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David Tiktinsky - SS623
U.S. Nuclear Regulatory Commission
Division of Waste Management
Washington, D.C. 20555

"NRC Technical Assistance
for Design Reviews"
Contract No. NRC-02-85-002
FIN D1016

Dear David:

Enclosed is our review of a series of ten documents, entitled "Summary Review of Thermomechanical Room-Scale Testing at WIPP". Please call me if you have any questions.

Sincerely,

Roger D. Hart
Program Manager

cc: R. Ballard, Engineering Branch
Office of the Director, NMSS
E. Wiggins, Division of Contracts
DWM Document Control Room

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ITASCA DOCUMENT REVIEW

File No.: 001-02-37

Document Title: Summary Review of Thermomechanical Room-Scale Testing at WIPP

Reviewer: Itasca Consulting Group, Inc.
(B. Brady, L. Lorig and K. Wahi)

Date Review Completed: 14 July 1987

Approved: Roger D. Hart

Date Approved: July 14, 1987

The documents examined for this review are listed below.

In-Situ Testing Plan Documents

(1) "Waste Isolation Pilot Plant (WIPP) Research and Development Program: In Situ Testing Plan March 1982" by Rudolph V. Matalucci, Charles L. Christensen, Thomas O. Hunter, Martin A. Molecke, and Darrell E. Munson (SAND81-2628, January 1984)

(2) "Implementation of Thermal/Structural Interactions In Situ Tests at the Waste Isolation Pilot Plant Facility," by Darrell E. Munson, Rudolph V. Matalucci, and Teresa M. Torres, (in Proceedings of the 2nd International Conference on the Mechanical Behavior of Salt (Hannover, Sept. 1984)

(3) "The Integrated In Situ Testing Program for the Waste Isolation Pilot Plant (WIPP) (Draft)," by Rudolph V. Matalucci (Sandia Report, 1986)

Pre-Test Reference Calculation Documents

(4) "Pretest Reference Calculation for the 18-W/m2 Mockup for Defense High-Level Waste (WIPP Room A In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0807, 1985a)

(5) "Pretest Reference Calculation for the Overtest for Simulated Defense High Level Waste (WIPP Room B In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0213, 1985b)

(6) "Pretest Reference Calculation for the 6.1 Meter (20 ft) Wide Drifts of the Geomechanical Evaluation (WIPP Room G In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0893, 1985c)

Comparative Analysis Calculation Documents

(7) "Numerical Simulation of the Creep Response of Model Salt Pillars" by J. G. Arguello and H. S. Morgan (SAND85-2429, January 1986)

(8) "Comparison Between Predicted and Measured South Drift Closures at the WIPP Using a Transient Creep Model for Salt" by D. E. Munson and A. F. Fossum (in Rock Mechanics: Key to Energy Production (Proceedings of the 27th U.S. Symposium on Rock Mechanics, University of Alabama, 1986), pp. 931-939. Littleton, Colorado: Society of Mining Engineers, Inc., 1986)

(9) "Early Results from the Thermal/Structural In-Situ Test Series at the WIPP" by D. E. Munson, T. M. Torres and D. A. Blankenship (in Rock Mechanics: Key to Energy Production (Proceedings of the 27th U.S. Symposium on Rock Mechanics, University of Alabama, 1986), pp. 923-930. Littleton, Colorado: Society of Mining Engineers, Inc., 1986)

Document Describing Methodology for Performing Parallel Design Calculations

(10) "Methodology for Performing Parallel Design Calculations (Nuclear Waste Repository Application)" by D. E. Munson and H. S. Morgan (SAND 85-0324, May 1986)

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(4) "Pretest Reference Calculation for the 18-W/m2 Mockup for Defense High-Level Waste (WIPP Room A In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0807, 1985a)

(5) "Pretest Reference Calculation for the Overtest for Simulated Defense High Level Waste (WIPP Room B In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0213, 1985b)

(6) "Pretest Reference Calculation for the 6.1 Meter (20 ft) Wide Drifts of the Geomechanical Evaluation (WIPP Room G In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0893, 1985c)

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SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM

Experience gained through thermomechanical room-scale testing at WIPP undoubtedly will influence site characterization plans for the Deaf Smith site. One of the primary purposes of these tests at WIPP is to generate data that will help validate computer models. The documents clearly state that the ultimate goal of the WIPP modeling effort is to develop modeling capabilities that are transferable from one salt site to another without a priori knowledge of room response at the new site. The intent to supplement (with WIPP data) the in-situ testing data from a salt site selected for characterization under the commercial high-level waste repository programs appears quite strong. The extensive data base generated from the WIPP tests should provide a good source of the data to improve the understanding of in-situ conditions and creep behavior at Deaf Smith. In fact, some of the information obtained at WIPP may be used directly by the DOE in support of license application. Furthermore, DOE may elect not to carry out a full-fledged in-situ testing program at that site; instead, it may use the WIPP testing programs as a justification for reducing the scope of test plan at the commercial site.

Thermomechanical room-scale testing at WIPP represents an important departure from earlier tests (e.g., Project Salt Vault) in that the in-situ tests at WIPP were designed to be compatible with available analysis methods. Because these methods were limited to consideration of two-dimensional problem geometries, tests were designed (Rooms G and H) to conform to 2-D analysis. Other tests (Rooms A and B) were instrumented most heavily at the mid-section, where end effects can be neglected with most confidence and response would be mostly two-dimensional.

Numerical calculations played an important role in all aspects of the WIPP in-situ testing. Four categories of calculations were involved: parametric studies, scoping calculations, reference calculations, and comparative analysis. The testing and modeling techniques used at WIPP are indeed state of the art and are expected to play a major role in the planning, conduct, and prediction of in-situ tests at Deaf Smith.

However, these papers have particular consequences for the NRC Waste Management Program in confirming that there is currently no capacity for predicting, to within a reasonable engineering tolerance, the response of salt to development of excavations. While one would not endorse the assertion in one paper (Munson and Fossum, 1986) that use of numerical models is the only method which can support the eventual assurance of the long-term adequacy of a repository design, it is certainly the case that it is essential to be able to predict room closures, pillar performance and emplacement hole performance, at least over the period of repository operation and canister retrievability. These issues concern both operating safety and waste retrievability. There is also the question of public confidence in an isolation system for which even the short-term performance cannot be predicted. Evaluation of seal and backfill performance requires the ability to predict creep behavior for longer time periods. This issue relates to the repository's ability to isolate waste from the accessible environment.

Model validation exercises may have been attempted prematurely without having a reasonable understanding of the fundamentals of creep behavior. An important question facing both DOE and NRC is whether it will be possible to validate any numerical model for use in accurately predicting long-term creep response of salt. Certainly, it is questionable whether any empirical approach can be used. It presently appears that micromechanical modeling approaches involving deformation mechanisms maps may have a better chance. There are those who argue that such validation may not be possible. Starfield and Cundall (1987), for example, argue that, instead of trying to validate a model, the aim should be to gain confidence in it and modify it accordingly. In this context, one area which may prove fruitful is in the analysis of salt diapers formed over geologic time periods. Qualitatively duplicating observed diaper formation undoubtedly would provide a measure of confidence in the selected salt creep behavior model.

The documents maintain the error common to most papers and reports on creep of rock salt—i.e., that the ranges of temperature, stress and moisture conditions under which the putative "creep law" (in this case, the WIPP reference model) has been developed are not reported. It is well known that, although it may be acceptable to use an empirical creep equation to interpolate strain rates from a data set, it is certainly unwise to use such an expression for purposes of extrapolation [see, for example, Jaeger and Cook (1979), p. 312].

One of the documents (Arguello and Morgan, 1986) indicates that discrepancies in South Drift-predicted and -measured data can be duplicated in bench-scale tests under similar temperature and stress conditions. The authors are hopeful that a series of carefully controlled bench-scale tests can be used to resolve the discrepancies. However, this may be possible only if the stress, temperature and moisture conditions in situ and in the test specimen are not significantly different.

Another document (Matalucci, 1986) presents what are considered to be vital features of in-situ testing in bedded salt. These include:

(1) full size in-situ tests and operational demonstrations;

(2) conduction of pre-fielding tests to evaluate instruments;

(3) test calculations which provide information on room geometries, instrument locations, excavation techniques, and anticipated measurement ranges; and

(4) collection of all test plans, calculations, design, construction and installation records in a test document file (largely a QA requirement).

Whereas the test plans give reasonable justifications for many aspects of the thermomechanical in-situ testing, they fail to provide some key information required by the NRC's GTP on In-Situ Testing During Site Characterization. These include: (1) a basis for determining test duration; and (2) the representativeness of the test location.

The study reported by Munson and Morgan (1986) uncovers potential problems with the use of sophisticated numerical models in predicting the thermomechanical response of underground structures. The study is significant to the NRC for the following reasons. The findings and lessons learned must be considered in planning the reviews of the Site Characterization Plan (SCP) and License Application (LA). It is concerned with repository design calculations and has generic and specific implications with respect to the reliability of results obtained with numerical models. The generic implication is that non-linear structural response predictions of a given repository system using different models can be vastly different. These differences can arise when either different computer programs (i.e., numerical formulations) are used or when the QA procedures for the execution of such calculations are inadequate or poorly enforced. Specific implications pertain to the proper choice of a computer program for handling large deformations and for repository design in bedded salt.

Difficulties in reconciling differences between results of parallel calculations in the study underscore the importance of gaining an understanding of significant mechanisms involved in a particular problem by progressing systematically from simple models to more complex models. For example, errors in slideline logic in one of the codes masked a more fundamental underlying problem involving the code's inherent inability to model large strain. This difference could have presumably been reconciled at an early stage by considering a simpler problem which did not require slideline capability.

