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Prediction of Thermally-Driven Fluid Flow at Different Scales

by

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Abstract

The U.S. Department of Energy is evaluating the potential of a proposed geologic repository for high-level nuclear waste at Yucca Mountain, NV. The spatial and temporal scales of a geologic repository prohibit the design of meaningful repository-scale experiments to predict performance. However, results from laboratory-scale experiments can be used with principles of similitude to help design meaningful field-scale experiments and to qualitatively predict the redistribution of moisture at the repository scale if the systems are sufficiently similar. Gas pressure is identified as a critical indicator of the formation of fluid flow regimes in similar although differently-sized physical systems. The time of maximum gas pressure formation and the gas volume are a function of the size of the physical system characterized by the length, L. Ambiguity is associated with assigning an appropriate and representative value to L for a particular system. The average of the minimum and maximum dimensions of the gas-pressure altered zone is determined to be the optimal characteristic length.

Introduction

The U.S. Department of Energy (DOE) is evaluating the potential for construction of a proposed geologic repository for high-level nuclear waste (HLW) at Yucca Mountain, NV. The repository would be situated in unsaturated, fractured, porous media approximately 300 m below ground surface and 200 m above the water table. The spatial and temporal scales of a geologic

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repository prohibit the design of meaningful repository-scale experiments to predict performance. Results from laboratory-scale experiments, however, may be used with principles of similitude to help design meaningful field-scale experiments. In this approach, different experimental scales are used to qualitatively predict the redistribution of moisture at the repository scale.

In this study, the redistribution of moisture through porous media resulting from a local heat source is investigated by comparing quantifiable observations from physical laboratory-scale experiments to numerical predictions of fluid flow at field and repository scale. This comparison is conducted using similitude analysis to assess whether dimensionless ratios relating mechanisms controlling mass and heat transfer (e.g., fluid flows and pressure gradients) have roughly the same numerical value in smaller-scale physical experiments as in numerically simulated experiments of larger scale systems. If so, these experiments can be used to predict processes anticipated at larger, more meaningful scales, such as for a field-scale experiment or a full-scale HLW repository. However, ambiguity is associated with assigning an appropriate and representative value to the characteristic length of differently-sized systems. Analyses are conducted to resolve this uncertainty.

Background

Predictive models used to simulate coupled thermal and hydraulic processes are intrinsically based upon conceptual models. If the conceptual model is inadequate or inappropriate for the application of interest, incorrect and possibly misleading predictions may result. Experiments conducted at the laboratory scale (Green et al., 1993; Evans, 1983, Rasmussen and Evans, 1987) and field scale (Patrick, 1986; Zimmerman et al., 1986; Ramirez, 1991) are important in the assessment of conceptual models. Conceptual models valid for a mountain-scale geologic HLW repository may be identified through the interactive process of testing mathematical models predicated on well-defined and constrained conceptual models formulated from smaller-scale physical laboratory- and field-scale observations.

Dimensional analysis of the pertinent mechanisms observed in similar thermal-hydrologic systems has provided a set of scaling laws that relate the time at which these processes occur to the size of the physical system (Dodge and Green, 1994). Gas pressure resulting from an internal heat source was identified as a critical indicator of the nature of thermally-induced redistribution of moisture through porous media during the heating phase of a geologic repository. If the scaling relationship is applicable for similar systems of different sizes, it is conjectured that all pertinent mechanisms (i.e., those governing the redistribution of liquid and water vapor) also abide by the same temporal and spatial scaling relationships.

A series of laboratory-scale cylindrical tests was specifically designed and conducted at the Center for Nuclear Waste Regulatory Analyses (CNWRA) to assess the validity of these scaling laws. Observations from the laboratory-scale tests are compared to predictive models of the field-scale Large Block Test (LBT) at Fran Ridge near Yucca Mountain (Lin, 1994) and the proposed HLW repository at Yucca Mountain to conduct this assessment.

