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THERMOMECHANICAL CALCULATIONS PERTAINING TO EXPERIMENTS IN THE YUCCA MOUNTAIN EXPLORATORY SHAFT

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Nuclear Waste Management Program

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1.0 INTRODUCTION

Waste Package Environment Tests are being planned for the NNWSI Exploratory Shaft to provide information about the near-field hydrological, thermal, and mechanical environment of the waste package for use in assessing the expected performance of the waste package subsystem. The rationale of the tests is driven by the need for this information, but is constrained by the measurement capabilities that can be applied in situ and by the ability of analytical and numerical models to use the data obtained with the measurements. A secondary purpose of the tests is to provide the option of testing certain components that might be part of the engineered barrier system.

The reference horizon for a candidate repository at Yucca Mountain is the densely welded, devitrified portion of the Topopah Spring Member of the Paintbrush tuff (Vieth, 1982). The water table at Yucca Mountain is more than 500 m below the central portion of the mountain; as a result, the Topopah Spring Member lies entirely within the unsaturated zone. The matrix porosity of the welded tuff is approximately 13 percent, and the rock has a fracture frequency of 0.8 to 3.9 fractures per meter (Dudley and Erdal, 1982).

The Waste Package Environment Tests will be located in drifts at a depth of approximately 310 m (1020 ft) in the Exploratory Shaft. The tests will be separated from one another by at least 6.1 m (20 ft) based on the need to avoid interaction of the individual tests. This planned minimum separation will be refined as scoping and design calculations proceed. The actual test locations within the access drift will be dependent on local geology.

The Waste Package Environment Tests will include measurements of several parameters as a function of location and time in the near-field environment. The tests include an accelerated thermal cycle to examine the cooling side of the thermal pulse. The parameters to be measured or derived include temperature, moisture content, pore water pressure, rock mass deformation, and rock mass stress changes. Temperatures and pore pressures will be used directly with the moisture content data to define the spatial distribution of liquid water with time around the emplacement hole. Rock mass deformation and

stress changes will be used with conceptual models of discontinuity stiffness (Goodman, 1980) to indirectly evaluate average fracture aperture changes; fracture closure might force fluid migration to occur primarily as flow in the porous matrix. This information can be used in fracture flow models where fracture flow mechanisms are dominant. Rock core samples will be obtained before and after the tests to allow laboratory determination of index properties such as porosity, permeability, and elastic modulus. Such index properties are needed to facilitate integration of Waste Package Environment Test results with the results of other Exploratory Shaft tests.

Electrical resistance heaters will be used to simulate the heat produced by radioactive decay. Preliminary calculations indicate that, with a heat loading of approximately 5 kW, the 100°C isotherm will reach a radial position approximately 1 m into the surrounding rock in approximately 3 months (Yow, 1985). This thermal loading is higher than that of the reference PWR spent fuel package (O'Neal et al., 1984). A stepped cooldown period of approximately 6 to 9 months may be used to allow the entire rock volume surrounding the heater to drop below 100°C. More refined calculations and modeling will be completed prior to testing to determine the expected time-temperature fields around the heaters. Actual heater power levels will be varied to achieve desired temperature profiles; this manipulation will be based on pretest calculations and on temperatures observed in the rock mass, as each test progresses. Field confirmation of temperature profiles will provide confidence that simulations of the near-field environment are based on realistic conditions.

Instruments will be installed in the rock mass around the heaters to measure temperature, moisture content, pore pressure, stress change, and displacement as a function of time and location. High-frequency electromagnetic (HFEM) measurements and other geophysical probes will be used to indirectly measure the moisture content in the rock before, during, and after thermal cycling. Preliminary calculations using the best available estimates for material properties are needed in order to anticipate the range of rock mass conditions to be experienced by the instruments.

2.0 DESIRED CALCULATIONS

Although several heated tests are planned, they only involve two basic configurations as far as the heat source is concerned. In one configuration, a 5-kW heater that is 6 m in length is placed in the deepest 6 m of a 12-m long, 0.30-m diameter horizontal hole. In the other configuration, a 4.25-kW heater that is 4.5 m in length is placed at the bottom of a 6-m deep vertical hole that is 0.30 m in diameter. In both cases, the full power (5 or 4.25 kW) is intended to be applied for approximately 13 weeks and then gradually decreased to zero during the following 26 weeks.

The desired calculational results are temperature, displacement, and stress change as a function of time and space in the vicinity of a heater.

The recommended thermomechanical properties were those for tuff unit II-NL with 80% saturation, as given in SNL Keystone Document 6310-85 (Nimick et al., 1984). The ambient temperature in the experimental area is expected to be ~25°C.

3.0 CALCULATIONAL METHODS

A variety of techniques are available to handle the desired calculations. They range from simple analytical solutions of the diffusion equation and linear thermoelasticity to relatively complex computer programs using finite element or finite difference techniques. In previous work (Montan, 1986) involving only thermal calculations, both ends of the spectrum were rather thoroughly investigated. The simple analytic calculations using constant "average" thermal properties and neglecting the heat of vaporization of water gave very similar results to the much more complicated finite difference calculations in which the heat of vaporization of water and accompanying changes in thermal properties were considered.

For the thermal and thermomechanical calculations being considered here, we have chosen to use the simple analytical solutions for a finite line source as embodied in the PLUS Family (Montan, 1987). In these programs, the source (heater) is represented by a line emplaced in an infinite, homogeneous, isotropic medium with constant material properties. Thus, the heater hole is not considered, nor is the latent heat of vaporization and the accompanying change of thermal properties.

The power was input as a constant for the first 13 weeks and then decreased in twelve 2-week long steps to zero at 37 weeks. The power input for the 6-m heater is shown in Fig. 1. The power input for the 4.5-m heater is almost the same, except for being reduced by a factor of 0.85.

The values of the material properties used were:

Thermal conductivity	2 W/m•K
Thermal diffusivity	10^{-6} m^2/s
Thermal expansion coefficient	10^{-5}/K
Young's modulus	15 GPa
Poisson's ratio	0.2
Ambient temperature	25°C

The temperatures calculated are actual, and the displacements and stresses are differential, caused by the temperature changes.

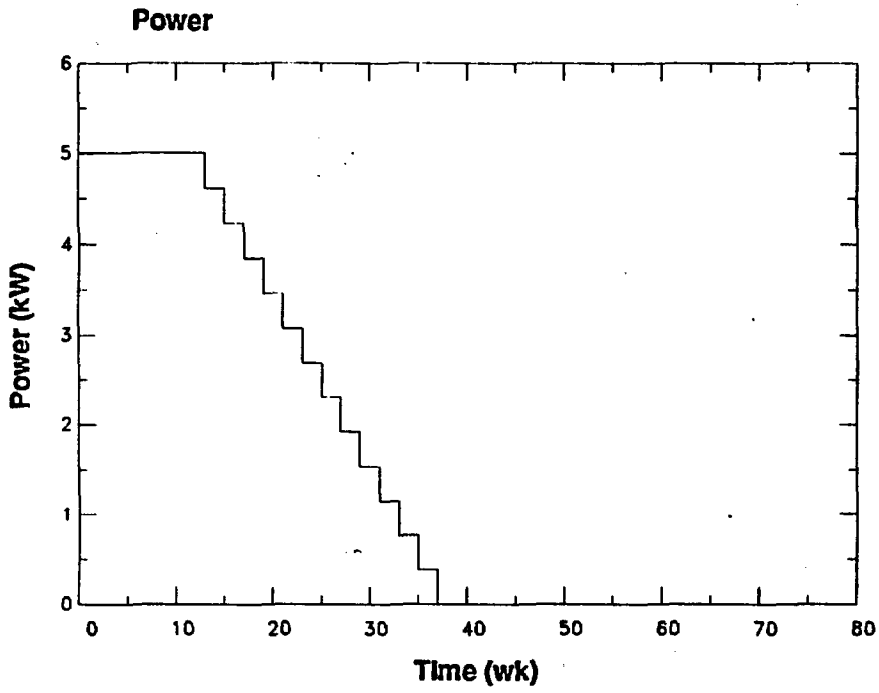


Figure 1. Power history for the 6-m heater.

4.0 CALCULATIONAL RESULTS

Three pairs of calculations were made using CELERY, TWIGS, and DAYLITE from the PLUS Family. Each pair consisted of a 6-m heater calculation and a 4.5-m heater calculation.

The CELERY calculations produced time histories of temperature, displacement, and stress change at 4 locations in the plane perpendicular to the heater and passing through its center. The locations were the position of the heater hole wall (0.15 m from heater center) and 0.5, 1.0, and 1.5 m from it, as shown in Fig. 2. The results are shown in Figs. 3 through 7. Since the points are in the plane of symmetry of the heater, the only displacement is radial and the radial, axial, and hoop (tangential) stresses are principal stresses.

Program TWIGS was used to calculate (in the same plane) temperature, displacement, and stresses as a function of distance from the hole wall at times of 6.5, 13, 26, 52, and 104 weeks. The results are shown in Figs. 8 through 12.

Program DAYLITE, which calculates and plots contours and vector and tensor fields, was used to examine a 6-by-6-m R-Z plane whose origin is the heater center. Calculations were performed at 6.5, 13, 26, and 52 weeks. Figures 13 through 20 show the results of these calculations at 13 and 26 weeks. Temperature and hoop stress (still a principal stress) are shown as contours, displacement is shown as a vector field, and principal stresses in the R-Z plane are shown as a tensor field.

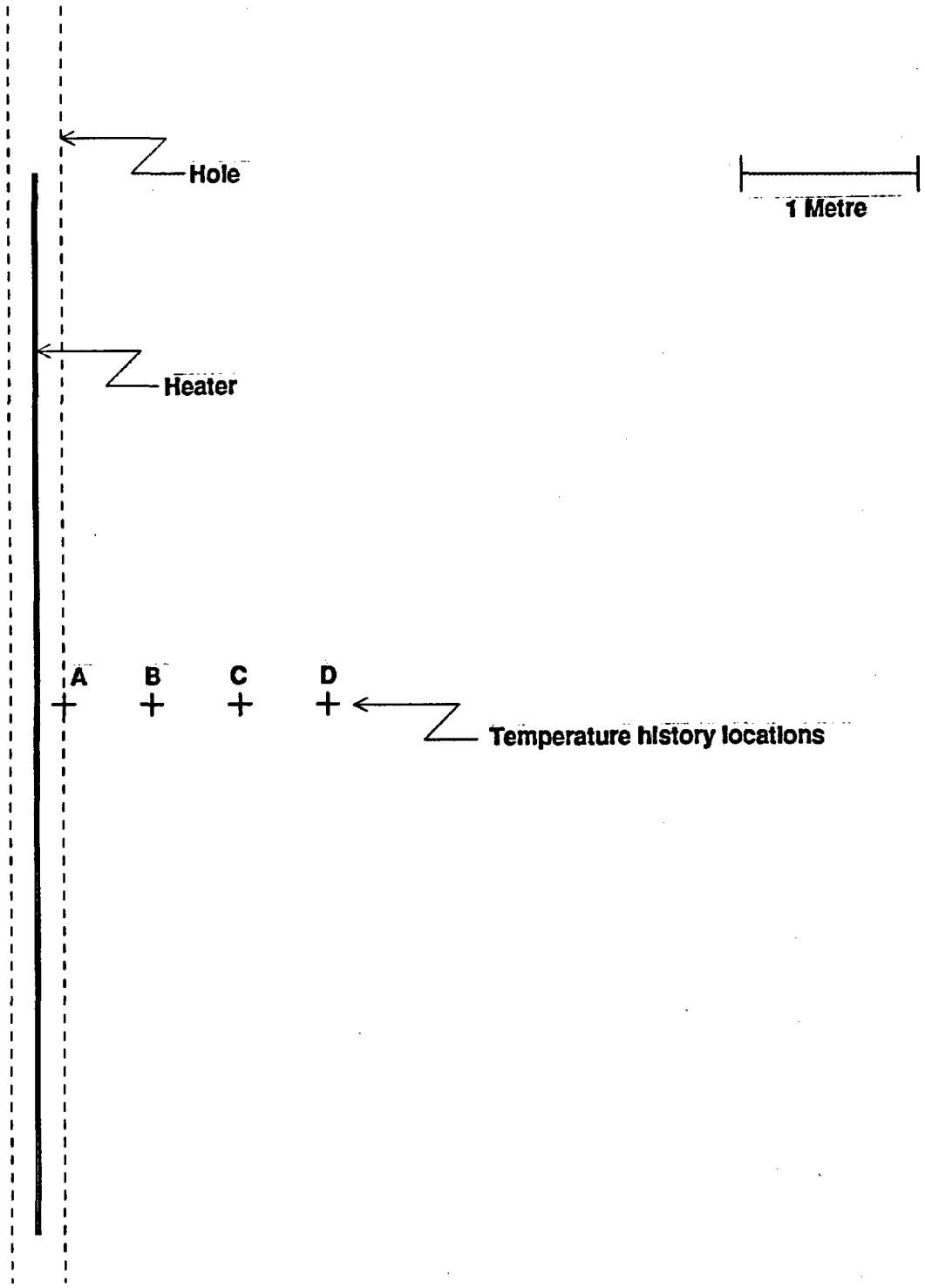
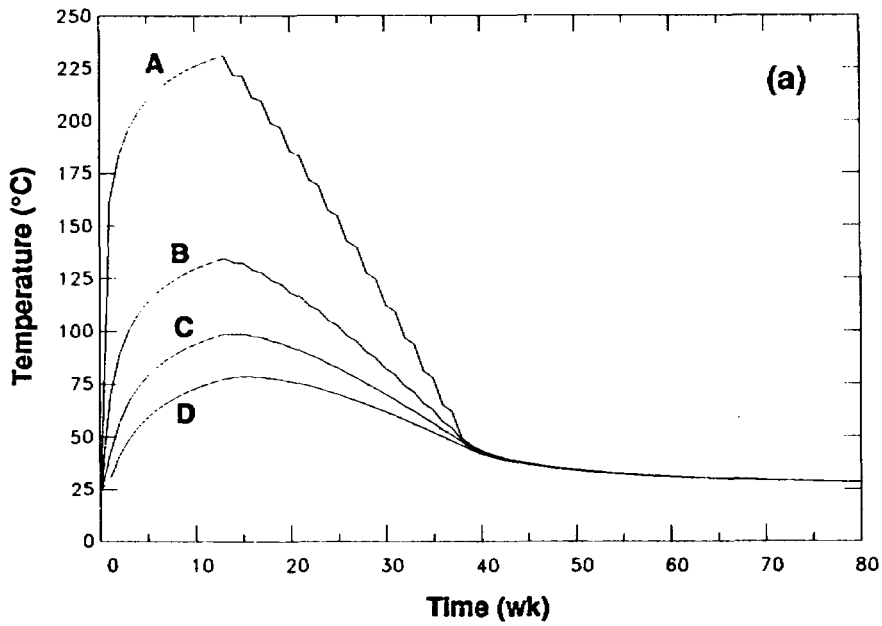


Figure 2. Geometry for the 6-m heater.



