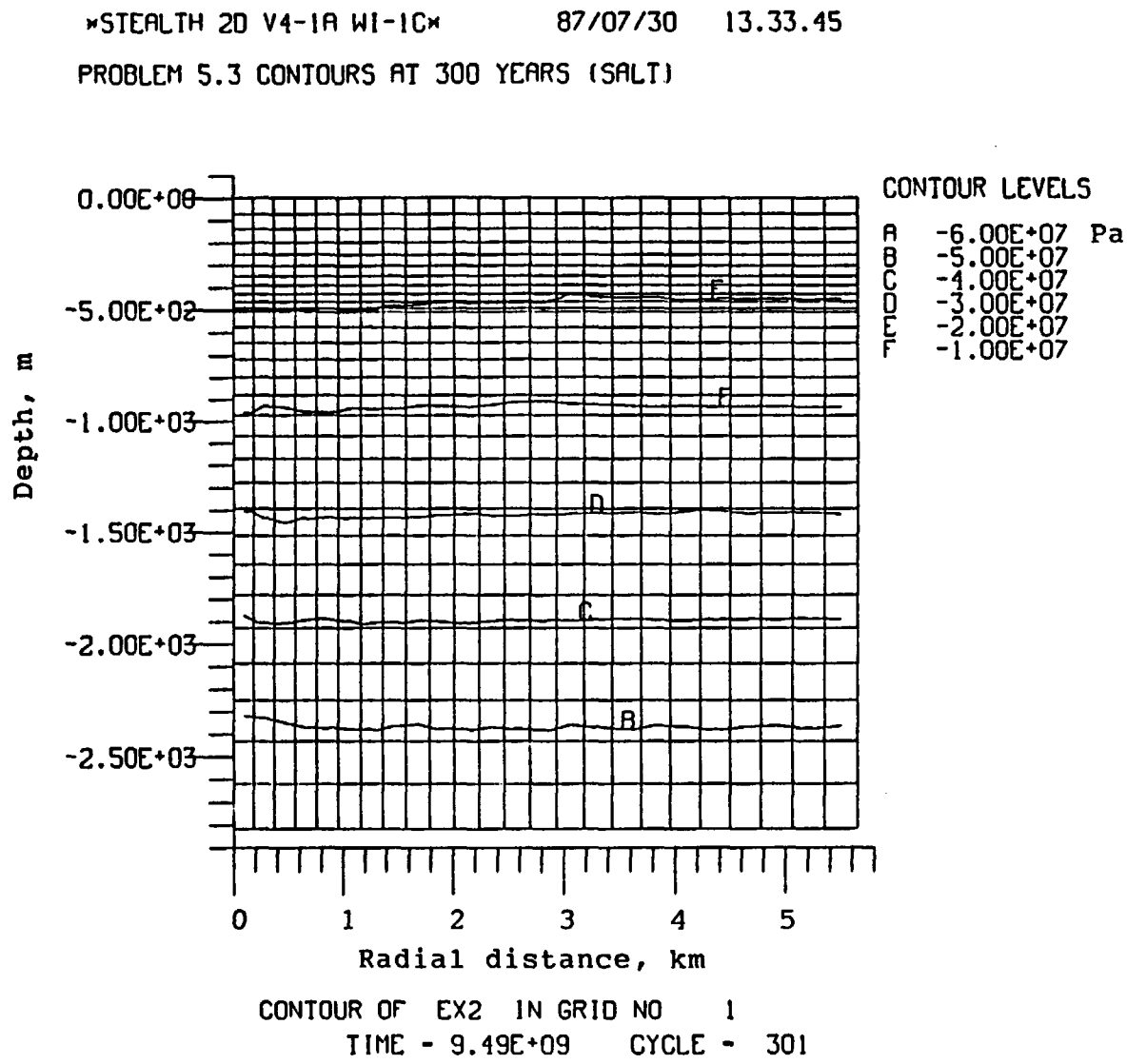


Figure 36. Contours of maximum principal stress at 300 years.

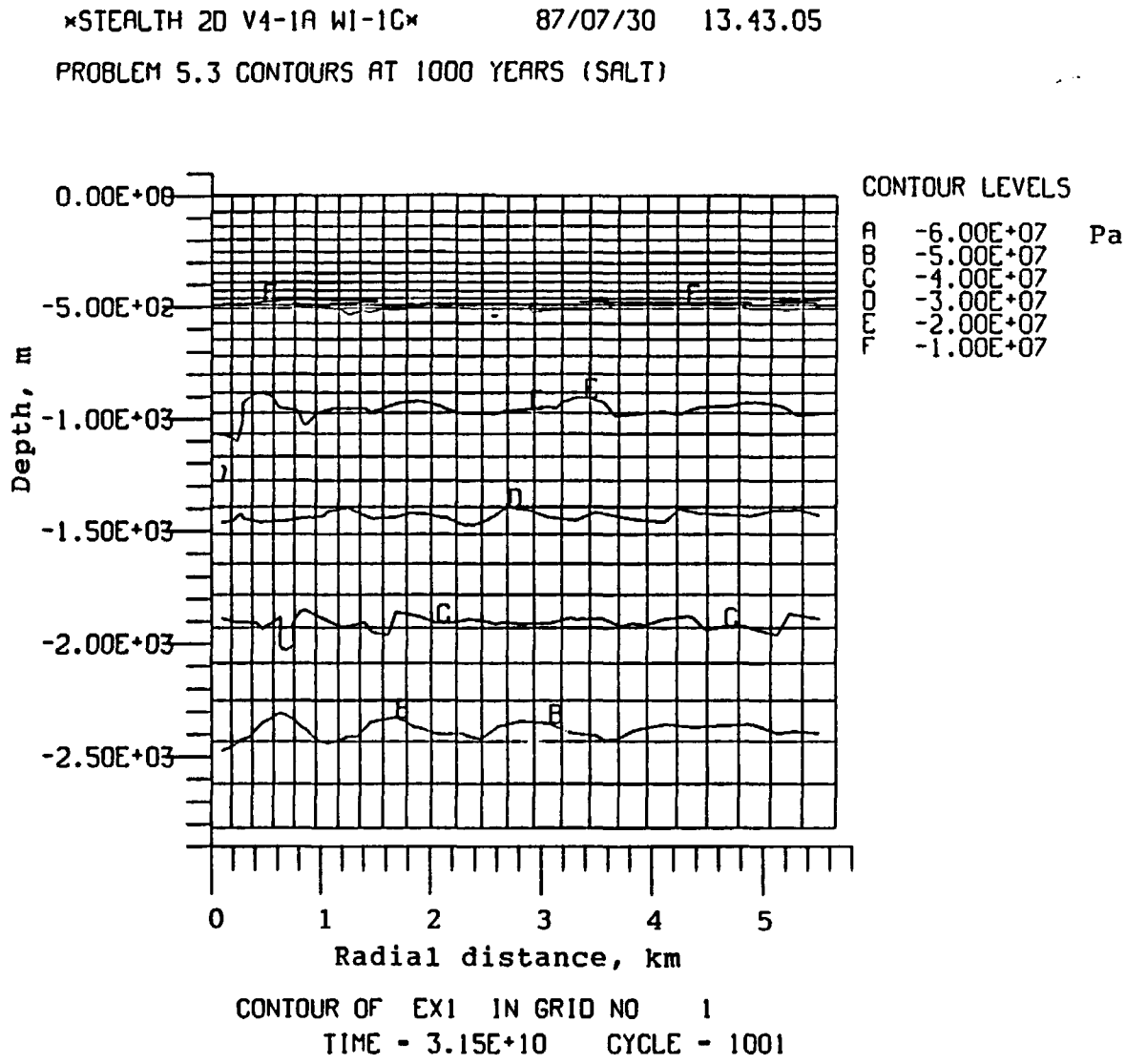


Figure 37. Contours of minimum principal stress at 1,000 years.

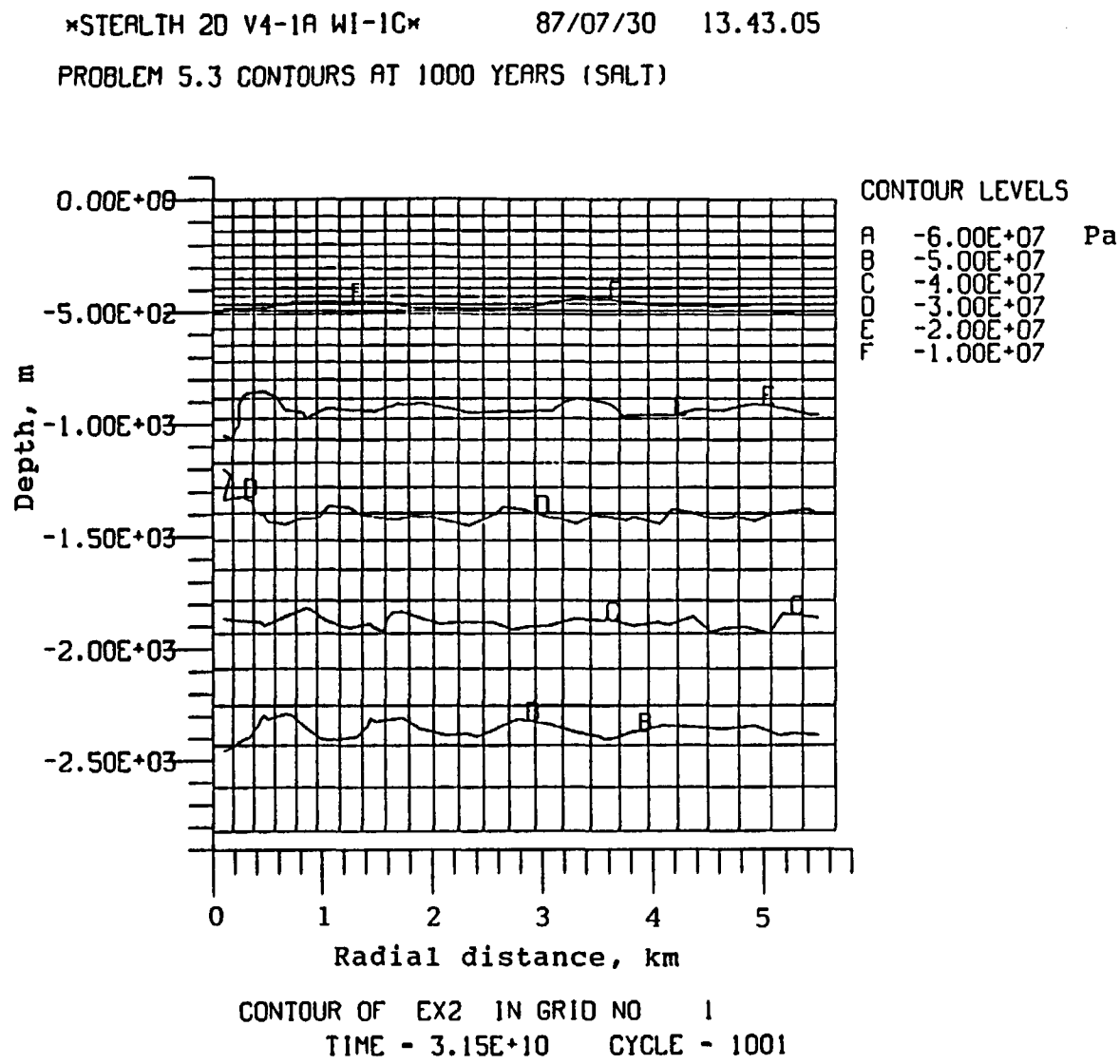


Figure 38. Contours of maximum principal stress at 1,000 years.

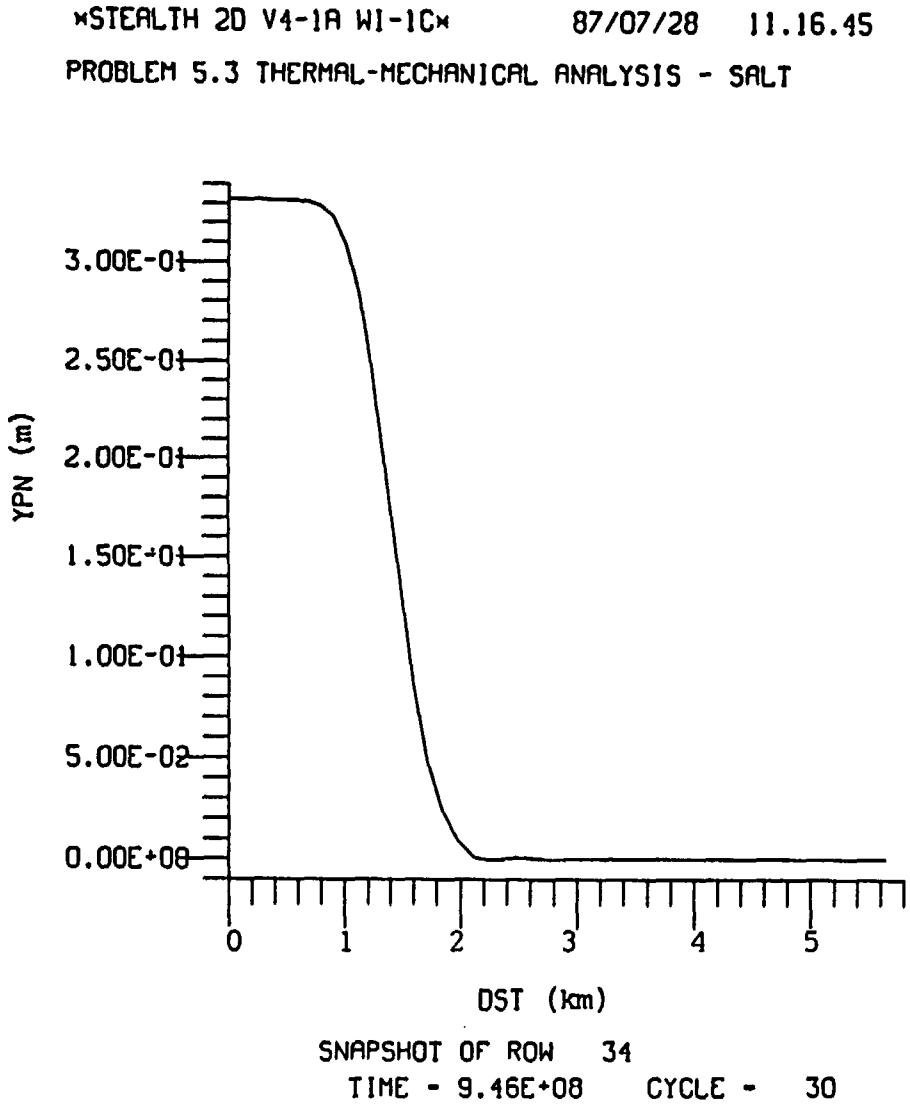


Figure 39. Ground Surface Displacement at 30 Years

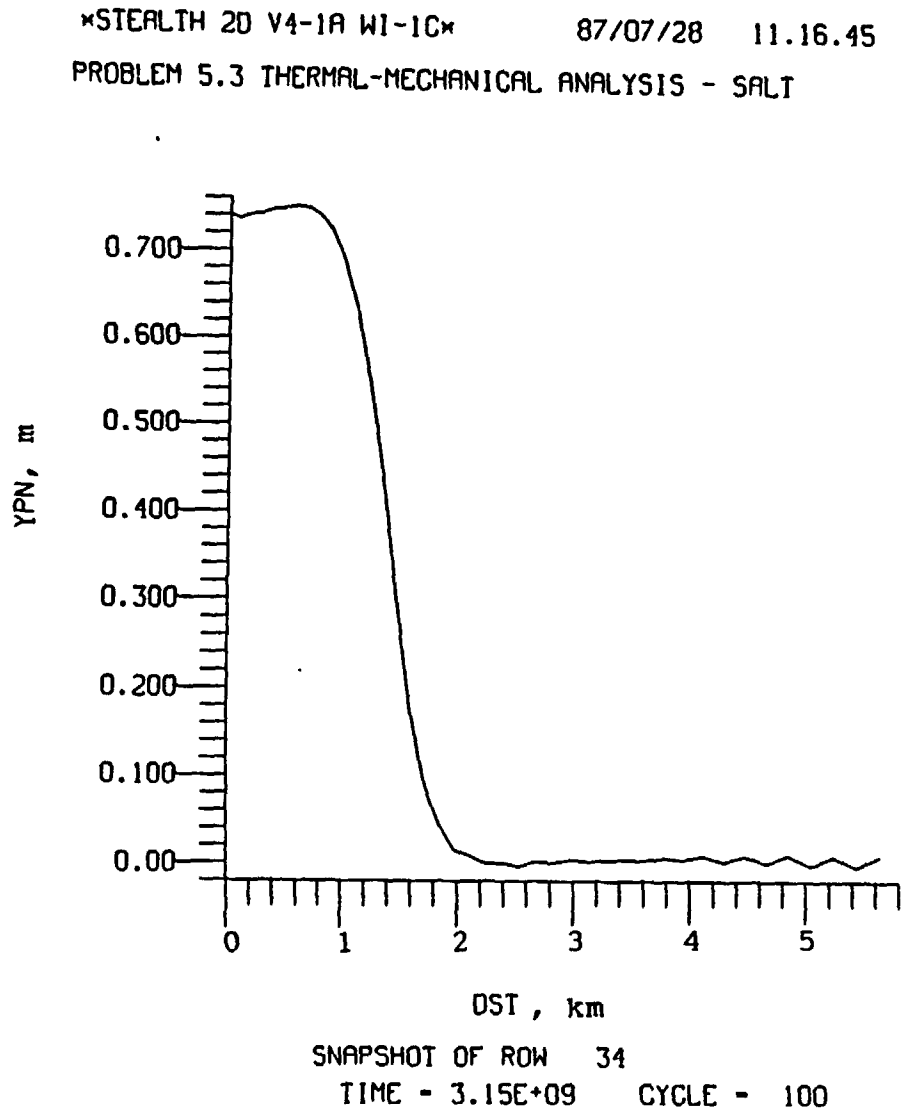


Figure 40. Ground surface displacement at 100 years.