SUMMARIES

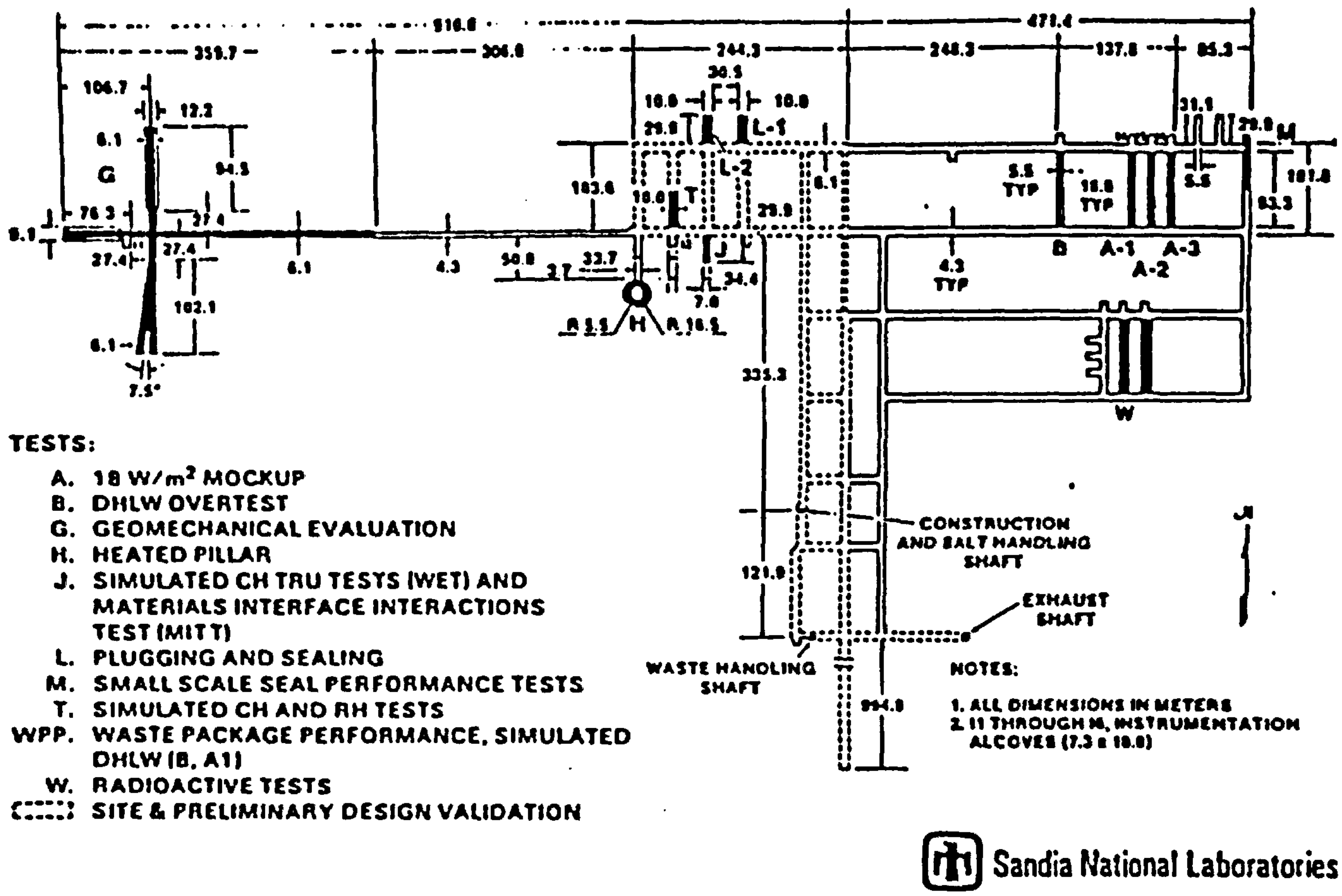
In-Situ Testing Plan Documents

(1) "Waste Isolation Pilot Plant (WIPP) Research and Development Program: In Situ Testing Plan March 1982" by Rudolph V. Matalucci, Charles L. Christensen, Thomas O. Hunter, Martin A. Molecke, and Darrell E. Munson (SAND81-2628, January 1984)

(2) "Implementation of Thermal/ Structural Interactions In Situ Tests at the Waste Isolation Pilot Plant Facility," by Darrell E. Munson, Rudolph V. Matalucci, and Teresa M. Torres, in (Proceedings of the 2nd International Conference on the Mechanical Behavior of Salt (Hannover, Sept. 1984)

(3) "The Integrated In Situ Testing Program for the Waste Isolation Pilot Plant (WIPP) (Draft)," by Rudolph V. Matalucci (Sandia Report, 1986)

These three documents summarize in-situ tests in the following areas: (1) site and preliminary design validation; (2) thermal/ structural interactions; (3) plugging and sealing; and (4) waste package performance. A plan view of test locations are shown in Fig. 1.



Note: all dimensions in meters

Exploratory Shaft = construction and salt-handling shaft

South Drift = drift (994.9m long) extending southward from drift connecting waste-handling and exhaust shafts

Room D = room located 85.3m east of Room A-3

Fig. 1 Underground Layout of the WIPP In-Situ Tests [Matalucci (1986), p. 4]

Site and preliminary design validation involves extensive testing in the 3.66m diameter exploratory shaft (also known as the construction and salt-handling shaft). The three areas of testing are: the lined shaft for hydrological measurements and liner deformation; the shaft liner key (designed to seal the liner bottom from seepage) for hydrological measurements and key strains; and an unlined portion of the shaft for closure and salt deformation. Entries leading northward from the exploratory shaft are instrumented with multipoint extensometers, rockbolt load cells, closure stations, and stress gauges for geomechanical measurements. The test panel consists of four 10x3.96m rooms separated by 30.18m pillars. Instrumentation is basically the same as for the entries.

The room-scale tests described for thermal/structural interaction (TSI) include the following.

1. Room A testing consists of an 18 W/m^2 DHLW mock-up of a reference repository room and thermal loading. Excavation of adjacent "guard" rooms allow the test to function as a "mine-by" test as well.

2. Room B consists of a DHLW overtest of thermal effects (also known as the accelerated room test)

3. Room D, a ventilation drift, was excavated prior to any TSI test room. Room D is geometrically identical to Room B and served as a demonstration room for excavation methods, drilling practice, geotechnical measurements, and instrumentation.

4. Room G consists of phased mining of a long drift, an intersection and a tapered pillar.

5. Room H consists of an 11m-diameter heated pillar test.

The experimental configuration of each of these tests are as follows.

The WIPP Room A Experiment is a mock-up for Defense High Level Waste (DHLW) storage with a thermal loading of 18 W/m^2. The experimental configuration consists of three long, parallel rooms with heaters emplaced in the floor. The cross-section of the rooms is similar to that planned for actual DHLW tests to be conducted in 1989. Resistance heaters placed in the floor are powered to simulate the $18 W/m^2$ thermal loading conditions in the center room (Room A2). Guard heaters in Rooms A1 and A3 are designed to provide an adiabatic boundary condition at mid-pillar locations. A plan view of the Room A Experiment is shown in Fig. 2. Following excavation, the experiment has two phases: the first is a six-month period for instrumentation and heater installation, and the second is a three-year period of heating with appropriate power decay to simulate the DHLW with a 30-year half-life. The rooms are instrumented with extensometers, inclinometers, stressmeters, pressure cells, thermocouples and heat flux gauges.

The Room B Experiment is the overtest for simulated DHLW. It consists of a single, long room with vertically emplaced heaters that provide a thermal load roughly four times the load associated with DHLW. The primary purpose of this experiment is to determine the margins of uncertainty for the DHLW emplacement room response. Room B has a length of 93.3m with the central 24.4m portion as the overtest heater section and guard heaters at the extremities of the central heater array. Room dimensions and heater locations are shown in Fig. 3. There are three phases planned for the Room B experiment. Phase I of the Room B experiment consists of a total period of 3.5 years— an initial six-month period for instrumentation and heater installation and a three-year heating period. Phase II involves backfilling of the room to demonstrate backfill emplacement methods and to test candidate backfill materials. Phase III involves testing the recommended procedures for canister retrieval from the hot, backfilled room. Instrumentation is the same as for Room A testing.

The Room G in-situ experiment consists of measuring the geomechanical response of several openings. The structures to be evaluated are: (1) three long, isolated drifts with different roof spans for determining the effect of width; (2) an isolated drift intersection to provide data for future 3-D calculations; and (3) a wedge pillar for yield and failure criteria. The plan is to monitor these openings for ten years. Initially, each of the three drifts will have a cross section of 6.1m (width) x 3.05m (height). Two of the three drifts will be widened one year after excavation. The general layout of Experiment G is shown in Fig. 4.

Room H consists of an isolated round 11m-diameter pillar surrounded by a room 5.5m high by 16.3m wide. The entire surface is heated by a 70 W/m^2 blanket heater intended to produce an estimated near-pillar temperature of 67°C at three years. Again, the purpose of this test is to evaluate the constitutive models, particularly at elevated temperature.

