PLANNING, DEVELOPING, AND FIELDING OF THERMAL/STRUCTURAL INTERACTIONS IN SITU TESTS FOR THE WASTE ISOLATION PILOT PLANT (WIPP)*

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ABSTRACT

Large-scale, well-instrumented underground tests to determine in situ thermal/structural response of bedded salt are being constructed in the (WIPP) facility in southeastern New Mexico. These tests are an essential component of a broad research and development program to resolve thermal/structural issues, to validate long-term prediction methods, and to develop a design basis for a future repository. They are the result of an extensive planning and evaluation procedure to determine the appropriate test configuration. All details of the tests, including background, decisions, design, site operations, and testing organization are explained. These procedures may be useful in development of other in situ tests.

INTRODUCTION

As a by-product of this nation's defense programs, remote and contact-handled transuranic and high-level radioactive reprocessing wastes exist at several locations around the country. Temporary, monitored storage of these wastes has been adequate, but a long-term solution for their permanent disposal is essential. Because these wastes represent a potential hazard to man, such disposal facilities must prevent access of the nuclides to the biosphere (and hence, man) for long periods of time.

The primary issues are the isolation characteristics of a repository site and the technical assurance that these characteristics are adequate. Resolution of the issues is obtainable through extensive research and development (R&D) to provide the technical basis for judging the merits of a given site or method. Such R&D is crucial because of the thermal and radiation conditions and the extended times required for decay of nuclides to safe levels of radioactivity. In this context, a highly integrated R&D program has evolved to provide the predictive and design technology base for future repositories of defense waste in salt. This program is encompassed under the Waste Isolation Pilot Plant (WIPP) Project, and the underground facility being constructed in southeastern New Mexico is the site for the in situ testing program (Fig. 1).

The WIPP Project is chartered by authorizing federal legislation (PL-96-164) for the "express purpose of providing a research and development facility to demonstrate the safe disposal of radioactive waste resulting from the defense activities and programs of the U.S. exempted from regulation by the Nuclear Regulatory Commission." The WIPP R&D Program provides the technical basis for systems design and safety and environmental assessments for future radioactive waste repositories for the defense programs. These designs and assessments are also applied to developing the WIPP full facility.

Two fundamental thermal/structural interaction (TSI) issues need to be resolved. First, stability of the repository during its operating life-time of 15 to 25 yr must be demonstrated. Second, it must be shown that the repository is sealed by creep closure of the openings in the long-term after decommissioning, and that movement of fluid toward, through, or away from the repository is unlikely. Proper resolution of these issues will provide confidence that the repository will not endanger public health and safety. To resolve these issues, Sandia National Laboratories has developed a comprehensive laboratory, computational, and in situ testing program.

This report is organized to give the necessary background for the TSI in situ tests by summarizing the general TSI R&D program, the approach to the TSI in situ tests, and the historical development of the tests. Specific in situ tests are then described in some detail. Finally, the organization and implementation of fielding the in situ tests is described and some relevant conclusions are drawn.

BACKGROUND

The WIPP project is a direct result of earlier work originating from National Academy of Sciences recommendations published in 1957 on disposing of radioactive waste in bedded-salt formations. Subsequent major studies include Project Salt Vault, which was a major program for demonstrating the emplacing, retrieving, and storing of radioactive waste.[1] At the conclusion of Project Salt Vault, further evaluations of salt basins in the US led to investigating bedded-salt deposits in southeastern New Mexico and eventually to development of a conceptual definition of the WIPP Project.

The Project has progressed through site characterization, design, and technology development leading to construction of the initial phase of the facility. Major portions of the characterization, design, and technology development are completed and have provided significant inputs to facility construction. Other activities will continue through the in situ testing and demonstration phases of the Project. Facility construction, now under way,

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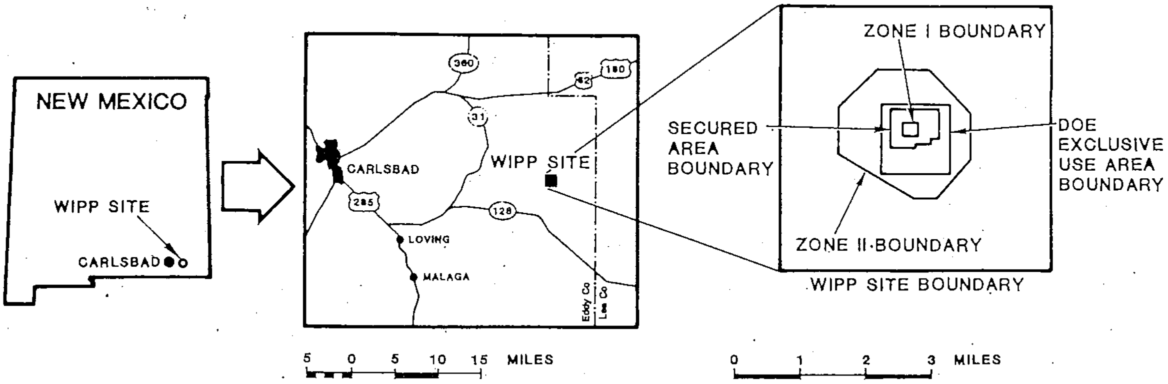


Fig. 1. General Location and Control Zones of the WIPP Site

began with the Site and Preliminary Design Validation (SPDV) program. This program used two exploratory shafts and about 4 km of underground drifts and rooms for direct observation of the site characteristics and for design validation of the transuranic (TRU) waste storage panel. The SPDV is complete, and development of the WIPP experimental areas is in progress. Plans for all the in situ tests in the experimental areas were described in an earlier document,[2] and are referenced extensively in this report. The overall WIPP R&D program is summarized in Fig. 2, where the major program areas are noted as site characterization and evaluation, repository development, and waste package interactions. This report concentrates on the TSI activities included in the repository development program. Of importance is the general TSI R&D program, the approach to the TSI in situ test definition, and the history of test development. Each of these topics is discussed in some detail.