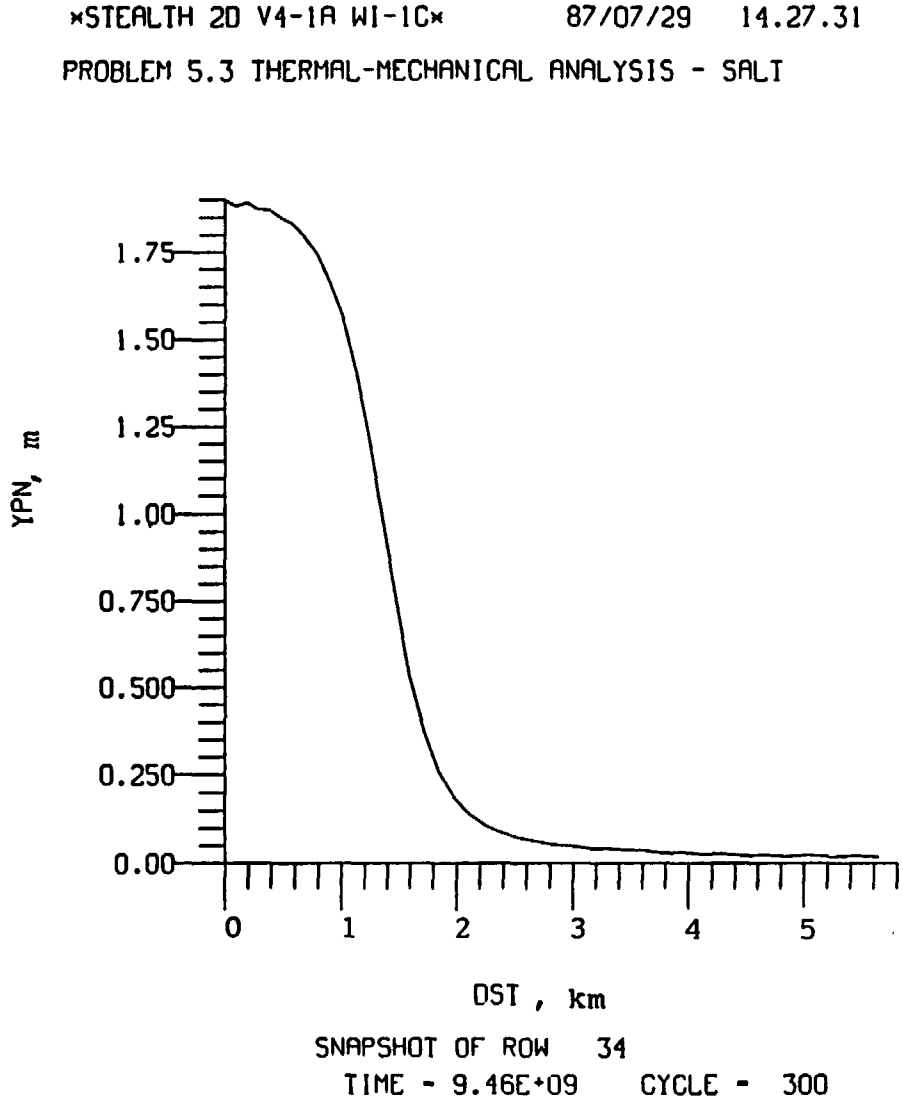


Figure 41. Ground surface displacement at 300 years.

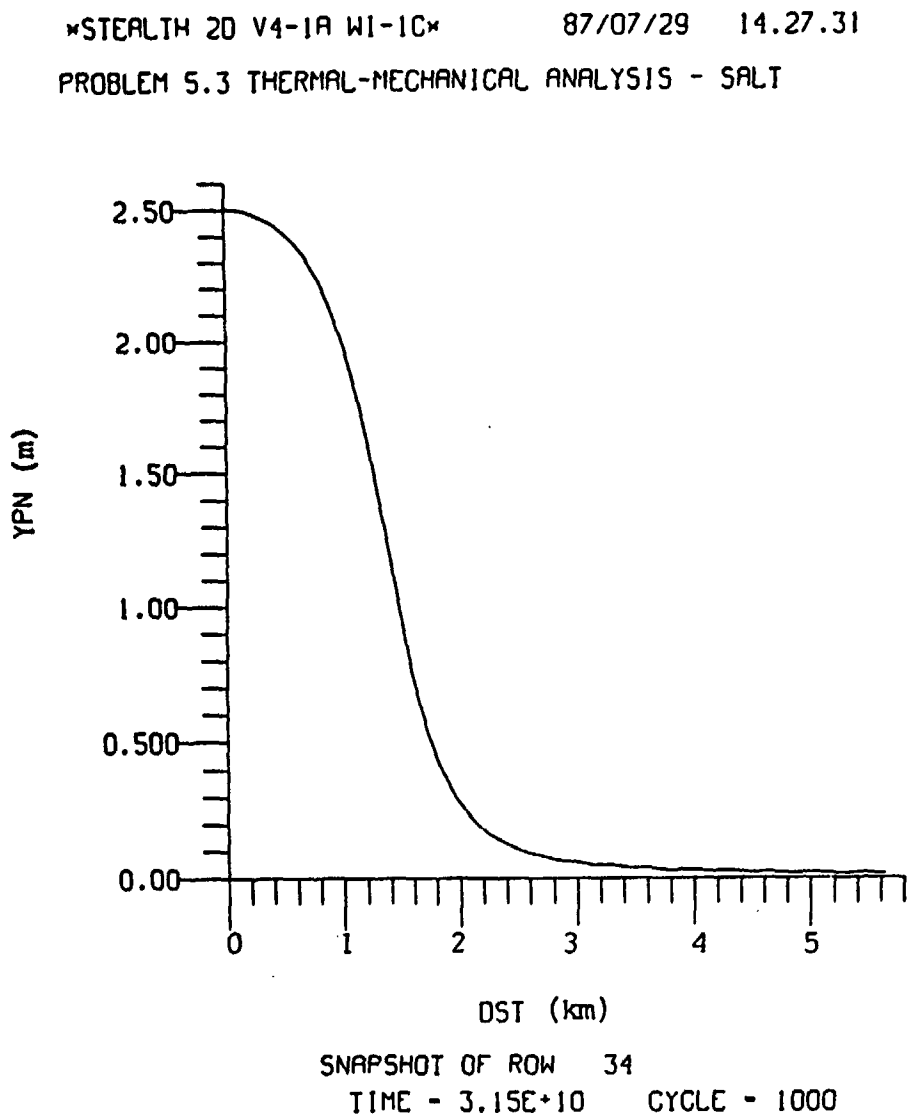


Figure 42. Ground Surface Displacement at 1000 Years

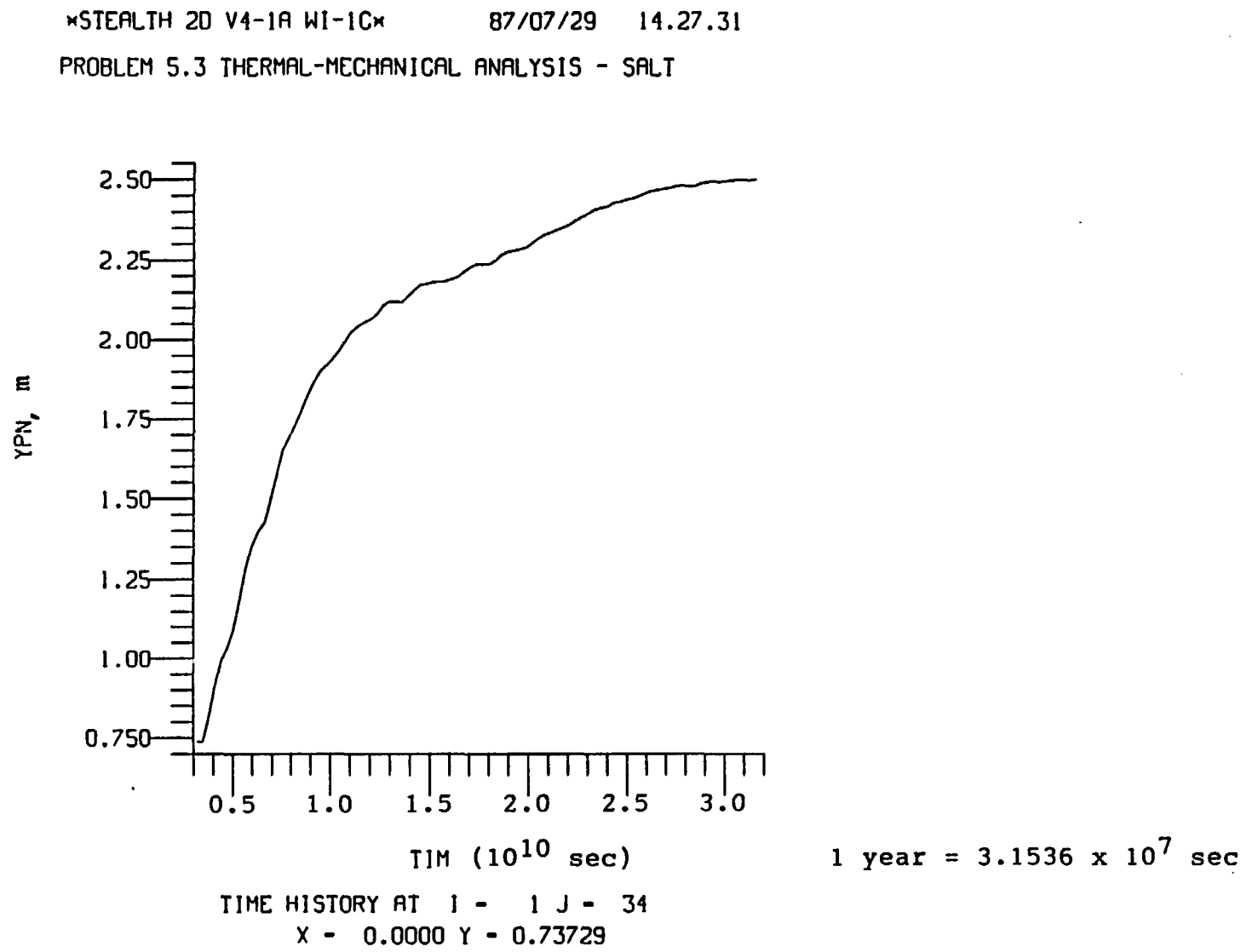


Figure 43. Displacement history of surface midpoint (100 - 1,000 years).

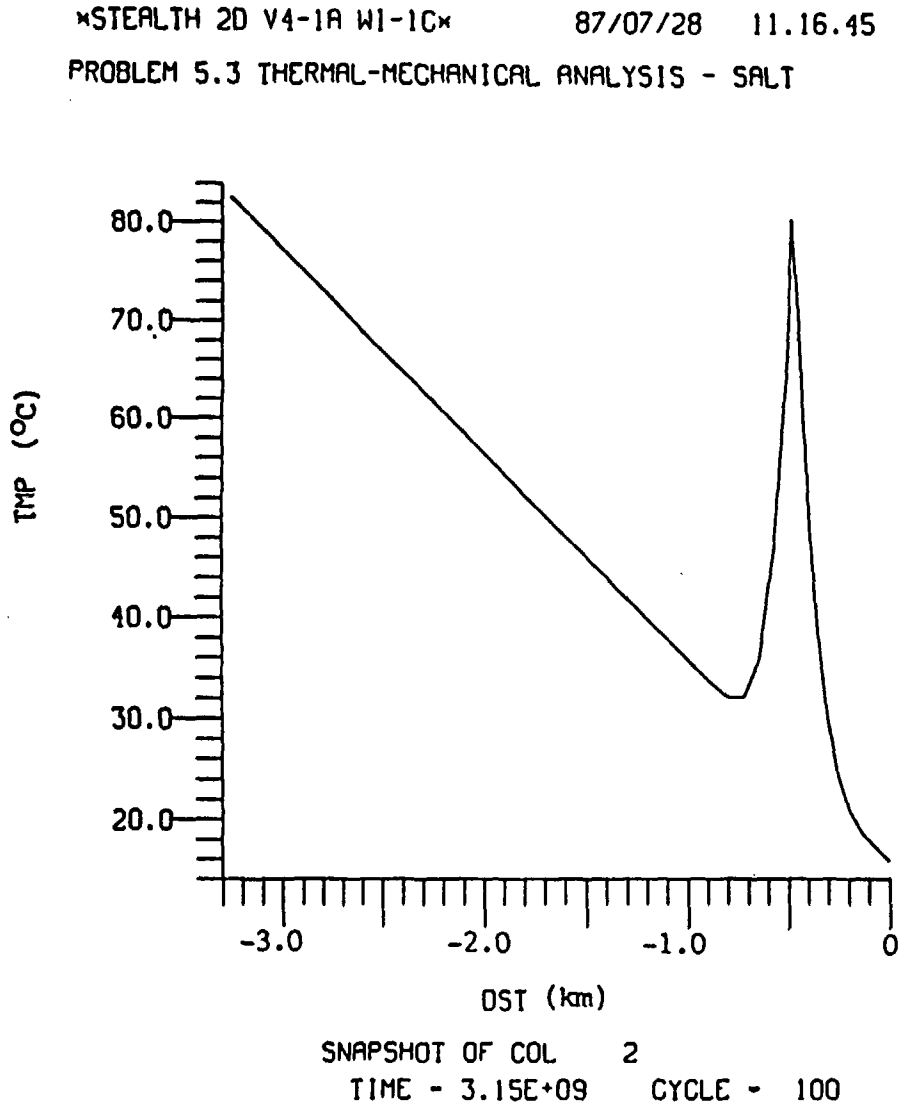


Figure 44. Temperature Distribution Along Vertical Centerline at 100 Years

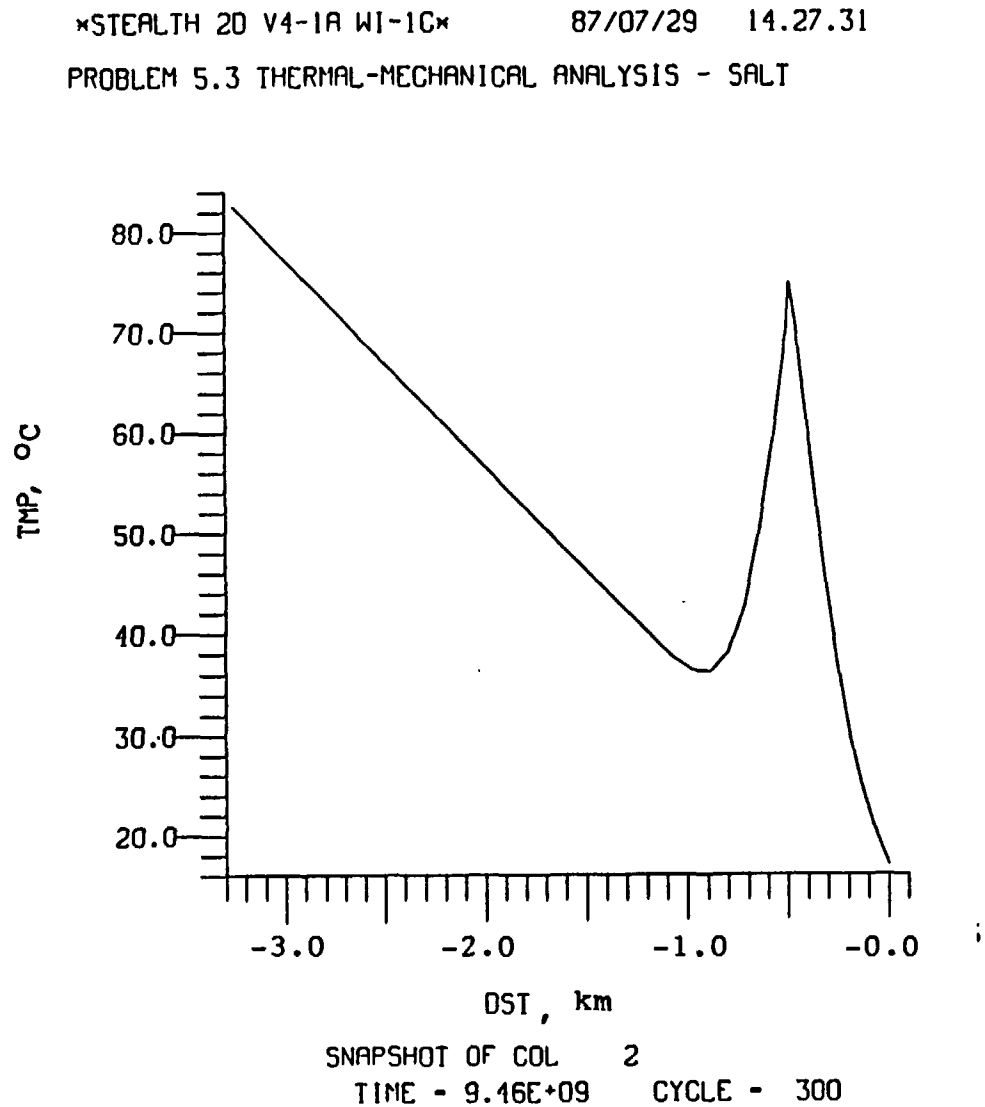


Figure 45. Temperature profile along vertical centerline at 300 years.

SECTION 6

Benchmark Problem 6.3

A prediction of the thermomechanical response of one of the two full scale heater tests (Heater Test #2) conducted at NSTF is the object of this problem. The predicted response is to be compared with field measurements of temperatures, displacements, and stresses.

An axisymmetric geometry was chosen for analyzing this problem with STEALTH 2D. The modeled region dimensions and location of the drift and heat sources were chosen as specified in Reference 2. In principle, it is possible to include a bilinear material model in STEALTH. However, a proper implementation would have required changes to many subroutines and inclusion of consistency tests. The primary reason for difficulties in implementing an apparently simple material model is related to the manner in which the stress tensor is formulated in this code. Another concern was with the lack of sufficient guidance in Reference 2 as to which component of stress to use in deciding the applicable pair of moduli. For these reasons, a single value of elastic modulus and Poisson's ratio was chosen; these were converted to a bulk modulus and shear modulus values for input to STEALTH. As in other problems, updates to the code were necessary for simulating the heater test. Specifically, updates were made to subroutines MYFNO, MYZSE, ZONSTR, EDTINP, DMPRO, GENCHK, ZONMDL, ZONZHE, ZONPRH, ZONSSS, RADLOS, and PLTTTL. These updates are listed in Table 23. Many of these updates are similar or identical to updates in some of the other problems. Updates to MYFNO define the temperature dependent heat capacity. The MYZSE updates allow a user-defined thermal load as a function of time. Another item of note is the temperature dependence of the coefficient of thermal expansion. A one-line update in ZONPRH handled this complexity. The purpose of all other updates has been stated in previous sections. In axisymmetry, it is not possible to define unequal horizontal stresses at the boundary when the axis of symmetry is a vertical line. Therefore, an average horizontal stress of 4.5 MPa was imposed at the boundary. The vertical stress on the top boundary was set to 2.0 MPa. Other boundary and initial conditions were selected as prescribed in Reference 2. The STEALTH 2D input data set for this problem is listed in Table 24 for the start run and Table 25 for the restart run. The mesh was generated with 15 I lines and 30 J lines. This gives a total of 450 nodes and 406 elements. The drift geometry was produced using point-by-point mesh generation option (Card Type 232) whereas other regions of the mesh were generated with automatic zoning options. The numerical mesh and appropriate boundary conditions in the model are shown in Figure 46. The thermal time-step size was controlled by the radius of the heater (other parameters being equal at start time). Since an opening exists in the mesh interior, it was necessary to first develop the excavation-induced state of stress. This was done in the first 200 computational cycles. The development of the excavation induced radial stress at some point above the roof is illustrated in Figure 47; the abcissa (labelled as TIM) is an indirect indicator of number of iterations. The total kinetic energy in the entire mesh reflects proximity to equilibrium. Theoretically, true

equilibrium exists when the kinetic energy is zero. Figure 48 illustrates how this energy approaches zero after first reaching a peak. The heater test begins at cycle 201 so that the reference time at cycle 200 (8.1588×10^6) should be Day 0 in the field test. A total of 1206 cycles (including 200 cycles for equilibrium) were needed to simulate 500 days of the heater test. This means the average stable time step was 0.5 day. For ease of interpretation, the chart below provides a correspondence between printout values of time in STEALTH 2D and the days from start of Heater Test #2.

