COUPLED FLUID FLOW AND SALT CREEP ANALYSIS: SUMMARY OF TECHNICAL WORK

John B. Case, Stephen Niou
John Pietz, Mike Wallace, and Jon Zurkoff
IT Corporation
2340 Alamo, S.E., Suite 306
Albuquerque, New Mexico 87106

ABSTRACT

Current investigations at the Waste Isolation Pilot Plant (WIPP) are evaluating the nature of hydrologic barriers for the isolation of transuranic radioactive waste at the repository horizon. An important issue is the time required for resaturation of the waste following closure of the repository. The resaturation time is affected by three coupled processes that occur simultaneously; these include salt creep, brine fluid flow, and waste consolidation. To evaluate these processes, a computer code, COUPLE, was developed that simultaneously solves several equations modeling these processes. This code is described and a sample problem solved to illustrate the code's capabilities. The preliminary analysis was conducted for fully coupled, partially coupled (fluid flow and salt creep), and uncoupled processes (flow only). The preliminary results indicate that the creep deformation reduces by several fold the void volume in the waste. The cumulative amount of brine needed to saturate the voids and the resaturation time are smaller in the case of fully or partially coupled flow than in cases where only brine inflow is considered.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), which is located in southeastern New Mexico, is a U.S. Department of Energy facility for the permanent disposal of transuranic radioactive wastes in rock salt. The purpose of WIPP is to isolate these wastes in compliance with 40 CFR 191 (1) regarding the long-term geologic isolation of radioactive wastes. The WIPP program consists of geochemical, hydrological, and geomechanical investigations to assure compliance. This paper describes a preliminary coupled hydrological-geomechanical analysis at the repository horizon that was part of this program.

The present disposal system may be viewed as a series of physical and chemical barriers that exist between the repository horizon and accessible environment. The physical barriers are the hydrologic characteristics of the bedded salt and associated interbeds of the Salado Formation, the seal system emplaced in the shafts of the repository, and the overlying formations, including the Culebra and Magenta dolomites. The chemical barriers include the chemical retardation characteristics of these same formations and seals.

The physical barrier systems possess different hydrologic characteristics from the standpoint of conducting analysis and addressing uncertainty in the performance of the repository. At the repository horizon, the existing salt formations are relatively impermeable. However, the process of excavation has relieved the existing state of lithostatic stress and fluid pressure and caused the development of a zone of disturbance and increased permeability near the waste rooms (2). Brine inflow rates will increase over the short term. The overlying dolomites are far removed from this zone of disturbance, and the natural or existing groundwater movements, though occurring through more permeable zones than salt, are not significantly affected by the repository environment.

This paper presents a preliminary analysis that addresses some of the issues of brine inflow near the repository horizon. A statement of the coupled fluid flow problem is presented, and the implications of coupled fluid flow to repository resaturation are discussed. The coupled fluid flow-salt creep model COUPLE that has been developed from theoretical considerations is then described. A preliminary analysis is then presented that demonstrates the model's capabilities to solve coupled fluid flow-salt creep problems.

STATEMENT OF THE PROBLEM

During the several stages of repository development and operation, several processes occur simultaneously that affect brine flow from the strata adjacent to the excavation. During this period, a transient flow system will develop with brine/gas flow towards the repository in response to the constant atmospheric pressure sink that exists at the excavation surface and the increase in permeability caused by stress relief near the excavation. Owing to the relative impermeability of the surrounding rock salt, the flow rates are small and the brines may be evaporated by the underground mine ventilation system. Wastes are then emplaced in repository rooms and isolated by seals emplaced in the panel access drifts and shafts. Brine and gas flows from the adjacent salt and interbeds towards the waste causing resaturation. Room void volume is simultaneously reduced by creep closure. The rate that the waste consolidates is affected by the rates at which brine saturates the voids and by the creep closure rates of the rooms. Room closure will increase the pore pressure and effective stresses with time. Because the rate at which brine flows to the room is dependent on pore pressure and effective stress, the several processes are coupled in that one process affects the other. The degree of coupling may be significant in determining how much brine may reach the waste and the time to repository resaturation.