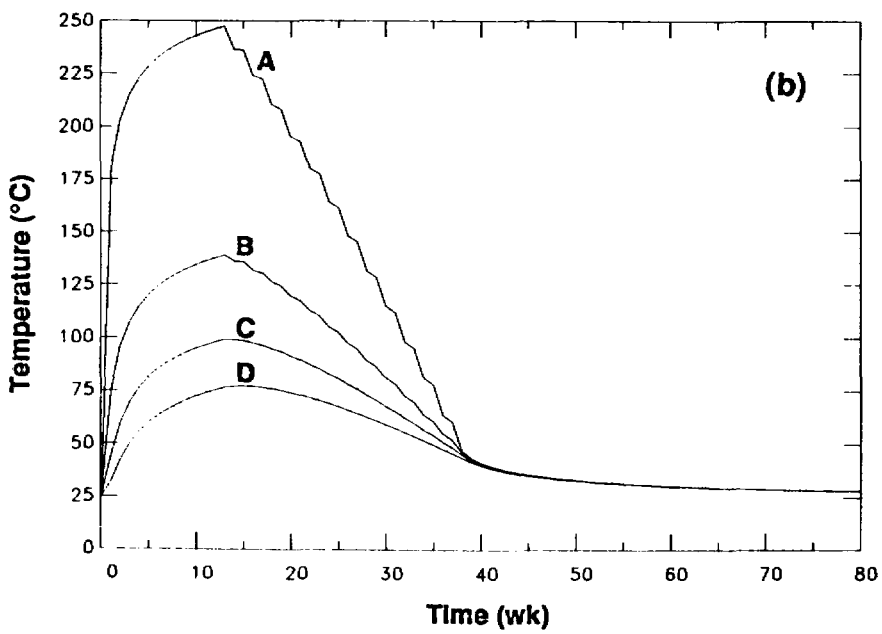


Figure 3. Temperature histories. (a) 6-m heater; and (b) 4.5-m heater.

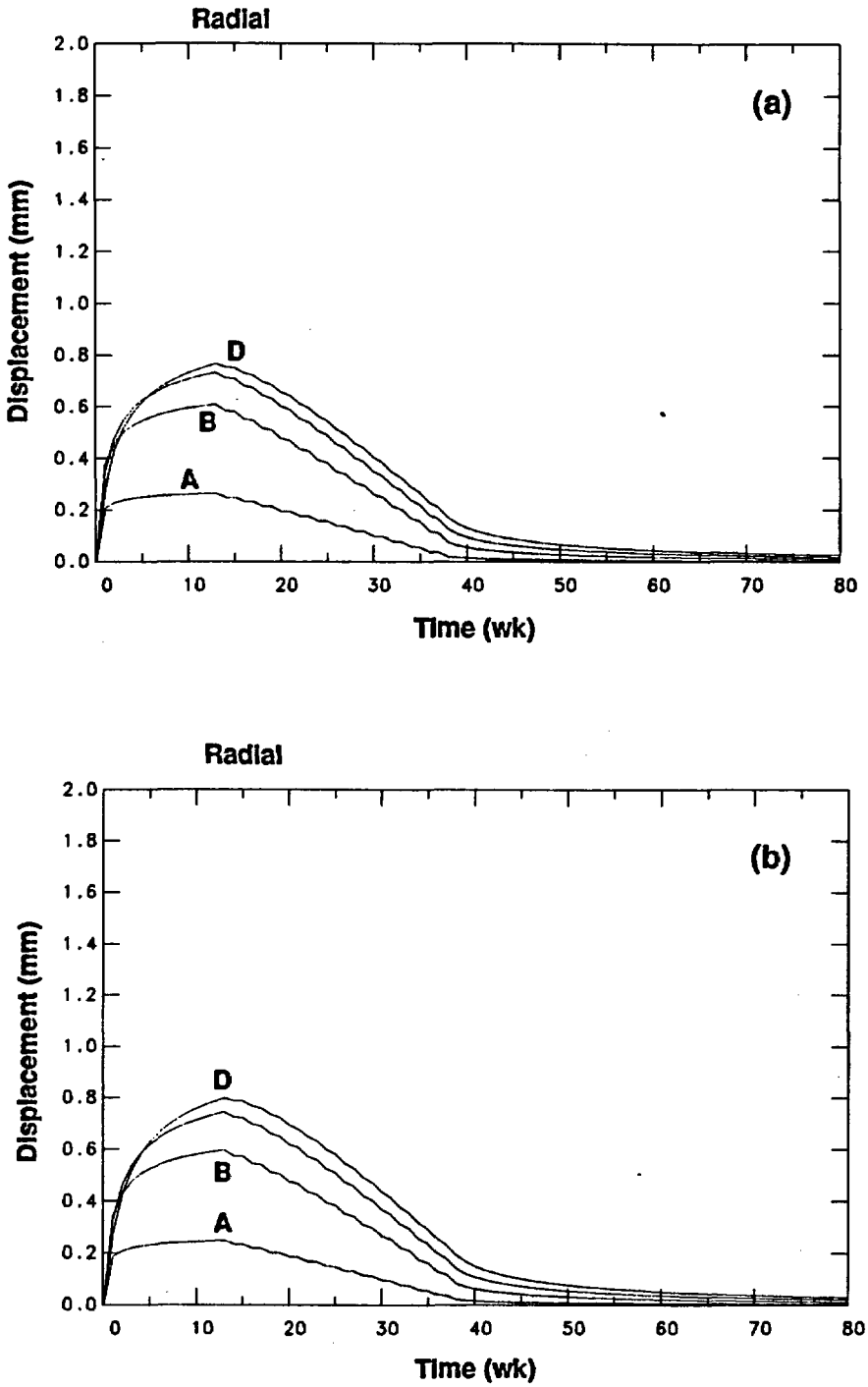
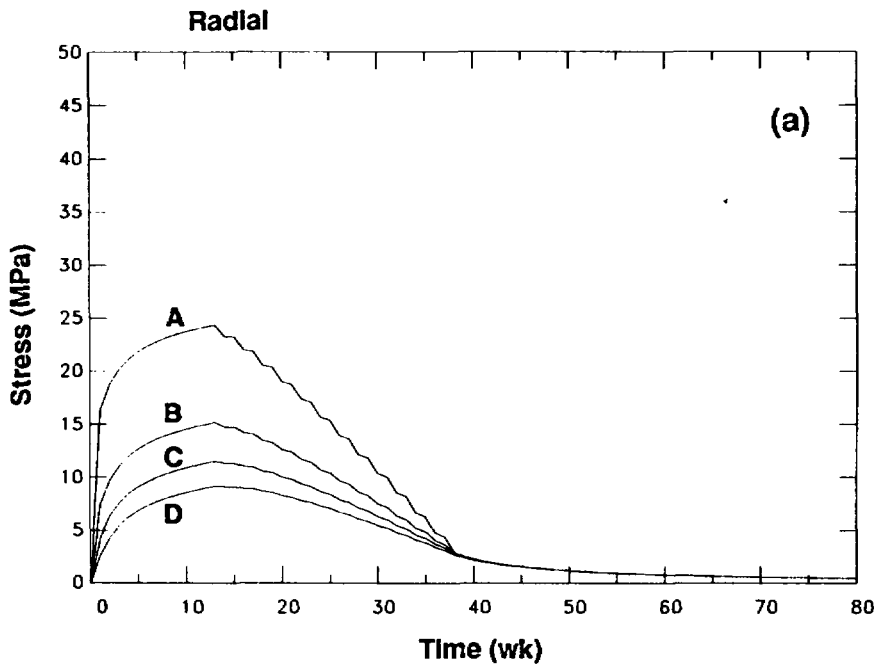


Figure 4. Radial displacement histories. (a) 6-m heater; and (b) 4.5-m heater.



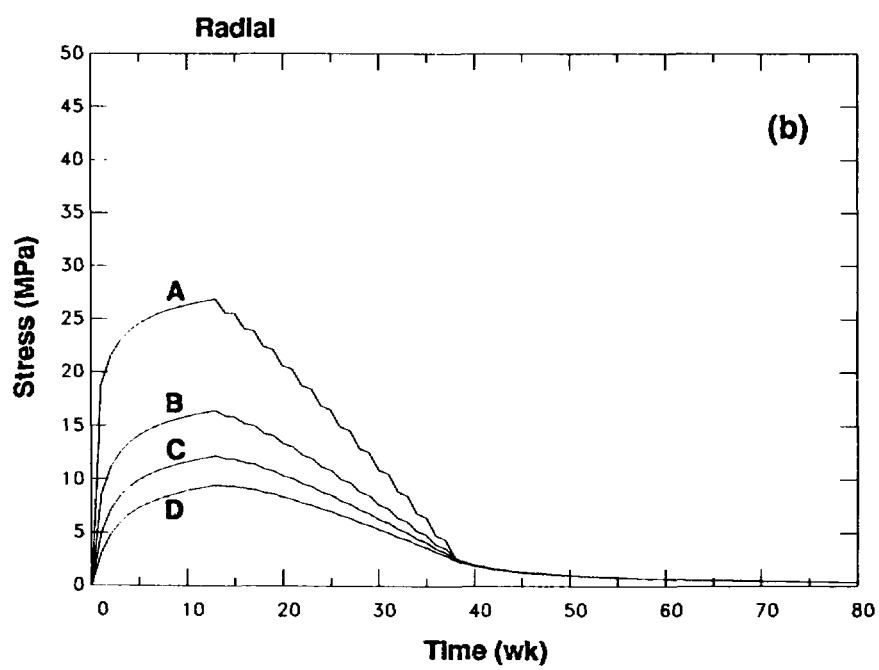
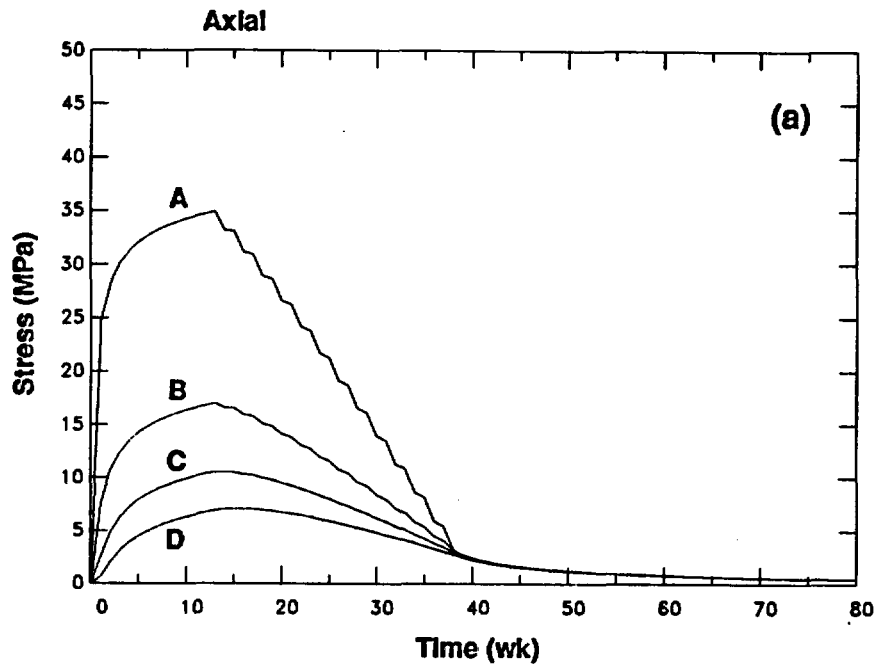


Figure 5. Radial stress histories. (a) 6-m heater; and (b) 4.5-m heater.



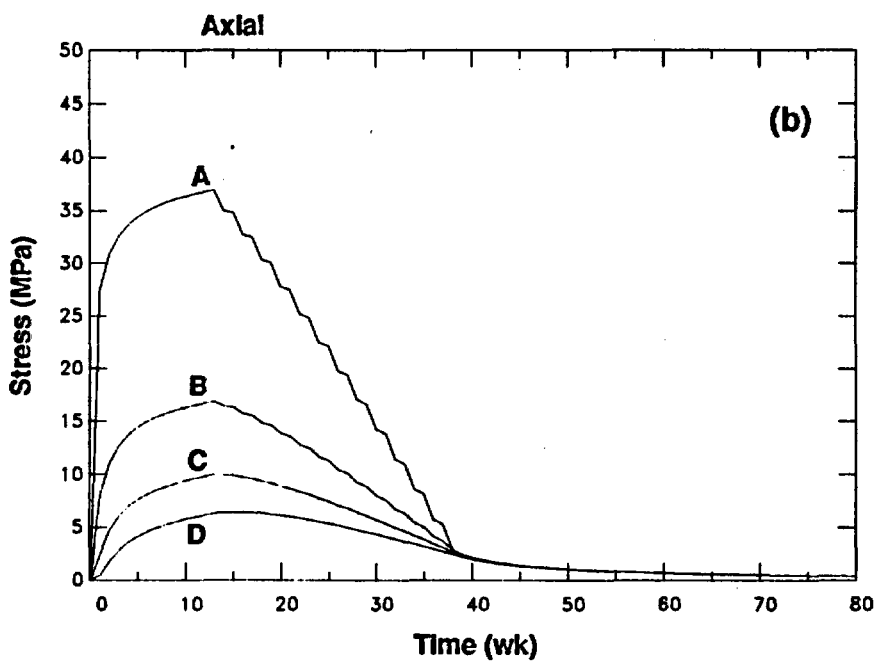
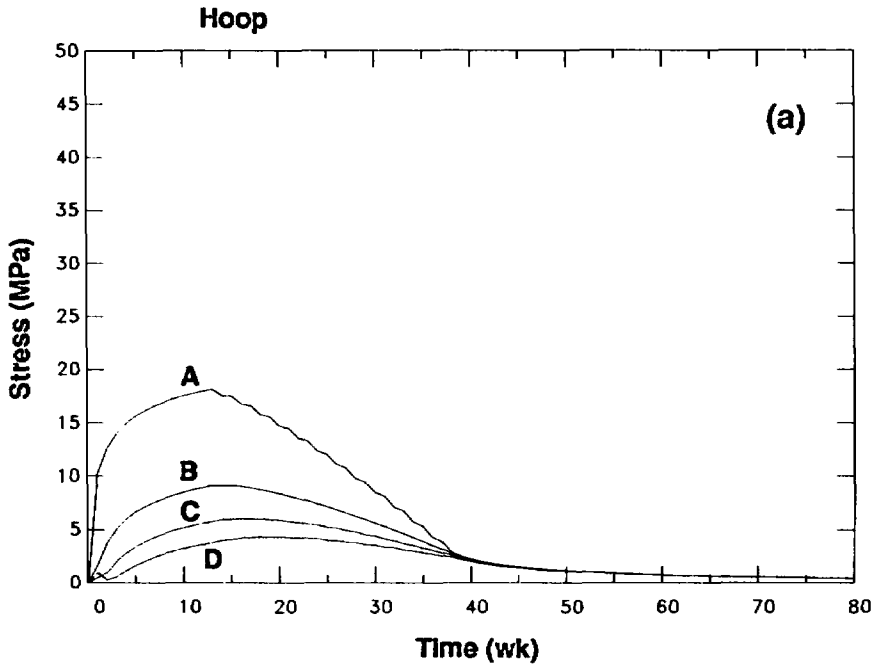


Figure 6. Axial stress histories. (a) 6-m heater; and (b) 4.5-m heater.