Heater Test Time	STEALTH 2D time (sec.)
Day 0	8.1588×10^6
2 Days	8.3316×10^6
100 Days	1.6799×10^7
200 Days	2.5439×10^7
259 Days	3.0536×10^7
300 Days	3.4079×10^7
350 Days	3.8399×10^7
360 Days	3.9263×10^7
500 Days	5.1359×10^7

All of the output specified in Reference 2 was obtained in the form of plots. Figure 49 presents the radial temperature distribution at 2.5 days in a horizontal section at a nominal depth of 4.5m. The vertical temperature profiles at 259 days at radii of 0.4m and 0.71m are shown in Figures 50 and 51, respectively. The radial temperature profiles at a depth of about 4.25m at 350 days is shown in Figure 52, and at 360 days is shown in Figure 53. The temperature history at heater midplane and 0.4m radius is given by Figure 54. The horizontal displacement history at a depth of 1.91m and radius of 1.77m is plotted in Figure 55. Histories of vertical displacement at a radius of 1.24m and depths of 3.7m, 4.6m and 5.5m are shown in Figures 56 through 58. Profiles of radial temperature distribution at heater midheight at 100, 200, and 300 days are included as Figures 59, 60, and 61. Profiles of major principal stress distribution at that location and those times are presented in Figures 62, 63, and 64. The minor principal stress profiles at heater midheight at the same times are given in Figures 65, 66 and 67. The computer generated profiles of displacement at heater midheight had poor resolution due to the initial non-alignment of nodes near that depth (see Figure 24) and due to very small absolute displacement. Hand-plotted profiles of vertical displacement <u>near</u> heater midheight at 100, 200, and 300 days are shown in Figure 68.

TABLE 23
Fortran Updates to STEALTH 2D for Problem 6.3

```
*ID PRB63BS
*C STEALTH
*D MYFNO.27,28
      VAL = FCA(4) * ( FCA(1) + FCA(2)*(VAR+273.) +
     1                 FCA(3)/(VAR+273.)**2 )
*I MYZSE.17
*CALL ZONVAR
*CALL TIMVAR
      DIMENSION WATS(3), DAYS(3)
C
C       ** HEATER VOLUME IS PI*R*R*H = 0.49087 CU. METER **
C           ** 1kW IS EQV. TO 2037.2 W/m**3  **
C
      DATA WATS / 2037.2, 6111.5, 10185.9 /
      DATA DAYS / 90., 226., 527. /
      DATA TREF / 1.0E8 /
*D MYZSE.22,23
      TDAY = (TIMN - TREF)/ 8.64E4
      POWER = 0.0
      IF(TDAY .LE. 0.0) GO TO 10
      IF(TDAY .LE. DAYS(1) ) POWER = WATS(1)
      IF(TDAY .GT. DAYS(1) ) POWER = WATS(2)
      IF(TDAY .GT. DAYS(2) ) POWER = WATS(3)
      IF(TDAY .GT. DAYS(3) ) POWER = 0.0
   10 ZSEN = POWER*DLTH + ZSEO
*I ZONSTR.42
C     ** DEFINE TOTAL STRESSES **
      SSUM = TXXN + TYYN
      SDIF = TXXN - TYYN
C       ** DEFINE PRINCIPAL STRESSES IN THE X-Y PLANE **
      SIG1 = SSUM/2. + SQRT(SDIF**2/4. + SXYN**2)
      SIG2 = SSUM/2. - SQRT(SDIF**2/4. + SXYN**2)
      SIG3 = TZZN
      PANG = 0.
      IF(SDIF .EQ. 0. .AND. SXYN .EQ. 0.)GO TO 71
C     ** PANG IS THE PRINCIPAL STRESS ORIENTATION IN DEG. **
      PANG = 28.6364 * ATAN2(2.*SXYN, SDIF)
   71 CONTINUE
      EX1N = AMAX1(SIG1,SIG2,SIG3)
      EX2N = AMIN1(SIG1,SIG2,SIG3)
      EX3N = PANG
*D FDTINP.547
C
C       ** RECORD #664 DEFINES A SUB-GRID FOR PLOTTING **
C
  640 MINIPL = IFIX(DTAFLD(1) + .1)
      MAXIPL = IFIX(DTAFLD(2) + .1)
      IF (MINIPL .GE. 1 .AND. MINIPL .LE. MAXGPT) GO TO 641
      CALL RGEERR(INPTYP,1,1,MAXGPT,MINIPL)
  641 IF (MAXIPL .GE. 1 .AND. MAXIPL .LE. MAXGPT) GO TO 642
      CALL RGEERR(INPTYP,2,1,MAXGPT,MAXIPL)
  642 IF(MINIPL .LE. MAXIPL) GO TO 643
      CALL LIMERR(INPTYP,MINIPL,MAXIPL,1,2)
  643 LMIN = 3
```

continued

TABLE 23
continued

```
      IF(NSPRO .EQ. 1 .OR. NSPRO .EQ. 11) GO TO 950
C
      MINJPL = IFIX(DTAFLD(3) + .1)
      MAXJPL = IFIX(DTAFLD(4) + .1)
      IF (MINJPL .GE. 1 .AND. MINJPL .LE. MAXROW) GO TO 644
      CALL RGEERR(INPTYP,1,1,MAXROW,MINJPL)
  644 IF (MAXJPL .GE. 1 .AND. MAXJPL .LE. MAXROW) GO TO 645
      CALL RGEERR(INPTYP,2,1,MAXROW,MAXJPL)
  645 IF(MINJPL .LE. MAXJPL) GO TO 646
      CALL LIMERR(INPTYP,MINJPL,MAXJPL,1,2)
  646 LMIN = 5
      GO TO 950
*I DMPPRO.24
      RETURN
*I GENCHK2.269
      TMPN = 17.00
      TXXN = -4.5E6
      TYYN = -2.0E6
      TZZN = TXXN
      IF(MPNO .EQ. 2) TXXN = 0.0
      IF(MPNO .EQ. 2) TYYN = 0.0
      IF(MPNO .EQ. 2) TZZN = 0.0
      PRHN = - (TXXN+TYYN+TZZN) / 3.
      TXX(I,JT) = TXXN
      TYY(I,JT) = TYYN
      TZZ(I,JT) = TZZN
*D GENCHK2.342,344
      TMPO = TMPN
*I ZONMDL.116
C
C       ** SET STRESSES TO ZERO IN AIR ZONES **
      IF(MPNN .NE. 2) GO TO 950
      PRHN = PRHO
      TXXN = TXXO
      TYYN = TYYO
      TZZN = TZZO
      TXYN = TXYO
      SXXN = SXXO
      SYYN = SYYO
      SZZN = SZZO
      SXYN = SXYO
      EX1N = EX1O
      EX2N = EX2O
      EX3N = EX3O
      EX4N = EX4O
  950 CONTINUE
*I ZONZHE2.57
      DATA  HCONV, TAMB / 1.00 , 17.00 /
C
*I ZONZHE2.67
      DO 5 LL = 1,NUMRM
      IF(MPNN .EQ. MPNRM(LL)) TMPO = TAMB
    5 CONTINUE
```

continued

TABLE 23
concluded

```
C
*D ZONZHE2.299
      IF(MPNN .EQ. MPNRM(LL) .AND. MPN(IC,JT) .NE. MPNRM(LL))
     1   GO TO 564
      IF(MPN(IC,JT) .EQ. MPNRM(LL)) GO TO 563
      GO TO 561
  563 DELY = (YPNOTL + YPNOTR)/2. - YCEN
      TSURF = (HCONV*TAMB + CONO*TMPO/DELY)/(HCONV+CONO/DELY)
      HTFHT = - HCONV * WOTOP * (TSURF-TAMB)
      GO TO 561
  564 DELY = YCENT - (YPNOTL+YPNOTR)/2.
      TSURF = (HCONV*TAMB + CONOT*TMPOT/DELY)/(HCONV+CONOT/DELY)
      HTFHT = - HCONV * WOTOP * (TAMB-TSURF)
  561 CONTINUE
C
*D ZONZHE2.348
      IF(MPNN .EQ. MPNRM(LL) .AND. MPN(IR,JC) .NE. MPNRM(LL))
     1  GO TO 583
      GO TO 582
  583 DELX = XCENR - (XPNOTR+XPNOBR)/2.
      TSURF = (HCONV*TAMB + CONOR*TMPOR/DELX)/(HCONV+CONOR/DELX)
      HTFHR = - HCONV * WORHT * (TAMB-TSURF)
  582 CONTINUE
*I ZONZHE2.369
      DO 769 LL = 1,NUMRM
      IF(MPNN .EQ. MPNRM(LL)) DLZHEH = ZER
  769 CONTINUE
*D ZONPRH.76,78
*D ZONPRH.84,85
      PRHRLV = EOS2 * (1./RLVN - 1./RLVO) + PRHO
      DTHETA = (ZHEN-ZHEO+ZSEN-ZSEO) / SHCO
      THETA = TMPO + DTHETA
C      ** TEMP. DEPENDENT ALPHA FOR BASALT **
      ALPHA = EOS8 + EOS9*THETA
      PRHZIE = THR * EOS2 * ALPHA * DTHETA
C     FROM A FUNCTION OF RELATIVE VOLUME (THERMOMECHANICAL)
*D ZONSSS.87,97
      SSSPRH = VAL
*I RADLOS.114
      IF(ABS(TMPS(II,LL)-TMPV(II,LL)).LT. 1.E-8)
     1     QAVRG(II,LL) = ZER
*I RADLOS.139
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*I RADLOS.160
      TMP(II+1,JC) = TMP(II+1,JC) + ENRDEN/SHC(II+1,JC)
*I RADLOS.180
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*I RADLOS.199
      TMP(II,JC) = TMP(II,JC) + ENRDEN/SHC(II,JC)
*D PLTTTL.53
   30 CALL PLTLBL(NPLT,MAXCDN,1,0.0,0.18,0.98,HGT,WID,0.0,CDN)
```

TABLE 24

STEALTH 2D Input Data Set for Problem 6.3 (Start Run)

```
TTL       PROBLEM 6.3 - Heater Test #2 - NSTF
PRB                                                   1.
PRO       2.0
DTS       4.0       1.
SYM       2.
GRD       1.        1.        15.       30.
END
MAT                                                   1.
111 BASALT1.0       3.0
112       1.0       2.0       2.0       2.0
114       1.0       3.0       3.0
121       1.0       2850.0
122       1.        1.        0.         2.5000E10
123       1.        -0.5      2.        1.             4.9E-6    6.1E-9
132       1.0        2.7713E08
134       1.0        1.1538E10
136       1.0        -1.0 E+12
152       1.0       1.0       1.53      0.001
154       1.0       9.0       1280.     -0.108       -4.80E7 2850.
111 AIR   2.0       1.0
112       2.0       1.        1.        2.
114       2.0       2.        2.
121       2.0       0.83
122       2.        1.        0.        1.0000E+06
136       2.          -1.0E+12
152       2.0       0.035
154       2.0       35.0
111 sourc 3.0       3.0
112       3.0       2.0       2.0       2.0
114       3.0       3.0       3.0       6.0
121       3.0       2850.0
122       3.        1.        0.         2.5000E10
123       3.        -0.5      2.        1.             4.9E-6    6.1E-9
132       3.0        2.7713E08
134       3.0        1.1538E10
136       3.0        -1.0 E+12
152       3.0       1.0       1.53      0.001
154       3.0       9.0       1280.     -0.108       -4.80E7 2850.
156       3.0       0.
END
GPT                                       2.        1.
211       1.        1.        1.        0.        -20.0
212       1.        0.        12.       2.
212       2.        0.        -20.      1.
212       3.        12.       -20.      3.
221       1.        1.        2.        1.        11.
221       2.        2.        3.        1.        11.
221       3.        3.        4.        1.        11.
221       4.        4.        15.       1.        11.
221       5.        1.        3.        12.       17.
221       6.        4.        15.       11.       14.
221       7.        4.        15.       14.       18.
221       8.        1.        9.        18.       24.
```

continued

TABLE 24
continued

221	9.	10.	15.	18.	30.		
221	10.	1.	7.	25.	30.		
221	11.	7.	10.	25.	30.		
221	12.	5.	7.	11.	16.		
247	1.	0.	0.25	-20.	14.5	1.	0.95
247	2.	0.25	0.30	-20.	14.5	1.	0.95
247	3.	0.55	0.32	-20.	14.5	1.	0.95
247	4.	0.87	9.13	-20.	14.5	1.05	0.95
247	6.	0.87	9.13	-5.5	2.5	1.05	1.0
247	7.	0.87	9.13	-3.0	3.0	1.05	1.0
247	9.	4.75	5.25	0.0	10.	1.05	1.0
247	10.	0.0	2.40	6.5	3.5	1.0	1.0
247	11.	2.3	2.45	5.9	4.156	1.0	1.0
257	10.	104.	85.5	-14.	4.156	1.0	
257	11.	80.5	90.	0.	4.1	1.0	
232	5.	1.	12.	0.	-4.66667		
232	5.	1.	13.	0.	-3.83333		
232	5.	1.	14.	0.	-3.0		
232	5.	1.	15.	0.	-2.25		
232	5.	1.	16.	0.	-1.50		
232	5.	1.	17.	0.	-0.75		
232	5.	2.	12.	0.25	-4.66667		
232	5.	2.	13.	0.25	-3.83333		
232	5.	2.	14.	0.25	-3.0		
232	5.	2.	15.	0.25	-2.25		
232	5.	2.	16.	0.25	-1.50		
232	5.	2.	17.	0.25	-0.75		
232	5.	3.	12.	0.55	-4.66667		
232	5.	3.	13.	0.55	-3.83333		
232	5.	3.	14.	0.55	-3.0		
232	5.	3.	15.	0.55	-2.25		
232	5.	3.	16.	0.55	-1.50		
232	5.	3.	17.	0.55	-0.75		
232	8.	1.	18.	0.	0.		
232	8.	1.	19.	0.	0.80		
232	8.	1.	20.	0.	1.70		
232	8.	1.	21.	0.	2.70		
232	8.	1.	22.	0.	4.00		
232	8.	1.	23.	0.	5.10		
232	8.	1.	24.	0.	5.72		
232	8.	2.	18.	0.25	0.		
232	8.	2.	19.	0.25	0.80		
232	8.	2.	20.	0.25	1.70		
232	8.	2.	21.	0.25	2.70		
232	8.	2.	22.	0.30	3.95		
232	8.	2.	23.	0.35	5.08		
232	8.	2.	24.	0.40	5.70		
232	8.	3.	18.	0.55	0.		
232	8.	3.	19.	0.55	0.80		
232	8.	3.	20.	0.55	1.70		
232	8.	3.	21.	0.55	2.70		
232	8.	3.	22.	0.60	3.85		
232	8.	3.	23.	0.70	5.06		

continued

TABLE 24
continued

232	8.	3.	24.	0.74	5.60
232	8.	4.	18.	0.87	0.
232	8.	4.	19.	0.87	0.80
232	8.	4.	20.	0.87	1.70
232	8.	4.	21.	0.87	2.70
232	8.	4.	22.	0.95	3.80
232	8.	4.	23.	1.00	5.00
232	8.	4.	24.	1.05	5.50
232	8.	5.	18.	1.43	0.
232	8.	5.	19.	1.43	0.80
232	8.	5.	20.	1.43	1.70
232	8.	5.	21.	1.43	2.70
232	8.	5.	22.	1.40	3.75
232	8.	5.	23.	1.38	4.90
232	8.	5.	24.	1.40	5.30
232	8.	6.	18.	1.99	0.
232	8.	6.	19.	1.99	0.80
232	8.	6.	20.	1.99	1.70
232	8.	6.	21.	1.99	2.70
232	8.	6.	22.	1.80	3.65
232	8.	6.	23.	1.70	4.70
232	8.	6.	24.	1.75	5.20
232	8.	7.	18.	2.55	0.
232	8.	7.	19.	2.55	0.80
232	8.	7.	20.	2.55	1.70
232	8.	7.	21.	2.55	2.70
232	8.	7.	22.	2.45	3.50
232	8.	7.	23.	2.00	4.32
232	8.	7.	24.	2.20	5.00
232	8.	8.	18.	3.25	0.
232	8.	8.	19.	3.20	0.80
232	8.	8.	20.	3.15	1.70
232	8.	8.	21.	3.10	2.70
232	8.	8.	22.	3.00	3.50
232	8.	8.	23.	2.80	4.32
232	8.	8.	24.	2.90	5.00
232	8.	9.	18.	4.00	0.
232	8.	9.	19.	3.96	0.80
232	8.	9.	20.	3.90	1.70
232	8.	9.	21.	3.87	2.70
232	8.	9.	22.	3.82	3.50
232	8.	9.	23.	3.75	4.32
232	8.	9.	24.	3.80	5.00
232	12.	5.	11.	1.24	-5.50
232	12.	5.	12.	1.24	-4.60
232	12.	5.	13.	1.24	-3.70
232	12.	5.	14.	1.24	-2.80
232	12.	5.	15.	1.24	-1.91
232	12.	5.	16.	1.24	-1.40
232	12.	6.	11.	1.77	-5.50
232	12.	6.	12.	1.77	-4.60
232	12.	6.	13.	1.77	-3.70
232	12.	6.	14.	1.77	-2.80

continued

TABLE 24
continued

```
232     12.     6.      15.     1.77    -1.91
232     12.     6.      16.     1.77    -1.40
232     12.     7.      11.     2.67    -5.50
232     12.     7.      12.     2.67    -4.60
232     12.     7.      13.     2.67    -3.70
232     12.     7.      14.     2.67    -2.80
232     12.     7.      15.     2.67    -1.91
232     12.     7.      16.     2.67    -1.40
END
ZON                                             1.
311         1.0     1.0     15.0    1.0     30.0
311         2.0     1.0     7.0     18.0    23.0
311         3.0     1.0     2.0     11.0    14.0
321         1.0     1.0
321         2.0     2.0
321         3.0     3.0
322         1.0     1.0
322         2.0     1.0
322         3.0     1.0
341         1.0
341         2.0
341         3.0
371     1.          5.67E-8 273.
372     1.      1.      7.      18.     23.     2.0
373     1.      3.      0.9     0.9     0.9
END
BDY                                             1.
411     1.0     1.0     1.0     15.0    1.0
411     2.0     15.0    1.0     15.0    30.0
411     3.0     15.0    30.0    1.0     30.0
411     4.0     1.0     30.0    1.0     1.0
412     1.0     1.0     6.0     2.0     3.0
412     2.0     1.0     2.0     2.0     1.0
412     3.0     1.0     2.0     2.0     3.0
412     4.0     1.0     6.0     5.0     2.0
422     1.0     1.0
422     3.0     3.0
423     1.0     1.0
423     3.0     3.0
431     1.0     1.0     0.0         1.0E+49
432     1.      +4.50000E6
431     3.0     1.0     0.0         1.0E+49
432     3.0     +2.00000E6
451     1.0     1.0     0.0         1.0E+49
452     1.0     17.0
451     3.0     1.0     0.0         1.0E+49
452     3.0     17.0
481     4.      1.      2.
481     1.      2.      3.
482     4.      1.      5.      5.      0.      0.05
482     1.      1.      5.      5.      0.      0.05
END
TIM                                             1.
```

continued

TABLE 24
concluded

```
511          4.32E04
512          2.16E04   4.32E04
513      1.1       0.95
514      -200.
521      2.84018E12   200.
END
EDT                                                  1.
611      2.
613      2.
616      2.
621      1.0       0.        200.      100.
622      1.0       15.       1.        30.
623      11.       14.       53.       54.       61.       62.       71.
623      72.       73.       91.       92.       93.       12.       15.
624      3.
641      1.        0.        200.      100.
671      1.        0.        200.      2.
674      1.        1.        71.       1.        5018.
674      2.        1.        72.       1.        3012.
674      3.        1.        71.       1.        4025.
674      4.        1.        72.       1.        13022.
674      5.        1.        5.        1.
END
END
```