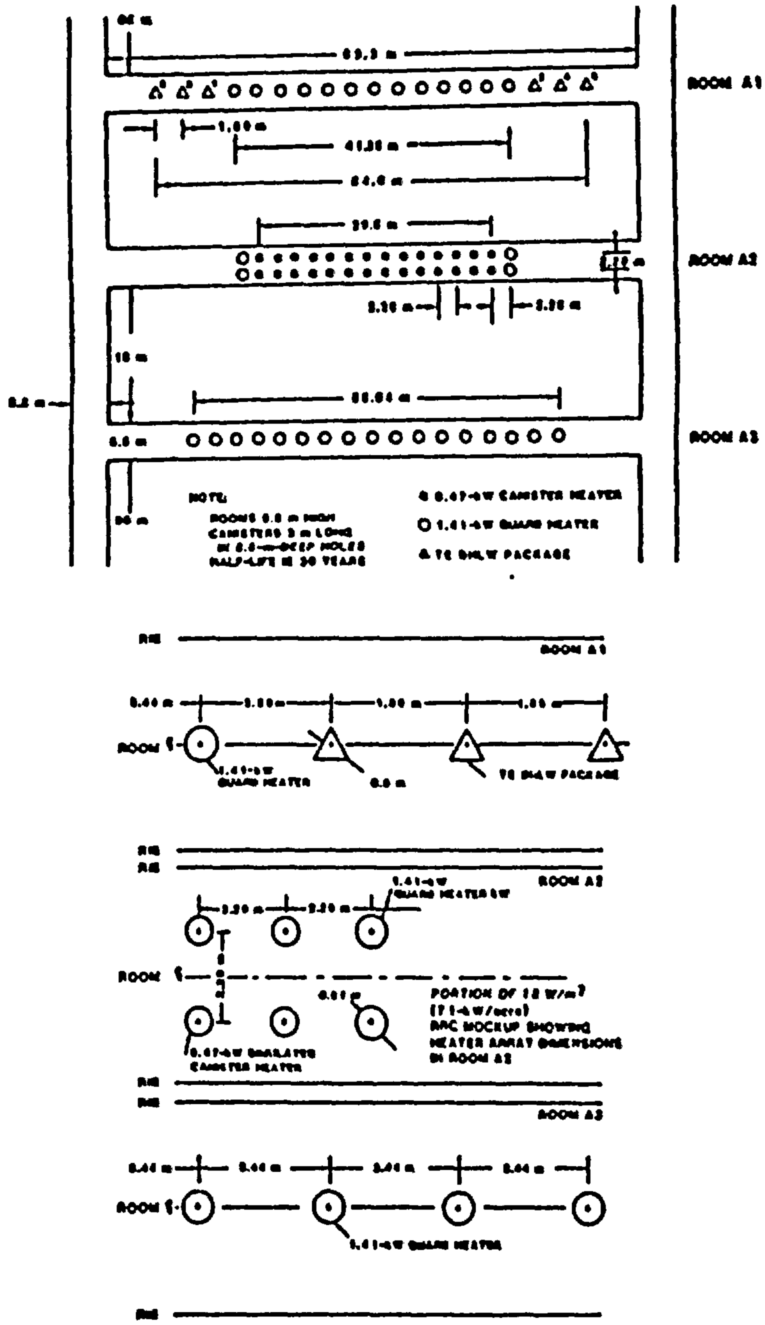


Fig. 2 Plan View of Room A Experiment and the Heater Emplacements [Morgan and Stone, 1985a]

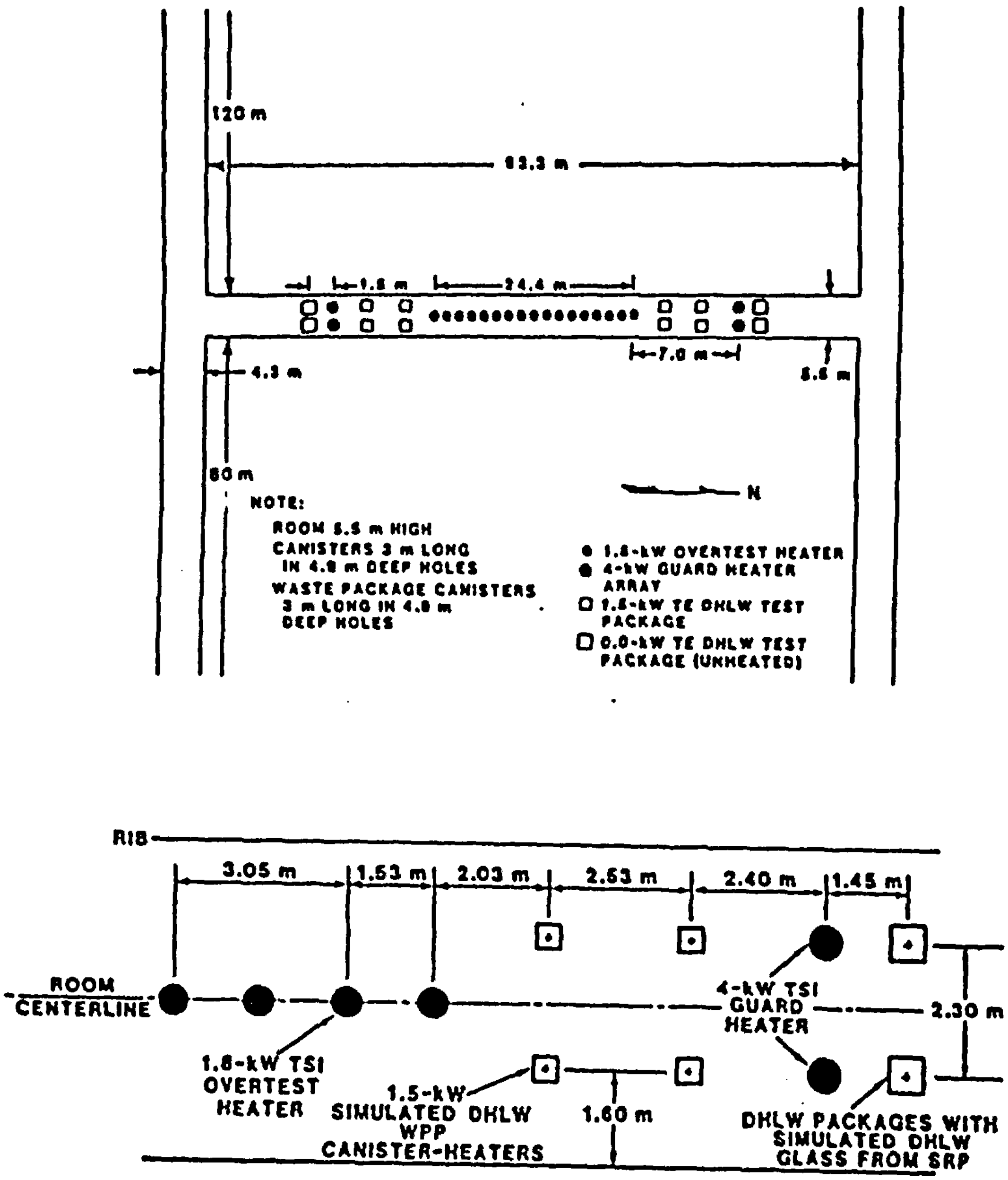


Fig. 3 Plan View of Room B and the Heater Emplacements [Morgan and Stone, 1985b]

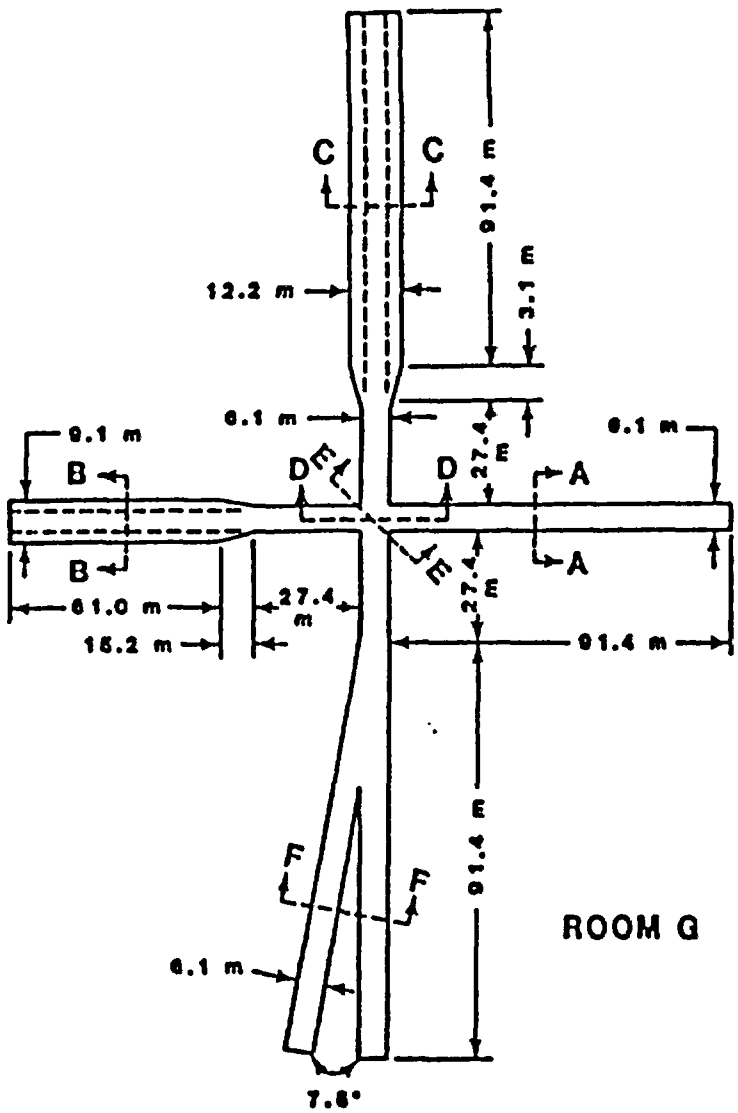


Fig. 4 General Layout Plan of the Geomechanical Evaluation (North is toward the top of the figure.) [Morgan and Stone, 1985c]

Other tests described as part of the thermal/structural interaction series include:

(1) In Situ Stress, hydraulic fracturing tests in long boreholes drilled horizontally along drift axes that will subsequently be excavated;

(2) Clay Seam Shear, in-situ direct shear tests of existing clay seam (Note: a friction coefficient of 0.4 was established from laboratory tests and engineering judgement.); and

(3) Acoustic Emissions Monitoring, in the tapered pillar (Room G) to detect initiation and location of yielding and fracturing in the pillar.