While the nature of the coupled processes of brine flow, waste consolidation, and salt creep have not been evaluated in detail, it is clear that the resaturation period is an important isolation period. Brine will flow towards the repository until such time as the repository is resaturated and repressurized. Radionuclides will not be released to the accessible environment by groundwater flow during this time.

During this period, creep closure in the main entries may result in consolidation of crushed salt in the presence of brine since it has been found that small amounts of moisture will significantly accelerate creep consolidation (3). Crushed salt creep consolidation will result in a significant reduction in permeability and possible encapsulation of the waste.

COUPLE MODEL DEVELOPMENT

The computer code COUPLE was developed to provide a preliminary analysis and an understanding of the coupled phenomena. A simplified flow chart for the code is presented in Fig. 1. The analysis is performed through the solution of a series of coupled relationships that describe brine flow, salt creep and waste consolidation phenomena subject to certain simplifying assumptions. These assumptions include:

- o The solids in the waste and brine reaching the room are incompressible relative to the compressibility of the skeletal waste structure.
- o The waste compacts according to a linearized effective stress versus void ratio relationship (4).
- o The air which is trapped in the rooms compresses according the ideal gas law, and the effects of air solubility in brine are ignored.
- o Long-term wall deformation of the room, which is assumed to be circular in shape, occurs due to secondary creep under isothermal conditions, with elastic and primary creep deformations ignored. The media is assumed to be isotropic and homogeneous extending some distance from the room.
- o The properties of the salt, brine, and waste are constant with respect to changes in temperature, pore pressure, total stress, and time.
- o The effects of elevation hydraulic potential are ignored.

The governing equation for one-dimensional transient flow through salt is derived as (5):

$$\frac{1}{\mu}(\nabla \bullet k\nabla p) = -(1-\phi)\,\alpha\,\frac{\partial\sigma_e}{\partial t} + \beta\frac{\partial p}{\partial t}$$

subject to the following boundary and initial conditions:

P(0,t) = room air pressure at the room boundary,
P(l,t) = farfield fluid pressure at some distance for all time, and
an initial pressure distribution of P(x,0) for 0 < x < l, steady state,

where

- ∇ = the del operator,
- k = intrinsic salt permeability,
- μ = brine viscosity,
- P = brine pressure
- ϕ = salt porosity,
- α = salt compressibility,
- σ_e = effective stress in the salt matrix,
- β = brine compressibility,
- t = time, and
- l = length of flow regime.

In the above relationship, flow occurs under constant temperature through the salt, with recharge occurring from interbeds or salt that may be at some distance from the room or an adjacent interbed near the room. The above relationship differs from the usual partial differential equation for groundwater flow in that total stress may change within the salt and the effects of elevation hydraulic potential are neglected. The total stress near the room which had been relieved by excavation is restored by saturation and pressurization of the voids in the room.

In the analysis of consolidation, the pore pressure in the room, "p", is a function of the degree to which the voids are compressed by creep of the surrounding rock salt. Two additional partial differential equations are derived from compatibility and continuity considerations for the waste, the brine and the trapped air:

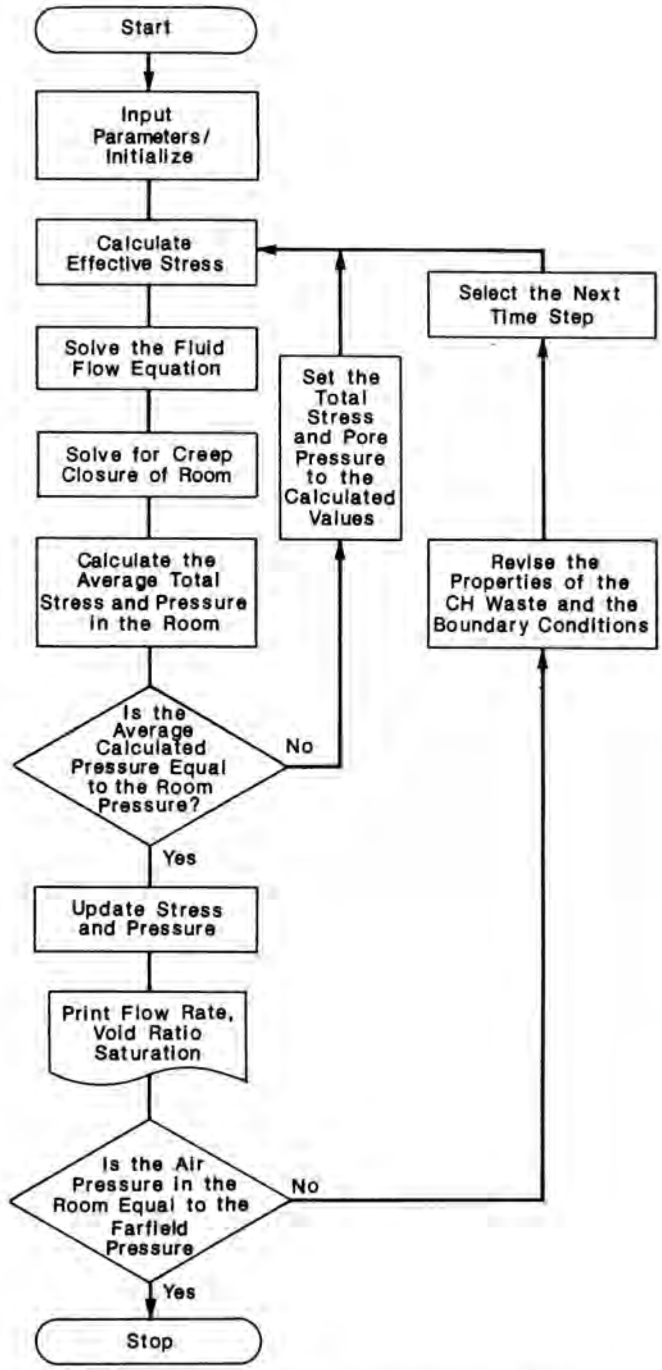

Fig. 1. Flow chart for program "COUPLE."

$$\left[a_v V_s + \frac{nRT}{p^2}\right] \frac{\partial p}{\partial t} - a_v V_s \frac{\partial \sigma}{\partial t} = \frac{\partial V_w}{\partial t}$$

$$-\frac{\partial p}{\partial t} + \frac{\partial \sigma}{\partial t} = \frac{2\ (1 + e)}{a_v}\ \dot{\epsilon}c' \left[\frac{\sqrt{3}}{2}\right]^{n'+1} \left[\frac{2(\sigma_o - \sigma)}{n\sigma_c}\right]^{n'}$$

where

- a_v = compressibility of the CH waste,
- V_s = volume of the solids per unit volume,
- V_w = volume of water per unit volume in the room,
- n = number of moles of gas per unit volume,
- R = universal gas constant,
- σ = total stress on the CH waste,
- e = void ratio of the waste,
- ϕ = initial porosity,
- $\dot{\epsilon}c'$, n' = creep constants of intact rock salt, and
- σ_o = farfield stress.

The above relations are solved by the implicit finite difference method subject to the condition that the brine flow rate from the salt is equal to the rate that brine accumulates in the room. The other boundary conditions include a constant pressure at the interbed and the farfield lithostatic state of stress. The initial conditions would assume atmospheric pressure in the waste and the absence of brine.

MODELING ANALYSIS AND RESULTS

A preliminary one-dimensional analysis was performed for purposes of investigating the nature of the coupled phenomena. The input properties for performing COUPLE analysis are comprised of the room geometry, the farfield and nearfield boundary conditions, the nearfield initial pressure condition in the waste, and the material properties of the CH waste, the salt, and the brine. These properties are summarized in Table I. Wherever possible, reference properties were used.

