HEAT AND MOISTURE TRANSFER IN UNSATURATED SOIL SURROUNDING AN IN SITU VITRIFICATION MELT POOL*

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ABSTRACT

An understanding of simultaneous transport of energy and moisture in the unsaturated region surrounding the in situ vitrification (ISV) melt is of important practical significance because of its potential impact on process safety and performance. It is postulated that under certain conditions vaporization of water could cause a pressure buildup beneath the melt that could lead to ejection of melt material. This study was initiated to investigate the potential for such pressure buildup.

Simplified numerical simulations have been performed to evaluate the importance of initial water saturation, melt permeability and stray joule heating on gas phase pressure and direction of gas flow. Results from these analyses indicate that the combination of low soil permeability and high initial water saturation may lead to excessive gas pressures in the region below the melt.

INTRODUCTION

An understanding of simultaneous transport of energy and moisture in the unsaturated region surrounding the in situ vitrification (ISV) melt is of important practical significance because of its potential impact on process safety and performance. It is postulated that under certain conditions, vaporization of water could cause a pressure buildup beneath the melt that could lead to ejection of melt material. Recent full-scale ISV tests (1), in which considerable molten glass was ejected from the melt, have focused attention on the need for enhancing the understanding of these phenomena. This study was initiated in part to investigate potential causes and solutions for such events in both contaminated soil and buried waste applications.

During the ISV process, the region surrounding the melt experiences high temperatures due to conduction and convection of heat from the high temperature melt zone (Fig. 1). This heating vaporizes the liquid water, causing pressurization of the gas phase and subsequent gas flow, both towards and away from the melt. The moisture that flows away from the melt condenses in the cooler soil forming a water bank which may act as a barrier and prevent the migration of contaminants away from the melt zone. The water bank may also act as a pressure barrier and if pressures in the gas phase become sufficiently high, expulsion of melt material may occur.

The process of energy and moisture transfer in unsaturated porous media is controlled by gradients in temperatures and attendant gradients in liquid saturations, moisture concentrations, and liquid and gas phase densities and pressures. A simple description of the process is as follows. Heat from the melt pool is conducted outward through the surrounding soil region. Since temperatures in this region exceed vaporization temperature of the pore water, the region is divided into gas-saturated and partially liquid-saturated regions by an advancing vaporization zone. The conditions surrounding a melt pool at some time during processing are shown in Fig. 1; four zones are depicted. In the inner dry zone, heat transfer occurs primarily by conduction. This zone is characterized by extensive cracking and enhanced permeability. At the front of the advancing vaporization zone, where the temperature is the prevailing boiling point temperature, the soil contains partially saturated voids, while at the trailing edge the voids are dry. In the vaporization zone, the liquid phase vaporizes causing increases in gas phase pressures and water vapor concentrations. The increase in gas phase pressures results in gas flow and transport of moisture into the cooler outer conduction

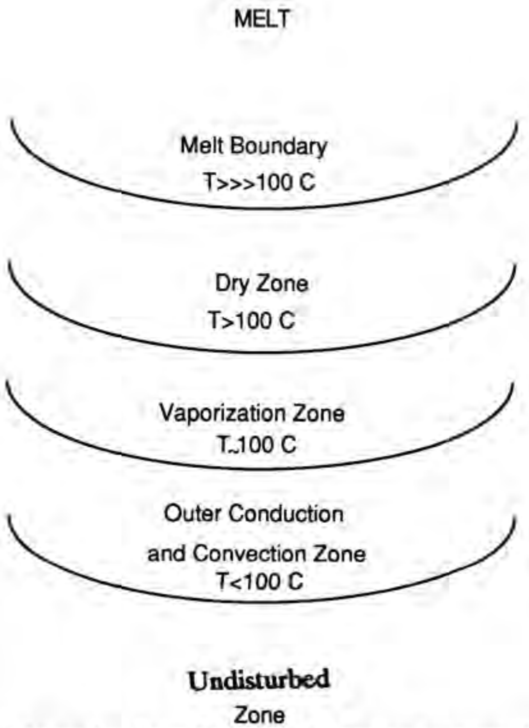

Fig. 1. Schematic of conditions in the region surrounding the ISV melt.