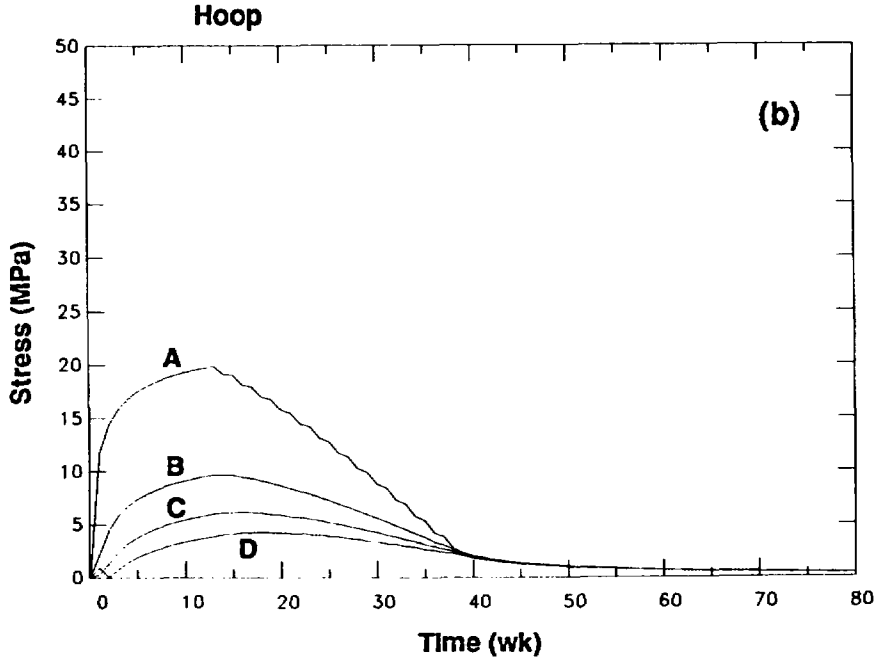
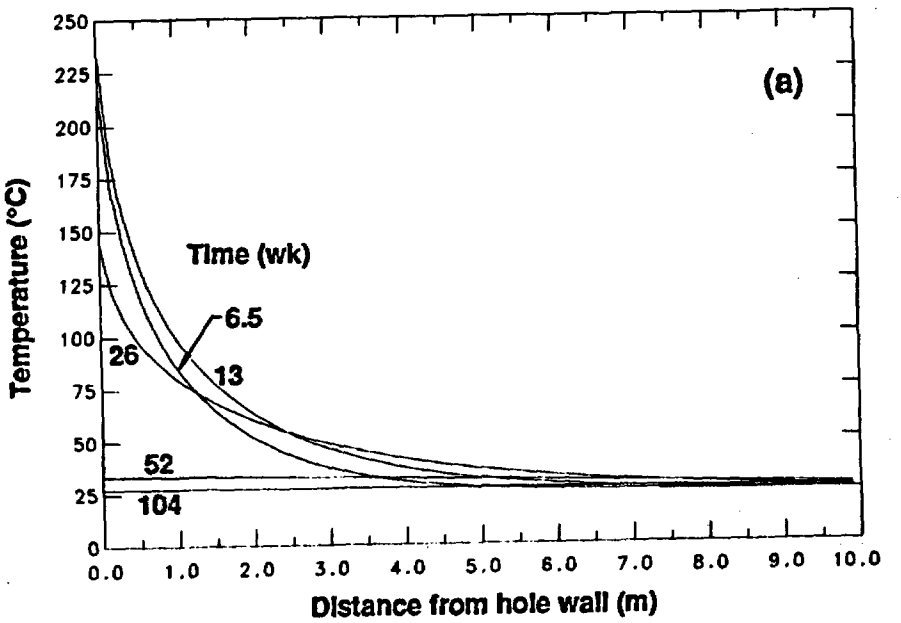


Figure 7. Hoop stress histories. (a) 6-m heater; and (b) 4.5-m heater.



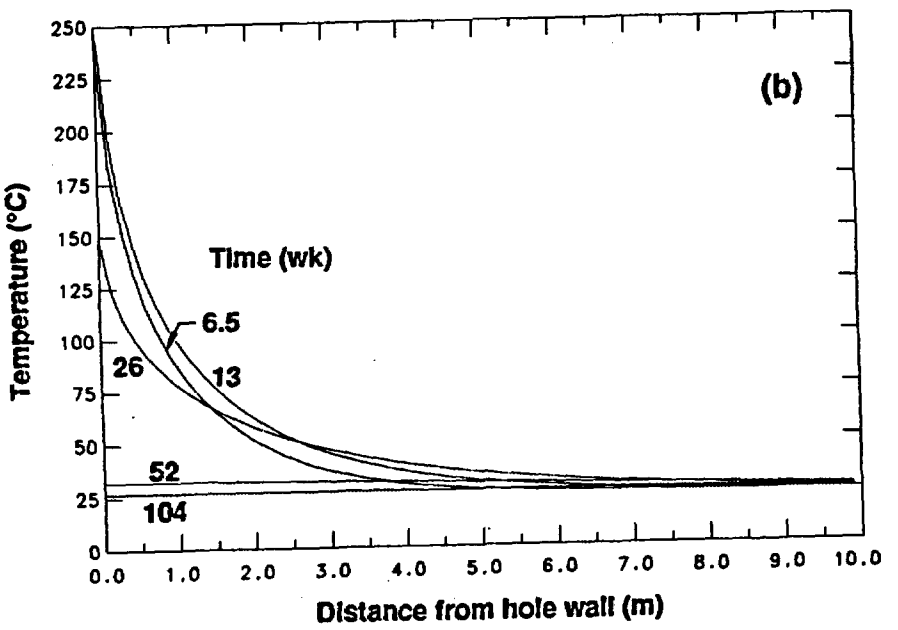
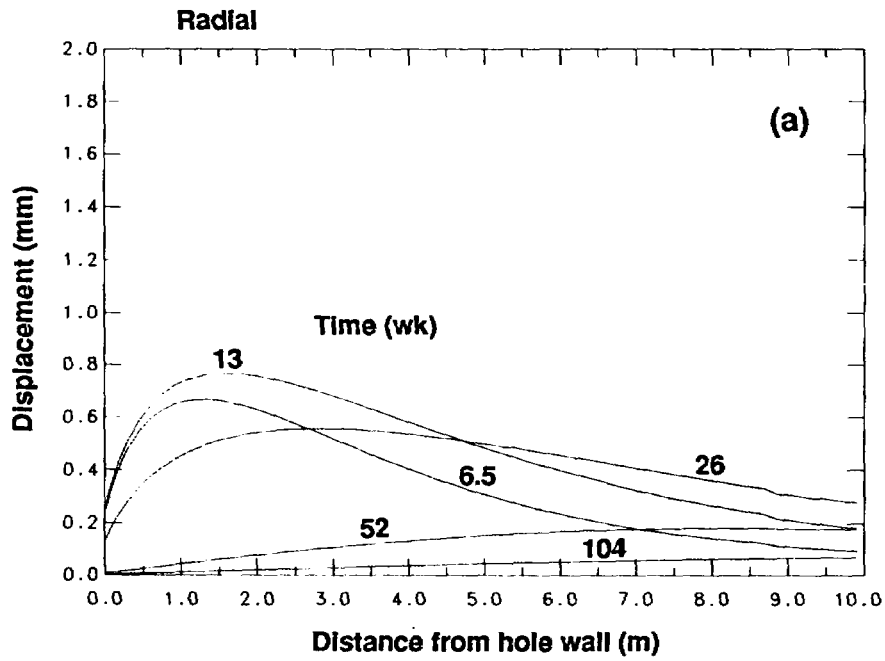


Figure 8. Temperature vs. distance. (a) 6-m heater; and (b) 4.5-m heater.



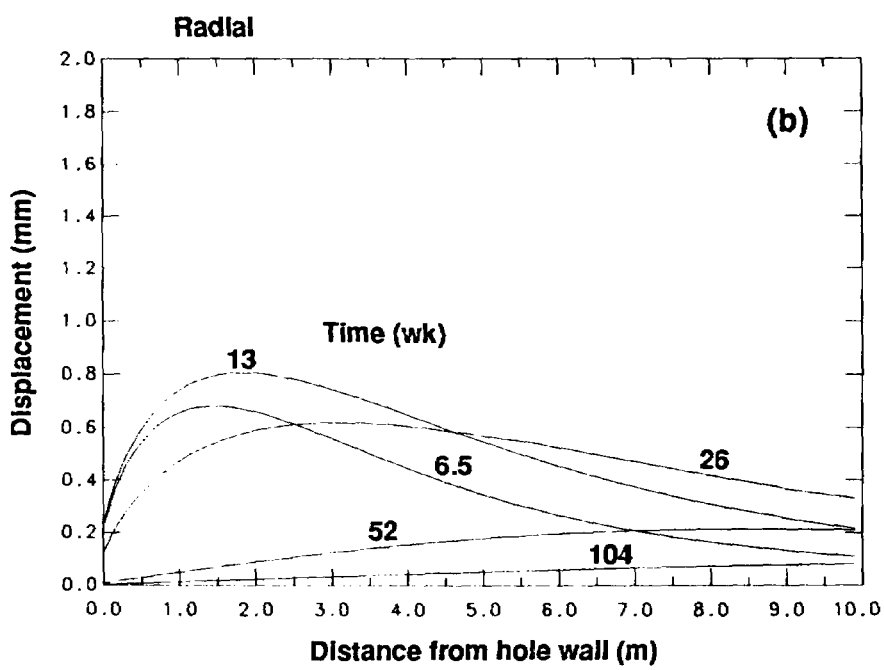
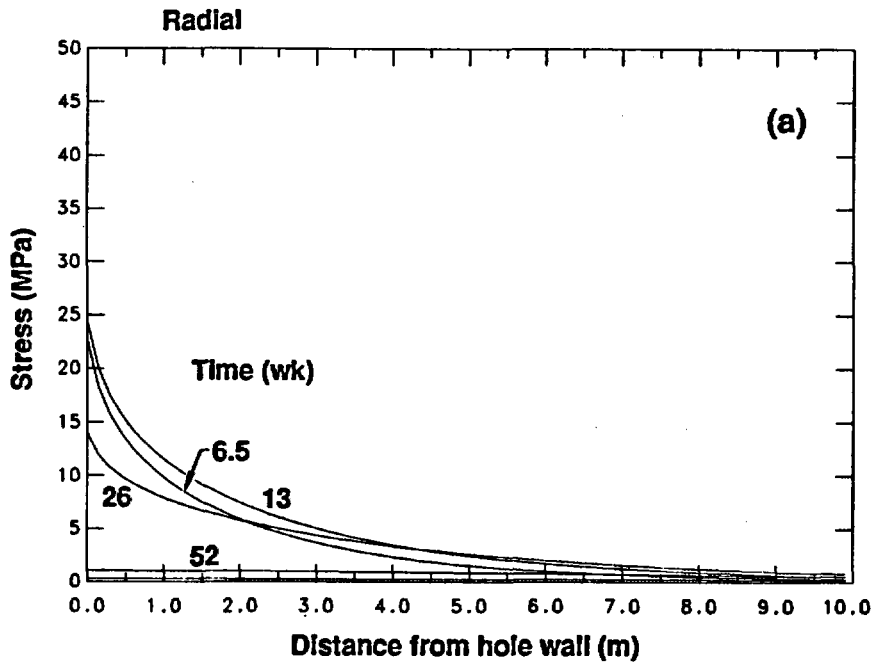


Figure 9. Radial displacement vs. distance. (a) 6-m heater; and (b) 4.5-m heater.