Definition of the waste properties (in particular the compressibility) is difficult because of the varied nature of the waste form (scrap metal, paper and rags, etc.). In the preliminary analysis it was assumed that the waste properties are the same as the contact handled (CH) waste properties containing 40 percent by volume of scrap metal that were used in a previous analysis of the potential for brine flow through boreholes penetrating the WIPP CH waste (6). A detailed description of the estimated compressibility and the initial void ratio of 7.0 for the CH waste is contained in the appendix of this reference. The properties of the salt are based on the reference thermomechanical properties (7) and recent insitu permeability measurements using the guarded straddle packer system (8). The combined permeability measurements near the entry are shown in Fig. 2 and apparently indicate that there is a relationship of permeability with test interval depth. The data indicate that permeability is reduced by two orders of magnitude (10^{-4} to 10^{-6} md) over a depth of from 1 to 14 m. To account for stress relief effects near the repository, an intrinsic permeability of 10^{-5} md was selected.

In the example problem that is presented for illustration purposes, it was assumed that a general drawdown occurs near the repository and the recharge zones are at a distance of 200 m from the repository, with the farfield pressure assumed to be equal to a static column of brine (8.1 MPa) at the repository horizon. It is noted that actual farfield hydrostatic pressures may be higher and approximately equal to the lithostatic stress.

The problem analyzed represents a crude approximation to the actual flow regime. Nevertheless, it is believed the coupled nature of salt creep and brine flow may be investigated. The flow analyses conducted were either fully coupled (flow-creep-waste), partially coupled (flow-creep), or not coupled at all.

The results of the preliminary analysis are summarized in a series of time-history plots of flow

TABLE I

Reference Properties for Preliminary Coupled Fluid Flow and Salt Creep Analysis

	Parameter	Property	Units	Reference
1.	Geometry			
	Radius, a	3.56	m	
2.	CH Waste Properties and Initial Conditions			
	Void ratio, e	7.02	--	6
	Compressibility, a_v	24	$(MPa)^{-1}$	6
	Air pressure, P_{atm}	0.101	MPa	6
3.	Salt Properties and Boundary Conditions			
	Empirical constant, $\dot{\epsilon}c'$	2.43×10^{-10}	day^{-1}	7
	Salt compressibility, α	4.83×10^{-5}	MPa^{-1}	7
	Stress exponent, n	4.9	--	
	Farfield stress, σ_o	15	MPa	2
	Intrinsic salt permeability, k	10^{-5}	md	8
	Intrinsic salt porosity, ϕ	0.01	--	9
4.	Fluid Properties and Boundary Conditions			
	Brine viscosity, μ	.0013	kg/(m-sec)	10
	Brine compressibility, β	4.4×10^{-4}	$(MPa)^{-1}$	11
	Farfield brine pressure, p	8.1	MPa	see text

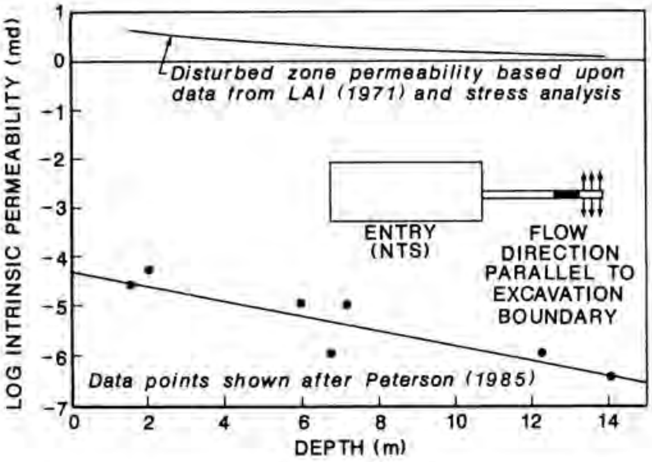

Fig. 2. Relationship of salt permeability with depth near the excavation.