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and convection zone where the water vapor condenses, forming a water bank of increased liquid saturation. This increase in liquid saturation increases both the relative permeability of the water bank and the resistance to gas flow, while gravity forces act to drive the water in the downward direction. Simultaneously, capillary and buoyancy forces induce flow of some of this liquid back towards the vaporization and thermally-altered zones, where the liquid again vaporizes and the cycle is repeated. Since gas phase pressures and water vapor concentrations also decrease towards the melt, some moisture transfers from the vaporization zone towards the inner dry zone where it may either enter the melt or traverse the altered zone of high permeability and exit at the ground surface.

The relative magnitudes of the various driving forces controlling gas phase pressure and direction of mass transfer are strongly dependent on physical properties of the treated soil and process variables such as heating rate and melt front velocity. In this article, four one-dimensional test cases are examined to determine the effects of melt permeability, water saturation and stray joule heating on gas phase pressures and direction of steam flow. Computer simulations were performed using the computer code TOUGH (2).

NUMERICAL STUDIES

The idealized problem domain used in each of the following four test cases is depicted in Fig. 2. To restrict the flow of moisture and heat in one dimension, vertical boundaries are specified as impermeable and thermally insulated. Boundary pressure and temperature, at x = 10 m, are fixed at P = 101330 Pa and T = 20°C. The melt boundary moves along x at a specified velocity of 5 cm/hr with T = 1400°C and P = 101330 Pa. Temperatures and pressures are held constant throughout the melt and are T = 1400°C and P = 101330 Pa.

Material properties are listed in Table I. The constitutive relationships used to define thermodynamic parameters are described in Ref. 1. Steam tables provide density, internal energy, enthalpy, viscosity and surface tension as a function of P and T. Saturation temperature is treated as a function of gas phase pressure only. Both the liquid water and soil phases are assumed incompressible.

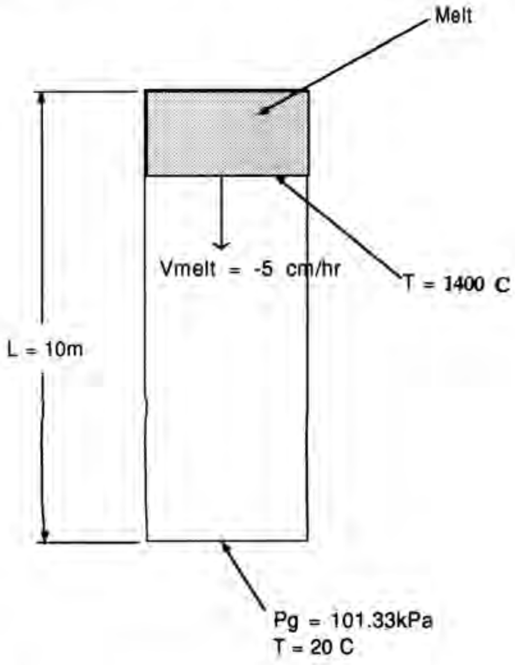

Fig. 2. One-dimensional problem domain.

Case 1

This case examines the combined effects of a low soil permeability (k = 2.5×10^{-13} m^2) and a relatively high initial soil water saturation (S_l = 0.5). Temperature, water saturation, gas phase pressure, and velocity profiles at 20 hours are shown in Fig. 3. As indicated in Fig. 3c, a water bank of increased water saturation has formed just ahead of the advancing melt front. In the region between the advancing melt front and the peak water saturation, the liquid is vaporizing causing a 20% increase in pressure up to 1.2 atmospheres as shown in Fig. 3a. Since pressure gradients are acting both towards and away from the melt, gas flows towards and away from the melt as shown in Fig. 3d. These trends in pressure, temperature, and water saturation remain similar at later times, with pressure remaining essentially constant.

Case 2

Here, case 1 is repeated with a very low melt permeability (k = 2.5×10^{-17} m^2). A low melt permeability prevents the upward escape of gas, resulting in a large pressurization at the melt front. Temperature, pressure, water saturation, and gas velocity profiles at 20 hours are shown in Fig. 4. Peak pressure is approximately 1.5 atmospheres. In case 2, peak pressure gradually increases as the melt front advances, reaching 2.5 atmospheres at 80 hours.