Theory

The thermal evolution of a HLW repository is characterized by three distinct phases. During the heating phase, radioactive decay of the waste causes a monotonic rise in temperature that may last several hundreds of years. During this phase, the rise in temperature at the heat source vaporizes liquid water which then moves away from the heat source due to gas-phase pressure gradients. Water movement occurs primarily as water vapor migrating away from the heat source resulting in drying of rock near the waste containers. Late in the thermal regime, after temperatures at the heat source have decreased, water transport occurs essentially only in the liquid phase. This is the cooling phase in the repository thermal regime. A transitional phase occurs between the heating and cooling phases during which water is transported as both vapor and liquid, potentially in opposing directions. The rate of temperature increase and decline; the maximum temperature; and the duration of the heating, transitional and cooling phases are all subject to the specific thermal loading program adopted for the repository.

A conceptual model of processes which dominate water transport through rock matrix during the heating phase of the thermal regime has been formulated. In this model it is presumed that the initial local high heating rates create large pressures in the gas phase because of gas confinement resulting from low permeable media and high liquid saturations. Permeability must be sufficiently low and saturations sufficiently high such that connectivity of the gas phase pathways is absent for this pressure to form. Gas will remain in confinement only if the gas pressure is insufficient to force gas pathways to open through the water-filled pores in the rock matrix. Since the movement of water through and out of the matrix pore space occurs over time, and not as an instantaneous pressure equilibrium process, gas pressure build-up and dissipation is a transient and not an instantaneous or steady-state process.

A dimensionless quantity, referred to as the *advection* number, Ad, has been formulated to identify whether differently-sized physical systems are similar (Dodge and Green, 1994). Systems which exhibit like values for the Ad number will respond similarly, in terms of coupled thermal-hydrologic mechanisms, according to this analysis. The advection number is defined as

$$Ad = \frac{\mu_g \dot{q}}{L\, k_{sat}\, \rho_s \rho_g\, g\, \beta_g\, C_s\, T_{avg}\, \Delta T_0} \left[1 + 0.622 \left(\frac{\rho_v}{\rho_g} \right) \left(\frac{h_{fg}}{R_{air}\, T_{avg}} \right) \right]$$

where μ_g is gas viscosity, $\dot{q}$ is the heat load, k_{sat} is permeability, ρ_s is the density of porous medium-gas mixture, ρ_g is the gas mixture (air and water vapor) density, g is gravity, β_g is the gas thermal coefficient, C_s is specific heat of porous medium-gas mixture, T_{avg} is a characteristic

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average temperature, ΔT_0 is the temperature difference between the heater and the boundary of the control volume, ρ_v is the density of water vapor, h_{fg} is the latent heat of vaporization for water and R_{air} is the ideal gas constant for air. The term L in Ad is a characteristic length. Ambiguity in selecting an appropriate value for this variable is investigated in this study.

The driving force for gas transport is a pressure gradient when Ad >> 1, but is diffusion or buoyancy when Ad < 1. For cases when Ad≈1, both pressure and density (or concentration) gradients are responsible for gas movement.

The presence of fractures does not preclude the formation of a gas pressure gradient, as evidenced in gas pressures measured during a heater experiment conducted in the highly-fractured, welded Grouse Canyon Formation in G-Tunnel at the Nevada Test Site (Ramirez, 1991). Gas pressures as great as three bars resulting from a 3300 watt heater were measured during this test. This observation supports the premise that gas pressure build-up occurs in rock matrix as a function of matrix permeability and the strength of the heat source, even though fractures may be present.

The time required for gas pressure to build-up was evaluated using dimensionless forms of the equations governing heat and mass flow through porous media. This evaluation indicates that for similar systems, the maximum gas pressure experienced by a system will occur at a characteristic time

$$\tau = \frac{L^2}{\alpha}$$

where τ is a dimensionless time constant and α is thermal diffusivity. This expression is analogous to the rate of thermal diffusion.

Application

The heating phase scaling law was evaluated using measured results from a laboratory-

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scale experiment and numerical simulation predictions of similar heat and mass transfer at field and repository scales. The observed or predicted maximum gas pressures, the distances over which the gas pressure difference occurs and the times at which the maximum gas pressure forms are compared using the thermal diffusion relationship to evaluate the utility of the heating phase scaling relationship.