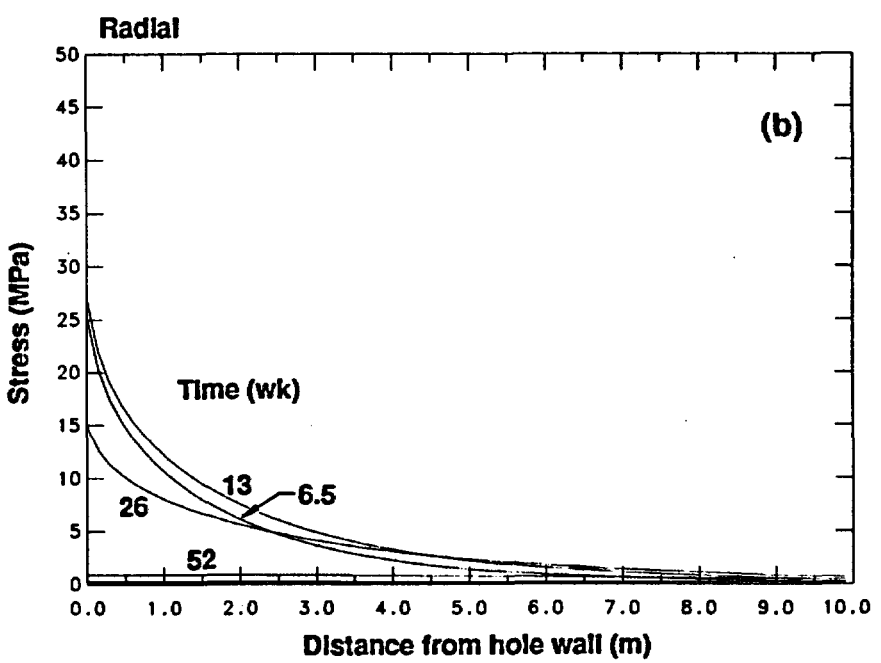
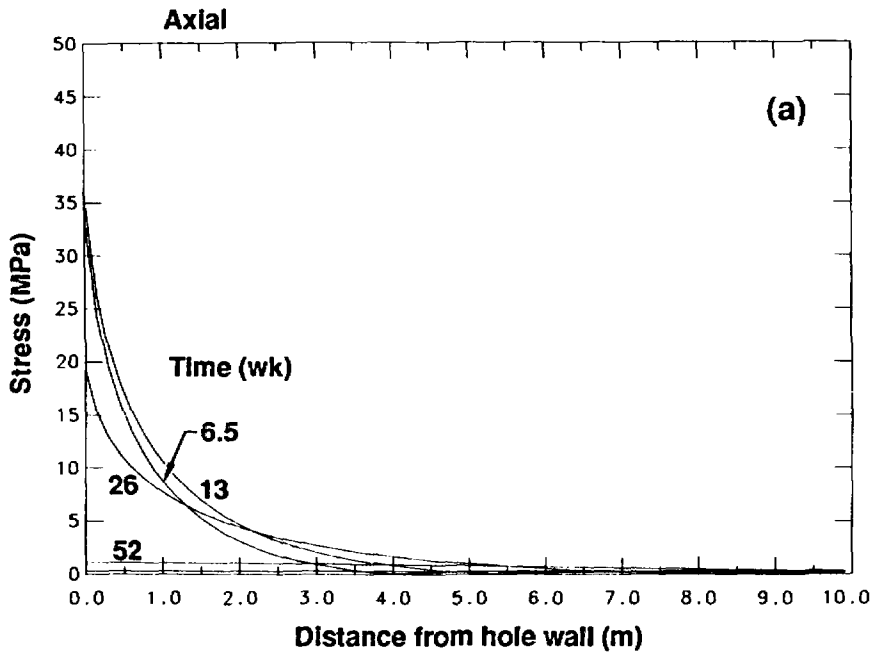


Figure 10. Radial stress vs. distance. (a) 6-m heater; and (b) 4.5-m heater.



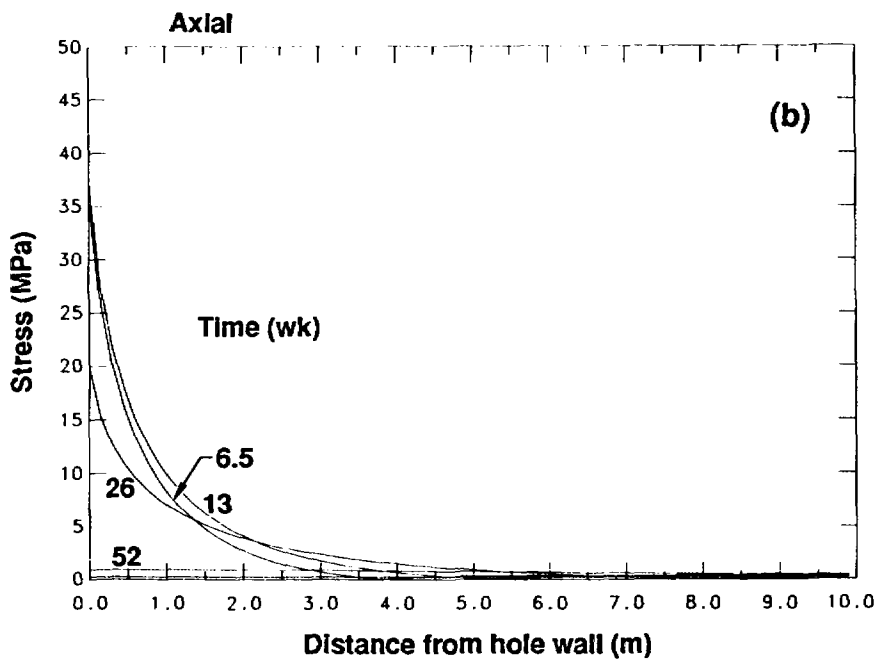
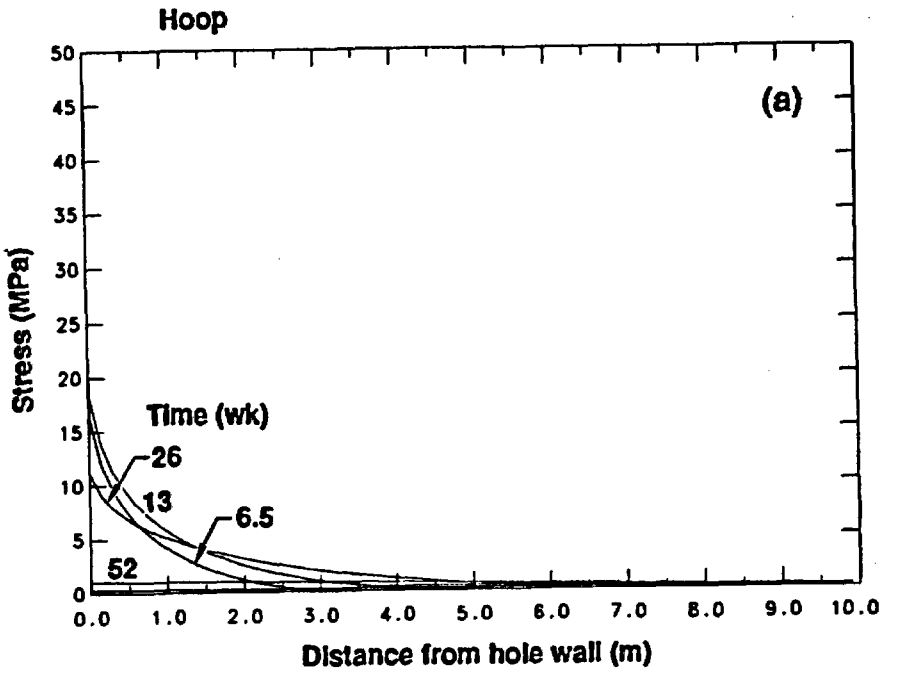


Figure 11. Axial stress vs. distance. (a) 6-m heater; and (b) 4.5-m heater.



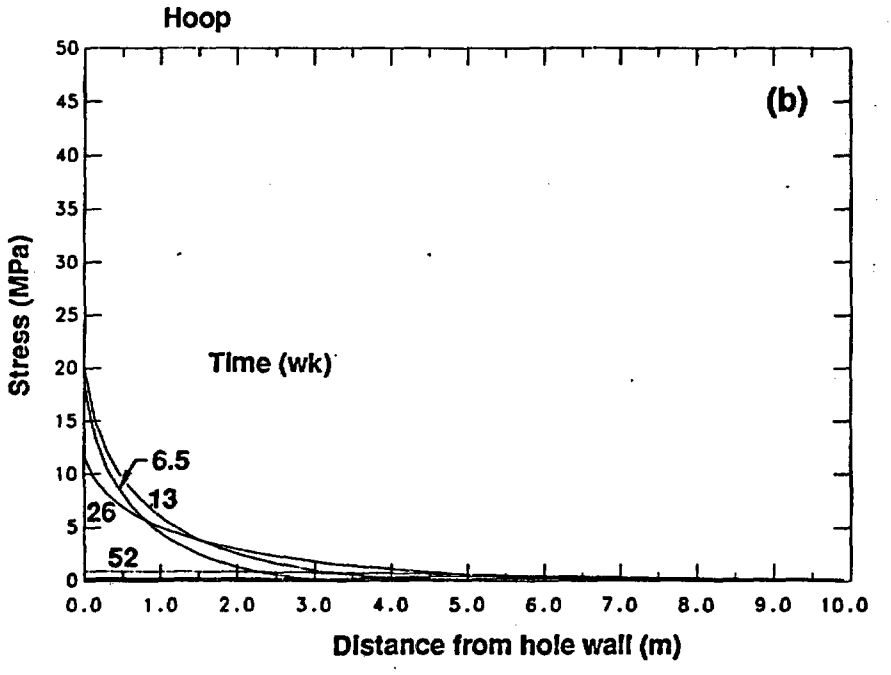


Figure 12. Hoop stress vs. distance. (a) 6-m heater; and (b) 4.5-m heater.

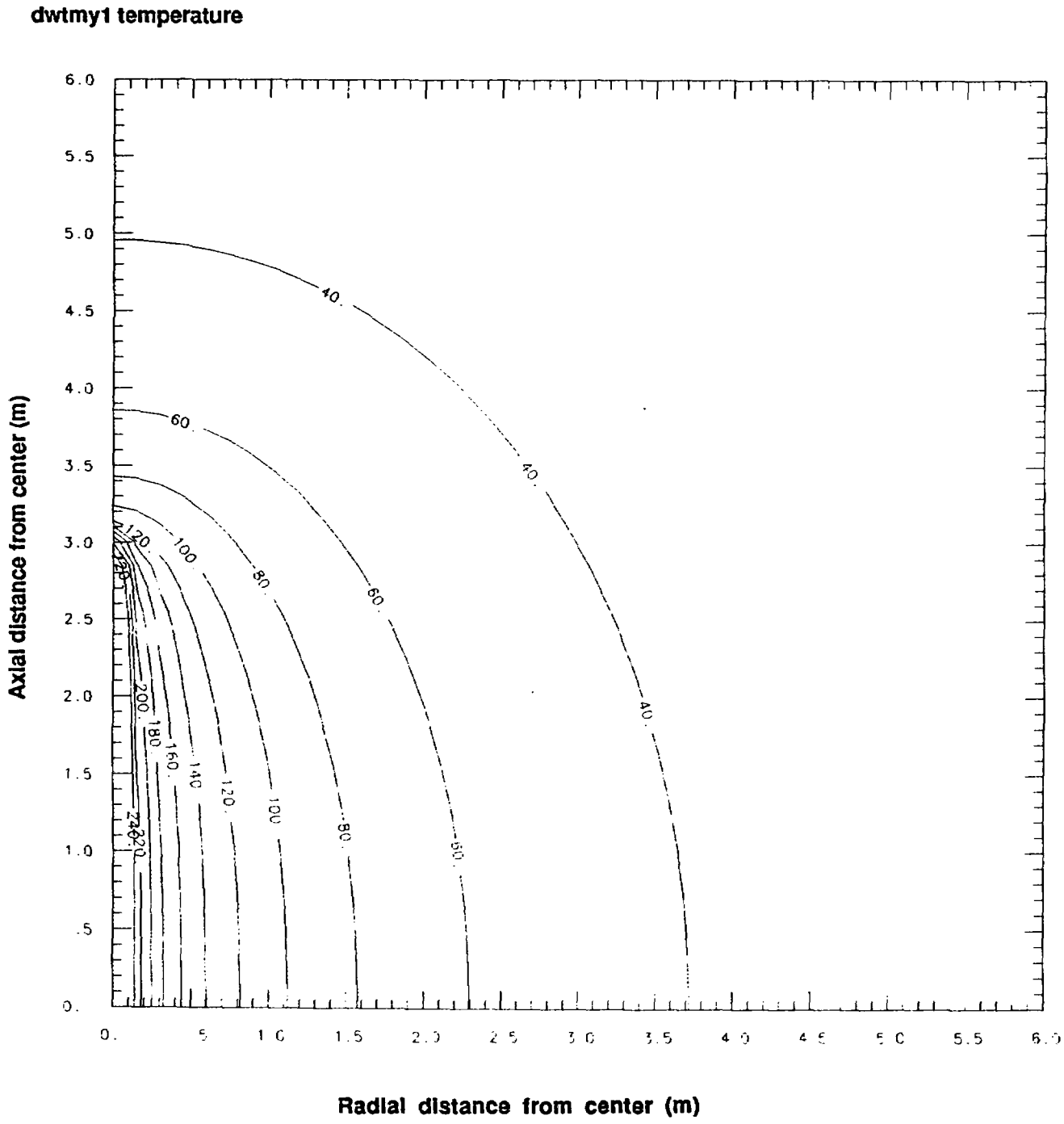


Figure 13a. Temperatures (°C) in the R-Z plane at 13 weeks; 6-m heater.

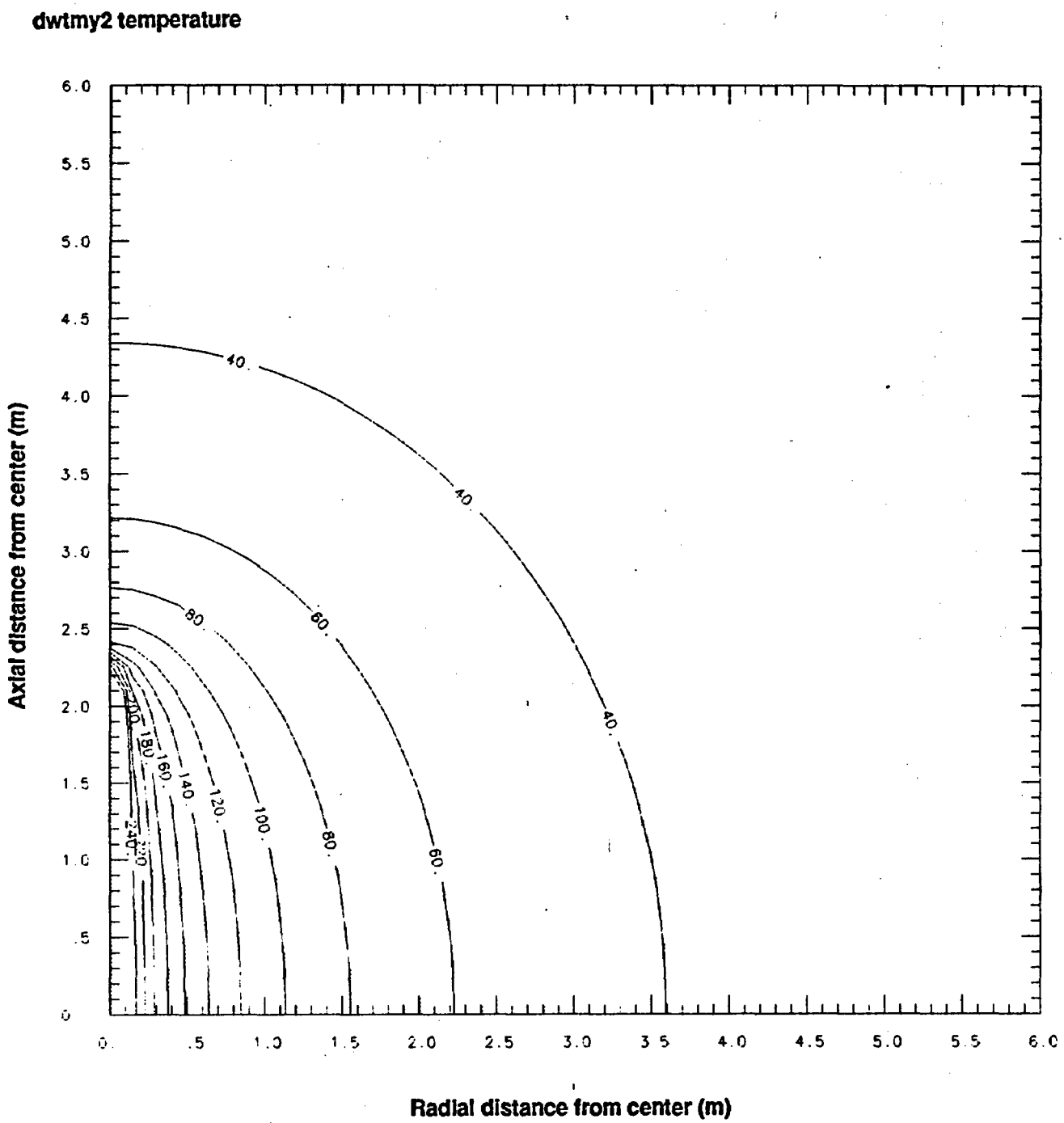


Figure 13b. Temperatures (°C) in the R-Z plane at 13 weeks; 4.5-m heater.