Case 3

Case 3 examines the effect of a high initial water saturation (S_l = 0.98). Other initial conditions are the same as in case 1 (Fig. 5). The high initial water saturation permits the formation of a water bank which acts as a barrier to gas flow, causing the majority of the gas to flow towards the melt. Attendant gas pressures also increase to 1.5 atmospheres and remain nearly constant during the simulation.

Case 4

In the previous cases the soil surrounding the melt is heated by conduction and convection only. Case 4 examines the added effect of stray joule heating in the soil region below the melt. Stray joule heating is likely to occur during fixed electrode applications in wet soils. To approximate stray joule heating, we assume heating of the form $Q = Q_o(S_l - 0.15)$, where Q_o is a specified heat source. Therefore, heating increases with saturation in an attempt to account for the accompanying increase in electrical conductivity.

The following scenario is simulated. The initial water saturation is assumed to be 0.5 down to a depth of 3 m and 0.15 at depths greater than 3 m. The gas phase pressure at the moving melt front is held fixed at atmospheric pressure. As the melt front moves downward at 5 cm/hr, a portion of the moisture initially in place flows away from the melt and condenses in the cooler outer zone forming a zone of increased saturation. Because of this saturation increase above initial saturation, joule heating occurs in the zone of increased saturation according to the stray joule heating equation. Here we have assumed that Q_0 = 288W. This stray heating zone moves downward ahead of the melt front. Eventually temperatures

TABLE I

Material Properties

Porosity	0.25
Soil density	2933 kg/m^3
Soil specific heat	1333 J/kg°C
Thermal conductivity	
liquid saturated	1.17 W/m°C
gas saturated	1.00 W/m°C
Relative permeability	
liquid	S^{*3}
gas	$(1 - S^{*3})$
where	$S^* = (S_l - S_{lr})/(1 - S_{lr})$
where	S_l = liquid saturation and S_{lr} = 0.15
Capillary pressure	$p_c = -5 \times 10^5 \times \sigma \times f$
where	$f = 1.417 S_g - 2.12 S_g^2 + 1.263 S_g^3$
where	$Sg = 1 - S^*$ with S^* defined above
where	σ = the water surface tension

in this zone reach the boiling point, water vaporizes, and gas phase pressures increase. This stray heating zone also becomes more mobile due to the increase in relative permeability with increasing water saturation and the action of gravity forces. As the ISV process continues, this stray heating zone increases in size and eventually reaches a electrically conductive zone between the depths of 5 to 6 m simulating steel waste containers that are present in some postulated ISV applications. Heating in this region is increased to simulate the possible preferential current flow through the highly conductive steel containers.

In this region we assume joule heating is approximated by $Q = 3Q_0(S_l - 0.15)$. Temperature, saturation and pressure profiles are shown at 30 and 60 hours in Figs. 6 and 7, respectively. The first feature to note is the extended vaporization zones (T = 100°C) at both output times in Figs. 6b and 7b. The attendant saturation profiles are more complex in this problem than in previous cases. Note the decrease in saturation between 5 and 6 m at 30 hours; this decrease is due to joule heating and vaporization in the highly conductive region. The pressure profiles indicate that stray joule heating may lead to high gas phase pressures over relatively large distances. Note that increased pressures occur over a distance of 3 to 4 m.

SUMMARY

Simplified numerical simulations have been performed to evaluate the importance of initial water saturation, melt permeability, and stray joule heating on gas phase pressure and direction of gas flow. Results from this analysis indicate that the combination of low soil permeability and high initial water saturation may lead to excessive gas pressures in the region below the melt. In fixed electrode applications, stray joule heating in the region below the melt may also lead to excessive gas pressures. It is unlikely that stray joule heating is a concern in moving electrode applications due to the electrically insulating dry region surrounding the melt.