Laboratory-Scale Experiment

A laboratory-scale experiment was conducted at CNWRA to provide quantitative measurement of the transient formation of a thermally-induced gas gradient in a partially-saturated, porous medium. The test medium was homogeneous and did not include fractures. Therefore, the test medium represented an intact matrix block. Moisture redistribution driven by an electrical heater located in a cylindrically-shaped disk was monitored using direct measurement of gas pressure and temperature both at the location of the axially placed heat source and at the cylinder boundaries. Moisture content in the interior of the cylinder was determined using density contrasts measured with a gamma-ray densitometer. A heat source of approximately 45 watts was imposed at the center of the 10.5 cm tall 30 cm diameter cylinder constructed of a cement slurry. The slurry had a measured porosity of 0.32 and a permeability of 2.0×10^{-18} m^2. A maximum gas pressure of about 20,000 Pa (or 0.2 bar) was observed about nine hours (3.23×10^4 sec) after application of heat (Figure 1).

Field Test

An *in situ* large block test (LBT) has been designed and is under construction at Fran Ridge near Yucca Mountain to observe coupled effects among thermal-hydrologic-mechanical-chemical processes (Lin et al., 1994). The objective of the thermal-hydrologic component of the experiment is to evaluate thermally-driven redistribution of moisture in a large block. The experimental medium consists of a 3 x 3 x 4.5 m tall pedestal of highly-fractured,welded tuff hewn

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from near-surface bedrock. A total of five cylindrically-shaped heaters is to be installed in a horizonal plane at a height of 1.5 m above the base of the block to provide the thermal source for the heater test. The vertical sides of the block are to be established as adiabatic with no fluid flow. The upper boundary of the block is to be open to the atmosphere. Accordingly, the upper boundary was maintained in the model at atmospheric pressure and the ambient temperature at 20 C. The block was modeled as a composite medium with porosities of 0.11 and 1.8 x 10^{-3} and permeabilities of 1.9 x 10^{-18} and 1.0 x 10^{-11} m^2 for the matrix and fractures, respectively. The van Genuchten α and n parameters were 5.5 x 10^{-7} m^{-1} and 1.798 for the matrix and 1.315 x 10^{-4} m^{-1} and 4.23 for the fractures, respectively.

Moisture and heat transfer through the block were simulated using a modified version of V-TOUGH (Pruess, 1987; Nitao, 1989). The maximum gas pressure difference was the difference between gas pressure measured at the heaters and the ambient gas pressure measured at the boundaries. The maximum gas pressure difference predicted in the simulations of the LBT was 22,000 Pa (0.22 bars) at 115 days after initiation of heating (Figure 1).

Yucca Mountain

A 1D numerical model of Yucca Mountain was formulated for simulation of mass and heat transfer through fractured, porous media resulting from the imposition of heat-generating HLW. A 1D model was selected in lieu of a possibly more representative model with greater dimensionality to permit higher resolution near the repository and the heat source. The model extended from ground surface with an assigned saturation of 0.5 and temperature of 15 C to full saturation and a temperature of 30 C at a depth of 600 m. A transient heat source representative of an extended-dry repository (i.e., 114 kW/acre) was assigned to the repository horizon located at a depth of 375 m. The upper and lower boundaries were characterized with no fluid flow and constant temperatures. The model was characterized as a uniform composite medium with the same property values as those assigned to the LBT model. Mass and heat transfer were also modeled with the modified version of V-TOUGH. A maximum gas pressure of about 42,000 Pa (0.42 bars) was predicted at the repository horizon (Figure 1).

Discussion

The advection numbers for the laboratory-, field- and Yucca Mountain-scale cases were calculated as 10^5, 6300 and >1000, respectively. Since all three values exceed unity and are numerically similar, advection is determined to be the driving force of gas, indicating that all three physical models are sufficiently similar to invoke the heating-phase scaling law.

Several candidate representations for L are evaluated for use in this dimensional analysis. Profiles of gas pressure difference versus distance at the time of maximum gas pressure for the field and Yucca Mountain scales are presented in Figure 2. Results are not included for the laboratory experiment since pressure was only measured at two locations in the laboratory experiment. As illustrated is this figure, the two pressure profiles are non-symmetric. This non-symmetry is a source of ambiguity in assigning a value to L. Candidate selections for L include either the minimum or the maximum distance from the heat source to that location where pressure is at ambient conditions. Alternatively, L could be assigned the total length of the pressure-altered zone or an average of the minimum and maximum dimensions of the pressure-altered zone. These four candidate choices for L are inserted into the heating-phase scaling law to predict times at which maximum gas pressures would occur and compared with times to maximum gas pressure either measured (as in the case of the laboratory experiment) or predicted (as in the case of the LBT and Yucca Mountain)(Table 1). As illustrated, most values are reasonable, however the designation of L as the average of the minimum and maximum dimensions to the gas-pressure altered zone provides the best agreement.