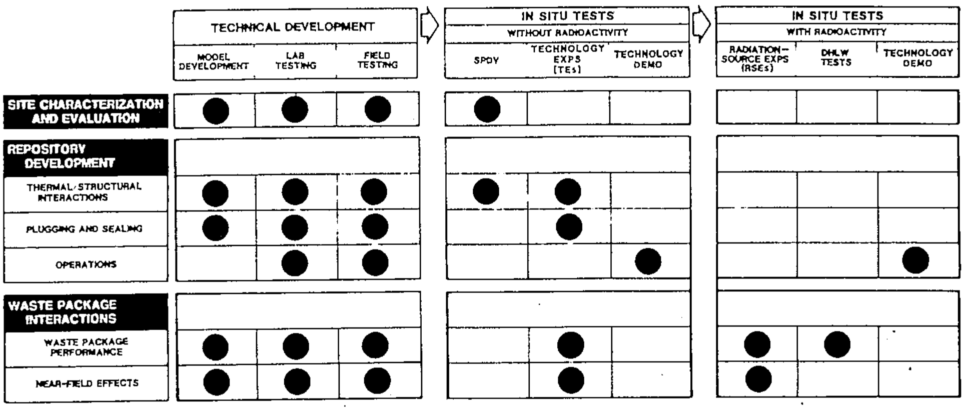
General TSI R&D Program

An important issue in repository development concerns the structural response of the underground openings, and whether the structural behavior of drifts, rooms, and shafts (possibly under heated conditions) can be predicted. Development of a repository in salt should not only provide for stable rooms and entries during the operational period for waste emplacement and possible retrieval, but also sufficient long-term rock deformation to eventually encapsulate the waste. Although the first requirement is typical of mine design, it is not ordinary because repository design emphasizes stability and not economic extraction, and because the heat generated by the waste requires knowledge of room response not previously considered in design. Salt, which undergoes time-dependent deformation or creep, is especially sensitive to rock temperature. This underground heat loading is beyond conventional mine experience and requires use of numerical simulation techniques to predict the behavior of the repository rooms and surrounding salt behavior projected forward in time for several thousands of years.

Both the prediction of short-term stability of the rooms and the long-term encapsulation requirements rely on adequate constitutive models, on material parameters, and on numerical analysis techniques (computer codes) to predict the effects of stress and heat on the salt. To assure adequacy of these prediction techniques requires extensive comparison with response histories of underground rooms. The in situ TSI tests will provide the data base for comparison and will ultimately help establish the valid predictive techniques for repository design.[1]

Constitutive Models: A series of comprehensive constitutive models of the creep response of salt were developed from extensive laboratory test data on the WIPP salt. The range of models reflects increasing sophistication as the constitutive behavior is better defined experimentally. Significant understanding of creep occurred through consideration of the micromechanical mechanisms of deformation and how these mechanisms control the creep process. The earliest WIPP models,[3] based on steady-state creep of a single thermally activated mechanism, still form the basis of our reference constitutive law[4,5] and predominate in current code calculations. Within the restriction of steady-state, more advanced models incorporate several mechanisms in accordance with the rules of the deformation mechanism map.[6] Other models incorporate plasticity concepts[7], and some incorporate transient creep response,[6,8] including unloading transients.[9] Although empirically based, these models are consistent with fundamental principles and are considered adequate except for fracture modeling. The principal future effort will be to model fractures and failure.

Code Development: A large and progressive collection of finite-element computer codes exists that treat two-dimensional (2D) structural problems. Many codes are capable of handling creep or time-dependent deformation and large strains, both essential requirements. They routinely are capable of incorporating material layers as required for bedded stratigraphies. In developing or specializing these codes to the calculations needed for repository design in bedded salt, slide lines for simulating clay seams are incorporated. Current codes are capable of doing mine sequence excavation simulations as well. Perhaps two needed areas of further improvement are the calculation of progressive failure and bed separation. Ultimately, the



	TECHNICAL DEVELOPMENT			IN SITU TESTS WITHOUT RADIOACTIVITY			IN SITU TESTS WITH RADIOACTIVITY		
	MODEL DEVELOPMENT	LAB TESTING	FIELD TESTING	SPDV	TECHNOLOGY EXPS (TEs)	TECHNOLOGY DEMO	RADIATION-SOURCE EXPS (RSEs)	DHLW TESTS	TECHNOLOGY DEMO
SITE CHARACTERIZATION AND EVALUATION	●	●	●	●					
REPOSITORY DEVELOPMENT									
THERMAL/STRUCTURAL INTERACTIONS	●	●	●	●	●				
PLUGGING AND SEALING	●	●	●		●				
OPERATIONS		●	●			●			●
WASTE PACKAGE INTERACTIONS									
WASTE PACKAGE PERFORMANCE	●	●	●		●		●	●	
NEAR-FIELD EFFECTS	●	●	●		●		●		

Fig. 2. WIPP Research and Development Program (after reference 2), black circles indicate areas of past, current, or future work

separate area of three-dimensional (3D) code development requires further effort.