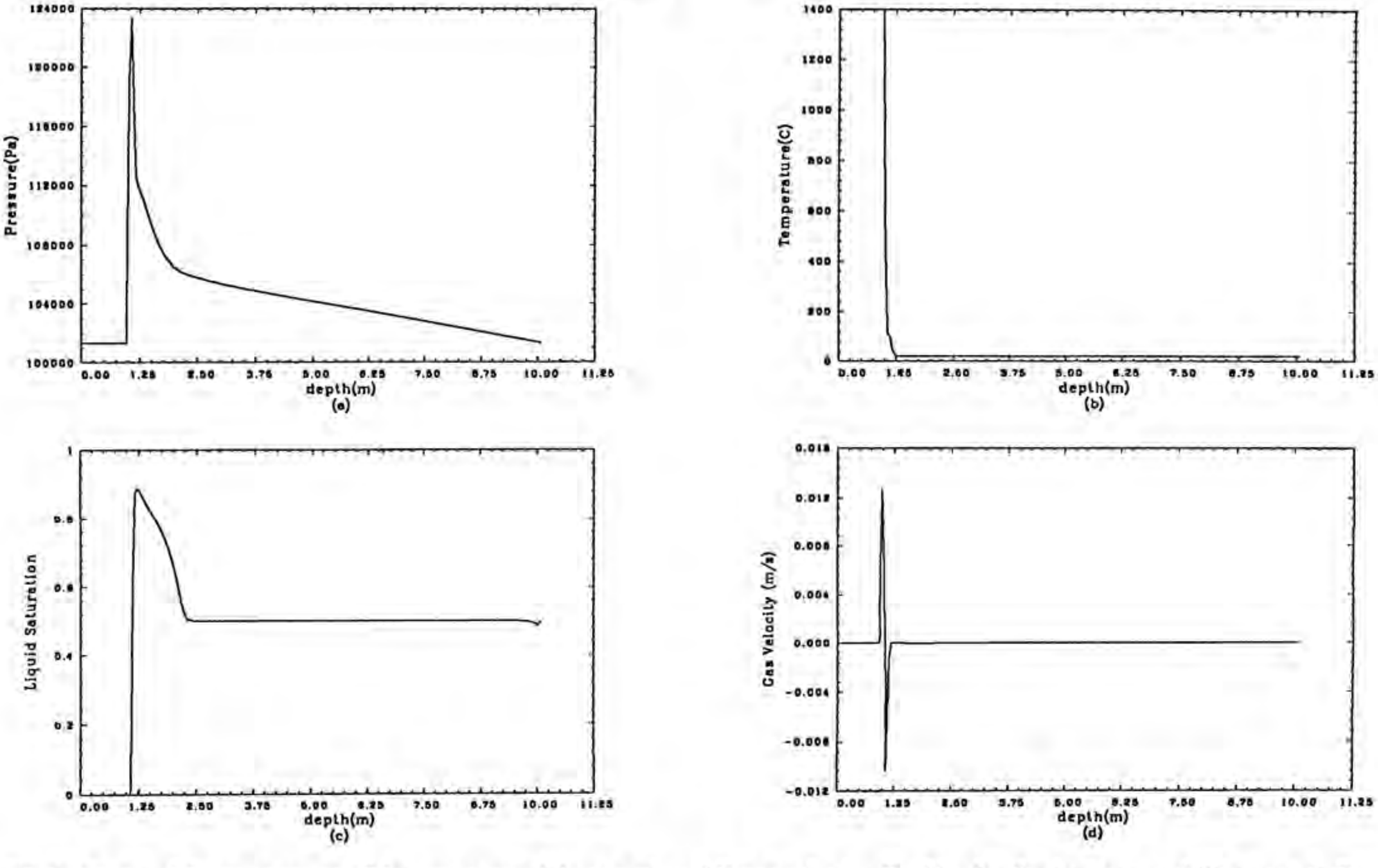

Fig. 3. Case 1, (a) gas pressure, (b) temperture, (c) saturation, (d) gas velocity. Profiles for the low permeability case at 20 hours.