Conclusions

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Three observations can be gained from these combined experimental/numerical results. First, the amplitude of the maximum gas pressure is roughly the same at all scales, although the maximum pressure increases slightly with the scale of the physical system. This observation supports the premise that the maximum gas pressure that can be experienced by a medium is a transient function of the maximum pore size present in the medium and the size of the system. This information is explicitly included in the laboratory-scale experiment through selection and size of the medium, and is implicitly incorporated in the numerical simulations through designation of the size and air-entry van Genuchten parameter α and the choice of L for all scales.

Second, the transient formation of gas pressure is affected by the size of the physical system. Gas migration through larger systems requires longer times; however, the maximum pore size modulates the maximum allowable pressure as the volume of gas confinement expands during gas generation.

Third, the time and volume size of maximum gas pressure formation is a function of the size of the physical system. The size of the physical system is defined using L, the characteristic length. The average between the minimum and maximum dimensions of the gas-pressure altered zone is determined to be an adequately representative characteristic length.

References

Dodge, F.T. and R.T. Green. 1994. Pressure-Driven Gas Flow in Heated Partially-Saturated Porous Media. Proceedings of the Fifth International High-Level Waste Management Conference. LaGrange, IL:American Nuclear Society.

Evans, D.D. 1983. Unsaturated Flow and Transport Through Fractured Rock - Related to High-Level Waste Repositories. Final Report - Phase I. NUREG/CR-3206. Washington DC:Nuclear Regulatory Commission.

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Green, R.T., R.D. Manteufel, F.T. Dodge and S.J. Svedeman. 1993. Theoretical and Experimental of Thermohydrologic Processes in a Partially Saturated, Fractured Porous Medium. NUREG/CR-6026. Washington DC:Nuclear Regulatory Commission.

Lin W., D.G. Wilder, J.A Blink, S.C. Blair, T.A. Buscheck, D.A. Chestnut, W.E. Glassey, K. Lee, and J.J Roberts. 1994. The Testing of Thermal-Mechanical-Hydrological-Chemical Processes Using a Large Block. Proceedings of the Fifth International High-Level Waste Management Conference. LaGrange, IL:American Nuclear Society.

Nitao, J.J. 1989. V-TOUGH. An Enhanced Version of the TOUGH Code for the Thermal and Hydrologic Simulation of Large-Scale problems in Nuclear Waste Isolation UCID-21954. Lawrence, CA:Lawrence Livermore National Laboratory.

Patrick, W.C. 1986. Spent Fuel Test - Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite. Final Report. UCRL-553702. Lawrence, CA:Lawrence Livermore National Laboratory.

Pruess, K. 1987. TOUGH. User's Guide. NUREG/CR-4645. Berkeley, CA:Lawrence Berkeley Laboratory.

Ramirez, A.L. 1991. Prototype Barrier System Field Test (PEBSFT) Final Report. UCRL-ID-106159. Lawrence, CA:Lawrence Livermore National Laboratory.

Rasmussen, T.C. and D.D. Evans. 1986. Unsaturated Flow and Transport Through Fractured

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Rock - Related to High-Level Waste Repositories. Final Report - Phase II. NUREG/CR-4655. Washington DC:Nuclear Regulatory Commission.

Figure Captions

Figure 1. Maximum gas pressure (Pa) difference versus time (s)

Figure 2. Maximum gas pressure (Pa) difference versus distance (m)

Table 1. Comparison of candidate characteristic length, L, selections. Gas pressure in first column was observed at the laboratory scale and predicted at the field (LBT) and repository (Yucca Mt) scales.

characteristic length	gas pressure	minimum distance		maximum distance		total distance		average distance	
scale	time (s)	L (m)	time (s)	L (m)	time (s)	L (m)	time (s)	L (m)	time (s)
laboratory	3.23×10^4	0.15	3.23×10^4	0.15	3.23×10^4	0.15	3.23×10^4	0.15	3.23×10^4
LBT	9.0×10^6	0.85	1.04×10^6	2.35	7.93×10^6	3.2	1.47×10^6	1.6	6.67×10^6
Yucca Mt	2.2×10^9	25	8.98×0^8	70	7.03×10^9	95	1.30×10^{10}	45	2.91×10^9