The most significant effort in code development is in the first stage of code verification. A method of testing the numerics and basic physics of a code is essential at this stage. Such a test is difficult because of the complexity of the codes and applications. Simple checks are obtained through comparisons to analytical solutions. The next step, now complete for the codes used in WIPP calculations, was a "benchmarking" process in which nine different codes were compared against each other for two well-controlled boundary value problems.[10] While scatter in results occurred, most codes gave equivalent answers suggesting independent consistency of the code physics and mathematics. Further methods of assuring calculational quality control and code correctness are being investigated. As demonstrated later, these codes played a key role in developing the WIPP in situ tests.

Previous Underground Tests: In developing the WIPP in situ tests, it was found absolutely essential to investigate previous underground tests and to understand their strengths and deficiencies. Although a few large-scale underground tests were fielded in salt, the most comprehensive was the Project Salt Vault tests in a Lyons, Kansas mine.[1] Many elements of that program are found in more extended form in the current WIPP program. These Project Salt Vault results were extensively analyzed.[1,11-13] The in situ thermal/structural experiments were three-dimensional in configuration and the final displacements were small. This, combined with laboratory properties based on model pillar tests, caused some uncertainty in analyzing results. Recently a large collection of unanalyzed data became available from a 25-m-dia cavity in the Asse Mine in Germany.[14] Material properties and modeling efforts support these underground tests in a manner similar to the WIPP program.[15]

Thermal fields around heaters were measured in several in situ mine tests in Asse, Germany; Avery Island, LA; and southeastern New Mexico. Some of these thermal tests included measurements of thermally induced displacements and stresses. Test results were valuable in providing assurance that thermal fields can now be predicted in the near field through use of a variety of thermal codes.

The other source of underground structural data is commercial mines. Closure data for isolated, two-dimensional drifts over more than 8 yr has been reported for deep Canadian potash mines. Analysis of some of these results through the use of current WIPP constitutive models has had some success.[16,17] Very large deformations were measured in a commercial high-extraction potash mine in southeastern New Mexico,[18] but remain unanalyzed. In the potash tests, analyses are prevented from being definitive because of a lack of precise material properties coupled with limited knowledge of the geologic setting, and because of isothermal conditions. Although the analyses were useful in formulating the WIPP tests, the limitations are largely removed in the WIPP tests through control of test configuration, extensive site characterization, and technology development.

Approach to the WIPP In Situ Tests: The WIPP R&D program and previous underground tests resulted in a distinct approach to developing the WIPP in situ tests. This approach consisted of

1. Assessing the state of the art for a technology area
2. Determining the logical steps for advancing the technology
3. Designing the underground experiment to validate the developed technology.

In each major technology area, existing technology was extensively surveyed, resulting in a status determination. Based on this, significant issues in advancing the technology were identified that could be resolved or confirmed by underground testing. Appropriate tests were then designed.

In the area of constitutive modeling, advancement can occur by resolution of the scale effects (if any), local stratigraphy variation, failure aspects, clay seam response, and large-scale backfill response. In the code area, technology advancement requires validating calculations for large-scale geologic settings; validating the combined effects of stress, temperature, geologic setting, and room geometry; and determining the existing and created stress field. Advancement can occur in the area of operation and demonstration through evaluation of a reference repository module and through recovery operations in a heated backfilled room. Overtest conditions will help explore the limits of structural response. In the area of design criteria, observed performance compared to current criteria aids in developing realistic criteria.

Because these experiments may contribute substantially to validating design procedures and long-term predictions, the duration of the test was intentionally made as long as possible. However, experiments had to be timely because results would strongly influence future experiments with high-level waste and decisions on repository development. Also keeping in mind the ultimate goal of prediction capabilities, plans were made for simple, highly reliable measurements and suitable geometries were selected to correspond with current numerical capabilities.

Historical Development of Tests: A very strict philosophy of test development was adopted at the outset. Planning was the key, and all plans were to be fully documented and reviewed. Flow of the process for the in situ tests is shown in Fig. 3. Relevant documents are shown that stem directly from the WIPP R&D Program which controls the goals and need for the in situ tests. The first planning document, the WIPP In Situ Testing Plan,[2] drew on many sources crucial to the TSI tests,[19-21] and also on careful evaluation of the status of the technology discussed earlier. In addition to the normal approvals by Sandia technical reviewers and management, the plans were critically reviewed by a special panel of high-level management and technical personnel who understood the program but were not directly involved. After these reviews and approvals, we obtained final DOE/WIPP Project Office review and approval. Extensive distribution of the final document was made to National Academy of Science Board members, state committees, and private individuals.

After publication of the WIPP In Situ Testing Plan, individual test plans were written for each TSI test, all but one of which are now published. Preliminary plans were reviewed by another more specialized peer review group composed of nationally recognized technical people from rock mechanics, numerical simulation, and field test and instrumentation disciplines. This peer review required written criticism before a detailed discussion of each experiment. Improvements and alterations recommended by the peer review were documented and incorporated into the tests, as appropriate. Internal Sandia technical review and management approval was also required, as was DOE/WIPP Project Office approval. Crucial parts of the plans, such as gage information, reside in a controlled updatable computer file. The test plans are active, working documents.