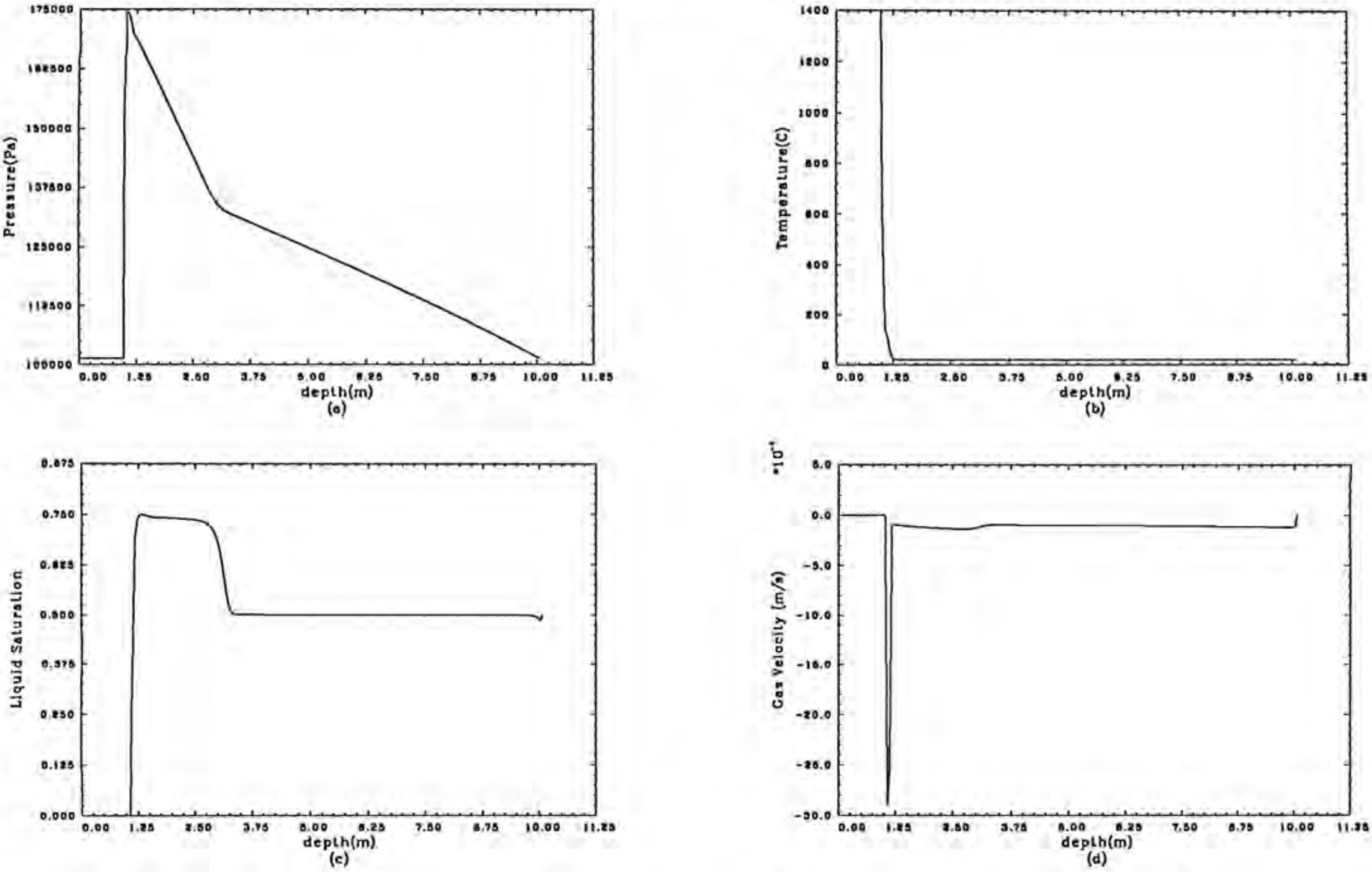

Fig. 4. Case 2, (a) gas pressure, (b) tempreature, (c) saturation, (d) gas velocity. Profiles for the very low permeability case at 20 hours.

Initial water saturations greater than 0.5 may lead to a high saturation water bank which acts as a barrier to gas migration away from the melt. Although this condition will limit the migration of contaminants away from the melt, it can also lead to excessive gas pressures if the gas cannot escape. Venting to the confinement hood may be necessary in some applications.