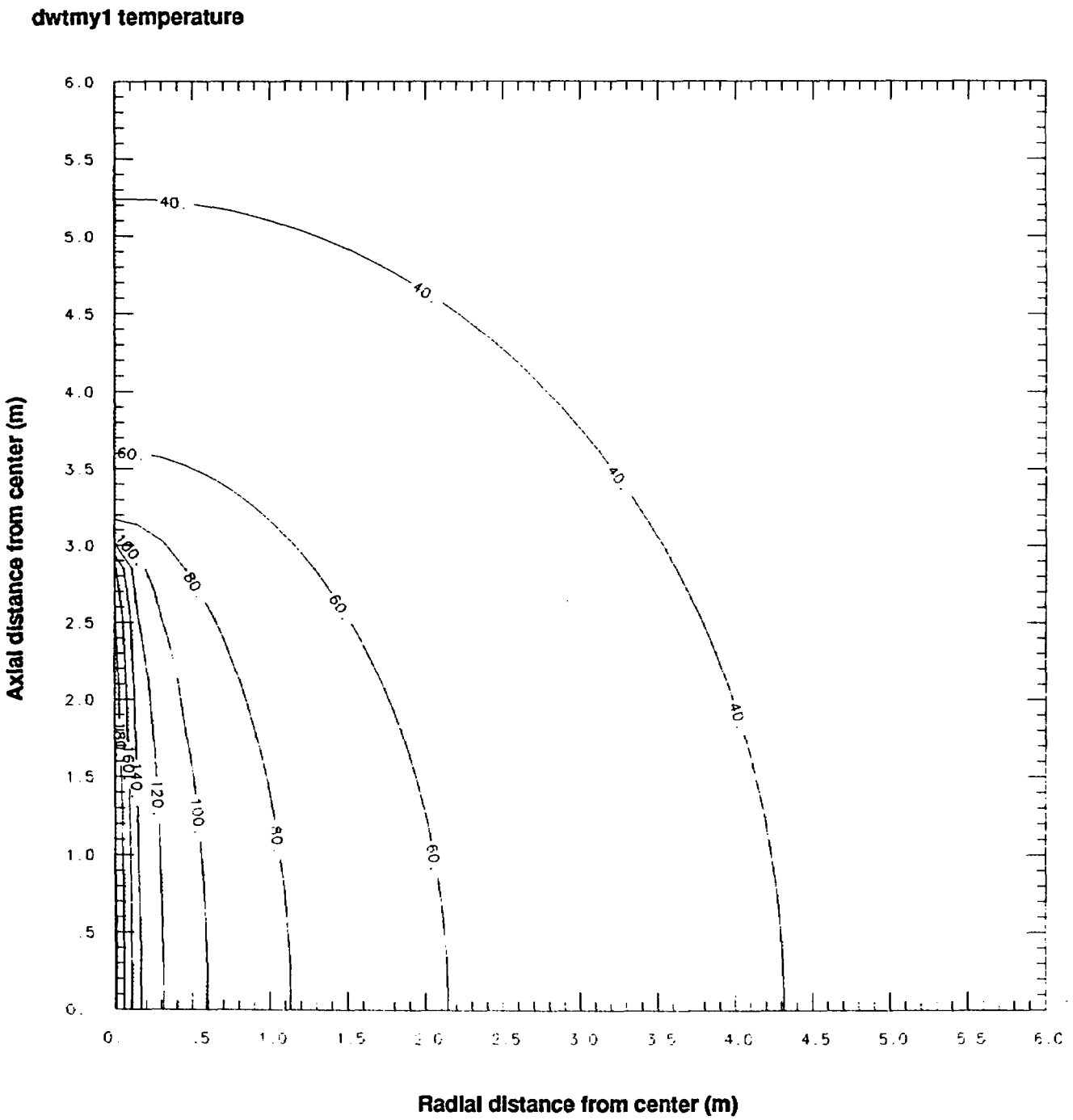


Figure 14a. Temperatures (°C) in the R-Z plane at 26 weeks; 6-m heater.

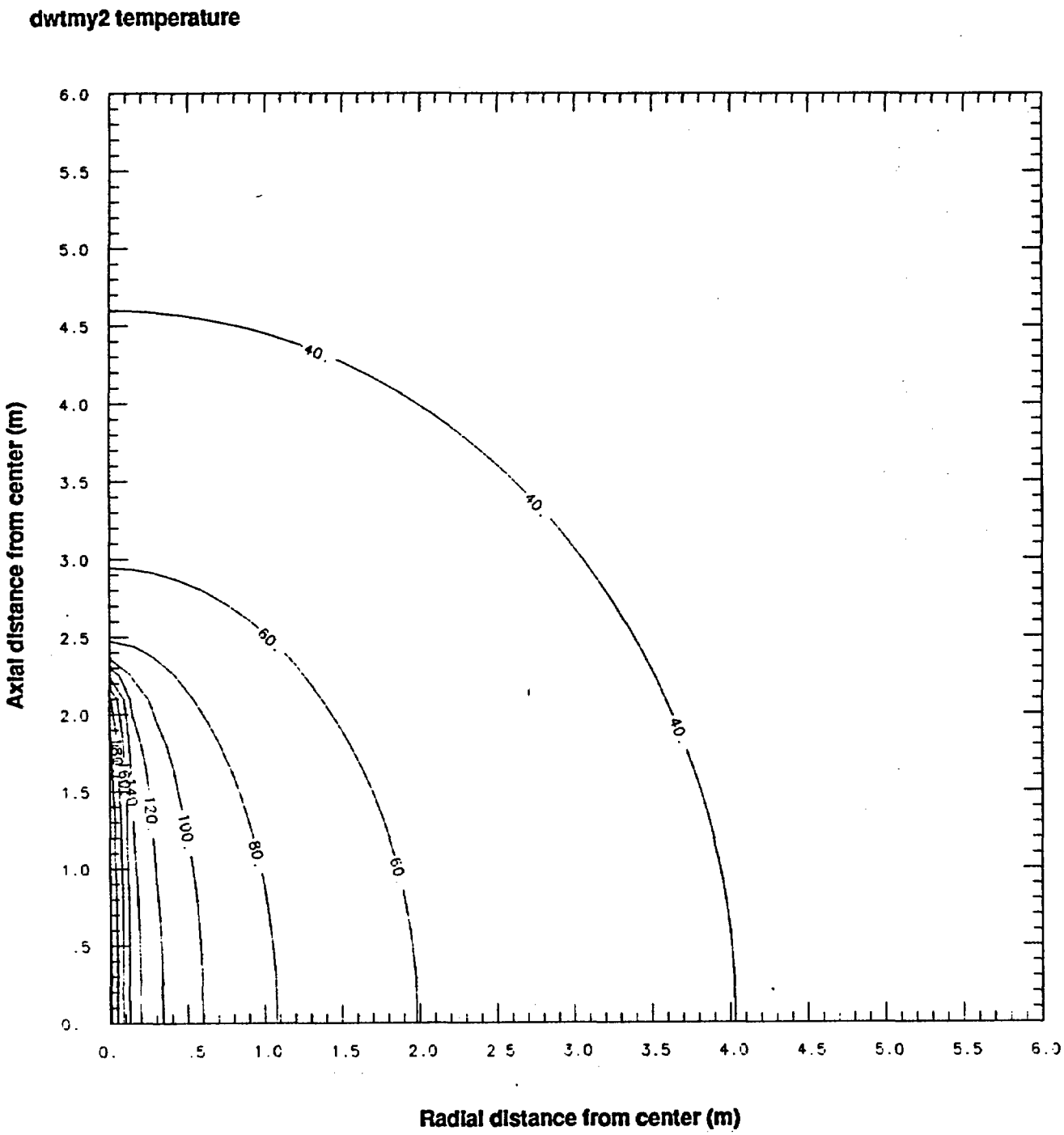


Figure 14b. Temperatures (°C) in the R-Z plane at 26 weeks; 4.5-m heater.

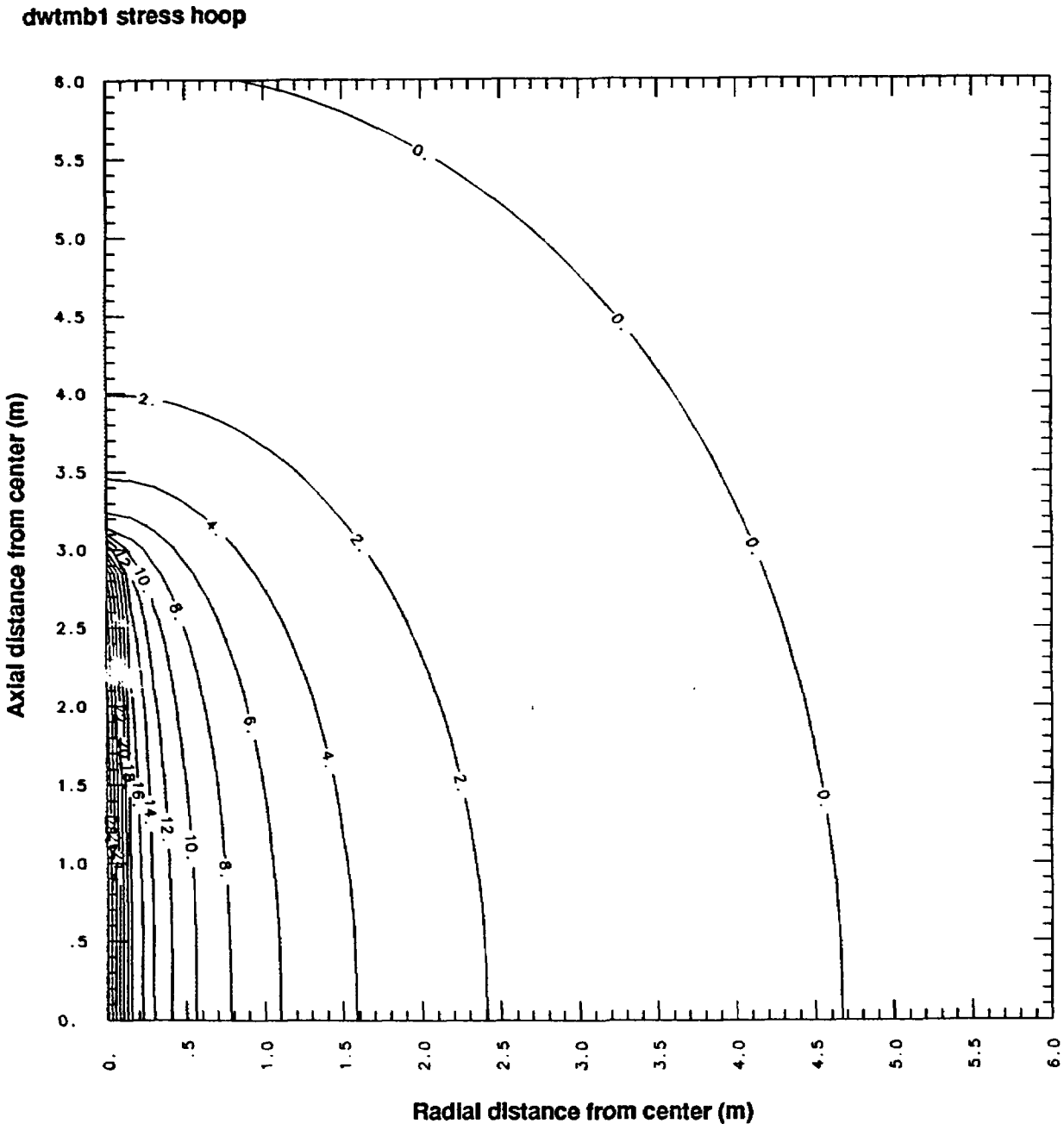


Figure 15a. Hoop stress (MPa) in the R-Z plane at 13 weeks; 6-m heater.