TABLE 25

STEALTH 2D Input Data Set for Problem 6.3 (Restart Run)

```
TTL     PROBLEM 6.3 - Heater Test #2 - NSTF
PRB                                                 2.
SOR     2.        8.15880E06
END
TIM
511        4.32E04
512        2.16E04   4.32E04
513     1.1       1.00
514     -200.
521      5.13588E7  1400.
END
EDT                                                 1.
611     1.
613     1.
616     1.
621     1.0       8.15880E06  4.320E07  8.640E06
621     2.        8.15880E06 2.2378E07 2.2378E07
621     3.        8.15880E06 3.0240E07 3.0240E07
622     1.0       15.       1.0       30.
623     11.       14.       53.       54.       61.       62.       71.
623     72.       73.       91.       92.       93.       12.       15.
624     3.
641     1.0       8.15880E06  4.320E07  8.640E06
641     2.        8.15880E06 2.2378E07 2.2378E07
641     3.        8.15880E06 3.0240E07 3.0240E07
671     1.0       8.15880E06  4.320E07  4.320E05
674     1.        1.        61.       1.        3013.
674     2.        1.        11.       1.        6015.
674     3.        1.        14.       1.        5013.
674     4.        1.        14.       1.        5012.
674     5.        1.        14.       1.        5011.
674     6.        2.        61.                            8.3316E6 13.
674     7.        2.        61.                           3.05364E7 3000.
674     8.        2.        61.                           3.05364E7 4000.
674     9.        2.        61.                           3.92628E7 13.
674     10.       2.        61.                           1.67988E7 13.
674     11.       2.        91.                           1.67988E7 13.
674     12.       2.        92.                           1.67988E7 13.
674     13.       2.        14.                           1.67988E7 13.
674     14.       2.        61.                           2.54388E7 13.
674     15.       2.        91.                           2.54388E7 13.
674     16.       2.        92.                           2.54388E7 13.
674     17.       2.        14.                           2.54388E7 13.
674     18.       2.        61.                           3.40788E7 13.
674     19.       2.        91.                           3.40788E7 13.
674     20.       2.        92.                           3.40788E7 13.
674     21.       2.        14.                           3.40788E7 13.
674     22.       2.        61.                           3.40788E7 5000.
674     23.       2.        91.                           3.40788E7 5000.
674     24.       2.        92.                           3.40788E7 5000.
674     25.       2.        11.                           3.40788E7 5000.
674     26.       2.        11.                           3.40788E7 4000.
674     27.       2.        61.                           3.83988E7 13.
```

continued

TABLE 25
concluded

```
END
END
```

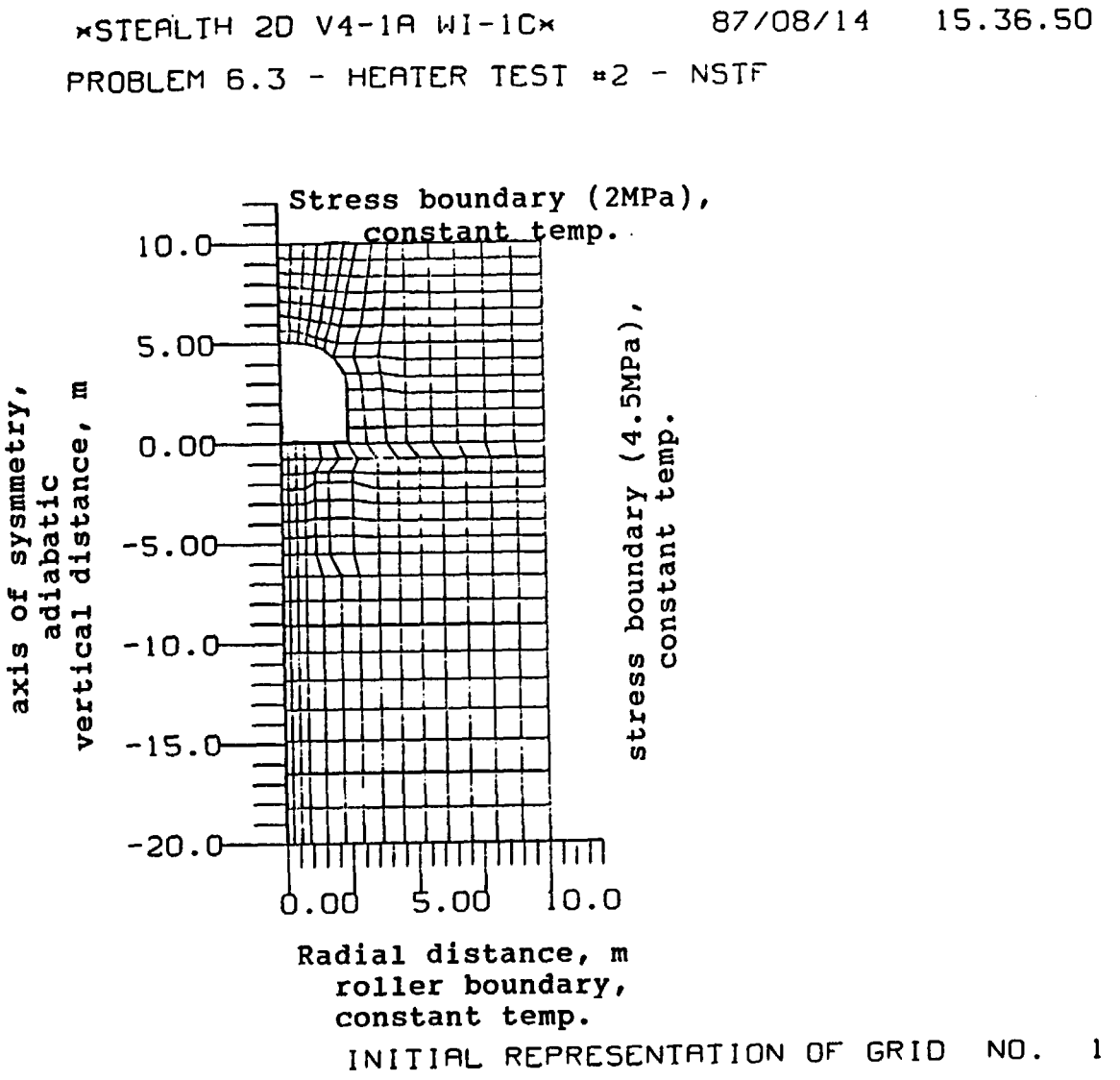


Figure 46. Initial mesh configuration and boundary conditions, Problem. 6.3.

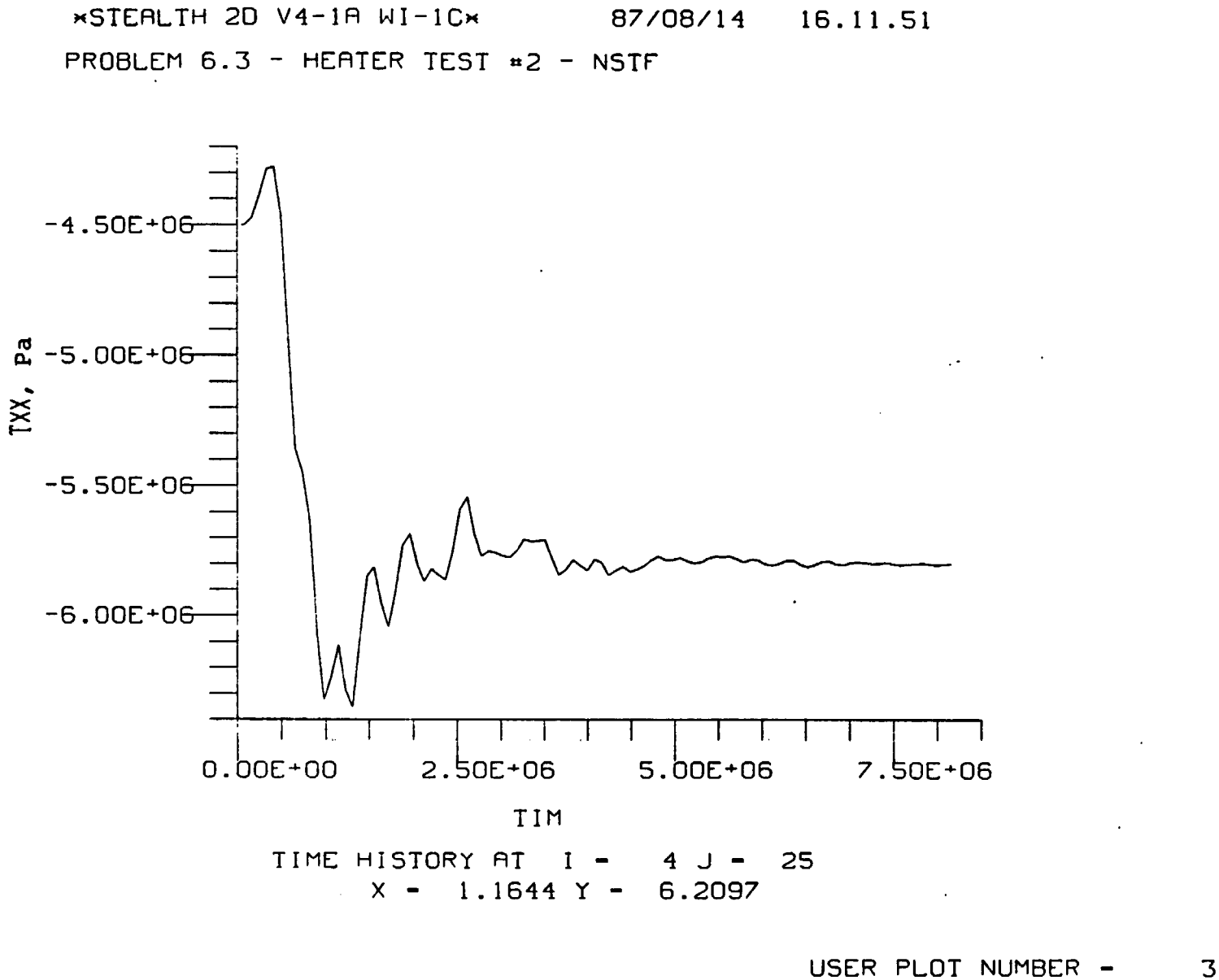


Figure 47. Equilibration of excavation-induced radial stress above the roof.

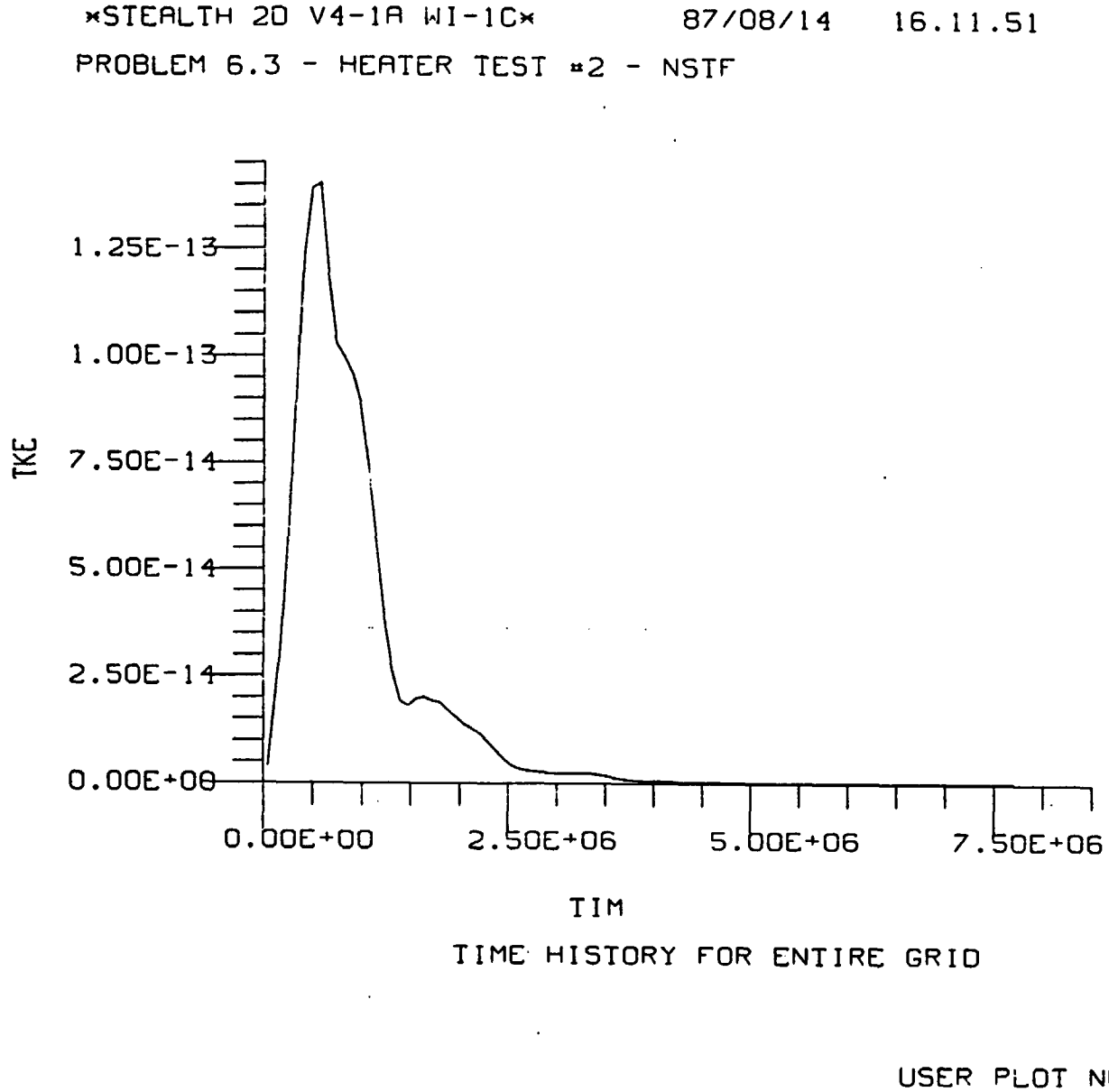


Figure 48. Total kinetic energy in the mesh; reduction with successive iterations indicates approach to equilibrium.

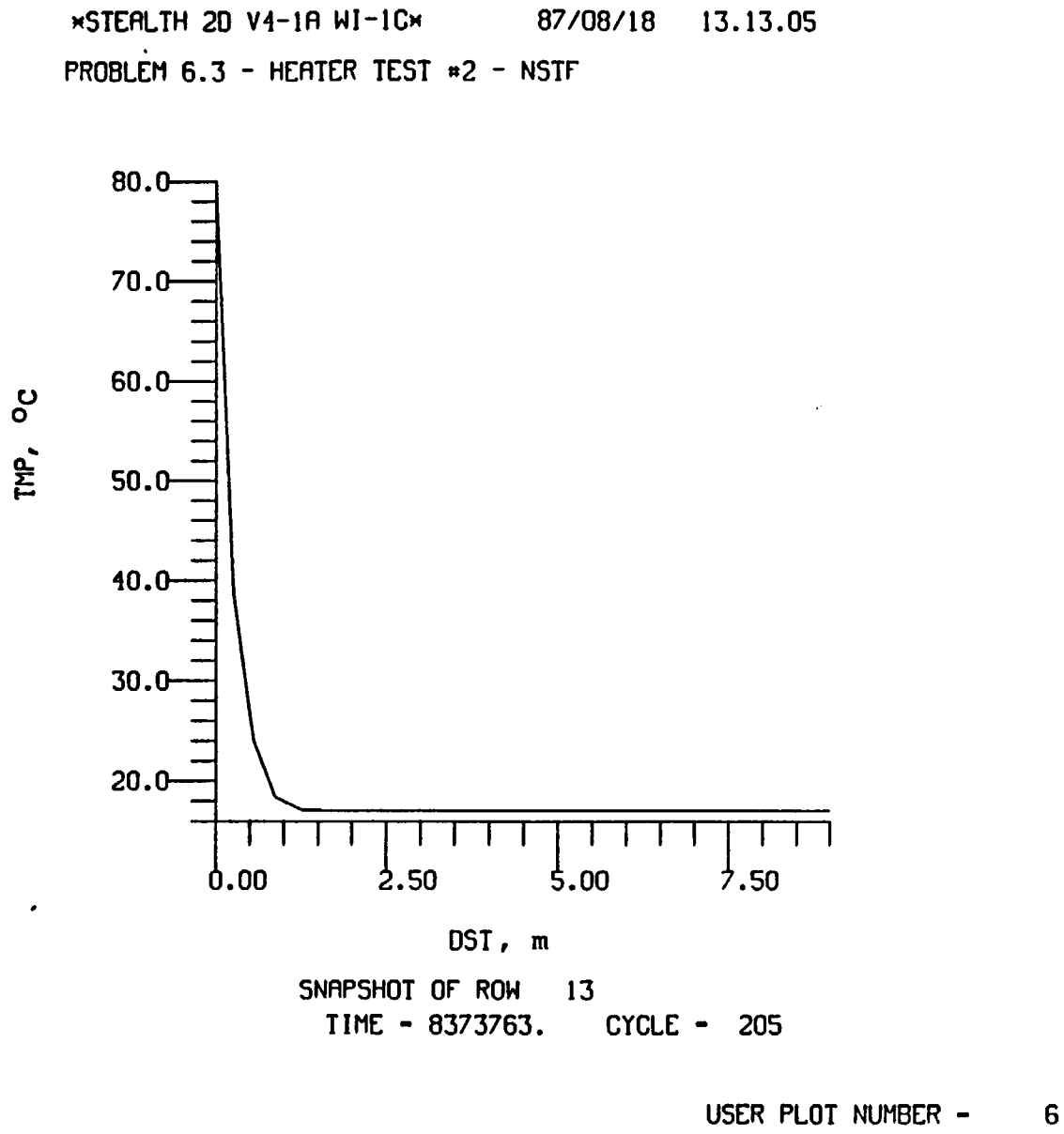


Figure 49. Radial Temperature Distribution at a depth of 4.5m after 2.5 days.