It is apparent from this study that site specific material properties, such as those presented in Table I, should be determined prior to field processing. Simple analysis can then be performed to help determine operating procedures and technical specifications required to avoid off-normal events.

REFERENCES

1. "Report on Defense Plant Wastes," Vol 3, No 17, pp 143, August 16, 1991.
2. K. PRUESS, "Tough User's Guide," NUREG/CR-4645 SAND 86-7104, June 1987.

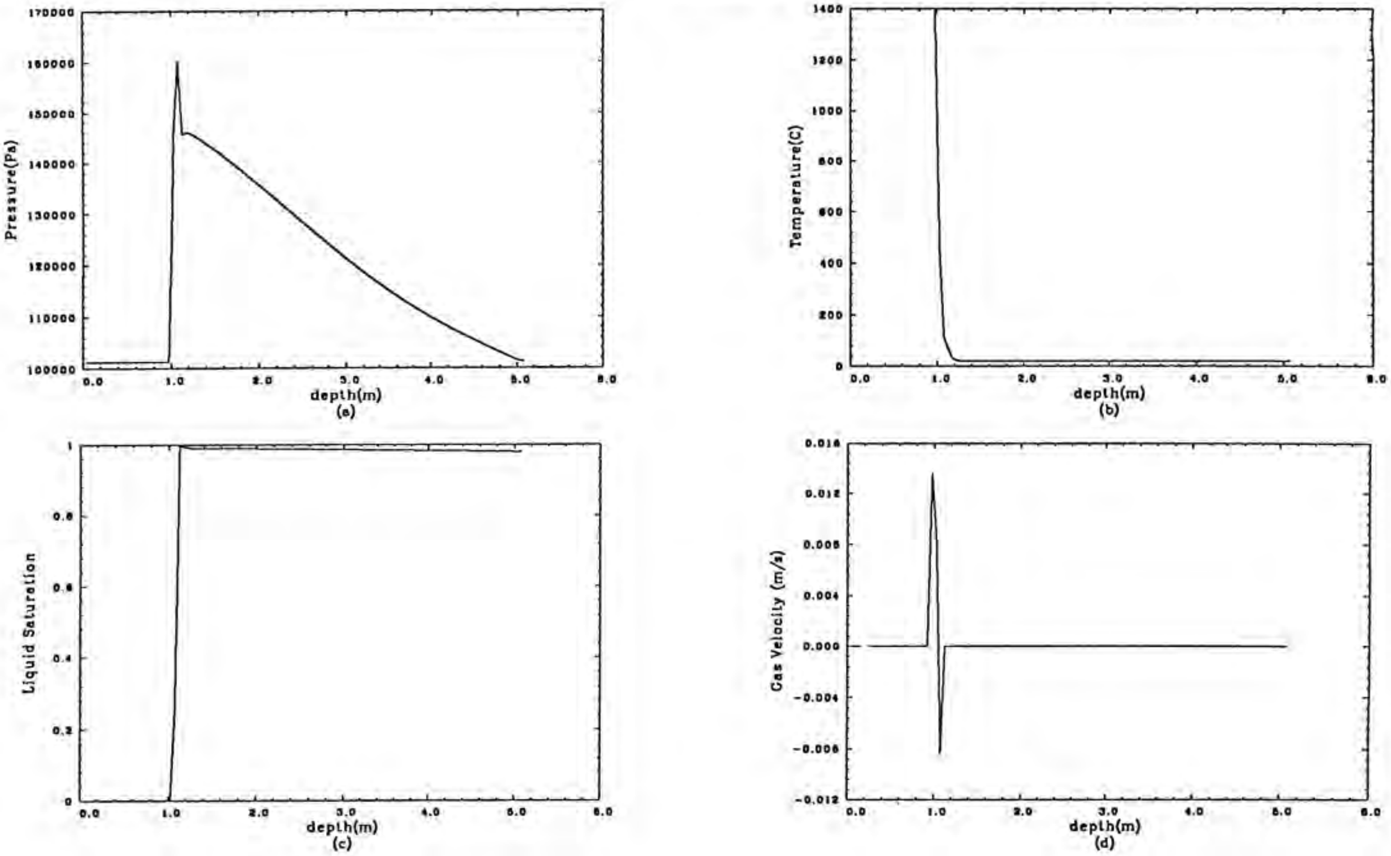

Fig. 5. Case 3, (a) gas pressure, (b) temperature, (c) saturation, (d) gas velocity. Profiles for the high initial saturation case at 20 hours.