Pre-Test Reference Calculation Documents

(4) "Pretest Reference Calculation for the 18-W/m^2 Mockup for Defense High-Level Waste (WIPP Room A In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0807, 1985a)

(5) "Pretest Reference Calculation for the Overtest for Simulated Defense High Level Waste (WIPP Room B In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0213, 1985b)

(6) "Pretest Reference Calculation for the 6.1 Meter (20 ft) Wide Drifts of the Geomechanical Evaluation (WIPP Room G In Situ Experiment)" by H. S. Morgan and C. M. Stone (SAND85-0893, 1985c)

The pre-test reference calculations follow the scoping calculations (used to establish the location, range and sensitivity of instruments). The reference calculations use the design thermal loading, the mapped stratigraphy and any final, last-minute test modifications. Pre-test reference calculations for three in-situ tests (WIPP Room A, WIPP Room B and WIPP Room G) are reported in the three documents published by Sandia.

Different, yet related, aspects of the structural response of unheated and heated underground excavations are addressed by the set of three documents. Each one of the documents reports the design and execution of a pre-test calculation for the subject in-situ test. Furthermore, response predictions of thermal (if applicable) and mechanical behavior at selected locations are presented.

The locations at which histories of various parameters are monitored during calculations are also the sites of measurements of temperature, displacement, and stress during the in-situ testing.

In all analyses, two-dimensional planar configurations were used in which the rooms were assumed to be infinitely long, corresponding to a plane strain condition—i.e., zero strain in the direction of the room axis. Additionally, symmetry about room centerlines were used for all studies. Thermal calculations were performed using COYOTE, a two-dimensional FE code with 8-noded isoparametric, quadrilateral elements. Mechanical calculations were performed using SANCHO, a two-dimensional FE code with 4-noded, isoparametric, quadrilateral elements. The output (transient thermal response) from the COYOTE calculation served as input (prescribed temperature distribution at each timestep) to the SANCHO simulation. Because the finite element meshes for COYOTE and SANCHO were not the same, the interpolation code MERLIN (Gartling, 1981) was used to map the COYOTE solution onto the SANCHO mesh.

The stratigraphy for each calculation consisted of five different materials. The mechanical properties, constitutive models, and the slip characteristics are the same in each calculation.

Elastic-plastic behavior was assumed for anhydrite and polyhalite with plasticity governed by the Drucker-Prager failure criterion. Only secondary creep was considered for halite and argillaceous halite. The reference constitutive model for halite and argillaceous halite is defined by:

$$\dot{\epsilon}_{ij} = - \frac{\nu}{E} \dot{\sigma}_{kk} \delta_{ij} + \frac{1 + \nu}{E} \dot{\sigma}_{ij} + \dot{\epsilon}_{ij}^{c} + 3\alpha \dot{T} \delta_{ij} \qquad (1)$$

where $\dot{\epsilon}_{ij}$ are the components of total strain rate,

σ_{ij} are the components of the stress tensor,

ν is Poisson's ratio,

E is Young's modulus,

T is absolute temperature,

α is coefficient of linear thermal expansion, and

$\dot{\epsilon}_{ij}^{c}$ are components of creep strain rate.

For secondary creep, the magnitude of creep strain rate, $|\dot{\epsilon}^c_{ij}|$, can be stated in terms of the effective creep strain rate, $\dot{\bar{\epsilon}}^c$, or the effective stress, $\bar{\sigma}$:

$$|\dot{\epsilon}^c_{ij}| = (3/2)^{1/2}\,\dot{\bar{\epsilon}} \qquad (2)$$

$$\dot{\bar{\epsilon}} = D\,\bar{\sigma}^n \exp(-Q/RT), \qquad (3)$$

where

$$\dot{\bar{\epsilon}} = \left[(2/3)\,\dot{\epsilon}^c_{ij}\,\dot{\epsilon}^c_{ij} \right]^{1/2} \qquad (4)$$

and

$$\bar{\sigma} = \left[(3/2)\,\sigma'_{ij}\,\sigma'_{ij} \right]^{1/2} \qquad (5)$$

In the above equations, σ'_{ij} are the deviatoric stress components and D, N, Q/R are constants for the empirical creep law. At the clay seam locations, a frictional sliding model is used with a coefficient of friction of 0.4. No thickness or any other mechanical property or constitutive behavior is associated with clay seams.

The results are presented in the form of deformed meshes, contours of stress, contours of temperature, profiles of stress, and displacement at selected values of time. Time histories of temperature, displacement, and closure at each instrument location are also provided. In most cases, a single location represents several instrument types. In general, the nodal locations in the finite element mesh do not coincide with instrument locations; therefore, interpolation is necessary.

The numerical model simulation for Room A consists of a thermal model and a structural model. Although the planned test period is 3.5 years, the numerical simulations were carried out to a period of 5 years. A volumetric heat source is used to approximate the discrete thermal loading of the canisters. The entire stratigraphy within the confines of the model was assigned the thermal properties of salt. A non-linear thermal conductivity model was used. The room area was assigned an equivalent thermal conductivity that allowed approximation of radiation heat transfer by equivalent conduction. All boundaries were assumed to be adiabatic, and the entire mesh was given an initial temperature of 300K. The mechanical boundary conditions are shown in Fig. 5.

The thermal response calculation indicates that, for the planned life of the experiment (3.5 years), the boundary locations are adequate. For a longer experiment, it would be necessary to extend the top and bottom boundary locations. The largest temperature increase is at thermocouple locations adjacent to the heater at heater midheight. This temperature increase is about 45K at 3.5 years and 50.5K at 5 years. The temperature increase at the floor surface is 23K at 3.5 years and 29K at 5 years. The roof and pillar wall show temperature increases that are slightly smaller than those at the floor.

The deformation response calculation indicates that slip is greatest along "Clay F", a clay seam below the floor horizon. The slip is much smaller along Clay J (above the roof), with the clay seams showing negligible or no slip. The vertical closure is 0.57m at 3.5 years and 0.96m at 5 years. The horizontal closure is 0.61m at 3.5 years and 1.04m at 5 years. The pillar shortening is 0.23m at 3.5 years and 0.36m at 5 years. Prior to heating, the vertical displacement in the floor is nearly equal to the vertical displacement of the roof. After heater power is turned on, the floor moves much faster than the roof. At the end of five years, the net vertical floor displacement is three times that of the roof. The stress concentrations are high immediately after excavation. However, as the salt creeps, the concentrations begin to dissipate and much of the load is transferred to the stiffer, non-creeping anhydrite layers. The in-plane and out-of-plane horizontal stresses in the anhydrite layers are much greater than other stresses in anhydrite and all stresses in other layers.

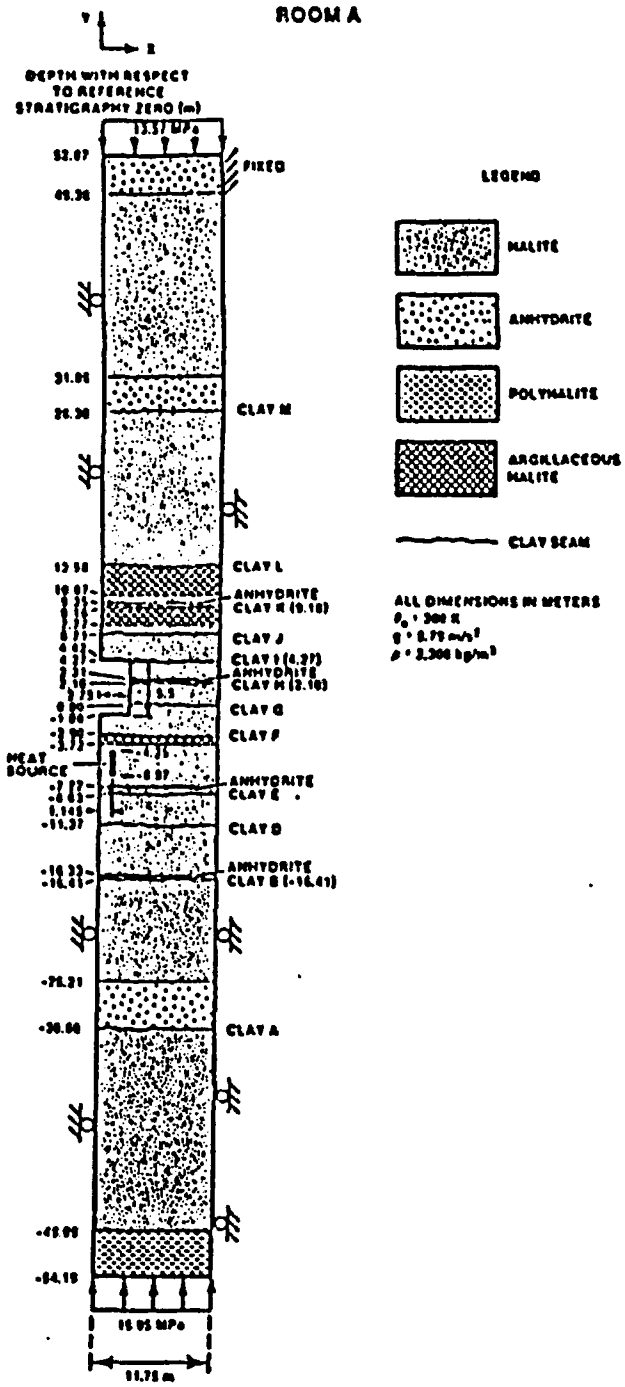


Fig. 5 Room A2 Configuration Used in Pre-Test Reference Calculations [Morgan and Stone, 1985a]