Each TSI test has a principal investigator (PI) responsible for both technical and fielding aspects of the test who draws upon specialized support groups for implementation. The primary support groups are instrumentation, data acquisition, engineering design, fielding, and analysis. In addition, all activities are conducted through two special liaison functions: one with the WIPP Project Office and contract design group, and one with the WIPP Site Management. These two functions are especially critical because of the magnitude of the construction needed to develop the experimental areas.

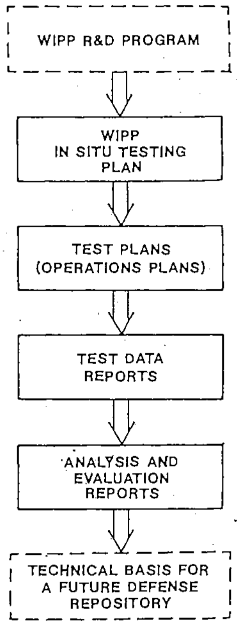


Fig. 3. Documentation Associated With Each WIPP In Situ Test (after reference 2)

Even though the test plans control the tests, they are not the principal control of the construction contractor. The contractor performs to specifications and special provisions defined in the contract package established by the architect/engineer. As a consequence, portions of the test requirements that interface directly with the construction must be incorporated very early into the contract specifications and special provisions. Assuring that this interface is properly made is essential to achieving good TSI tests because the rooms which are excavated are themselves the TSI experiments. Misunderstandings between the construction contract and the goals of the principal investigator can be averted only with considerable care and communication at an early stage of facility design. Construction changes after initiation of the construction contract are difficult and expensive.

Having presented relevant background information, the WIPP in situ tests for TSI will be described.

THE WIPP TSI IN SITU TESTS

The TSI underground tests consist of the following six major individual tests:

1. 18-W/m^2 Mockup
2. Defense High-Level Waste (DHLW) Overtest
3. Geomechanical Evaluation
4. Heated Pillar

5. In Situ Stress

6. Direct Shear of Clay Seams

The first four tests require excavated rooms, and the in situ stress field requires some controlled excavation. The in situ direct shear of clay seam test has no direct interface with construction.

Location and Stratigraphy: The plan view of Fig. 4 shows the location of the WIPP R&D test areas (Technology Experiments) with respect to other underground areas and surface boundary of Zone II. With respect to the WIPP R&D TSI in situ tests, Fig. 5 identifies the major TSI tests as Rooms A(1-3), B, G, and H. The clay seam and the in situ stress test areas are located in the entry drifts. Other test locations pertain to other portions of the experimental program.

The facility horizon is located in a very thick evaporite sequence of the Salado Formation, a small portion of which is given by the stratigraphic section of Fig. 6. In this general horizon, the TSI tests to the west (left portion of Fig. 5) are excavated at a floor level of about 658 m below the surface. This elevation places the rooms (G and H) in a layer of high-purity salt. The TSI tests rooms (B and A) to the east (right portion of Fig. 5) are at a floor elevation of about 652 m below the surface. These rooms are positioned so that the heaters are centrally located in the high-purity salt.

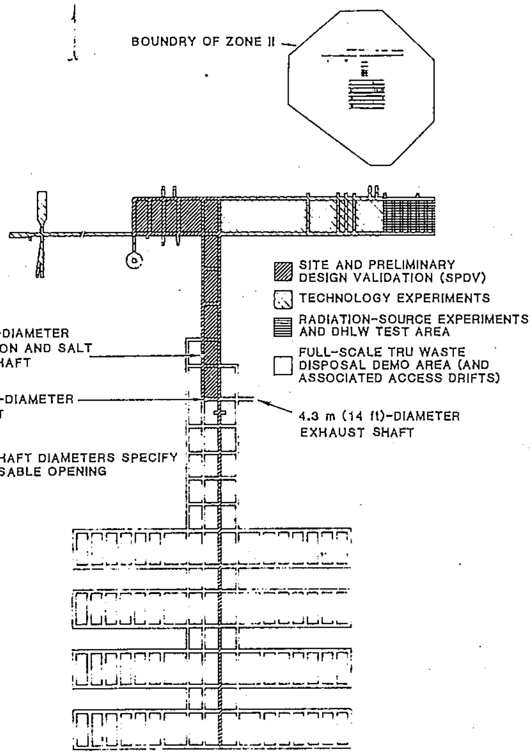


Fig. 4. WIPP Underground Layout

Test Configurations: After an extensive evaluation of WIPP program needs, previous underground testing, numerical analysis methods, and constitutive modeling, it was clear that resolution of remaining R&D issues in predicting thermal/structural response for repository development in salt would require an integrated series of large-scale underground tests. These tests fall into three categories:

1. Tests of room response where the underground configuration matches closely the conditions that can be simulated with typical two-dimensional code calculations.

2. Tests involving heaters simulating canisters in repository-like configurations that are geometrically more complex than the two-dimensional configuration.