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Fig 1

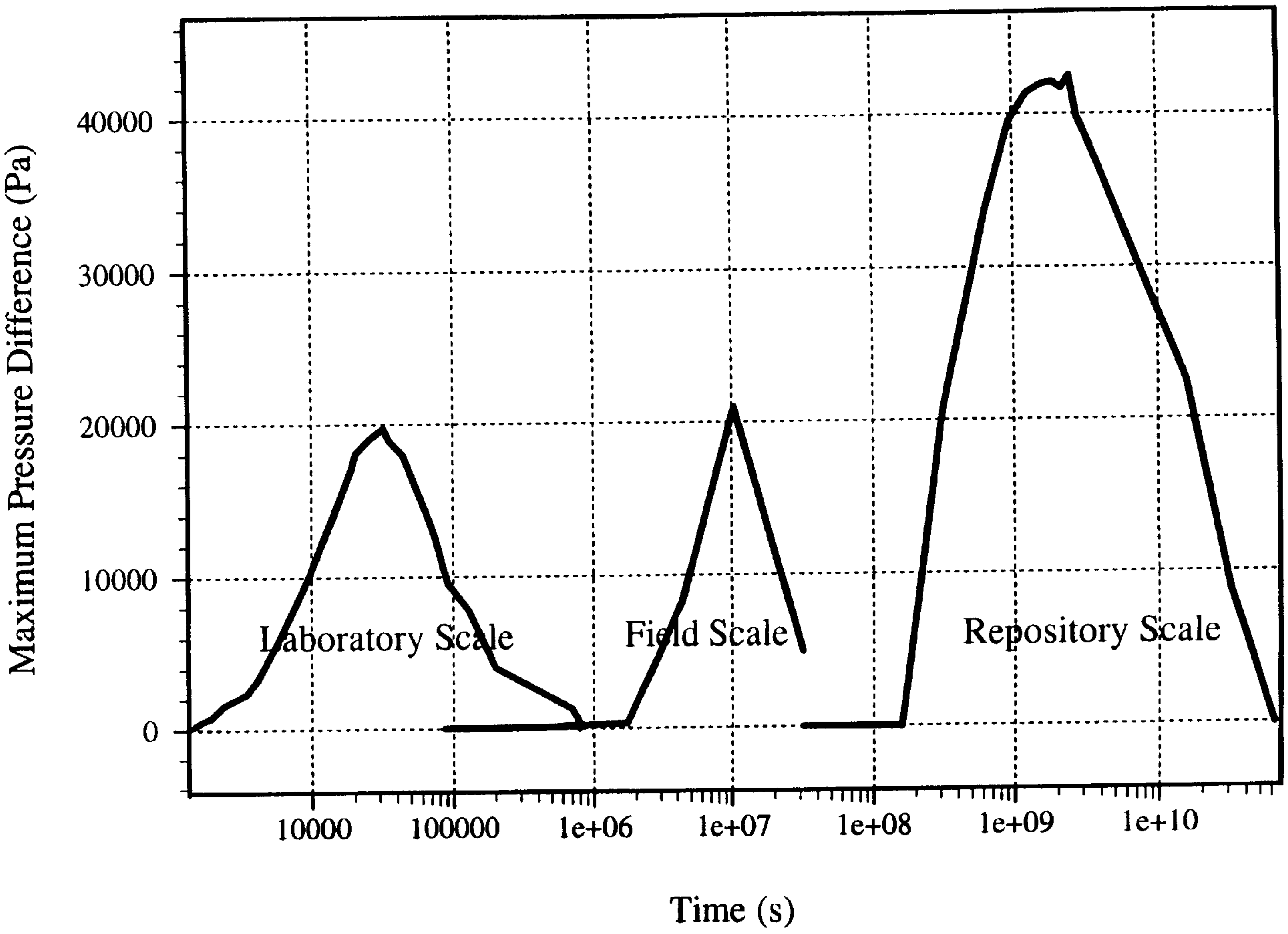
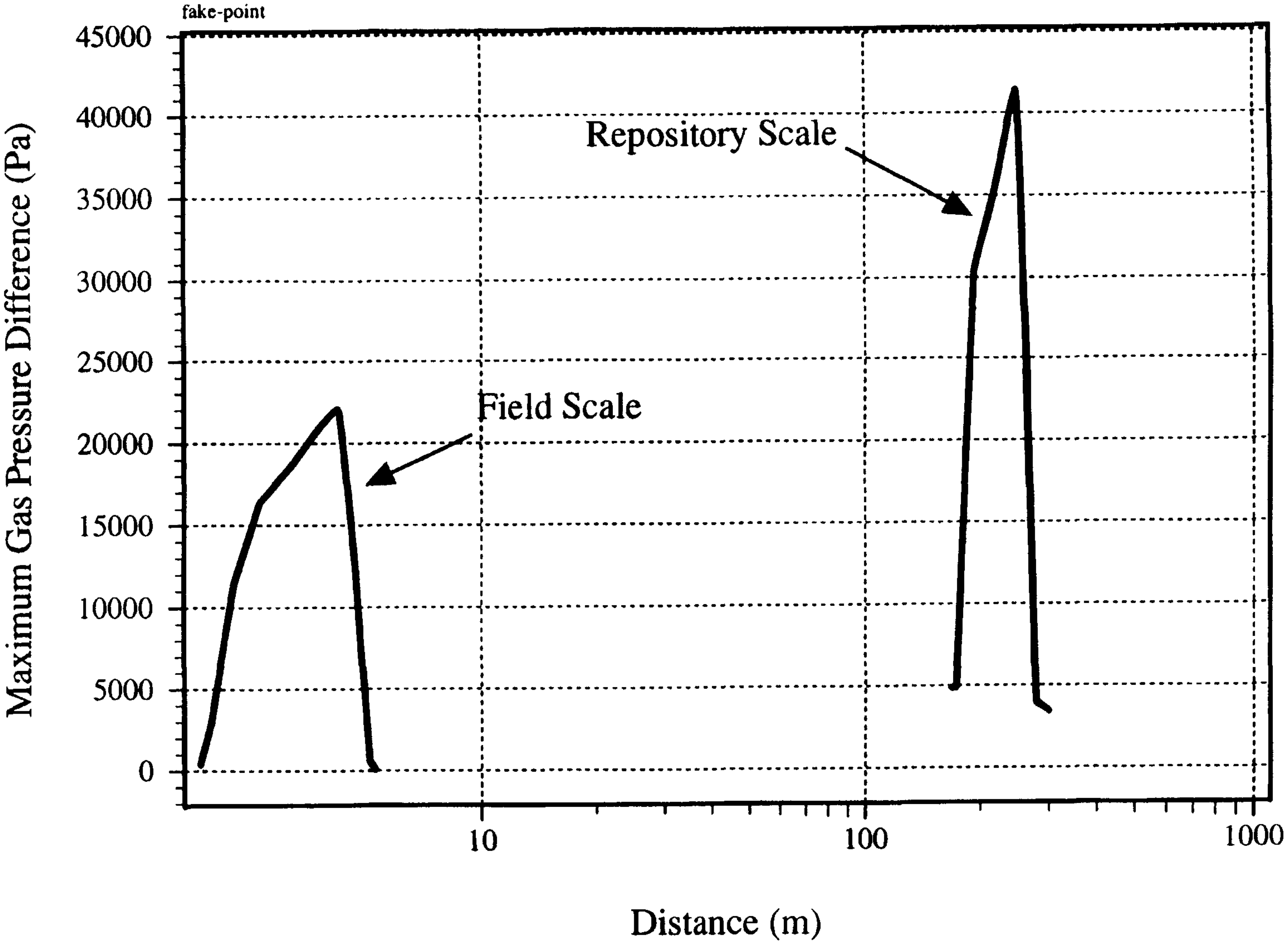

Maximum Pressure Difference (Pa)
40000
30000
20000
10000
0
Laboratory Scale
Field Scale
Repository Scale
10000
100000
1e+06
1e+07
1e+08
1e+09
1e+10
Time (s)

Fig 2


fake-point
Maximum Gas Pressure Difference (Pa)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Repository Scale
Field Scale
10
100
1000
Distance (m)

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