The pre-test reference calculations for the first phase of the WIPP Room B Experiment are presented in the second document (Morgan and Stone, 1985b). The two-dimensional model configuration is shown in Fig. 6. The thermal loading was approximated with a line source located on the left symmetry plane. The thermal properties of halite were assigned to all materials in the stratigraphy. Except for the manner in which the heat source was modeled, the COYOTE model for Room B was analogous to the Room A model. The thermal response calculation predicts that, two years after the start of the Room B experiment, the entire room cross-section has been heated to over 325K. After five years, temperatures of over 350K are predicted throughout the room. The temperature at five years is between 450K and 475K near the heaters. Boundary effects on thermal response become evident sometime between 3.5 and 4.0 years. Localized temperature increase at five years near the heat source is as much as 169K. The largest temperature increase at the floor surface is 61K at 5 years. Increases at those locations at a time of 3.5 years are 164K and 55K, respectively. Much smaller temperature increases are predicted for the roof and the pillar.

As was the case in the Room A calculation, the largest slip predicted in the Room B calculation occurs along Clay F, with a small amount of slip along Clay J. The Room B vertical and horizontal closures at 6 months are both about 3cm. After heat is turned on, the closure rates increase substantially. At 3.5 years, the vertical and horizontal closures are predicted to be 0.64m and 0.43m, respectively. At 5 years these closures are 0.87m and 0.60m. Pillar shortening is 0.19m at 3.5 years and 0.25m at 5 years. The predicted displacement of the floor (0.46m) is 2.5 times that of the roof (0.18m) at 3.5 years. The floor displacement of 0.60m at 5 years is 2.1 times the roof displacement of 0.28m.

Contours of effective stress at different times indicate that, immediately after excavation, stress concentrations exist around the room and are large in the corners. The deviatoric stresses (and thus, the effective stress) dissipate by a time of six months, when much of the load has been transferred to the anhydrite layers. Effective stress builds up again after heating begins but dissipates with time after one year. Horizontal stress (in-plane) profiles through the pillar do not vary much with time, but the vertical and out-of-plane horizontal stress profiles show the peak stress location moving deeper into the pillar with time. The shape of the profile for these two components also changes significantly with time. This contrasts sharply with the Room A stress response in which the profiles of a given stress component remain relatively unchanged from six months to five years. Despite some very large stresses in the anhydrite layers, no yield-

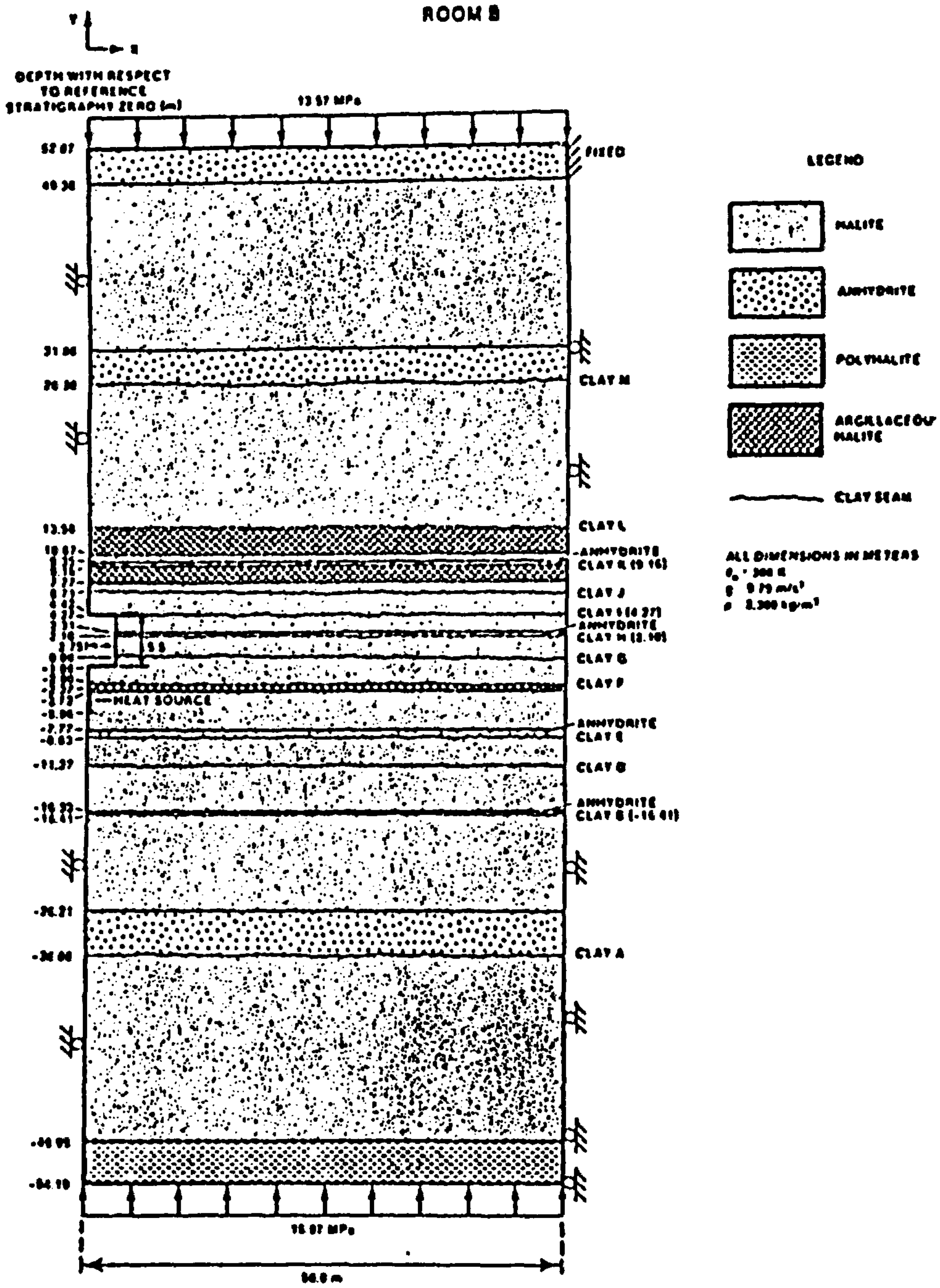


Fig. 6 Room B Configuration Used in Pretest Reference Calculations [Morgan and Stone, 1985b]

ing is predicted because the mean stresses are also high. On the room floor, tensile stresses develop in the horizontal direction when thermal load is applied.

The third document (SAND 85-0893) reports the pre-test reference calculation for the east portion of the east-west drift of the Room G in-situ experiment. The pre-test calculation applies only to the 6.1m x 3.05m drift geometry. The general layout of Experiment G is shown in Fig. 4. The pre-test calculation is for the cross-section A-A on Fig. 4. Calculations for the wider drifts (2-D), the drift intersection (3-D), and the wedge pillar (3-D) are planned for the future. The configuration for the pre-test calculation is shown in Figure 7.

The displacements and slip are small throughout the ten-year simulation period. The horizontal closure is greater than vertical closure except at very early times. After ten years of deformation in the ambient environment, the horizontal closure is 0.093m, the vertical closure is 0.078m, and the pillar shortening is 0.04m. Alternately, the horizontal and vertical closures after 10 years are 1.5% and 2.6% when expressed as fractions of width and height of the room. Displacement histories show that the roof sag is 50% higher than the floor heave. Just after excavation, stress contours are concentrated around the room with the highest stresses at the corners. In less than six months, much of the concentrations have dissipated and loads have been transferred to anhydrite. Due to the presumed dependence of yield on mean stress, no yield occurs in anhydrite because mean stresses are also high when stresses are high. Stress profiles through the pillar are similar at different times, except at time zero. There is a small, systematic decrease with time in the stresses in salt near the pillar wall. As was the case with Room A and Room B predictions, relatively high horizontal stresses develop in the anhydrite layers.