3. Specialized tests to resolve specific problems.

Typical numerical simulations of real three-dimensional repository room configurations through the use of two-dimensional codes require both geometric abstractions of the actual configuration and realistic material constitutive models. To decouple geometry and constitutive behavior, simple intermediate underground results are required from tests specifically made to closely approximate two-dimensional conditions. Such simple tests (category 1) are checks on adequacy of the constitutive models developed from small laboratory samples for large in situ rock masses. Assurance of proper constitutive models for use in calculating response of more complex real repository room situations (category 2) benefits from the information found in the simple configurations. All that remains is to provide special tests for calculational inputs that can best be obtained or verified from in situ tests (category 3).

Two tests are planned that will permit an evaluation of the overall calculational adequacy of current numeric methods--the Reference Repository Condition (RRC) 18-W/m^2 Mockup for DHLW[21] (Room A) and the Overtest for DHLW[19] (Room B). Perhaps the most relevant aspect of both tests is that they simulate (mock up) proposed or possible repository configurations for DHLW. As a result of the simulation, they will act as the first important demonstration and full-scale prototype tests in the actual salt underground environment.

The 18-W/m^2 Mockup of the RRC (Room A) ultimately will form an important data base for thermal/structural calculations used for designing a repository and for developing performance prediction techniques. Because the laboratory and numerical analyses of the DHLW tests are well advanced, the full-scale mockup will be very useful in determining the adequacy of current knowledge before experimental quantities of actual-DHLW is introduced into the WIPP. Predicting the behavior of this room or any other test room requires refining the predictive technique through comparison with in situ test