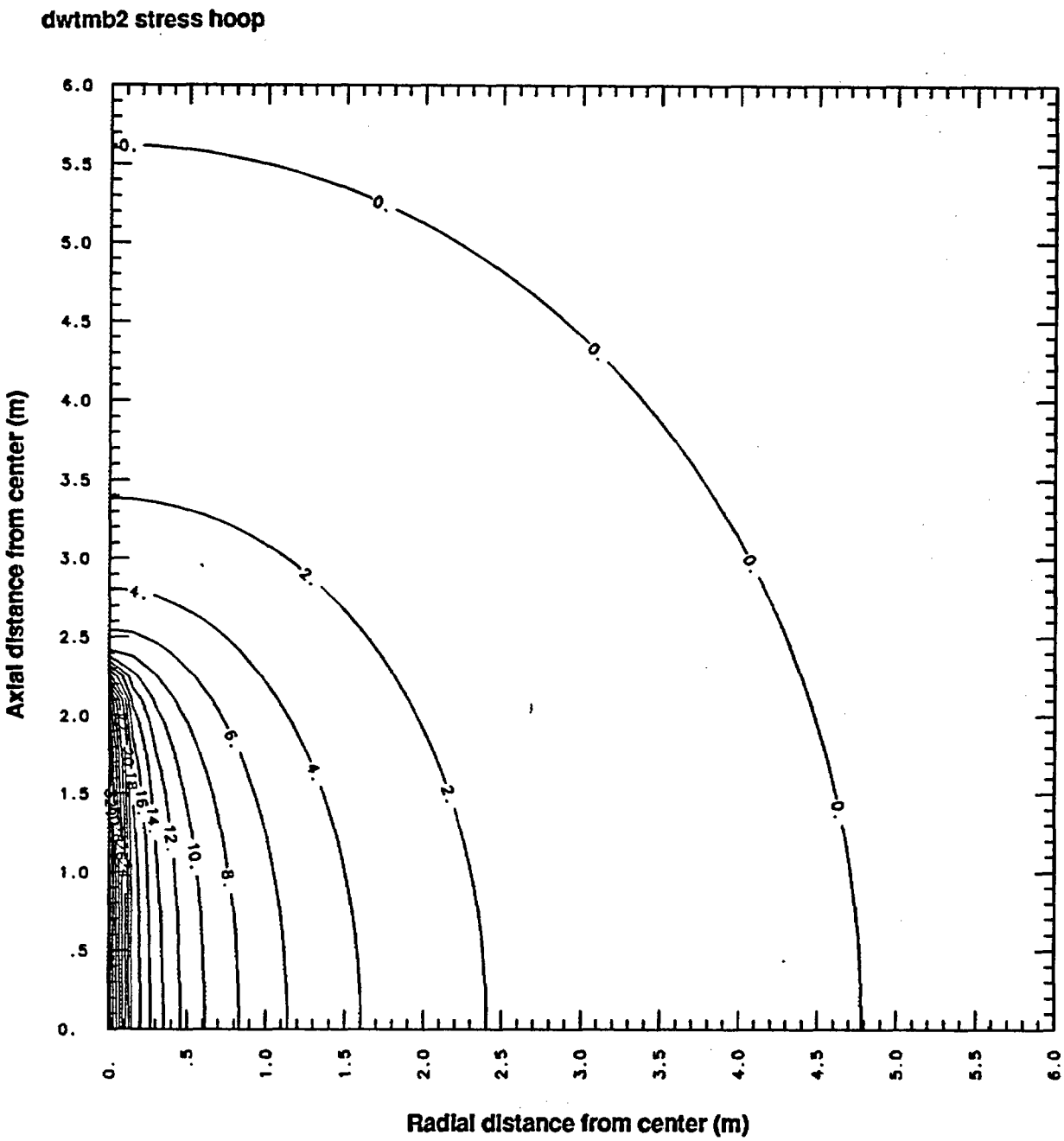


Figure 15b. Hoop stress (MPa) in the R-Z plane at 13 weeks; 4.5-m heater.

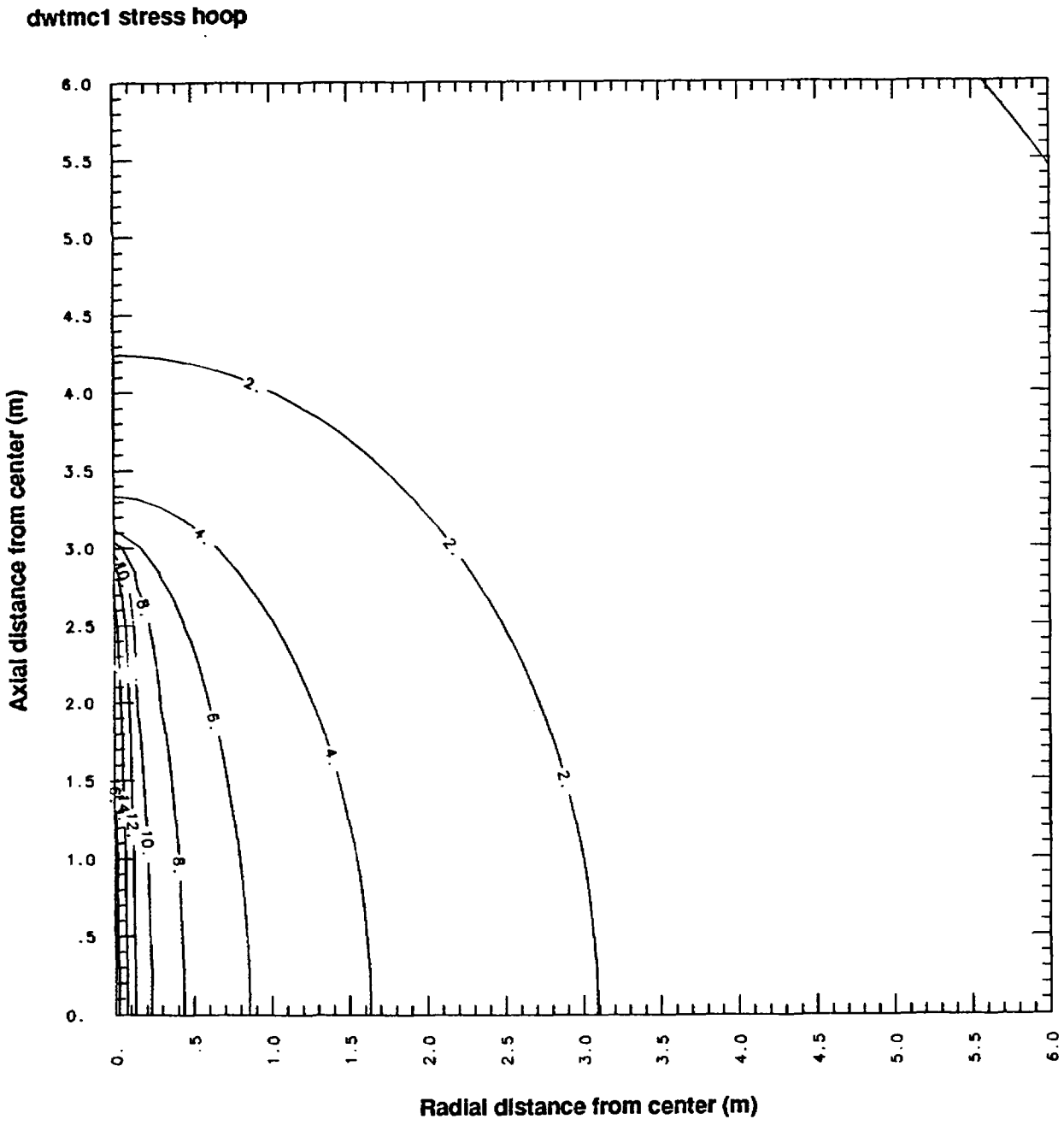


Figure 16a. Hoop stress (MPa) in the R-Z plane at 26 weeks; 6-m heater.

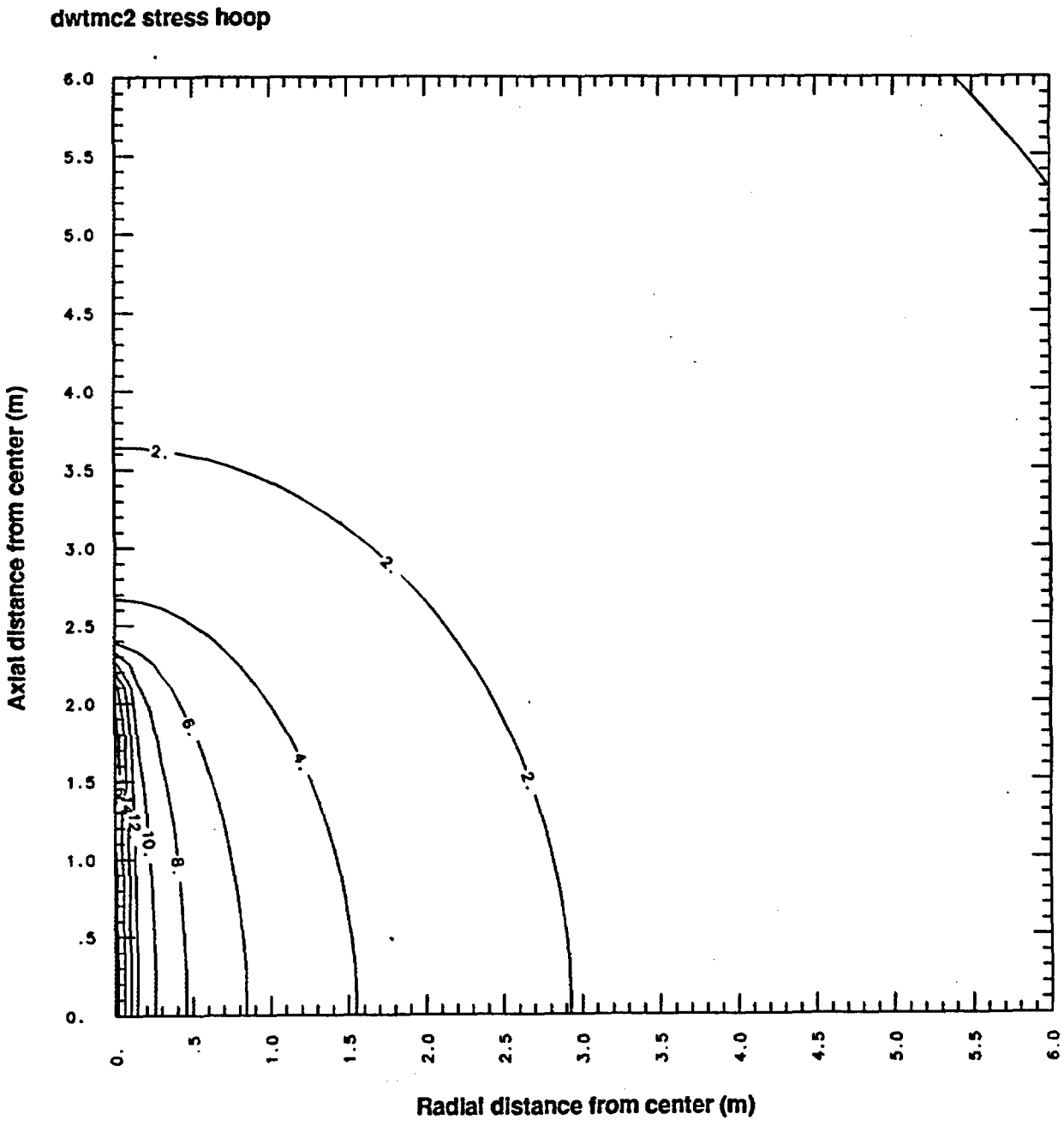


Figure 16b. Hoop stress (MPa) in the R-Z plane at 26 weeks; 4.5-m heater.

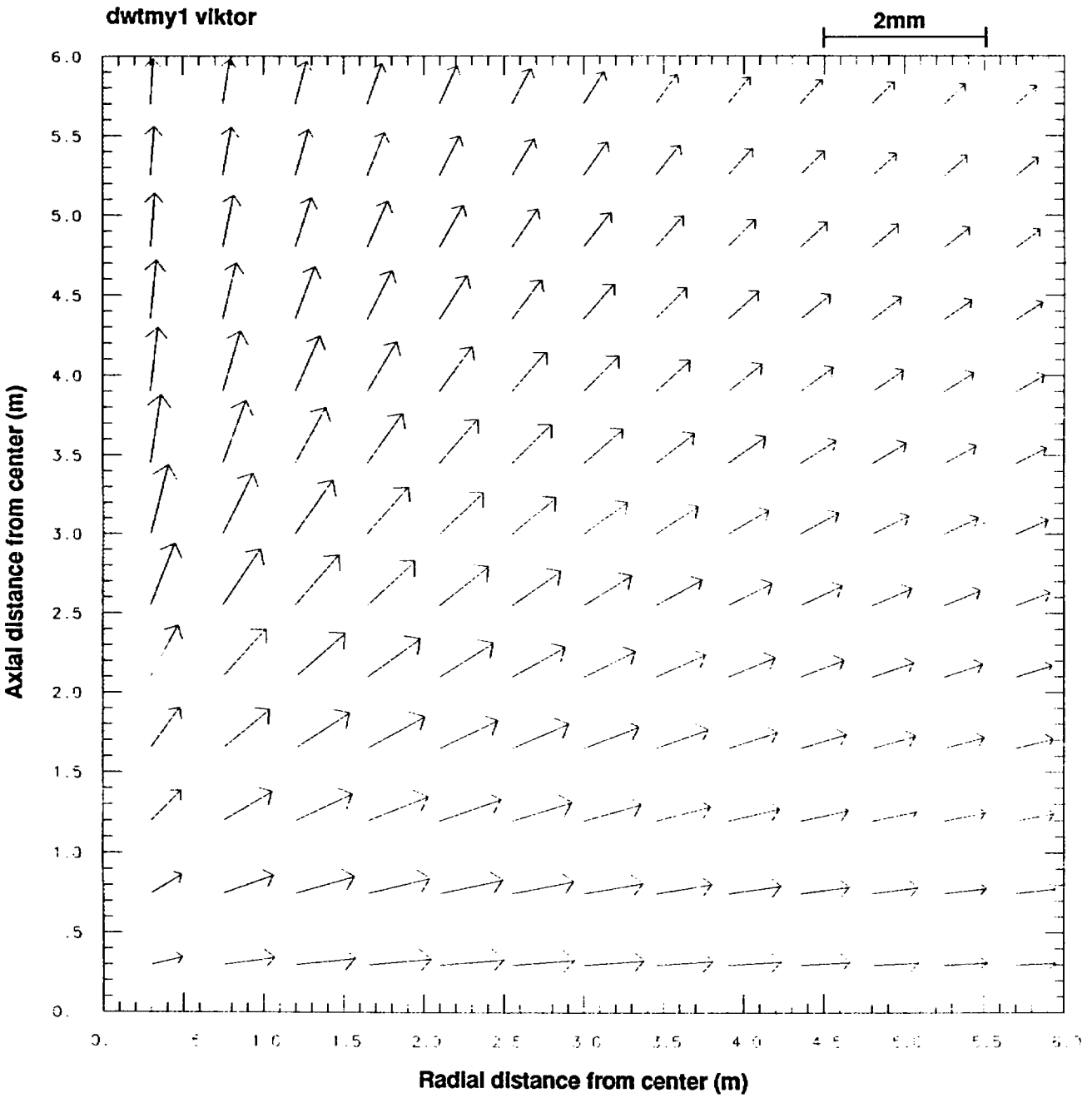


Figure 17a. Displacements in the R-Z plane at 13 weeks; 6-m heater.