<u>Comparative Analysis Calculation Documents</u>

(1) "Numerical Simulation of the Creep Response of Model Salt Pillars" by J. G. Arguello and H. S. Morgan (SAND85-2429, January 1986)

(2) "Comparison Between Predicted and Measured South Drift Closures at the WIPP Using a Transient Creep Model for Salt" by D. E. Munson and A. F. Fossum (in <u>Rock Mechanics: Key to Energy Production (Proceedings of the 27th U.S. Symposium on Rock Mechanics, University of Alabama, 1986)</u>, pp. 931-939. Littleton, Colorado: Society of Mining Engineers, Inc., 1986)

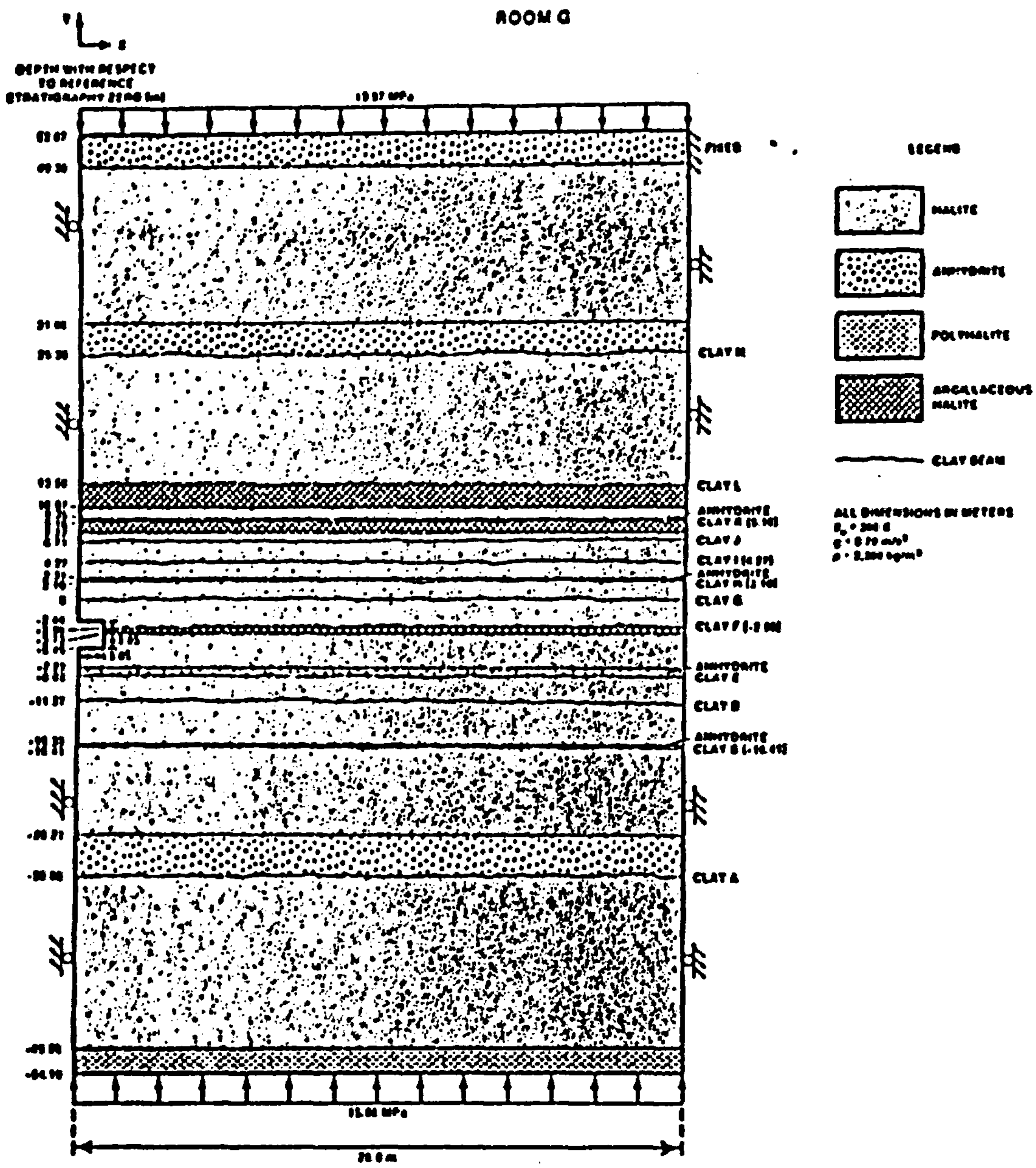


Fig. 7 Room G Configuration in the Pretest Reference Calculation [Morgan and Stone, 1985c]

(3) "Early Results from the Thermal/Structural In-Situ Test Series at the WIPP" by D. E. Munson, T. M. Torres and D. A. Blankenship (in Rock Mechanics: Key to Energy Production (Proceedings of the 27th U.S. Symposium on Rock Mechanics, University of Alabama, 1986), pp 923-930. Littleton, Colorado: Society of Mining Engineers, Inc., 1986)

The document by Munson et al. (1986) describes the excavation of Room D (located 85.3m east of Room A-3) at the WIPP, the instrumentation installed in the room, and a comparison between measured room performance and the results of computed room performance in modeling studies. Close supervisory control and achievement of prescribed tolerances is indicated in the review of excavation practice. The geotechnical model of the WIPP site and the computational scheme used to analyze it, SANCHO, are described. The results of computation of room closure, when compared with field measurements, are in significant disagreement, which is most marked in early elapsed time after excavation. The paper acknowledges some possible shortcomings in the constitutive equations, material constants, or generalization from the uniaxial stress state used in salt characterization.

The document by Munson and Fossum (1986) presents a comparison and analysis of the observed and computed performance of the South Drift (located south of the drift connecting the waste-handling and exhaust shaft) at WIPP. In this exercise, the computer code used is SPECTROM-32, a RE/SPEC code. This code implements a multi-mechanism secondary creep model and also handles primary creep, with provision for non-associative Drucker-Prager plasticity. Again, no acceptable degree of correspondence is demonstrated between calculated and observed room closure, and detailed examination of the results suggest that neither the early response nor the long-term response of the room is satisfactorily represented simultaneously by the modeling scheme. A valuable aspect of the document is the attention which is given to the micromechanics of salt deformation, with constitutive equations proposed to represent particular parts of the deformation map. However, the domain of most interest in modeling repository performance is regarded as least well understood from a micromechanical perspective.

The report by Arguello and Morgan (1986) consists of a series of comparisons between the results of some bench-scale ($0.008m^3$) model tests of a loaded heated model pillar of salt and analyses of stress and displacement in the pillar using a reference finite element code. The FE code (SANCHO) implements the currently preferred empirical expressions which account for the time, temperature and stress dependent deformation of salt. Although no close correspondence is achieved between the deformations in the model and the calculated deformations, the level of correspondence is sufficiently encouraging as to justify identification of sources of the observed discrepancy between observed and computed response. In the case where the model contained artificial planes of weakness simulating clay seams in the natural prototype, there was divergence between model and analysis sufficient to introduce doubts about both the physical model work and the analytical scheme.

<u>Document Describing Methodology for Performing Parallel Design Calculations</u>

> "Methodology for Performing Parallel Design Calculations (Nuclear Waste Repository Application)" by D. E. Munson and H. S. Morgan (SAND85-0324, May 1986)

This document describes a methodology for performing parallel (yet independent) design calculations that have applications to geologic disposal of nuclear waste. The results of an earlier benchmarking study (Morgan et al., 1981) conducted for WIPP appear to have inspired, at least in part, the idea for this study. That benchmarking exercise amply demonstrated that it is possible to get significantly different answers to a well defined problem even when established computer codes are utilized by experienced people. The methodology, according to the authors is, "a framework containing several necessary elements of the process whereby parallel calculations can be performed in a controlled, but independent, manner." The methodology was formulated before the start of test problems and contains five "essential features" that regulate the performance of parallel design calculations. These features, quoted verbatim, are:

(1) a procedure for selecting, on a competitive basis, qualified analysts and codes;

(2) a formal method of transmitting information between an impartial monitor controlling the problem definition and the analysts;

(3) a multiple-level quality assurance (QA) system with procedures for checking the calculation inputs and for tracking modifications to code software;

(4) a technical monitor and control framework for reconciling differences between the results of the two parallel calculations; and

(5) a formal mechanism for adjudicating irreconcilable differences between the two parallel calculations."

Two monitors were selected—one for administrative control (contract monitor) and one for computational control (technical monitor). Each analyst had to perform the calculations without any knowledge of the progress (or results) of the other analyst. The technical monitor could not, therefore, release information to either analyst about the progress or results of the other. A formal, competitive selection process was used to select one of the two analysts (participants). The other participant was selected from within Sandia. The statement of work was developed around two boundary value problems that substituted for an actual design problem. The document gives a detailed account of the contractor selection process. The two analysts were RE/SPEC, Inc. and Sandia National Labs. A formal procedure was used to transmit the parallel calculation problems to both analysts. Complete problem descriptions were prepared by the monitors and given to the analysts. However, the analysts were expected to submit a restatement of the problem along with a numerical (finite element) mesh, thermal load calculation, boundary tractions and initial stress conditions. Each initial restatement as well as boundary stress calculations had errors, which were corrected or resolved by the monitors before authorizing the start of parallel calculations. Each participant had a written quality control plan at the outset. The document candidly notes that, "[b]ecause of schedule and work load pressures, Sandia followed their QA procedures for only the unheated problem." In any event, the formal QA program was found to eliminate code input errors.

The document reports in considerable detail the application of this methodology to two carefully chosen test problems that contain representative stratigraphy of a bedded salt site. These two boundary-value problems were used to test and demonstrate the methodology. In one problem (the unheated case), the mechanical response of an emplacement room for transuranic waste was to be computed for a 10-year simulation period. This calculation also represented an update to the reference calculation for the WIPP storage rooms for TRU waste. In the second problem, the thermomechanical response of a typical room (e.g., WIPP Room A), in an infinite array of emplacement rooms, with a thermal load of 18 W/m^2 was to be simulated for a period of 5 years. This thermal load is equivalent to the heat applied to the rooms of a heated three-room array comprising the 18 W/m^2 Mockup for Defense High Level Waste In-Situ Experiment.

Each calculation used a two-dimensional plane strain idealization of a single, long room in an infinite array of long, parallel rooms. The stratigraphy, opening dimensions, boundary conditions, and model dimensions are described in sufficient detail in the document. The physical, thermal and mechanical properties are also given. The constitutive model for salt included only the secondary creep, and the coefficients of the empirical creep law were assumed to be independent of temperature.