rate versus time (Fig. 3A), cumulative flow versus time (Fig. 3B), total stress and pore pressure versus time (Figs. 3C and 3D), and volumetric saturation versus time (Fig. 3E). (See the next page for Fig. 3.) The flow rate in the flow-only case is invariant with time, while the flow rates diminish with time in the case of partially or fully coupled phenomena. As creep closure and waste consolidation occurs, pore pressures develop within the CH waste, which results in a reduction of hydraulic gradients and a reduction in flow rate with time. For approximately 3,000 years, the room pressures are low, and the fully coupled and partially coupled cases are nearly identical. After 3,000 years, the void space in the fully coupled case has been reduced more significantly and room pressures start to develop.

A comparison of total stress or room pore pressure development between the partially coupled case and the fully coupled case indicates that the effective stress development in the waste is approximately the same. Effective stress development is small owing to the relatively high compressibility of waste. However, it should be noted that compressibility of the waste forms are variable and that a preponderance of a stiffer waste from could potentially influence the consolidation process.

CONCLUSIONS

The preliminary results to date provide interesting insight into the repository resaturation issues. The results indicate that the creep deformation reduces by several fold the void volume in the waste. This results in an increase in the waste effective and pore pressures, which in turn slows down the brine flow rate. The cumulative amount of brine needed to saturate the voids and that could potentially contact the waste is thus smaller in the case of a fully coupled or partially coupled analysis, while the resaturation time is shorter in duration than in the case considering only brine inflow. Future work will evaluate the sensitivity of results to properties and the two-dimensional nonhomogeneous flow regime.

REFERENCES

1. U.S. ENVIRONMENTAL PROTECTION AGENCY, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," 40 CFR 191, Washington D.C. (1985).

2. J. B. CASE and P. C. KELSALL, "Coupled Processes in Repository Sealing," Paper presented at the International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratory (1985).

3. J. B. CASE, J. L. WITHIAM, and P. C. KELSALL, "Laboratory Investigation of Crushed Salt Consolidation," Paper to be presented at the 28th U.S. Symposium on Rock Mechanics (in preparation), Tucson, Arizona (1987).

4. R. F. SCOTT, *PRINCIPLES OF SOIL MECHANICS*, 550 p., Addison Wesley Publishing Company, Inc., Reading, Massachusetts.

5. J. BEAR, *DYNAMICS OF FLUID IN POROUS MEDIA*, 764 pp. American Elsevier Publishing Co., Inc., New York.

6. U.S. DEPARTMENT OF ENERGY, "Analysis of Potential Impacts of Brine Flow Through Boreholes Penetrating the WIPP Storage Facility," TME 3155, U.S. DOE, Albuquerque, New Mexico (1982).

7. R. D. KRIEG, *REFERENCE STRATIGRAPHY AND ROCK PROPERTIES FOR THE WASTE ISOLATION PILOT PLANT (WIPP) PROJECT*, SAND 83-1908, Albuquerque, New Mexico (1983).

8. F. V. PETERSON, P. LAGUS, J. BROWN, and K. LIE, *WIPP HORIZON INSITU PERMEABILITY MEASUREMENTS, FINAL REPORT*, SAND 85-1766, Albuquerque, New Mexico (1985).

9. INTERNATIONAL TECHNOLOGY CORPORATION, *ASSESSMENT OF CRUSHED SALT CONSOLIDATION AND FRACTURE HEALING PROCESSES IN A NUCLEAR WASTE REPOSITORY*, BMI/ONWI-546, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio (1984).