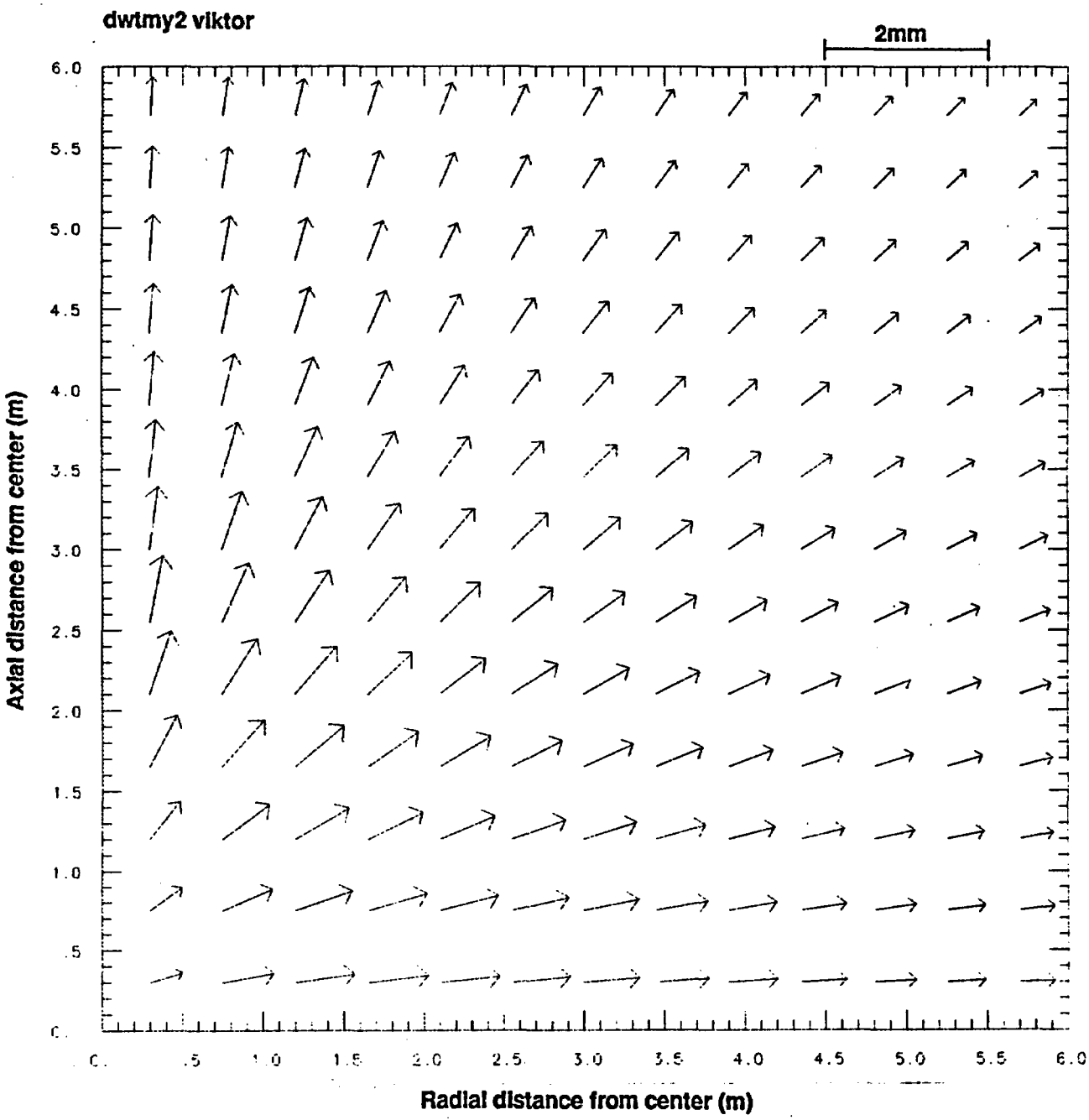


Figure 17b. Displacements in the R-Z plane at 13 weeks; 4.5-m heater.

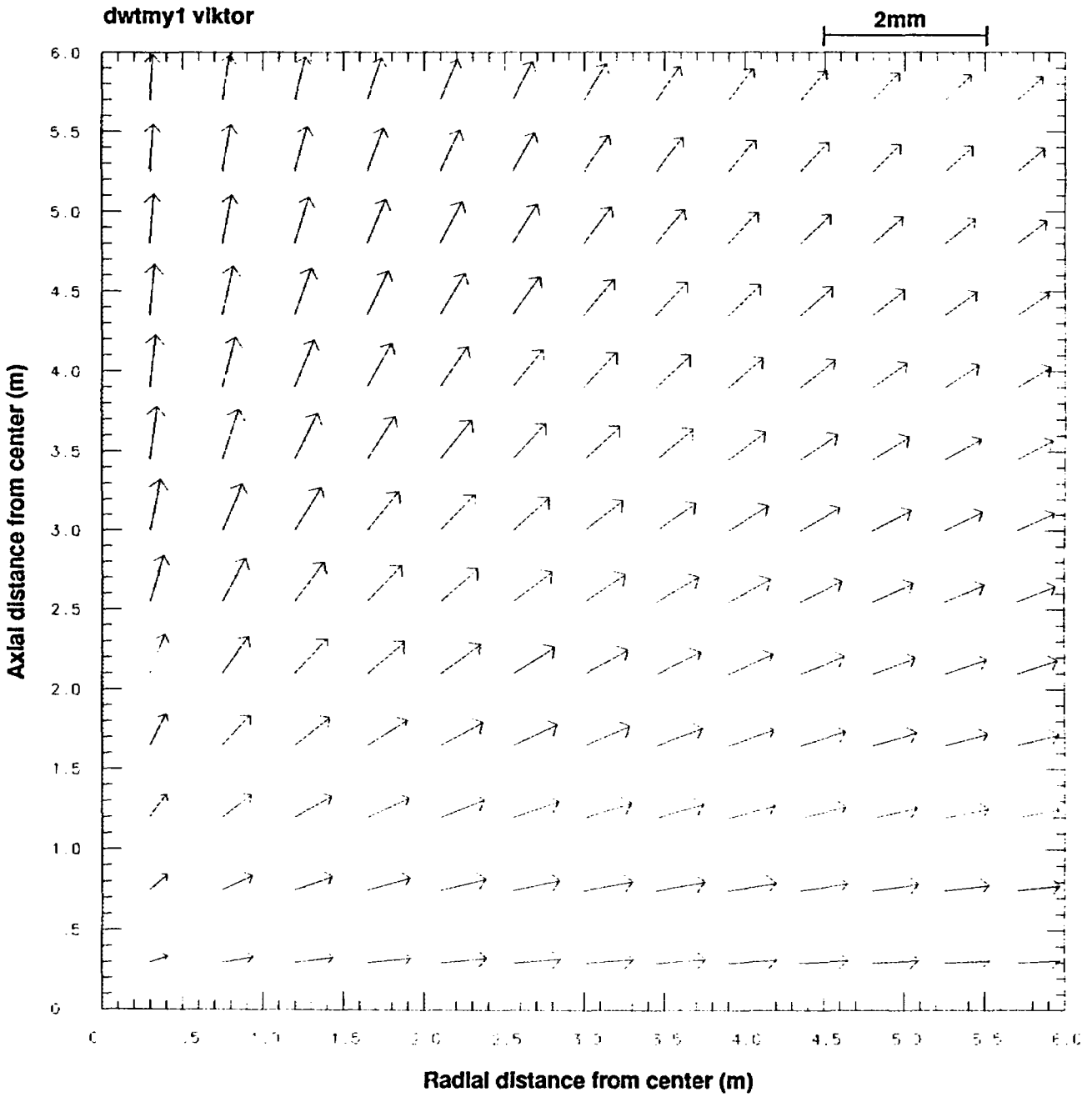


Figure 18a. Displacements in the R-Z plane at 26 weeks; 6-m heater.

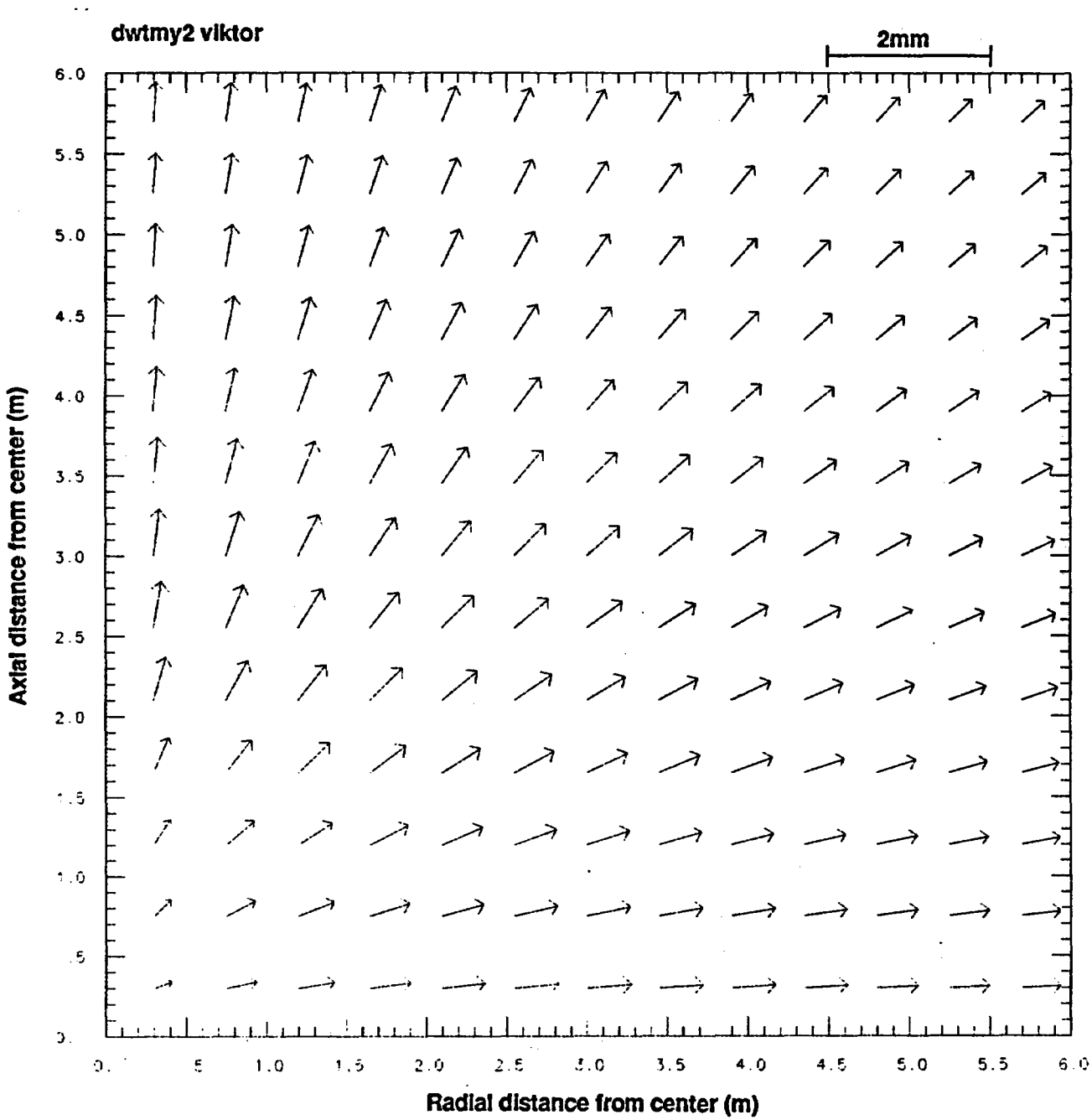


Figure 18b. Displacements in the R-Z plane at 26 weeks; 4.5-m heater.

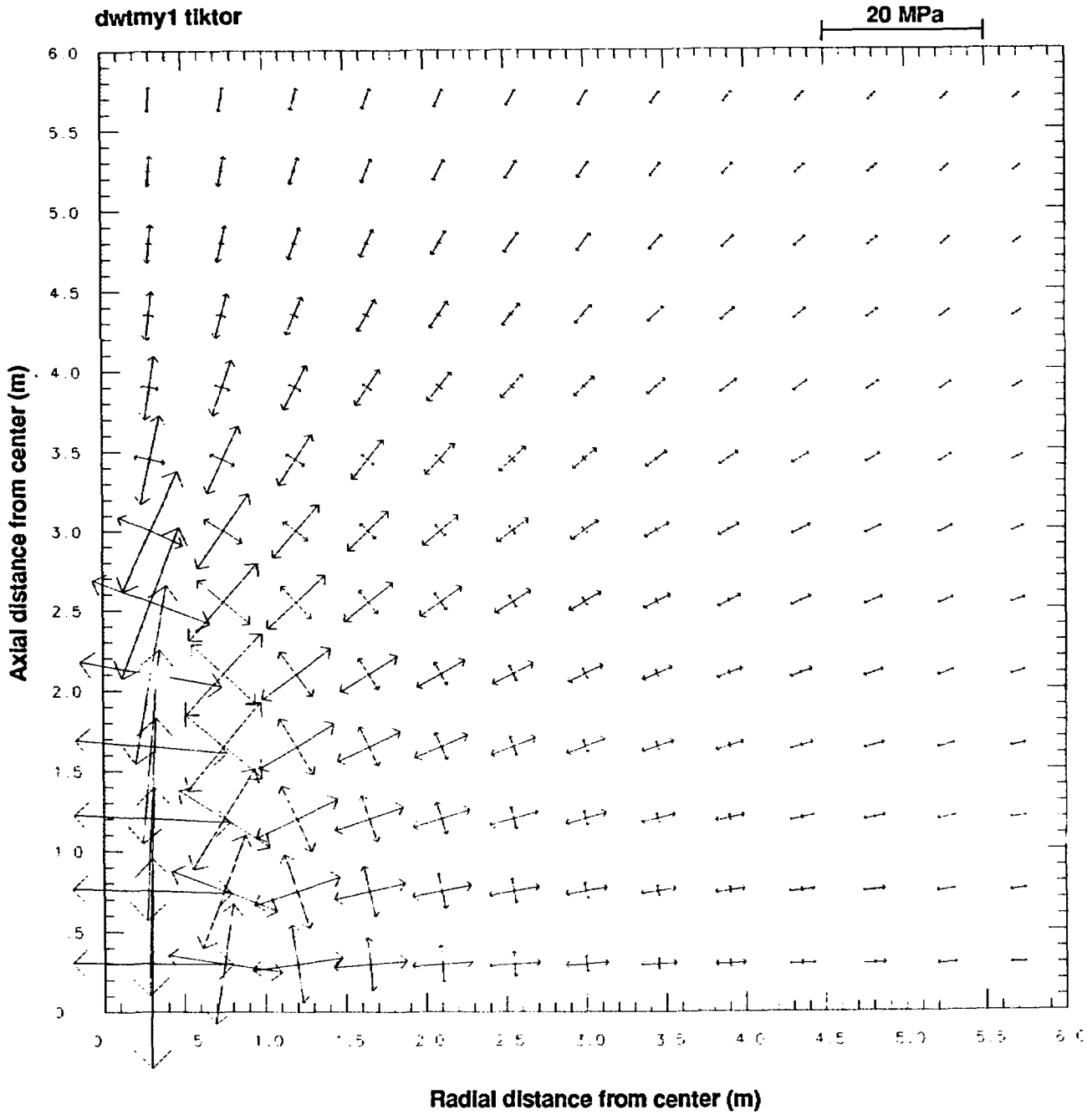


Figure 19a. Principal stresses in the R-Z plane at 13 weeks; 6-m heater.