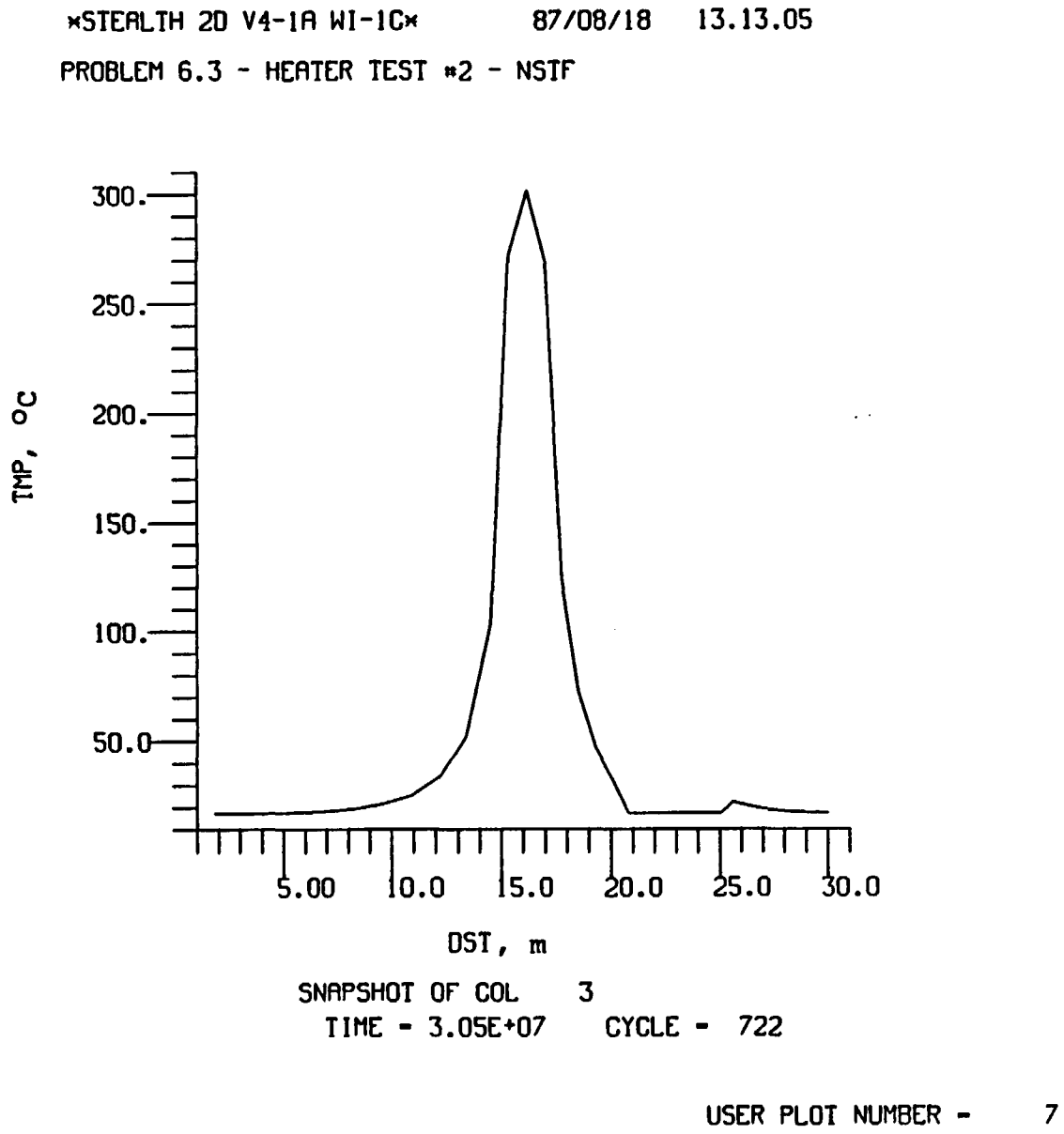


Figure 50. Vertical temperature profile at 0.4m radius after 259 days.

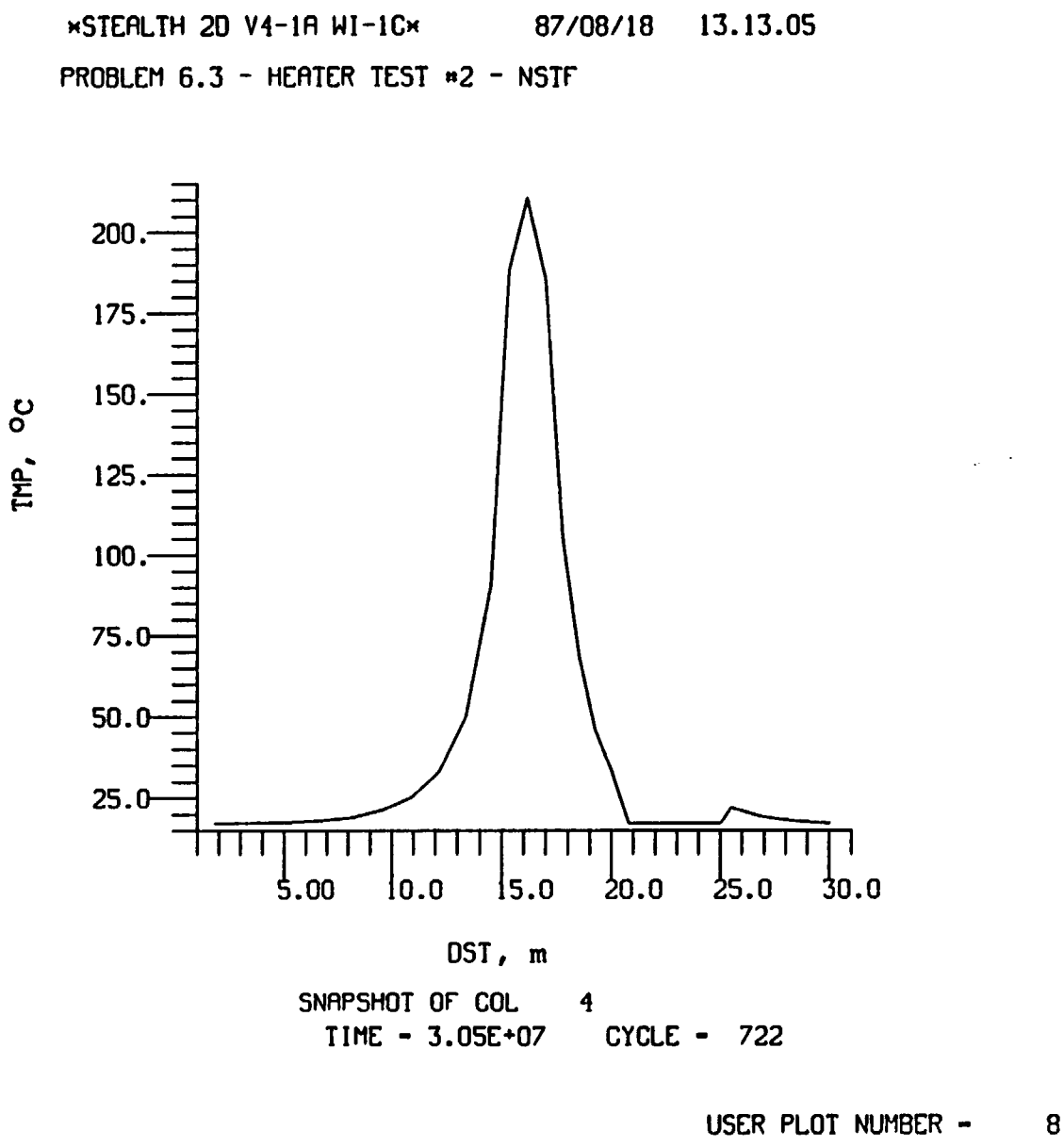


Figure 51. Vertical temperature profile at 0.71m radius after 259 days.

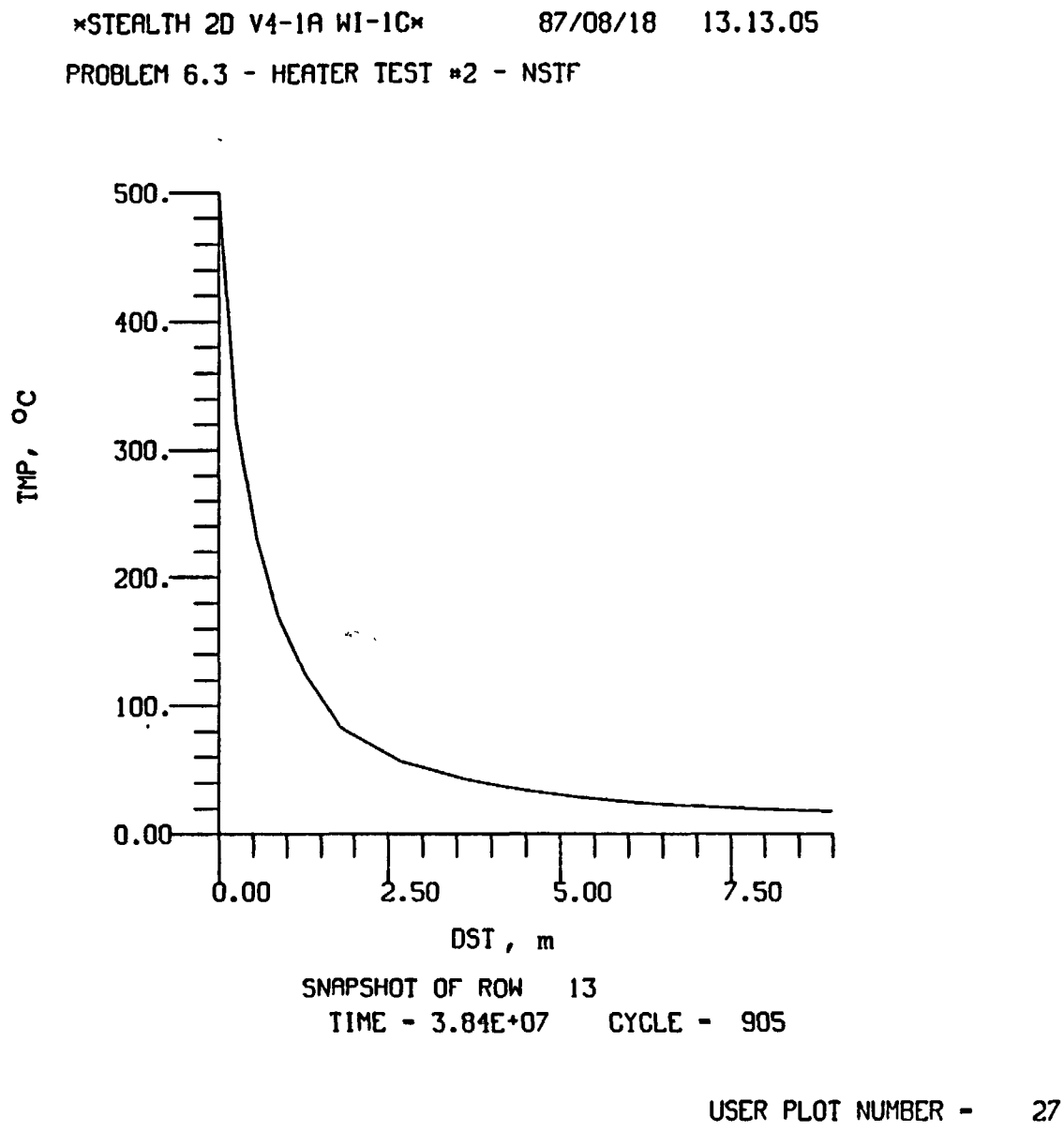


Figure 52. Radial temperature profile at 4.25m depth after 350 days.

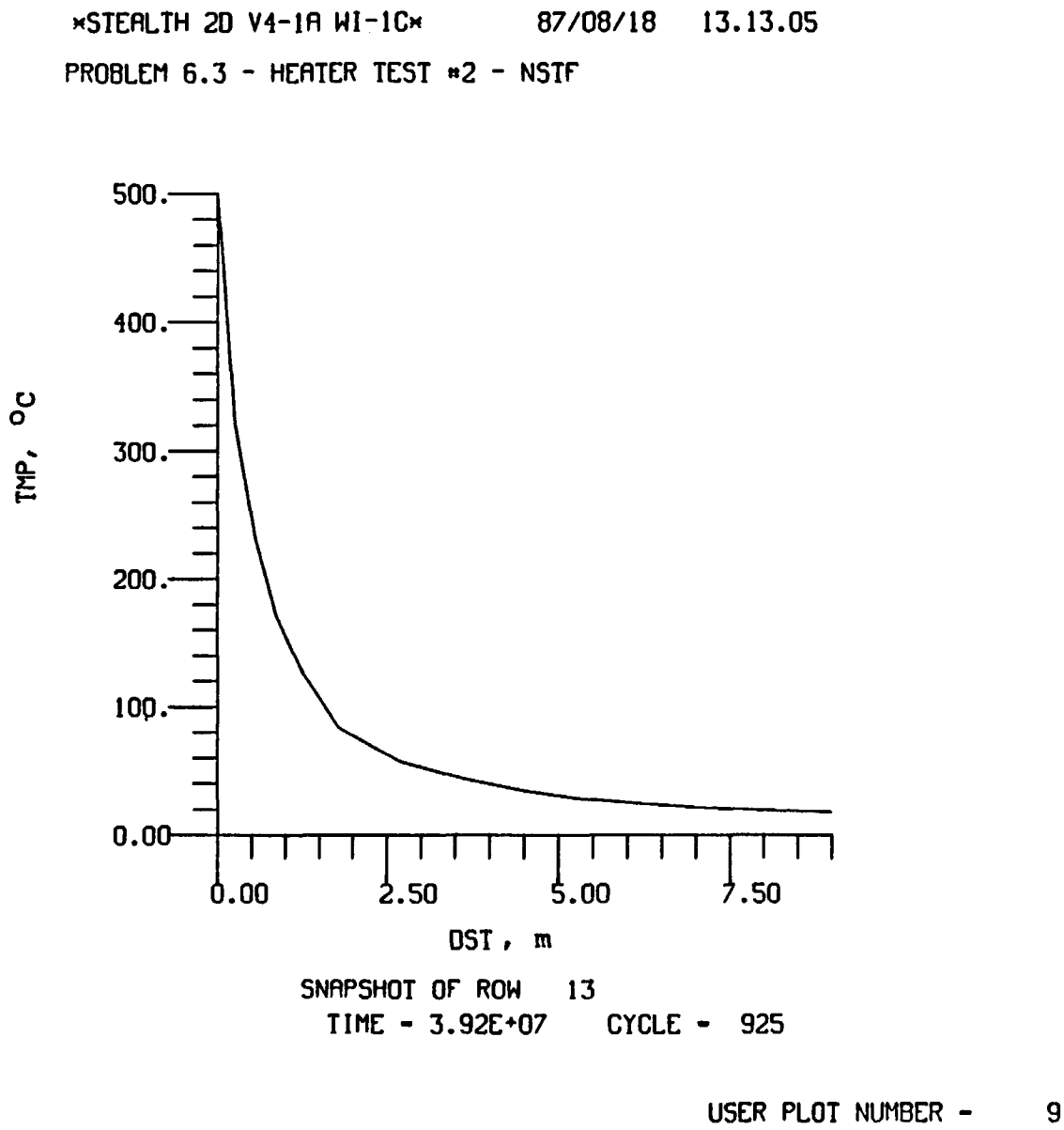


Figure 53. Radial temperature profile at 4.25m depth after 360 days.

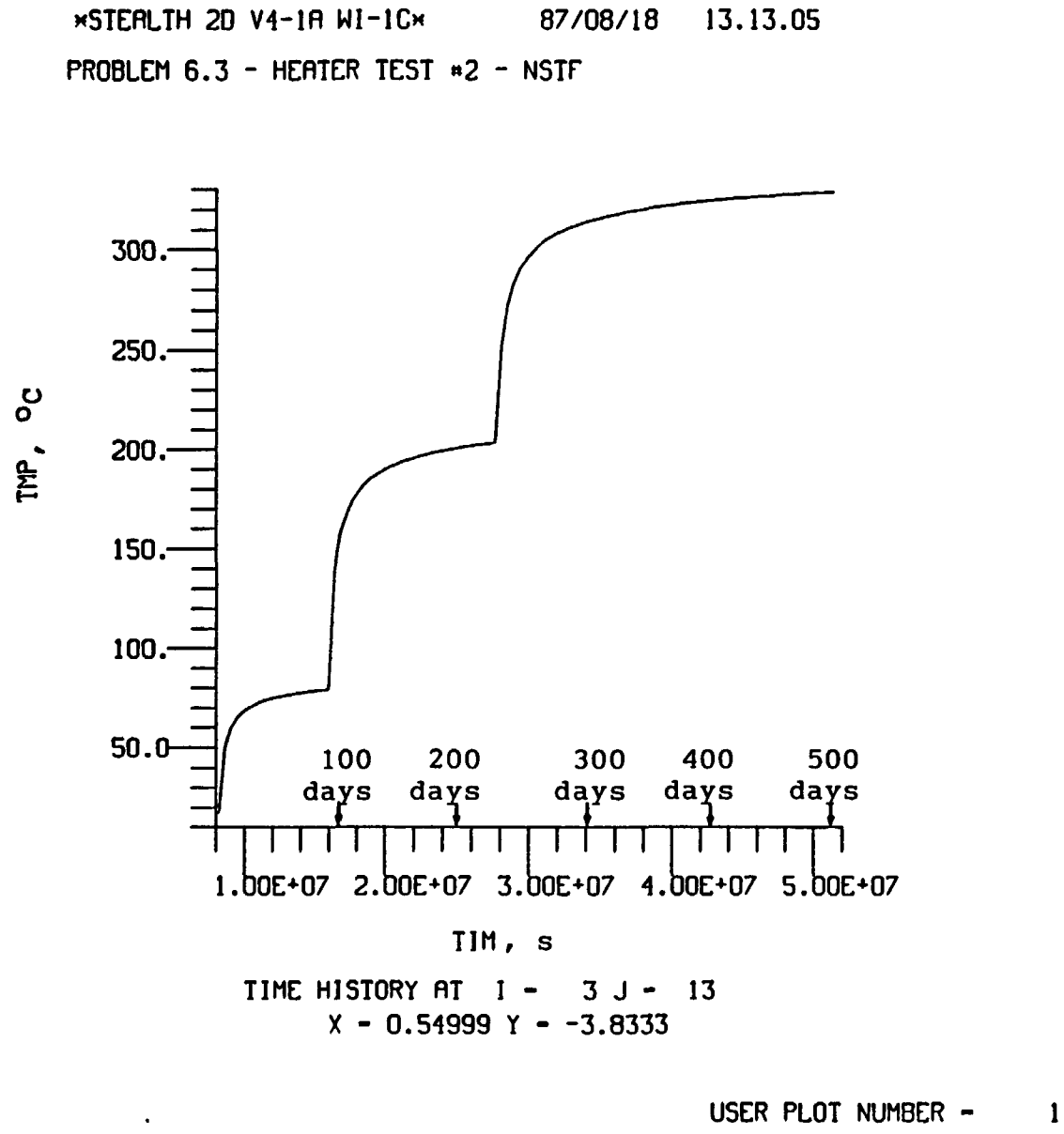


Figure 54. Temperature hsitory at heater midplane at 0.4m radius.