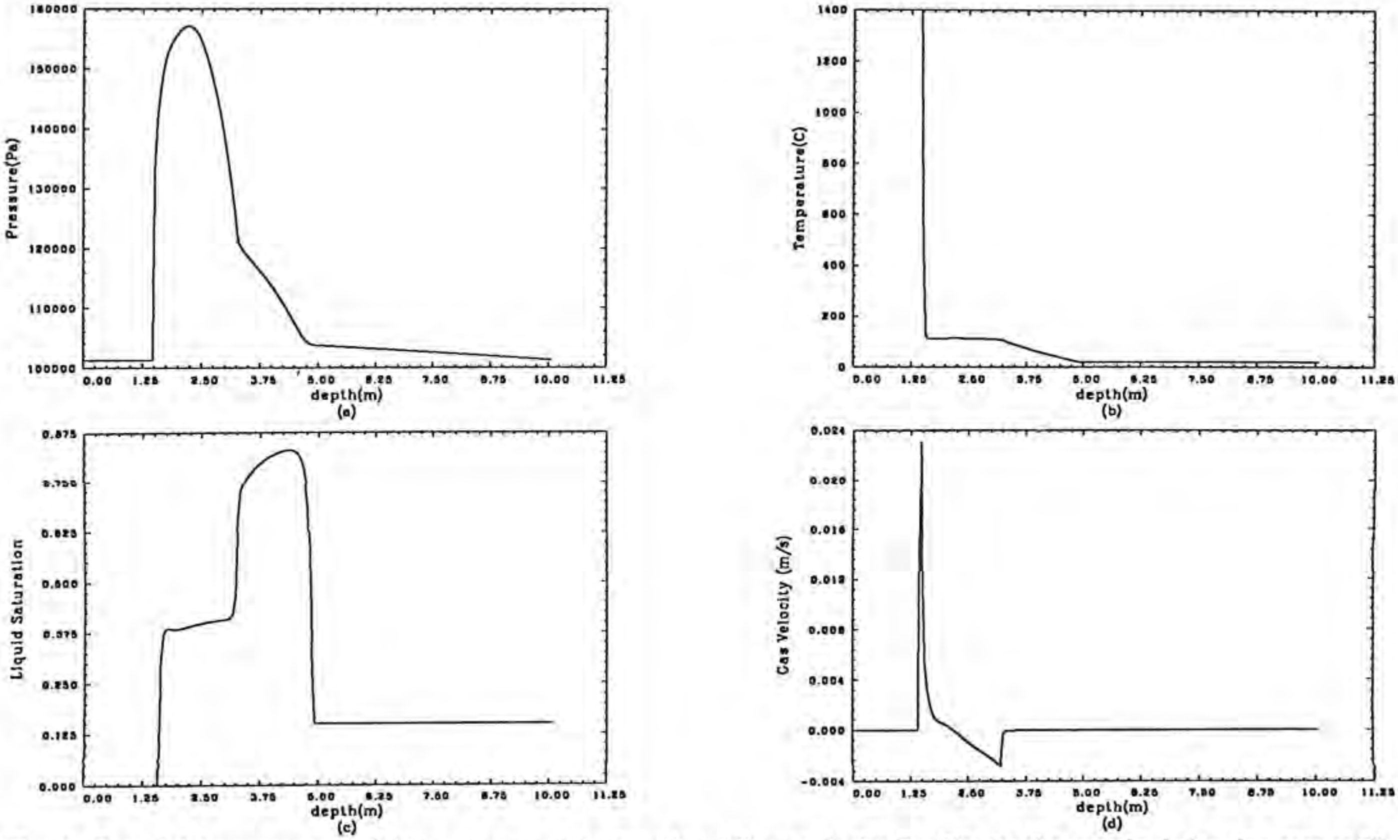

Fig. 6. Case 4, (a) gas pressure, (b) temperature, (c) saturation, (d) gas velocity. Profiles for the stray joule heating case at 30 hours.