Except for salt creep in halite layers, all other materials were modeled as elastic in the isothermal problem. For the heated parallel calculation, the anhydrite layers and the single polyhalite layer were modeled as elastic-plastic materials with Drucker-Prager failure criteria. Frictional sliding along clay seam interfaces was prescribed in both sets of calculations. In their analyses, RE/SPEC utilized the SPECTROM 41 code for thermal response and SPECTROM 32 for mechanical (or thermomechanical) response. The codes used by the Sandia analyst were COYOTE and SANCHO, for thermal and mechanical response, respectively.

"Initial" and "final" results are discussed in depth for both problems.

The output set required deformed meshes, displacement, closure, and temperature histories, stress and temperature contours, and stress profiles. However, the primary quantities for comparison purposes were the displacement and temperature history.

For the isothermal problem, the initial prediction of the roof displacement (at midpoint) using the SANCHO code was roughly 40% higher than that predicted by SPECTROM 32 at a simulation time of 10 years. The floor displacement predicted by SPECTROM 32 was about 42% higher—the net effect being that the vertical closure predictions show a very good agreement that is fortuitous and misleading. The horizontal displacements also show a disparity of about 40%. Interestingly enough, the stress profiles agree to within 5%.

For the heated problem, a comparison of thermal histories (monitored at four different locations) showed an agreement to within 1%. A comparison of the initial results for displacement histories, however, revealed qualitative and quantitative differences. At a simulation time of five years, the floor vertical displacements, vertical closure, and rib horizontal displacements predicted by SPECTROM were roughly 50% of those predicted by SANCHO.

A systematic procedure was employed in attempting to resolve the large discrepancies between the initial results. The intent of the discrepancy resolution was to identify the causes of differences and to eliminate errors, if possible. Due to larger discrepancies, it was decided to examine the heated problem first. The small strain/small deformation limitation inherent in SPECTROM was one suspected cause of the disparities. A third computer code, JAC (Biffle, 1984), which has both large- and small-strain capabilities, was employed to isolate the large deformation effects. An earlier benchmarking exercise (Morgan et al., 1981) had yielded a much better agreement between the predictions by SPECTROM and SANCHO. This fact indicated that the problem definition differences might also be responsible for the poorer agreement in the present study. Specifically, the introduction of a plasticity model and the prescription of a non-zero friction coefficient at sliding interfaces in the present calculation could have been additional sources of discrepancies. Other possible causes for the discrepancies that were investigated were input errors, element stiffness differences, timestep sizes, convergence tolerances, and meshing. Differences in element stiffnesses, timestep sizes, convergence tolerances, and meshing were determined not to have a great deal of significance. By designing and analyzing a simplified heated problem, errors were found in (1) the slideline algorithm of SPECTROM and (2) the boundary pressure in the SANCHO input data. After fixing these errors, the actual heated problem was reanalyzed. In the final results, the floor displacement and vertical closure differed by about 30%. The primary contributor for this difference was identified as being the small deformation limitation of the SPECTROM code.

The isothermal problem was also recomputed and the final results compared. For the isothermal problem, the floor displacements showed excellent agreement but the roof displacements, sidewall displacements, and vertical closures differed by 44%, 11% and 18%, respectively. (Note that the document has an error in that the 11% and 18% values have been transposed in the second paragraph on p. 29.) Unlike the heated problem, the primary contributor to differences in the final results of the isothermal was identified as the slideline algorithm (even after corrections in SPECTROM). The document concludes that "the parallel calculation test cases were quite successful in evaluating all of the methodology for obtaining future quality-assured parallel structural calculations." Findings listed at the end of the "Conclusions" section state, in essence, the following.

1. Direct presentation of the proposals to, and interaction with, the evaluation panel is important.

2. The evolutionary nature of sophisticated computer codes dictates a continual benchmark qualification process.

3. Direct discussions and formal transmittal of problem definition are crucial to accurate communication.

4. A formal QA program is extremely useful in elimination of trivial errors.

5. An impartial and technically-experienced monitor can be helpful not only in resolving discrepancies but also in making potential improvements to the codes or models.

PROBLEMS, LIMITATIONS AND DEFICIENCIES

In-Situ Testing Plan Documents

As previously mentioned, the testing plan documents present no clear rationale for determining various test durations or representativeness of test locations.

Pre-Test Reference Calculation Documents

In the Introduction and Concluding Remarks sections of each of the three documents, comments are made that suggest a purer scientific approach than is actually taken—or even necessary. Specifically, the assertion regarding parameter changes without a physical basis as being inconsistent with their objectives [see Morgan and Stone (1985c), p. 14] and the self-imposed requirement of modeling changes based on sound physics only (and not merely curve fitting) are somewhat contradictory considering that the creep model used is essentially an empirical law. The empirical creep law (especially without transient creep) does not have a clear physical basis. In numerical modeling, compromises are frequently necessary as far as lumping complex behavior(s) into quantifiable parameters that may or may not have physical significance. This is not to suggest that sound physics need not be applied, but merely emphasizing the notion that numerical models are meant to be a simplification of reality rather than an imitation of reality.

The choice of the Drucker-Prager criterion for defining the yielding of anhydrite is based on very limited data. It is likely that the constants chosen are highly non-conservative because no yield occurs even at fairly high deviatoric stresses. The material may also undergo brittle fracture for which the model apparently has no provision. Another weakness in the overall model is the inability to allow material separation under appropriate stress differentials. In the pre-test calculations, relatively thin anhydrite layers seem to restrict salt creep to a great extent. If allowed to fail (by cracking or plastic flow), the anhydrite layer(s) would not be able to confine the salt movement, as is the case in the present calculations. It would be interesting to see the effect of a lower yield strength or an absence of anhydrite layers altogether. The creep displacements predicted in the Room G drift appear unrealistically low—very likely due to the presence of artificially strong anhydrite.

It is not clear whether the statement that, "The thermal properties of all stratigraphic materials were assumed to be the same as those for halite" applies to thermal conductivity only or to thermal diffusivity as well. Also, was the coefficient of linear thermal expansion, α,the same or different for each material? The development of thermal stresses is a strong function of α, and α for halite is generally much higher than for other strata or rock types.

It is somewhat surprising that the slip along Clay G and/ or Clay H is negligible in the Room A and Room B response predictions. In a benchmark calculation for WIPP for a similar configuration, significant slip was predicted along a slideline near pillar midheight. Fig. 8, reproduced from Morgan et al (1981), indicates the slip magnitude for a slideline comparable to Clay H.

The decision to consider only secondary creep appears to have been based on parametric calculations for the South Drift [Morgan and Stone (1985b), p. 27]. However, the South Drift had no heating associated with it; therefore, neglecting transient creep in the Room A and Room B (both heated) pre-test calculations may not be a valid assumption.

It is stated on p.69 of the Room B document [Morgan and Stone (1985b)] that, "Deep in the pillar, ...vertical and out-of-plane stress components never deviate much from the initial lithostatic value." The results shown in Figs. 54 and 55 of the document contradict that statement.

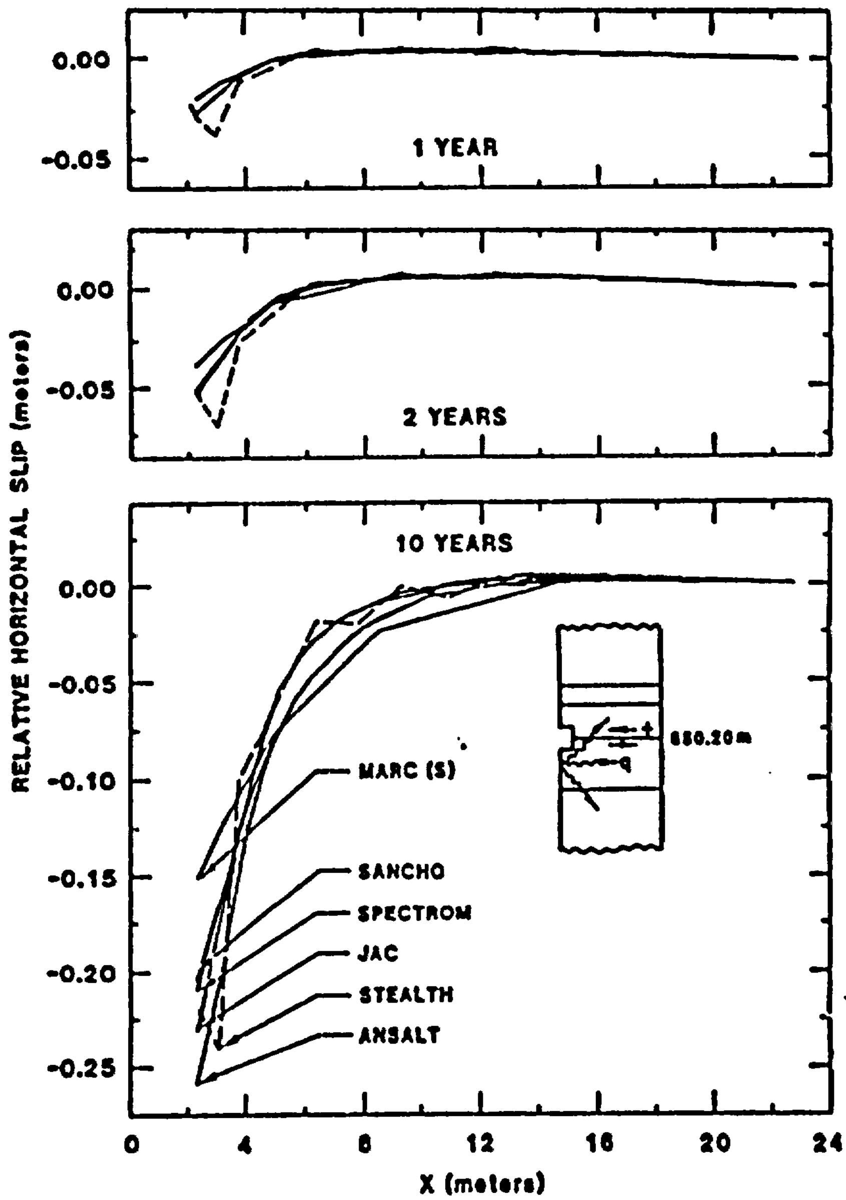


Fig. 8 Revised Relative Slip Across the 650.2m Slide Line for the Heated Room at One, Two and Ten Years [Morgan et al., 1981]

For Room B, only Phase I is modeled in the pre-test calculation. Phase II (backfilling) and Phase III (retrieval/re-excavation) of the experiment are also very important—both from a modeling and a licensing perspective. Only one part of the Room G Experiment is modeled that also happens to be the least complicated. Presumably, other calculations are being made or will be made to predict the response due to widening and the three-dimensional response.