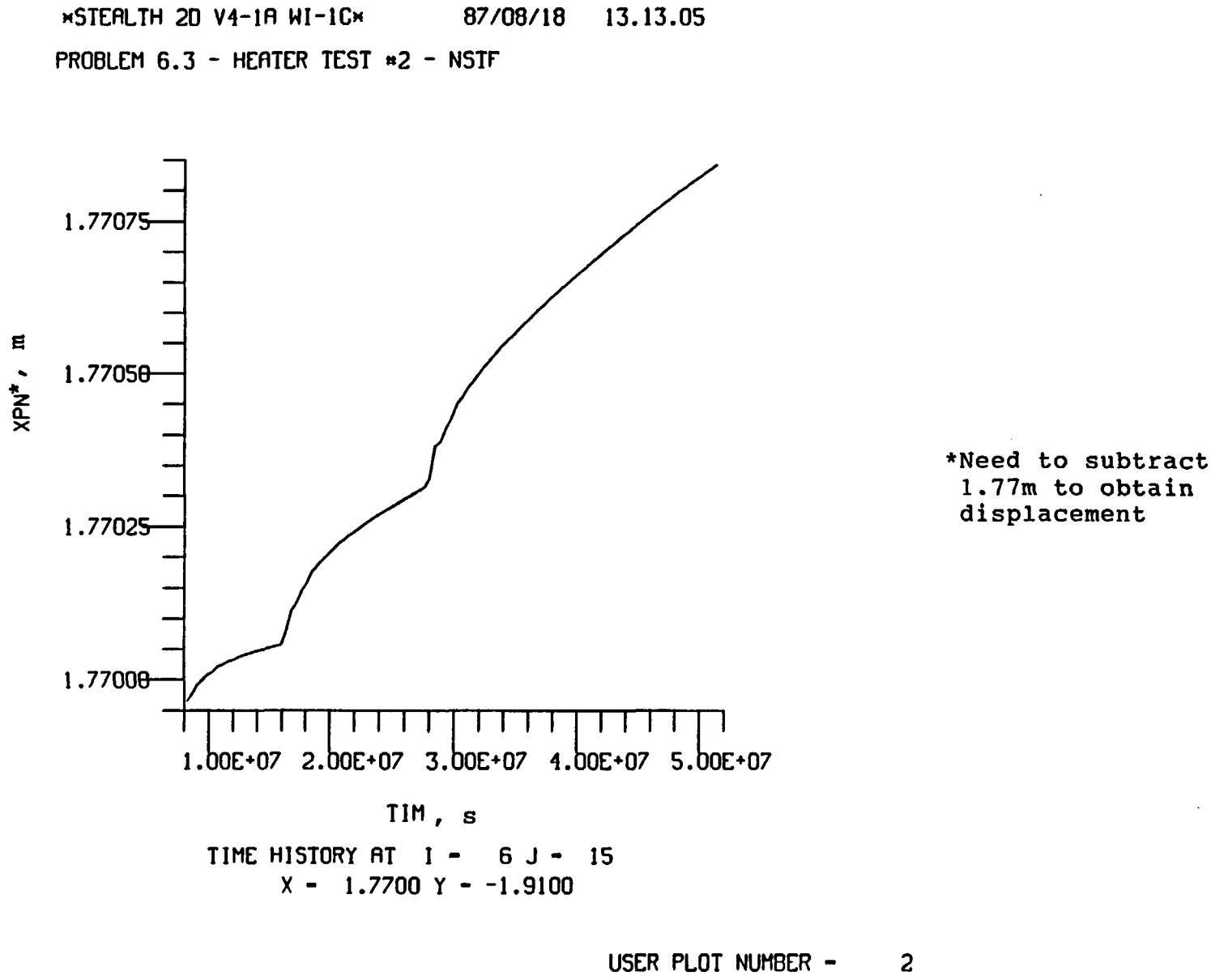
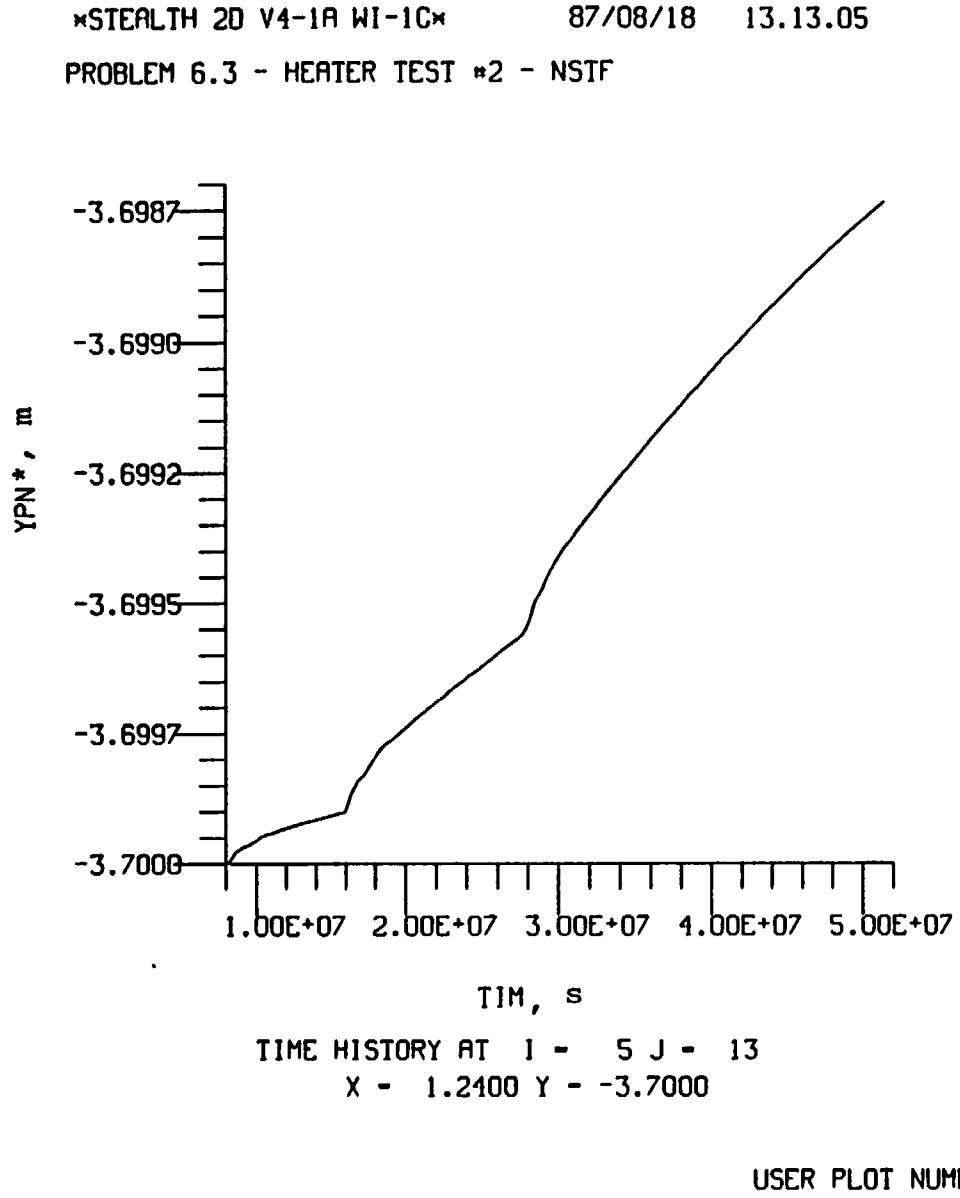


Figure 55. Horizontal "displacement" history at 1.91m depth and 1.77m radius.



*Need to subtract 3.7m to obtain vertical displacement

Figure 56. Vertical "displacement" history at 3.7m depth and 1.24m radius.

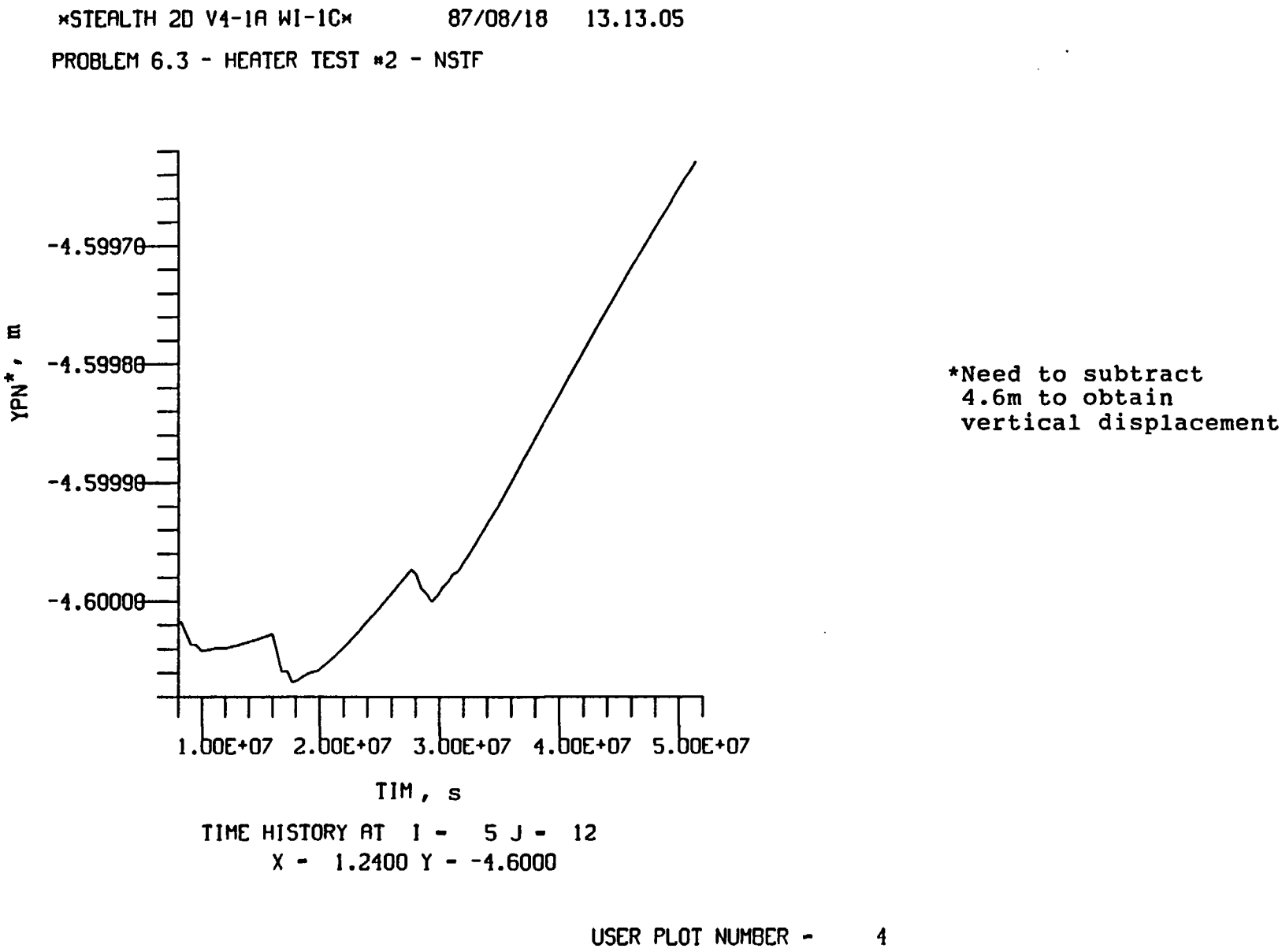
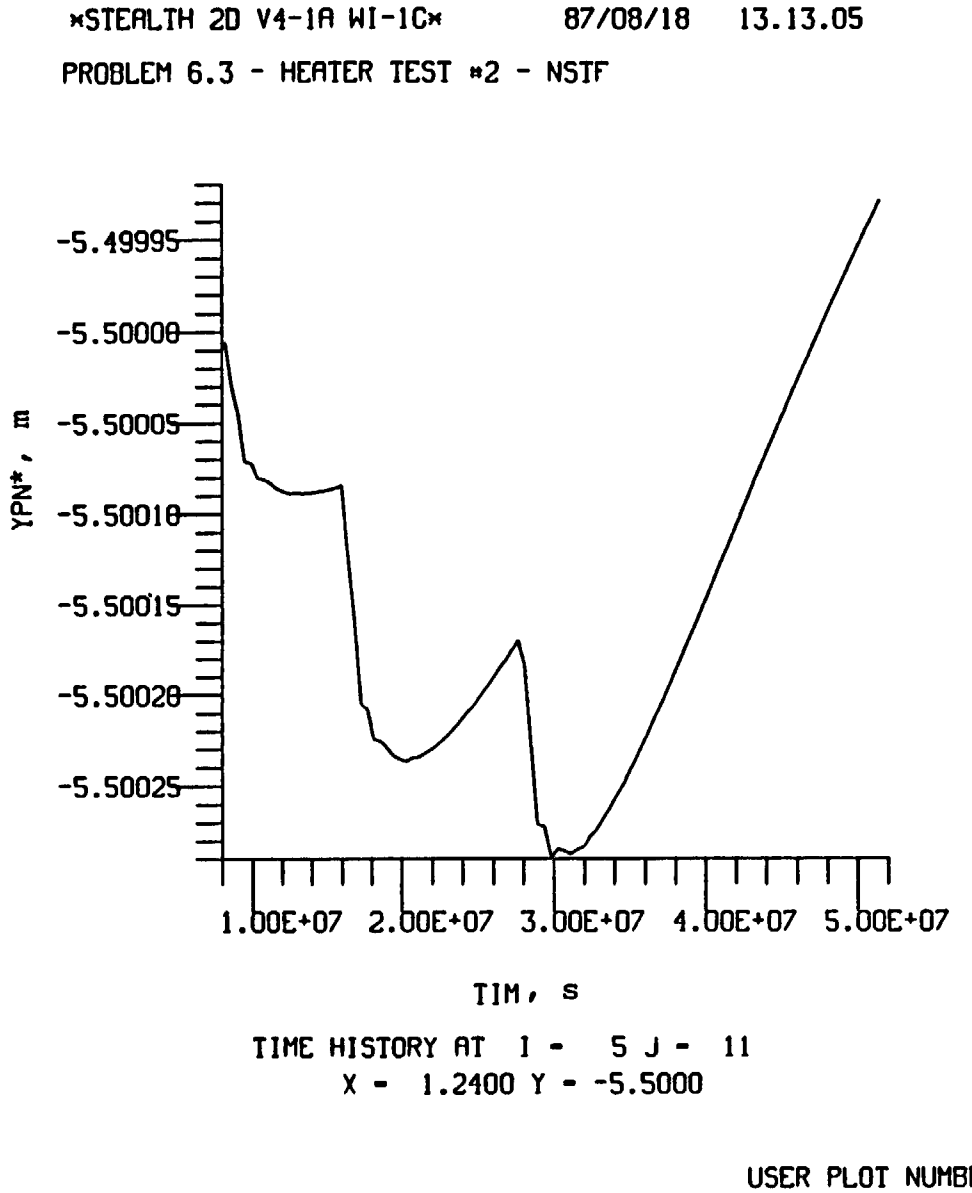


Figure 57. Vertical "displacement" history at 4.6m depth and 1.24m radius.



*Need to subtract 5.5m to obtain vertical displacement

Figure 58. Vertical displacement history at 5.5m depth and 1.24m radius.