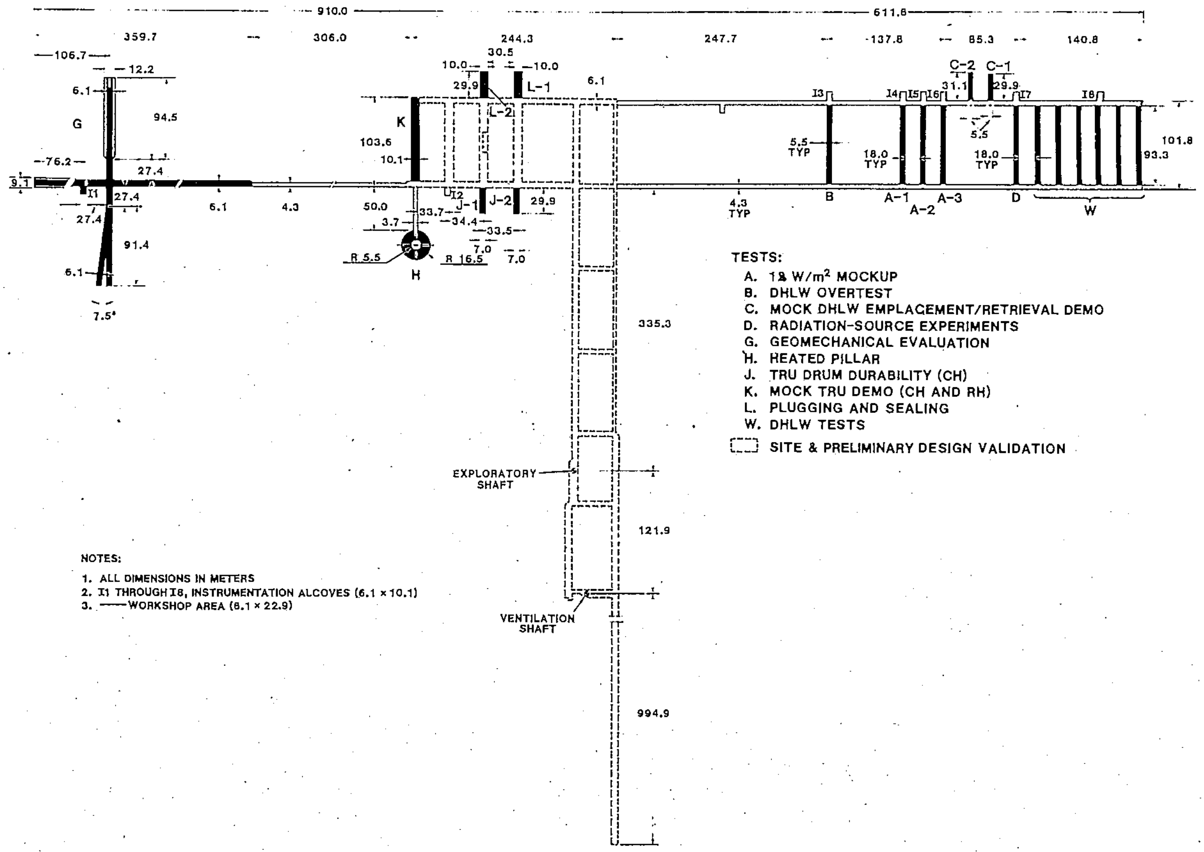


Fig. 5. Layout of In Situ Tests for WIPP

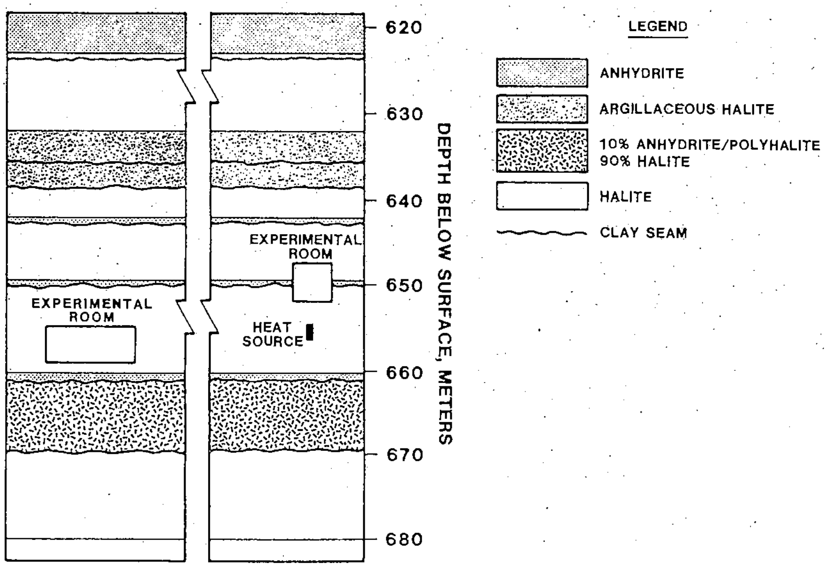


Fig. 6. Experimental Room Configurations in Reference WIPP Stratigraphy

results involving all the structural and thermal interactions expected in an actual repository. This refinement and the validation of constitutive models and numerical methods through comparison to the planned underground tests will yield a better technology for application to repository design and for assessing performance of repositories. It will also provide a realistic precursor to future DHLW tests planned for the WIPP at this horizon to assure safe operation and retrieval.

The Overtest (Room B) ultimately will form an important data base for thermal/structural calculations at a high temperature where the deformations are accelerated. These deformations are accelerated to provide, within a reasonable time frame, the large strains and deformations that would occur for the reference case only after a long time interval. In addition, this test addresses technical issues associated with room backfilling because plans are to backfill the hot room after 3 yr and then remove the backfill after 7 yr. The long-term isolation concept for waste in salt incorporates a stable, impermeable backfill in the repository rooms. The mechanics of this process must be understood on the large scale. Accelerated closure rates of the overtest room permit an exceptional test bed for evaluating backfill material behavior under full-scale conditions and for establishing methods of backfill emplacement and removal.

In the WIPP, two tests, the Heated Axisymmetric Pillar (Room H) and the Geomechanical Evaluation (Room G) are designed with configurations that are as near to two-dimensional geometry as possible. These tests form the basis of intermediate tests for verifying constitutive behavior.

The Heated Pillar experiment can be closely modeled with an axisymmetric geometry. In this configuration, code analysis occurs with little geometrical abstractions, and the experiment tests the constitutive model. Moreover, the material principally involved is only that in the heated pillar. This material can be very adequately characterized because it can be sampled around the entire periphery of the pillar and because its stratigraphy is exposed at the surface of the pillar.

The Geomechanical Evaluation test consists of three isolated, long drifts of various roof spans. Configurations of this type can be modeled quite accurately with two-dimensional codes. Again, in this configuration, code analysis can occur with very little geometrical abstraction. Moreover, the material involved is for the most part within a few radii of the drift. Changes in roof span therefore involve different volumes of material and, in a bedded sequence, different combinations of materials and clay seams. This material can be very adequately characterized because it can be sampled around the entire periphery of the drift. Portions of this test involve more complex geometries. The wedge pillar is designed to give information on the quasi-static yielding and failure of a pillar. Stresses at the apex of the wedge are large and diminish as the wedge thickness increases. The simple intersection formed by the cross-cut is to provide data for eventual 3D code calculations.

The most significant technical issue to be resolved by intermediate verification tests is whether the behavior of a large volume of salt in a natural setting is predictable from models based on site specific laboratory data. Resolution of this issue is essential in validating numerical analyses for design and performance predictions for bedded-salt repositories.

Two tests address very specific problems--the In Situ Stress and Direct Shear of a Clay Seam. In the first, an attempt is being made to define the in situ stress field through hydraulic fracturing methods. In calculations, in situ stress is an important boundary condition that influences the solutions markedly. Consequently, as precise a value as possible is required. The experiment is designed to reveal fundamental information about determination of stress in salt. In the second, an attempt is being made to determine the shear strength of a large area of clay seam. An in situ experiment on clay seam properties will be undertaken because of the difficulty of coring small samples and preserving the seam undisturbed for laboratory testing.

A summary follows of the principal R&D needs[2] that can be satisfied by in situ TSI testing.

1. Validate analytical techniques that include significant features of heat, stress, and complexity of configuration which codes should predict. This can be addressed by a mockup of the reference repository conditions (Room A).

2. Accelerate creep closure and evaluate structural aspects of heated backfill reconsolidation and removal, depending on predictive capability of analytical techniques. This is studied in an overtest of simulated DHLW test (Room B).

3. Verify analytical procedures including constitutive models by using a large volume of bedded salt with clay seams. This can be done through the use of an isolated 2D geometry that is simulated with 2D codes. This situation permits both a minimum of extraneous errors caused by geometry and the identification of errors from other sources. This test is also designed to give a section of 3D geometry to address 3D calculations and appropriate abstractions to 2D calculations and to explore the quasi-static failure criterion for a rock mass (Room G).

4. Verify modeling procedures used to evaluate material response at elevated temperature. This can be done by using a large, characterizable pillar of salt that is axially symmetric for simulation by a 2D code (Room H).