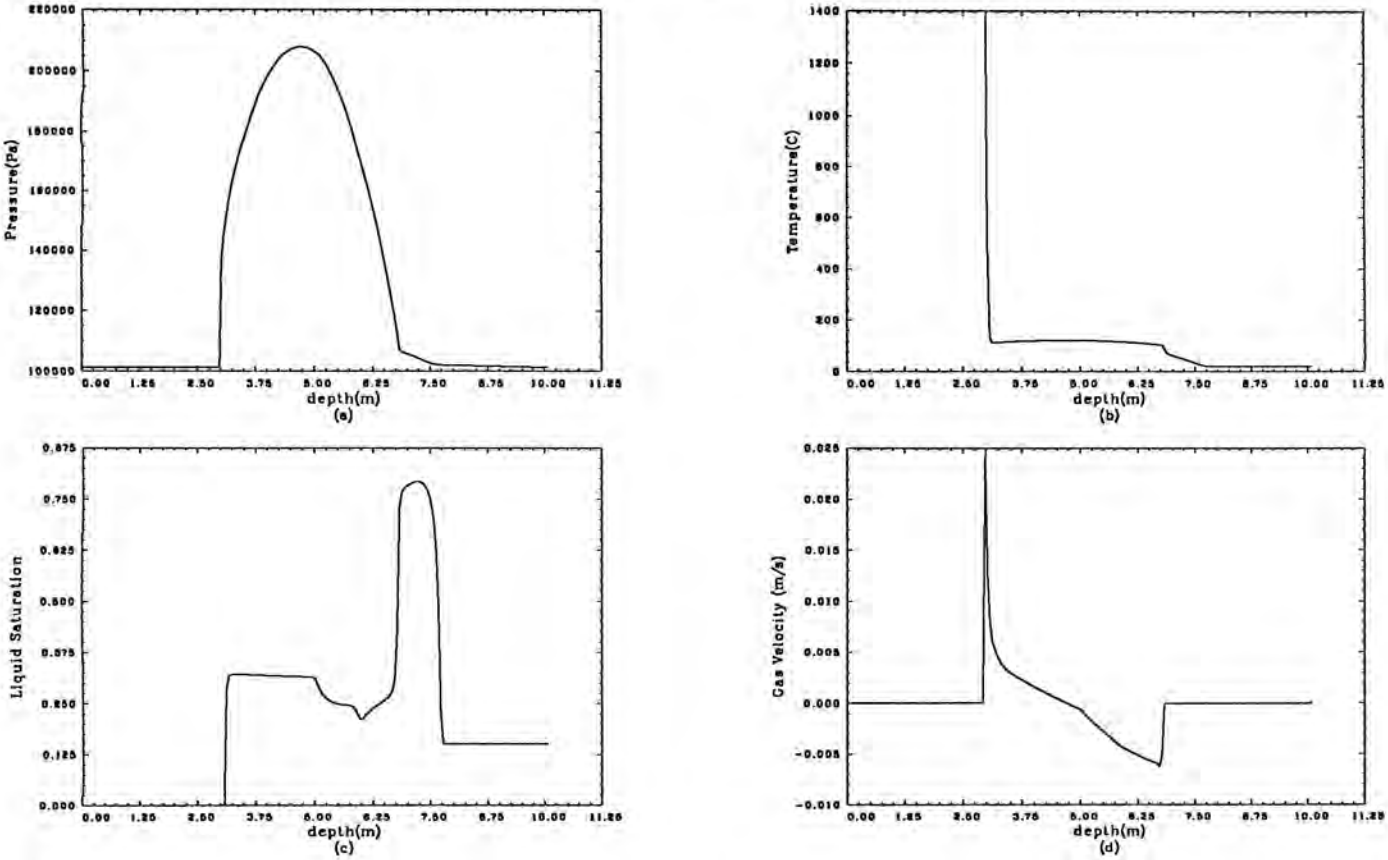

Fig. 7. Case 4, (a) gas pressure, (b) temperature, (c) saturation, (d) gas velocity. Profiles for the stray joule heating case at 60 hours.