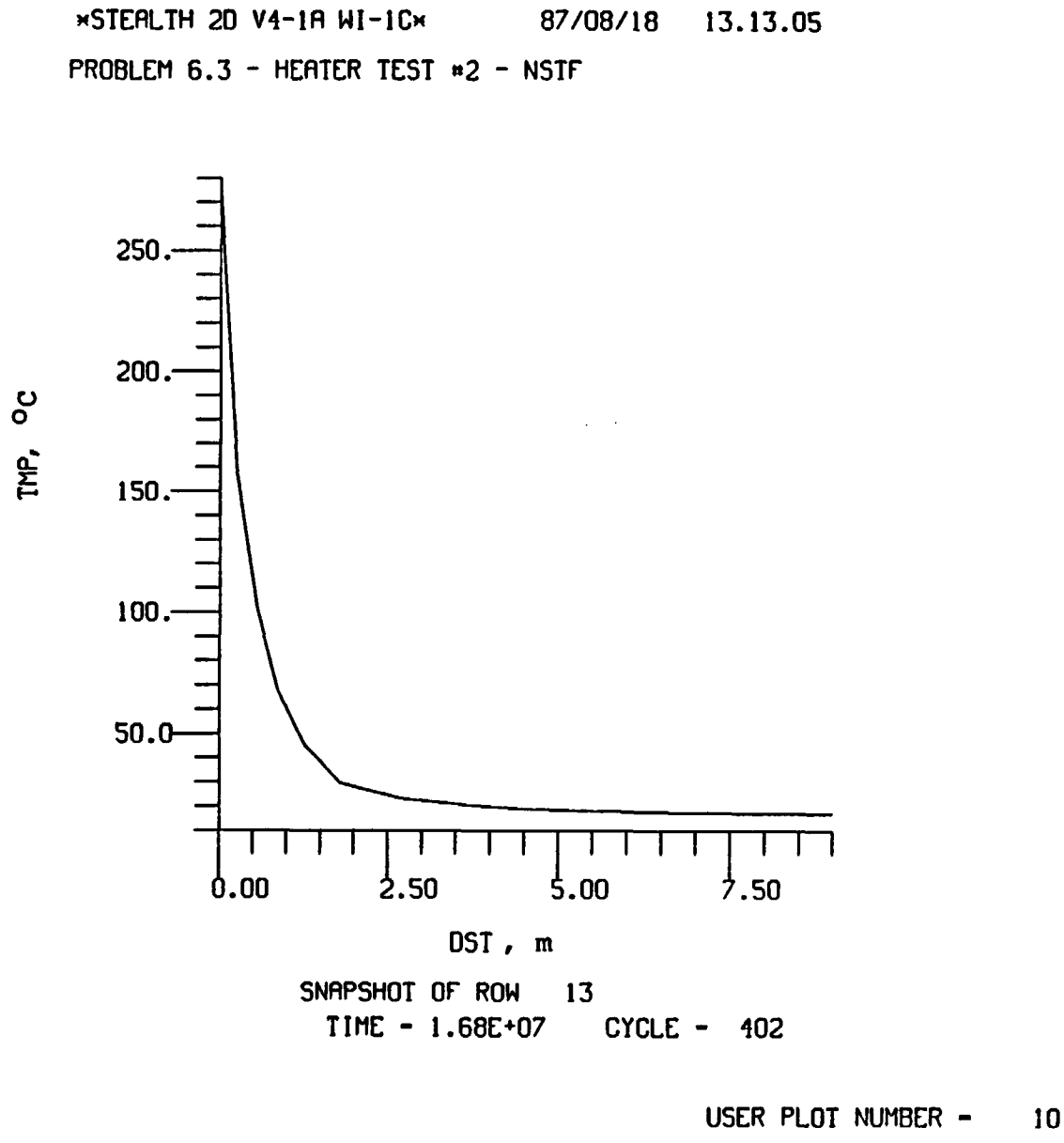


Figure 59. Radial temperature distribution at heater midheight at 100 days.

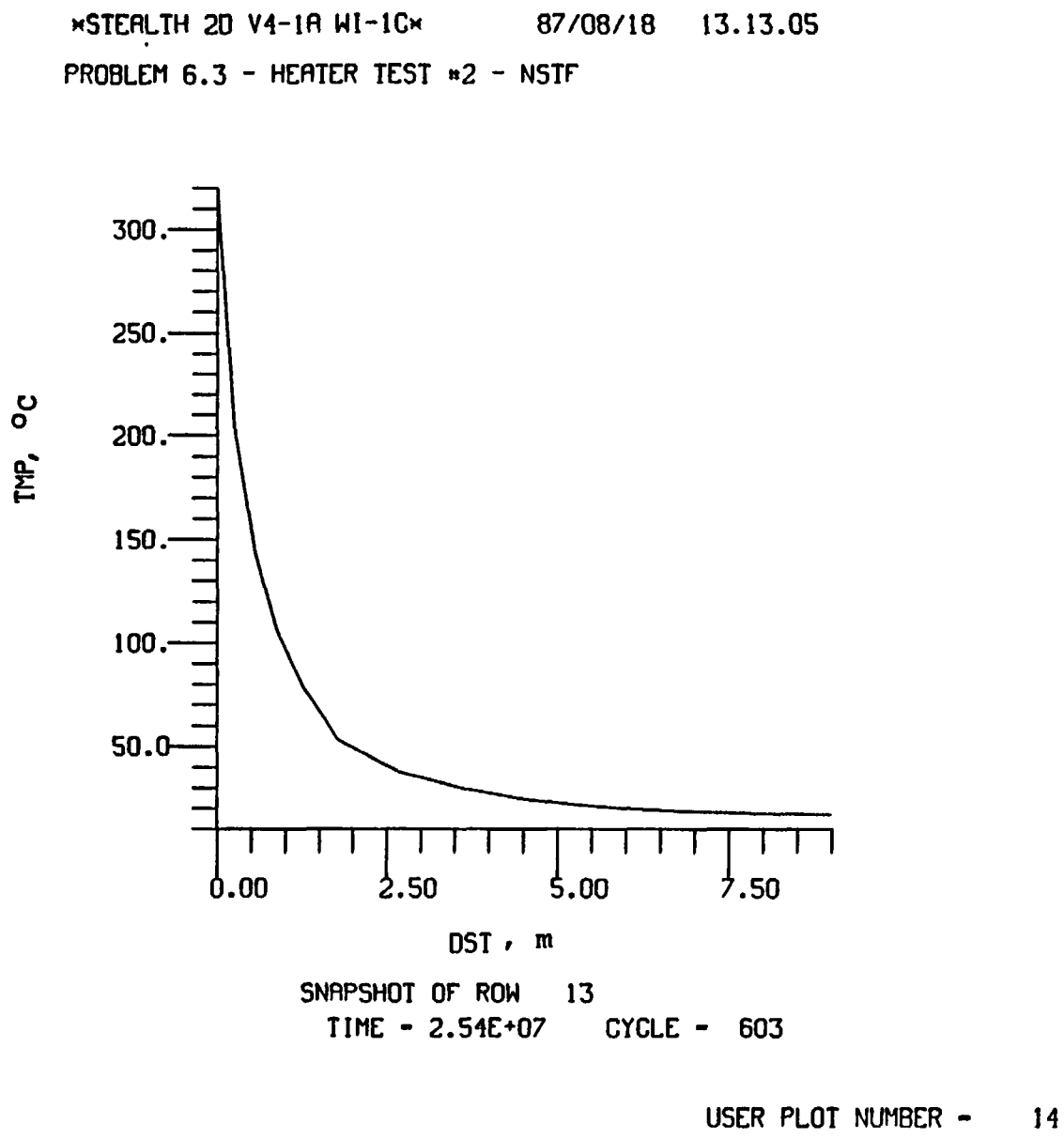


Figure 60. Radial temperature distribution at heater mid-height at 200 days.

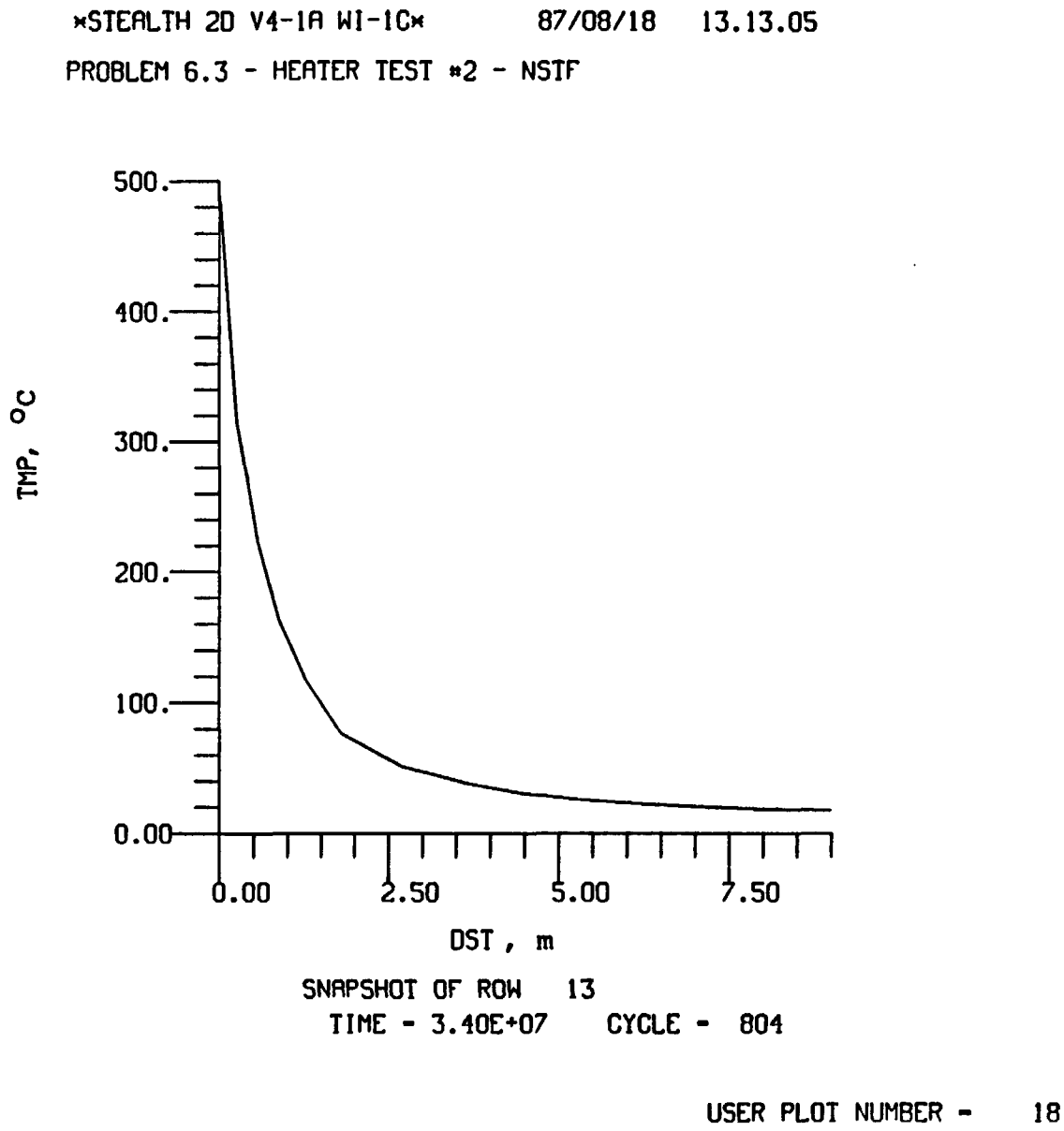


Figure 61. Radial temperature distribution at heater mid-height at 300 days.

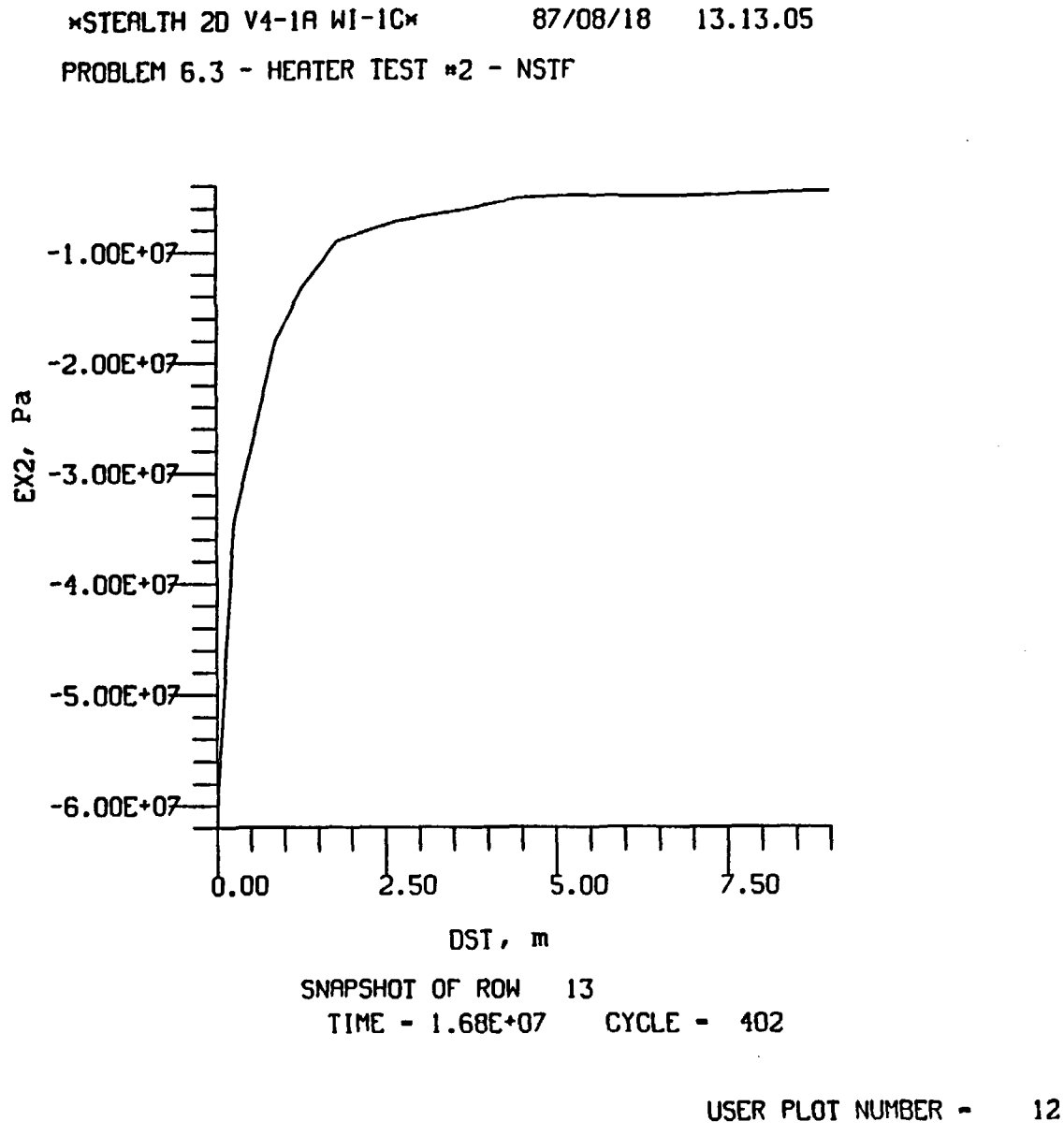


Figure 62. Major principal stress distribution at heater mid-height at 100 days.

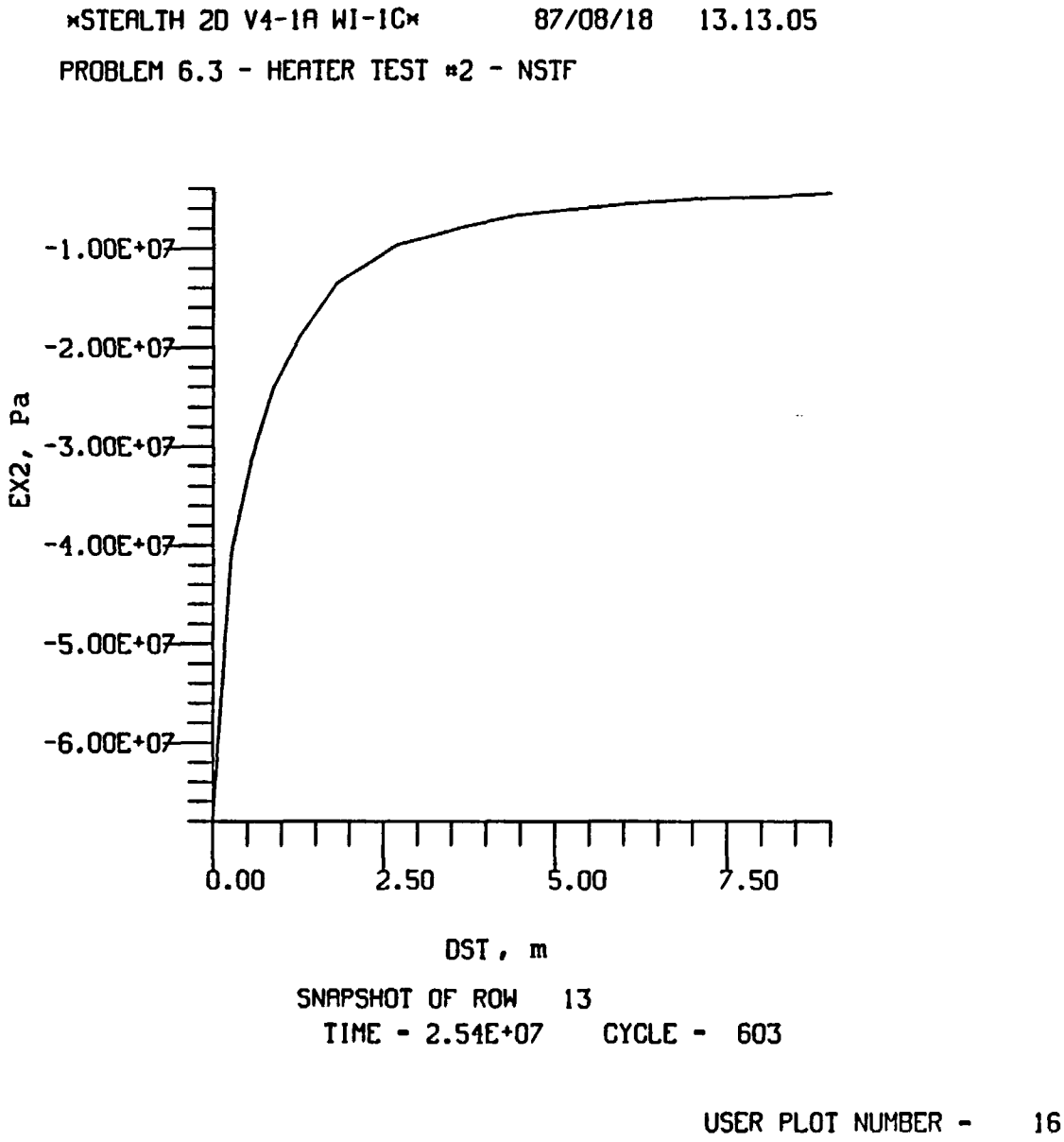


Figure 63. Major principal stress disbribution at heater mid-height at 200 days.