5. Verify the in situ stress field and the initial conditions for code simulation. (Access drift to Room G).

6. Verification of the in situ shear strength of clay seams. (An appropriate entry).

Physical Plan of the TSI Tests

Physical details of each test are described below:

18-W/m^2 Mockup: The configuration of the test is shown in Fig. 7. This test takes place in three rooms, each with a uniform cross section test portion of 5.5 m x 5.5 m, separated by two pillars 18 m thick. These rooms are effectively of infinite length when viewed with respect to the behavior in the middle of the room. In this guard room configuration, the test simulates a single repository room module and two pillar modules; the guard rooms provide proper simulation of a repository stress field about the central room; and the heaters in the guard room provide proper simulation of repository thermal histories in the two pillars and the central room. The total actual test section length is 74.5 m, and length between entries is 93.3 m. The extraction ratio is slightly less than 25 percent, and thermal loading is equivalent to 18 W/m^2 areal thermal load. A central canister room (A2) is the mockup of the reference repository configuration with simulated canisters; the outside guard rooms (A1 and A3) are geometrically correct and simulate thermal loading through a simplified heater array on the room centerline. This thermal load yields a maximum salt temperature of about 350 K near the heaters at 3 yr.

The reference test room, A2, is arranged as follows: Thermal loading is obtained from 28 0.47-kW simulated-waste canister/heaters 0.6 m in diameter by 2.7 m long, emplaced in holes 5.5 m deep in the floor of the room. The canister/ heater arrangement consists of a mockup of the expected canister shapes with an internal electrical heater simulating the thermal output of the waste. Emplacement is in two rows of heaters in a square array so that the canister/heaters are 2.3 m apart on centers. Four 1.41-kW guard heaters are used outboard of the canister/heater array to eliminate inappropriate end effects. The extra heat supplied by these guard heaters simulates the input of an infinite array of heaters beyond the central heater array. In the guard heaters, the container for the electrical heater need not be of the dimensions expected for the waste canister. In this case the diameter selected is 0.3 m.

Guard rooms A1 and A3 are similar. Each room is arranged as follows: The thermal loading is obtained from 1.41-kW heaters identical to the guard heaters in the central room and emplaced in a linear array along the room axis in holes 5.5 m deep in the floor spaced 3.4 m apart, center-to-center. To this symmetric arrangement, the six heaters planned for the waste package performance experiments are placed outboard of the guard heaters in Room A1 2.6 m away from the simulated waste section of the room. To balance the effect of heating from the waste package performance experiments, a comparable extension of the heater array will be made in Room A3 by using four additional guard heaters.

Instruments and gages planned for the room consist of temporary and permanent manual vertical andhorizontal closure stations established concurrently with excavation, permanent floor-andceiling displacement stations composed of paired remote-reading extensometers in opposed 15-m-deep boreholes in floor and ceiling, paired remotereading opposed horizontal extensometers in 15-m-deep boreholes in the ribs, permanent remote-reading floor-ceiling and rib-to-rib closure gages, permanent manual-reading floorceiling stations, remote-reading stress gages, inclinometers, and thermocouples. The thermocouple arrays are for both farand near-field measurements. Also, the mechanical influence of a clay seam will be monitored by relative extensometer measurements of the rib and pillar surfaces at designated locations. These instrument arrays for mechanical response measurements are shown schematically in Fig. 8. Thermocouple arrays for far-field temperature measurements are shown schematically in Fig. 9. Although not shown, a thermocouple array is located around several heaters to measure near-field and heater temperatures. Measurements will continue for at least 3 yr.

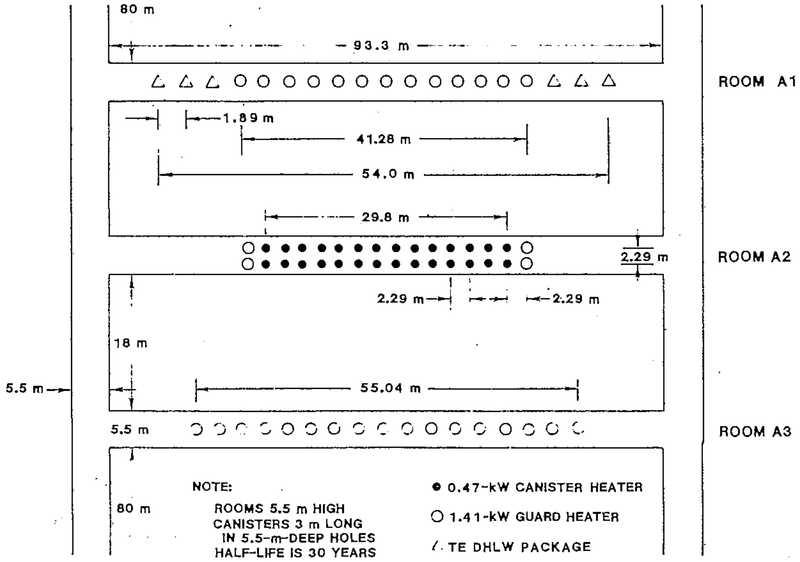


Fig. 7. Plan View Schematic of the Heater Emplacements for the 18-W/m^2 RRC Mockup Test

A specified excavation sequence for the room is designed to give instantaneous measurement of room closure and salt displacement response of the central room during mine-by of the guard rooms. This is accomplished by excavating and instrumenting the central room (A2) before excavating the outside rooms (A1 and A3). As these outside rooms are excavated, the increase in stress will produce instantaneous or short-time response in the central room (A2). In addition, these rooms, and the rooms of the other tests as well, will be instrumented immediately behind the excavation to obtain early-time response.