In the Room G response, it is not clear why the roof sag is 50% higher than the floor heave at ten years. One likely explanation is the larger distance from the free surface (roof horizon) to the nearest anhydrite layer above compared to the distance below the floor horizon to the nearest anhydrite layer. The manner in which anhydrite is modelled and the strength properties associated with the material have a major influence on the structural response of the opening.

Some typographical errors exist in the documents that may affect a proper interpretation. In the Room A document (Morgan and Stone, 1985a, p. 54), the temperature at thermocouple location '06' should be 316K (see Fig. 32, p. 53 in the document) and not 310K. On p. 58 of the same report, A1 and P1" should be "A13 and P7". In the Room G Document (Morgan and Stone, 1985c), the second paragraph on p. 41 gives incorrect percent pillar shortening and room closure. The phrase ". . . by only 1% in tens years and by an additional 0.5% at the center" should read ". . . by only 1.3% in ten years and by an additional 1.2% at the center".

Comparative Analysis Documents

Taken together, the three documents confirm that the current state of knowledge of materials science aspects of salt deformation may not be adequate to support the salt repository program. Much discussion by Munson and Fossum (1986) is concerned with strains that are not accounted for in testing of salt specimens in the laboratory, leading to errors in constitutive equations. However, it is possible that the key problem causing salt deformation to be underestimated numerically is that moisture conditions in situ are different from those in test specimens. Urai et al. (1986) have recently demonstrated that, in the temperature-stress domain of interest in repository conditions, even trace amounts of water have a significant effect of creep strain rates. The operating mechanism is called "dissolution creep", and it apparently operates in the "undefined mechanism" domain of the stress-temperature deformation map. Another problem causing salt deformation to be underestimated numerically is the small-strain formulation of the SPECTROM-32 code.

The Room D calculations are based on the WIPP reference stratigraphy in Fig. 9 of the document by Munson et al. (1986). The stratigraphy is primarily a geomechanical stratigraphy. There is no indication of how well the reference stratigraphy is understood or how well it corresponded to conditions encountered. Additionally, no mention is made of the hydrogeology of the test area.

It is clear from the many plots of pillar closure versus time in Arguello and Morgan (1986) that there is a deficiency in the algorithm representing primary creep. However, the expression written (on p. 23) to describe primary creep is introduced without supporting discussion and without explanation or definition of the terms appearing in it. The report makes excessive use of log-log plots, a device which is usually discouraged in experimental physics and mechanics.

The Engineering Review Group, in its review of the salt constitutive model (Balon, 1986), makes several salient points which bear repeating:

1. The coupling between steady-stae and transient creep should be re-examined.

2. The emphasis should be on utilizing simpler equations with fewer parameters and not attempt to derive a universal constitutive law for salt for a full range of stresses and properties.

3. More sensitivity analyses on parameters should be performed, and parameters with little influence on repository performance should be eliminated from the analysis.

4. Attempts should be made to take into account heterogeneities in the salt.

Document Describing Methodology for Preparing Parallel Design Calculations

The study was unique and reasonably thorough, and the authors were refreshingly candid about reporting procedural lapses and mistakes during the conduct of the analysis. Given the experience of the personnel involved in the project, however, some problems should have been anticipated. Specifically, it was known a priori that the SPECTROM 32 code has small displacement/small strain limitations. Further, large deformations were expected to occur, especially in the heated drift case. Despite that, the selection panel "judged the SPECTROM 32 code to be qualified for performing the parallel calculations." The assertion, on p. 14, that "the contract was awarded to the best-qualified contractor" is debatable since there were only two potential bidders, and the one selected possessed a code that had important limitations. Another problem that comes as no surprise is the issue of one of the analytical groups being in-house. As it turned out, "[b]ecause of schedule and work load pressures, Sandia followed their QA procedures for only the unheated problem." This relaxation demonstrates that, despite the best of intentions, double standards will surface if the situation allows. Ironically, an input error for the heated problem was made by the Sandia analysts that is attributable to the fact that QA procedures were not followed by Sandia for that particular problem.

Both SANCHO and SPECTROM 32 have the limitation that a separate thermal solution for a fixed (non-deforming) mesh must be obtained first. If the deformations are large, the spatial temperature distribution at any given time could be in error. This would lead to related errors in the thermomechanical response. From the depth and persistence of the study, it is clear that cost was not a major concern. It is unrealistic to expect that all the procedures, controls, and discrepancy resolution discussed in the document would be applied to the design calculations performed in support of high-level waste repositories. Unfortunately, time and cost constraints will dictate whether parallel calculations would be conducted in the first place and, if so, how detailed they ought to get.

At the risk of suggesting yet one more calculation, a comparison between SANCHO and SPECTROM 32 predictions of an elastic-plastic response (without creep) would have been interesting and useful. It would have further isolated the large deformation problem and might have uncovered other more basic differences. In the discrepancy resolution process, occasionally one sees a presumption of SANCHO being a better, more accurate code than SPECTROM 32.

RECOMMENDATIONS

Recommendations for Thermomechanical Room-Scale Testing in Salt

NRC should look carefully at the time these tests actually took and use that information as input to the NRC evaluation of SCP time schedules, considering all other tests that are supposed to be going on simultaneously.

Select a representative case (say, Room A or Room B) and perform a predictive response calculation with a different code or technique. Even a partial simulation to one or two years of response should be very valuable.

In addition to salt creep behavior, some attention should be given to anhydrite material behavior. Perhaps a different constitutive relation or material properties should be considered. The effect of various interface strength parmaters should also be evaluated.

It may be useful to perform calculations with halite as the only material to get an upper bound on creep deformation. This would also address the realistic possibilities of weak or pinched out anhydrite layers.

Obtain published data on the three experiments and compare with the predicted response. It may take Sandia much longer to publish a formal document on such a comparison. At least one document on the thermal response data from the Room A experiment is now published (Beraun and Moleske, 1987).

Follow closely any instrumentation related problems at WIPP. In interpreting extensometer measurements, recall that the results of pre-test calculations show that movement occurs at the location of the deepest anchor. This implies that the common assumption of zero movement at the deepest anchor may not be valid for salt. Compensation must, therefore, be made to account for the deep anchor movement when interpreting extensometer measurements.

Perform timely review of new documents on the subject in order for the reviews to be more meaningful and have a possible impact on the programs.

Be critically aware of selective application of modeling changes based on experimental data. Such changes should be universal and the effect of the change on previous "good" agreements should be investigated.

The procedure outlined in the report by Argeullo and Morgan (1986), comparing the results of physical model tests and computational analysis of the performance of the model, is a highly commendable method for validating a computer code for design analysis. Now that the deficiencies of empirical creep expressions, for both primary and secondary creep, have been revealed, it is an appropriate time to decide whether to attempt to reformulate the empirical expressions or to develop rigorous constitutive equations from the basic constitutive models.

In any reports on salt creep, where so-called creep laws are quoted, it should be mandatory to quote the temperature, states of stress, stress path and moisture conditions under which the creep parameters have been determined.

The apparent shortcomings in the knowledge of salt deformation mechanics and in the related constitutive reactions implemented in various creep codes suggest that a comprehensive review of the position is now due. This should include reviewing the conditions under which laboratory creep tests have been conducted, the moisture content of salt in situ and its variation during execution of closure studies, and an assessment of the relevance of the University of Utrecht work (Urai et al., 1986) to the WIPP problem.

Recommendations for Preparing Parallel Design Calculations

The methodology outlined and used in the analysis presented in Munson and Morgan (1986) is appropriate for design calculations. If parallel calculations are envisioned, the five elements (stated on p. 10 of the document) of the methodology should provide an excellent framework.

To be truly independent, the funding agency should not be a monitor and a participant at the same time.

The capabilities of a code should be evaluated thoroughly, and its limitations understood, prior to commissioning expensive calculations.

It may be unrealistic to carry out the methodology outlined by Munson and Morgan (1986) for practical applications with the level of detail (particularly, the discrepancy resolution) used in the Sandia study. However, the systematic approach and the concept of cooperation (rather than competition) should be followed, as was done in this study.

Instead of focusing on high accuracy or agreement within a certain percent, the aim should be to eliminate fundamental errors in the models and algorithms. Parallel design calculations are of limited value if two codes show an excellent agreement but have both left out important mechanisms (such as slip along joints for jointed rock).

Within reason, the QA process must be an integral part of sophisticated modeling efforts.

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