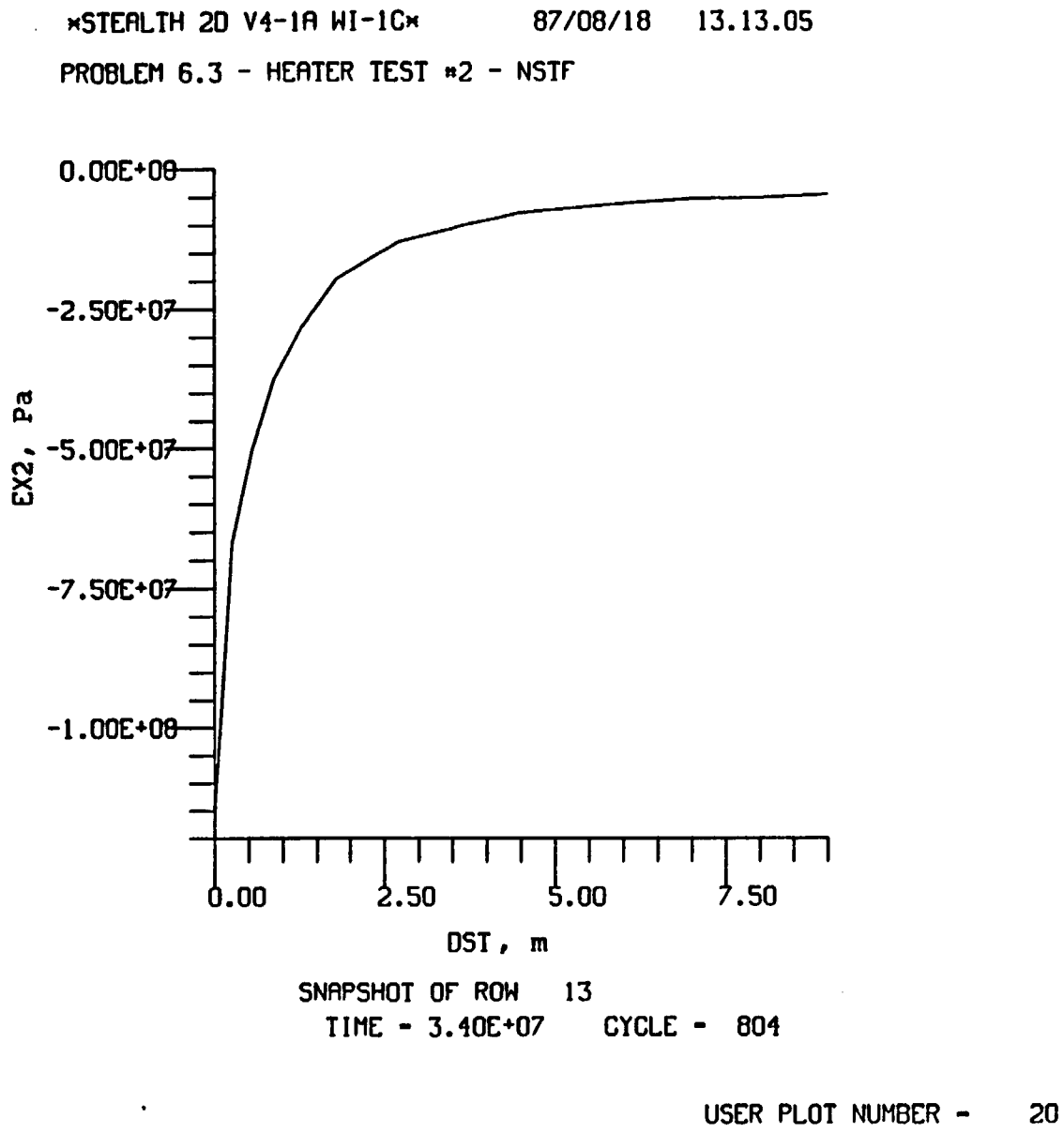


Figure 64. Major principal stress distribution at heater mid-height at 300 days.

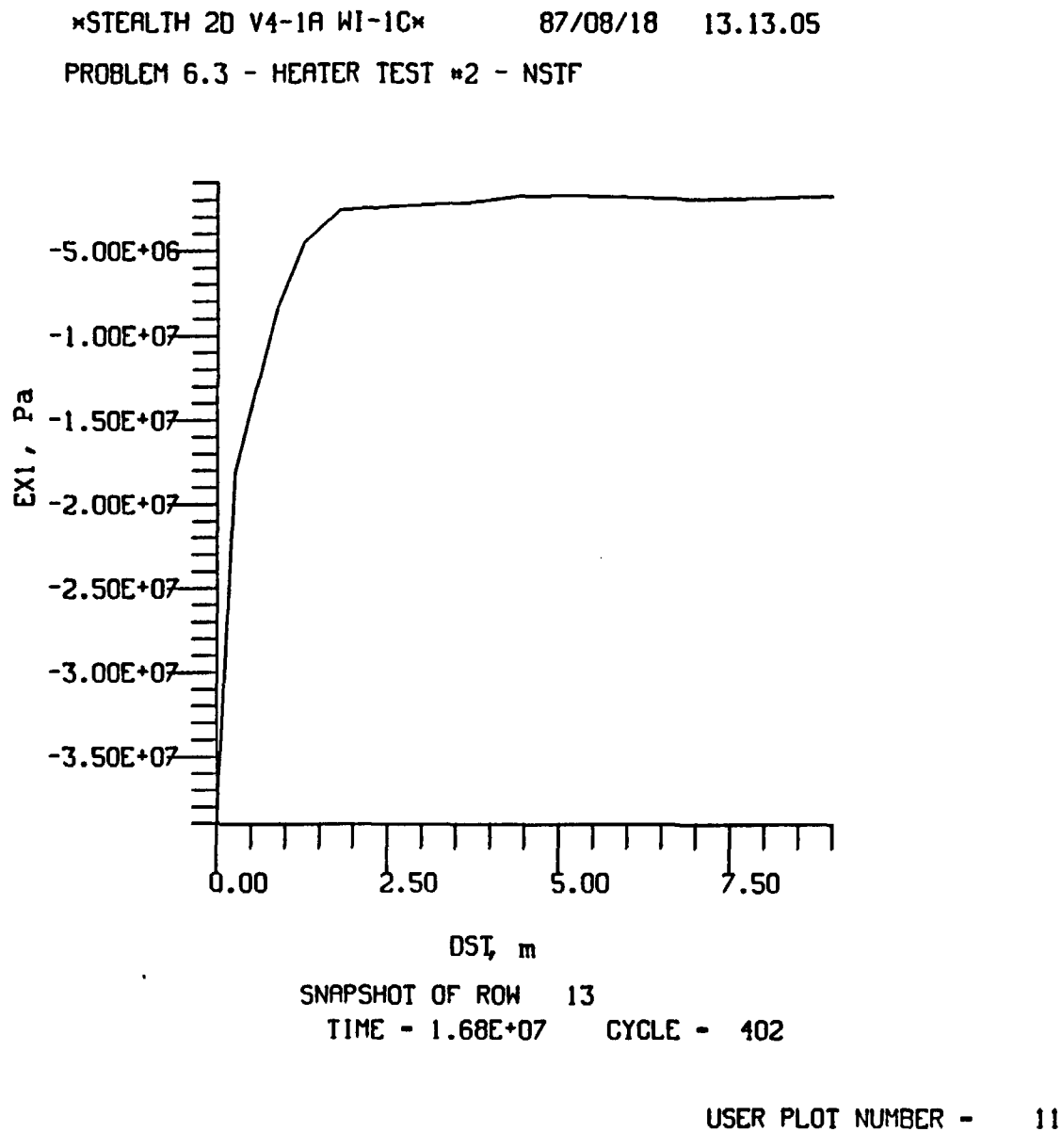


Figure 65. Minor principal stress distribution at heater mid-height at 100 days.

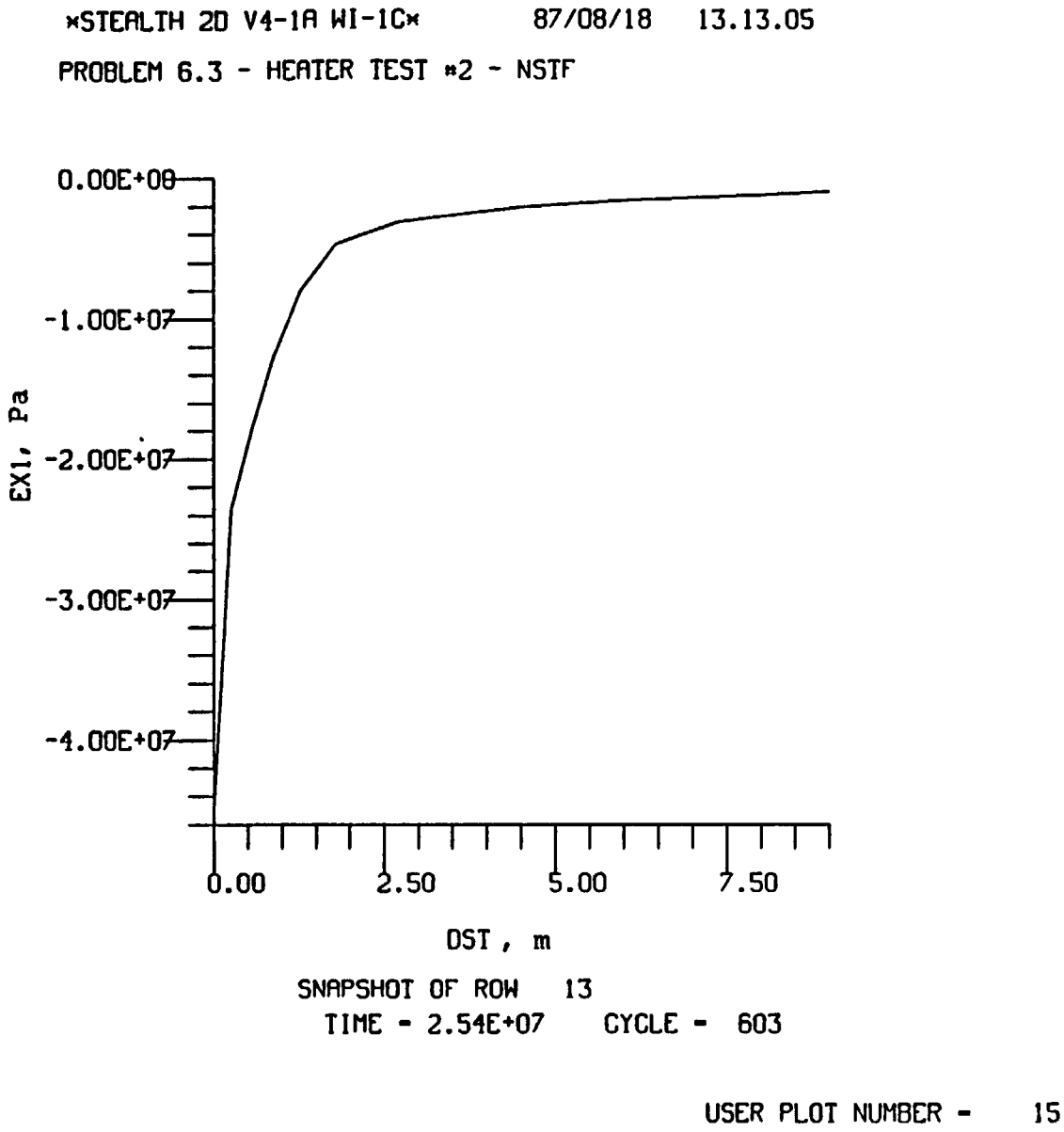


Figure 66. Minor principal stress distribution at heater mid-height at 200 days.

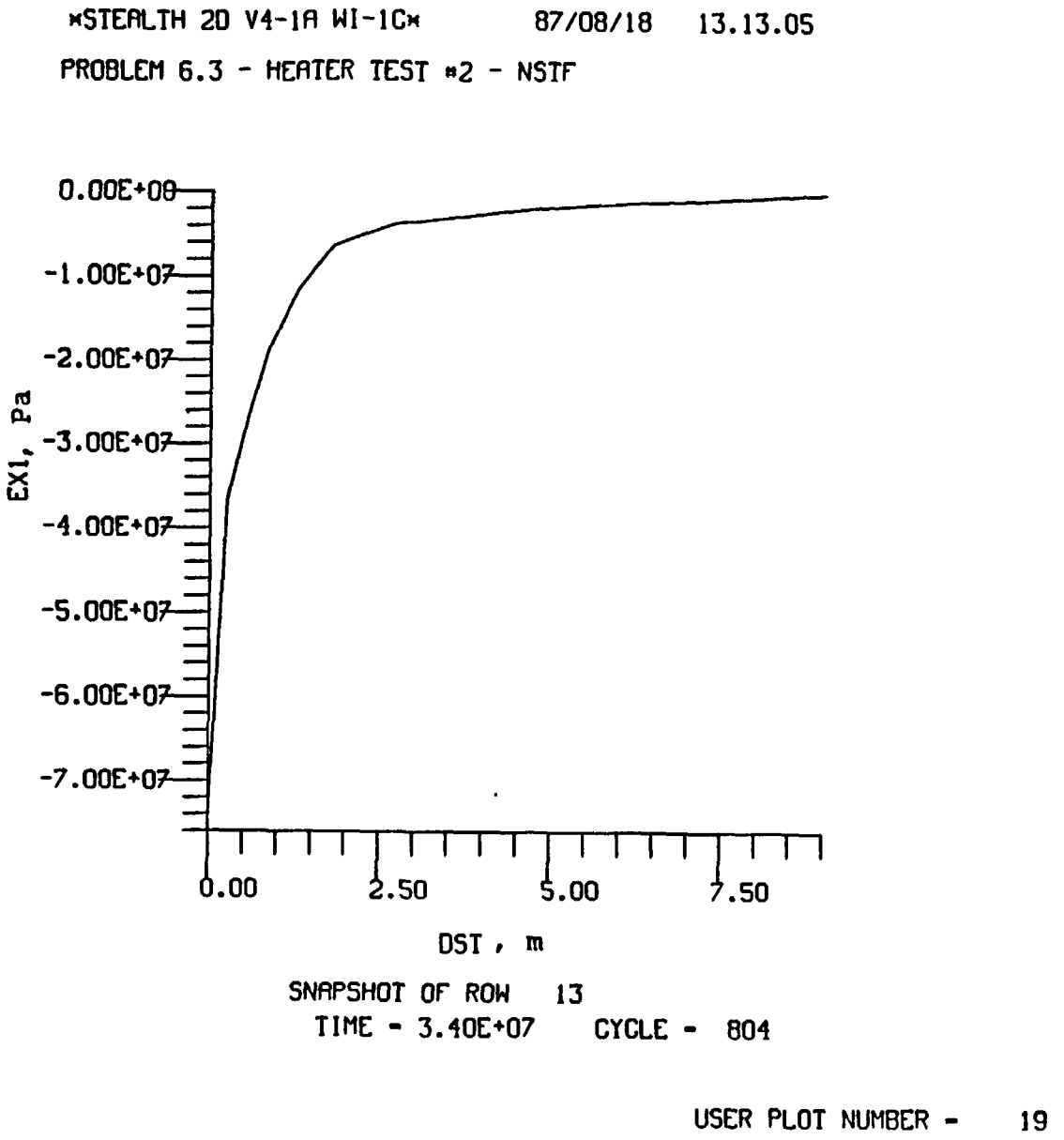


Figure 67. Minor principal stress distribution at heater mid-height at 300 days.

National Brand 12-188
Made in USA

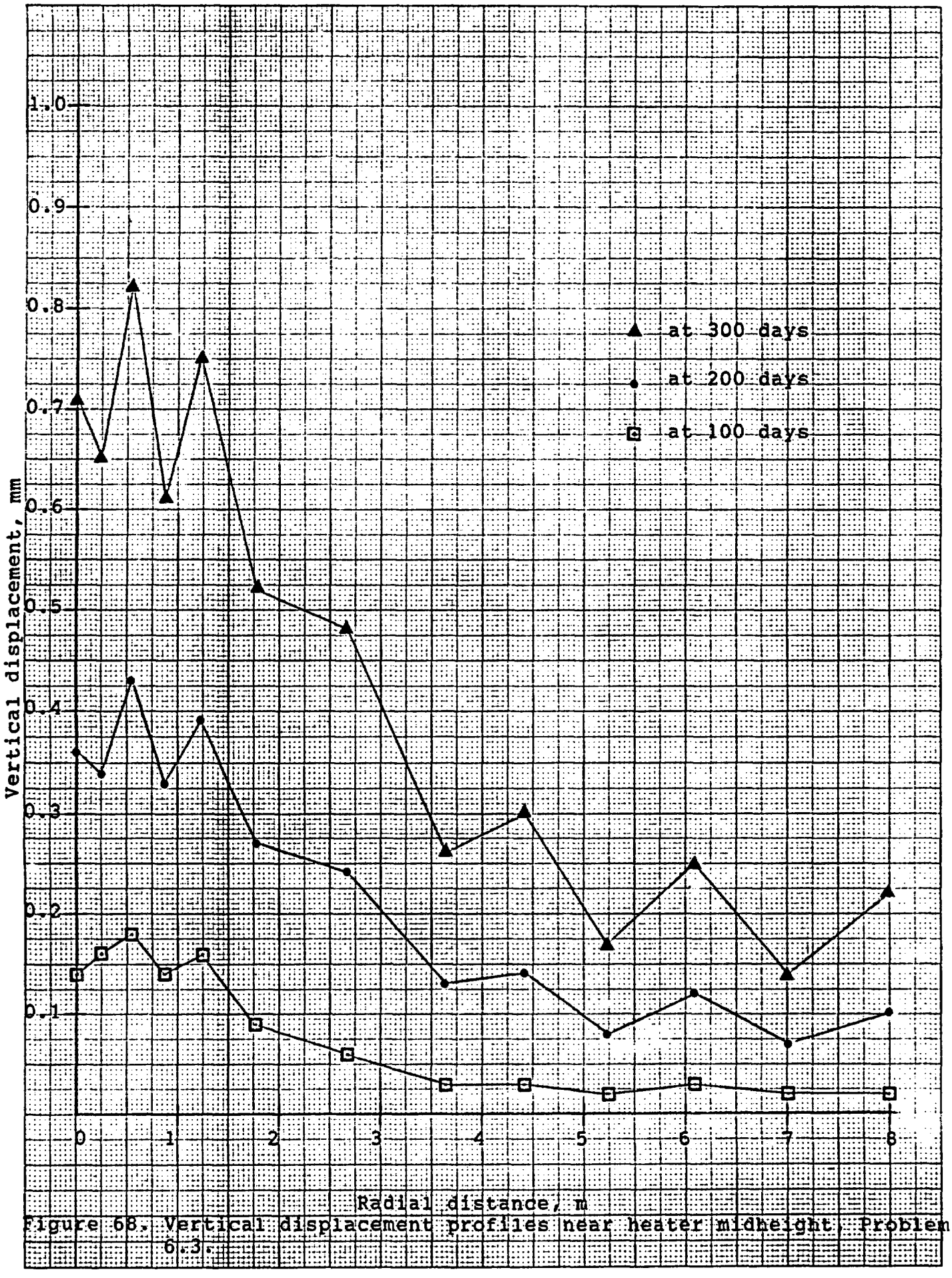


Figure 68. Vertical displacement profiles near heater midheight. Problem 6.3.

TABLE 26

Summary of CPU and I/O Times on CRAY-XMP

Benchmark Problem	CPU Time* (seconds)	I/O Time* (seconds)	"Memory* " (seconds)
2.9	88	95	24
3.5 VM	174	95	26
3.5 DP	172	86	21
5.2	2,549	2,857	1,072
5.3	916	454	129
6.3	955	616	198

* The time values given are for execution of successful runs for each problem. The CTSS system at Sandia reports memory usage in units of time.