10. R. A. FREEZE and J. A. CHERRY, *GROUNDWATER*, Prentice-Hall, Inc. (1975).

11. R. L. DAUGHERTY and J. B. FRANZINI, *FLUID MECHANICS WITH ENGINEERING APPLICATIONS*, McGraw-Hill, New York (1965).

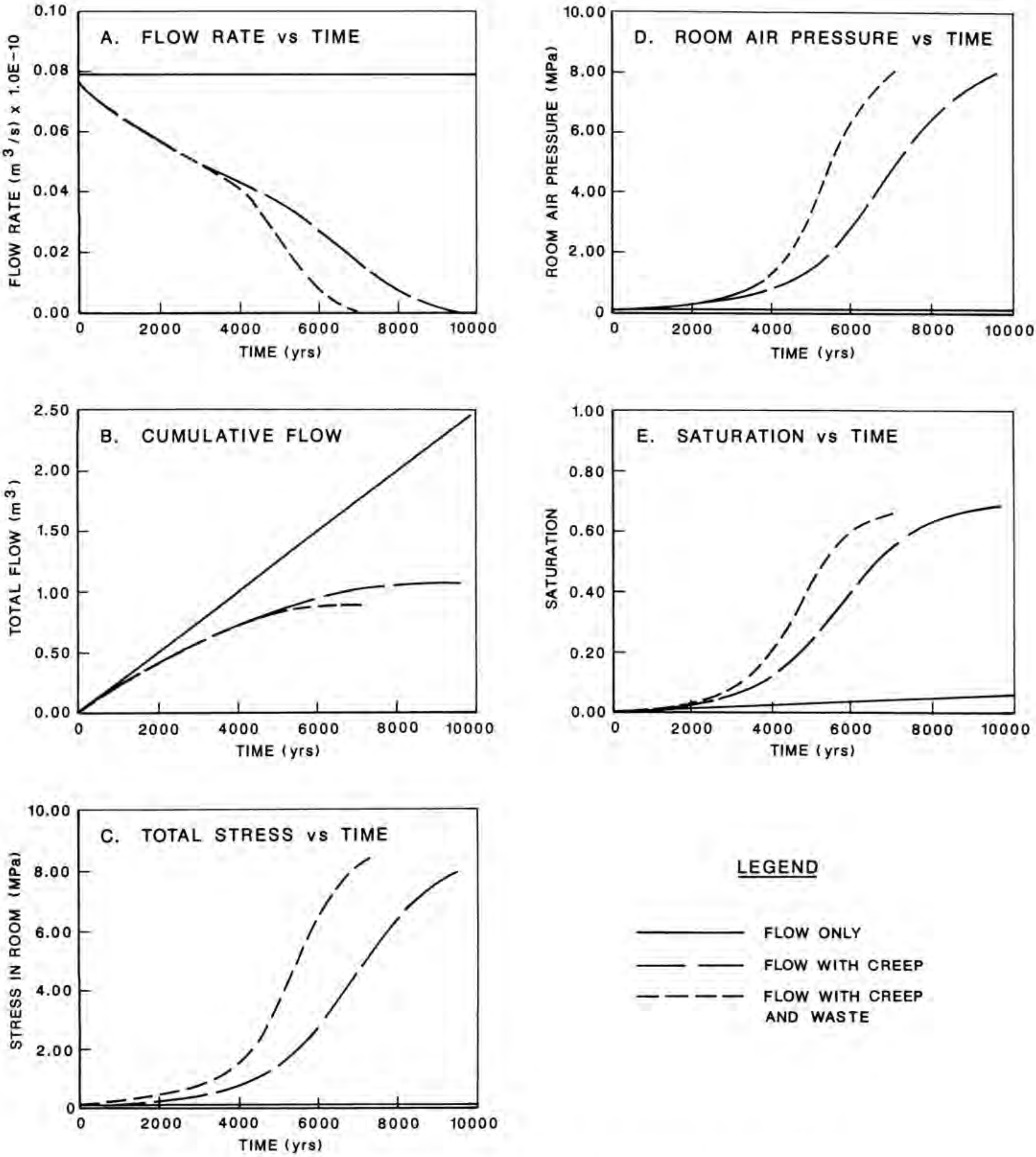

Fig. 3. Summary of time history plots from the preliminary coupled analysis.