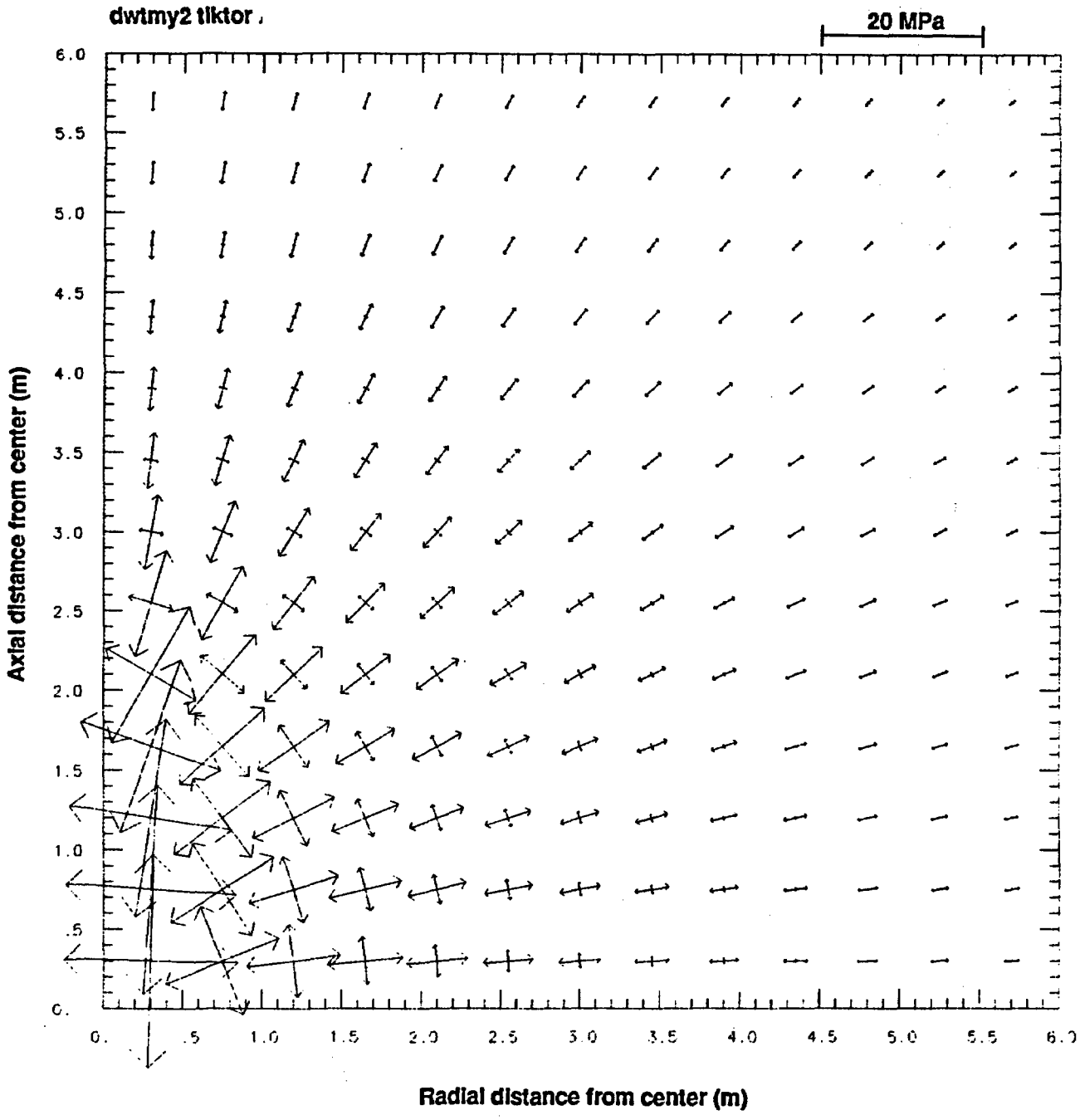


Figure 19b. Principal stresses in the R-Z plane at 13 weeks; 4.5-m heater.

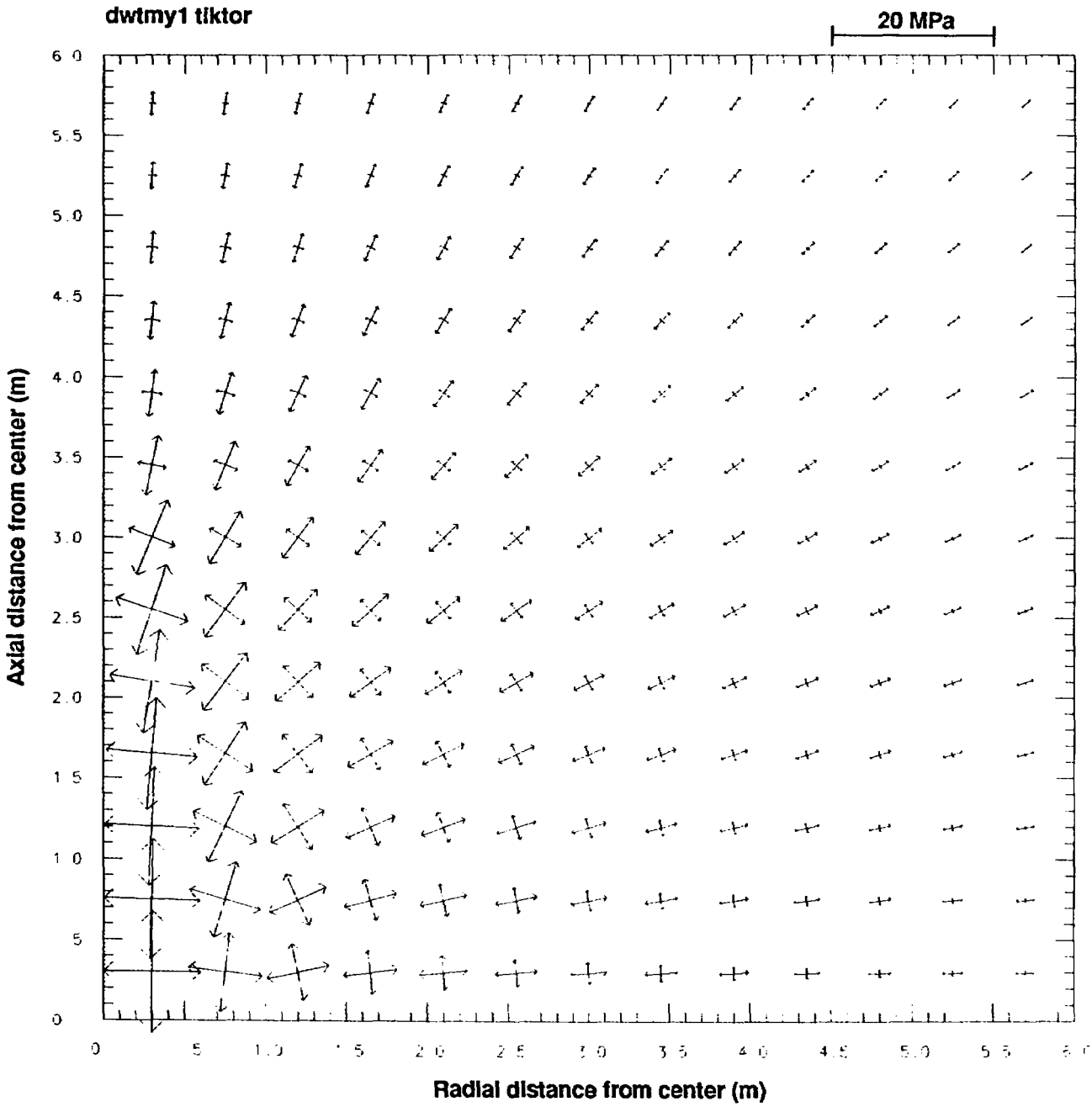


Figure 20a. Principal stresses in the R-Z plane at 26 weeks; 6-m heater.

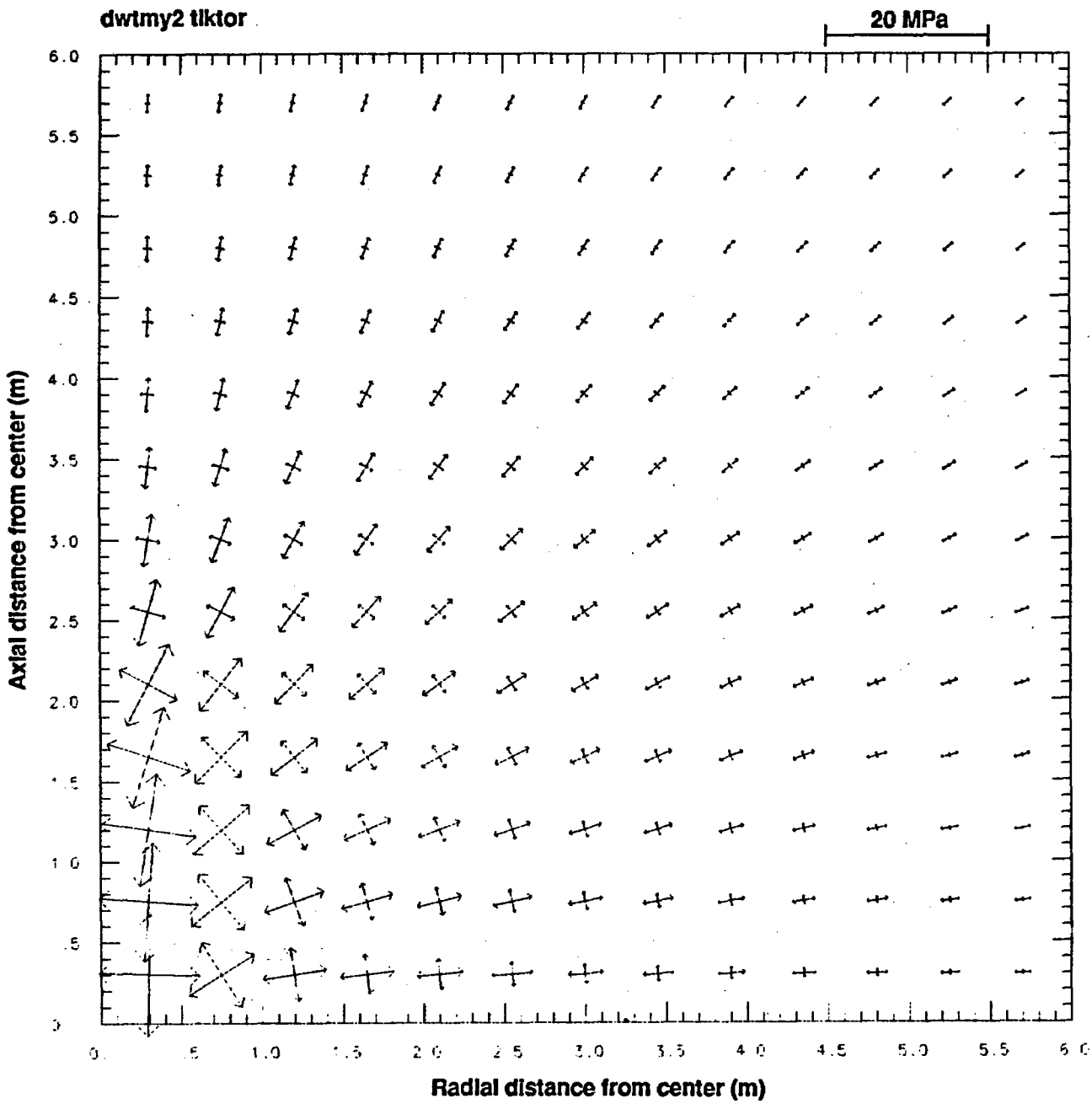


Figure 20b. Principal stresses in the R-Z plane at 26 weeks; 4.5-m heater.

5.0 SUMMARY AND CONCLUSIONS

Temperature, displacement, and stress changes were calculated in the vicinity of a heater (6 m or 4.5 m in length) emplaced in an infinite, homogeneous, isotropic medium whose thermal and mechanical properties are presumably similar to those at the 310-m depth for the planned exploratory shaft in Yucca Mountain. Although the planned power level for the 4.5-m heater is 15% less than the 6-m heater, the heater is 25% shorter, thus giving a linear power density 13% greater. Thus, the near-field effects of the 4.5-m heater should be slightly greater and, conversely, the 6-m heater should show higher effects in the far field. This is indeed what the calculations show. Maximum temperatures and stress changes that occur at the position of the heater hole are 247°C vs. 230°C and 37 MPa vs. 35 MPa for the 4.5-m vs. 6-m source. For maximum displacements that occur a few metres from the source center, the situation is reversed -- 0.8 mm for the 4.5-m heater, and 0.9 mm for the 6-m heater. These small differences are probably well within the uncertainties of the material properties (particularly the thermal expansion coefficient). Thus, the results should be lumped and rounded, giving the following recommended values for planning purposes:

Maximum temperature	250°C
Maximum displacement	1 mm
Maximum stress change	40 MPa

The in-situ stress field is not well known, but its maximum might be expected to be on the order of the lithostatic overburden stress which, at the planned 310-m depth, is ~7 MPa or less than 20% of the maximum calculated stress change.

The borehole containing the heater was not considered in this analysis and, thus, the displacements and stresses calculated in the vicinity of the borehole wall should not be considered realistic. Since the calculations are linear with respect to the thermal expansion coefficient and Young's modulus, the results may be scaled directly to obtain new values due to expected uncertainties in the properties used.

6.0 REFERENCES

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