Overtest: The test configuration, as shown in Fig. 10, consists of a uniform cross-section room test section 5.5 m wide x 5.5 m high x 74.4 m long. This room test section is a portion of a larger room constructed between two entries, one to the north and one to the south. The emplacement array consists of 17 1.8-kW test heaters spaced at intervals of 1.5 m center-to-center along the axis of the room. Additionally, outboard of the central array are eight waste package performance experiments. These heater emplacements are located in a staggered array four on each end of the central array. Guard heater arrays of 4 kW heaters are placed 2 m from each end of the central array. Outboard of the guard heaters are two unheated waste packages at each end of the array. Schematics of the instrument arrays are similar to those for Room A and are not shown.

After 2 to 3 yr of operation, this room will be backfilled according to recommended backfill practice and using developed backfill materials. The backfill will then be heated for another 3 or 4 yr to test backfill emplacement method and room response. After the test is completed, the room will be excavated to demonstrate prototype methods of canister retrieval.

Additional special gages to measure room closure and backfill stress and compaction will be installed before the room is backfilled. Results from these additional gages and core sample tests will be obtained throughout the backfill compaction period.

Heated Pillar: The test configuration, as shown in Fig. 11, consists of a drift 3.7 m wide x 3 m high x 50 m long that provides access to an annular room 11 m wide x 3 m high surrounding the test pillar, which is 5.5 m in radius.

The surface of the pillar is to be uniformly heated by a resistive blanket heater with an energy output of about 135 W/m^2. The heater will consist

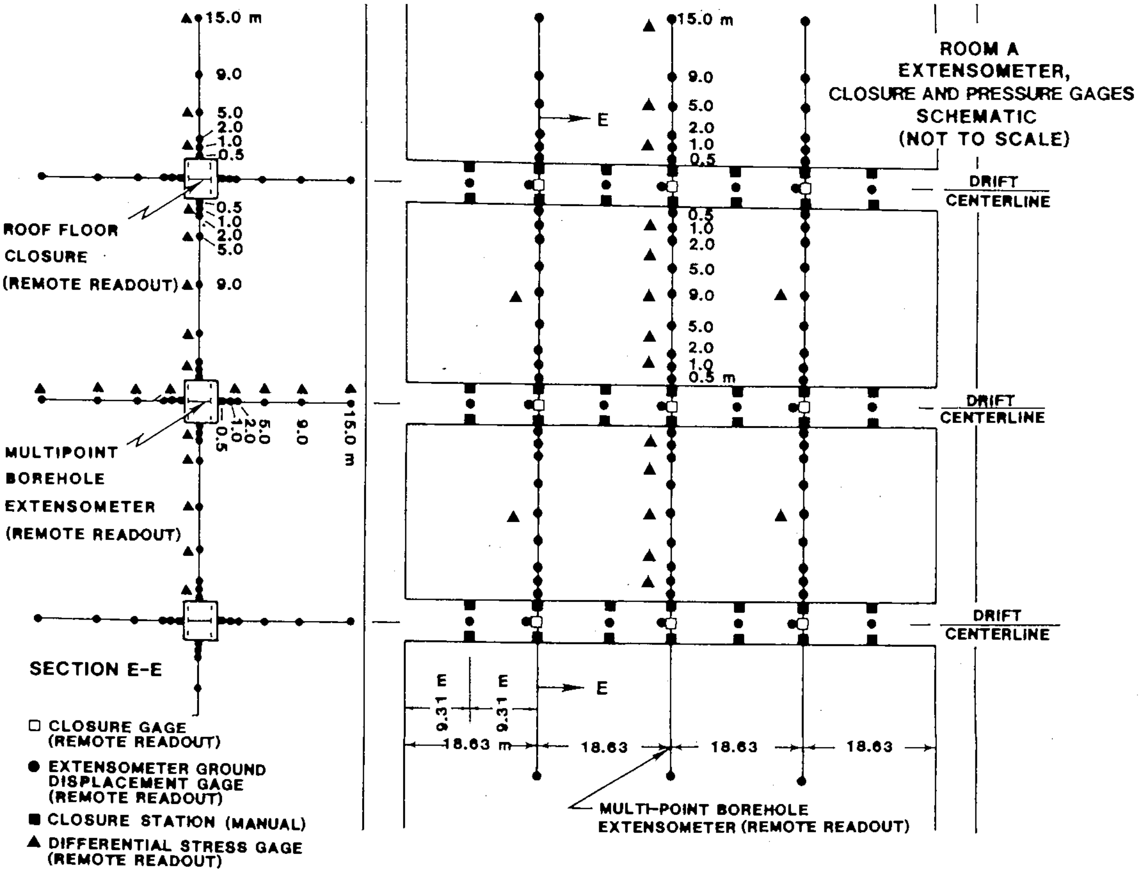


Fig. 8. Plan and Elevation Cross-Sectional Views of Geomechanical Gage Arrays for the 18-W/m^2 RRC Mockup Test

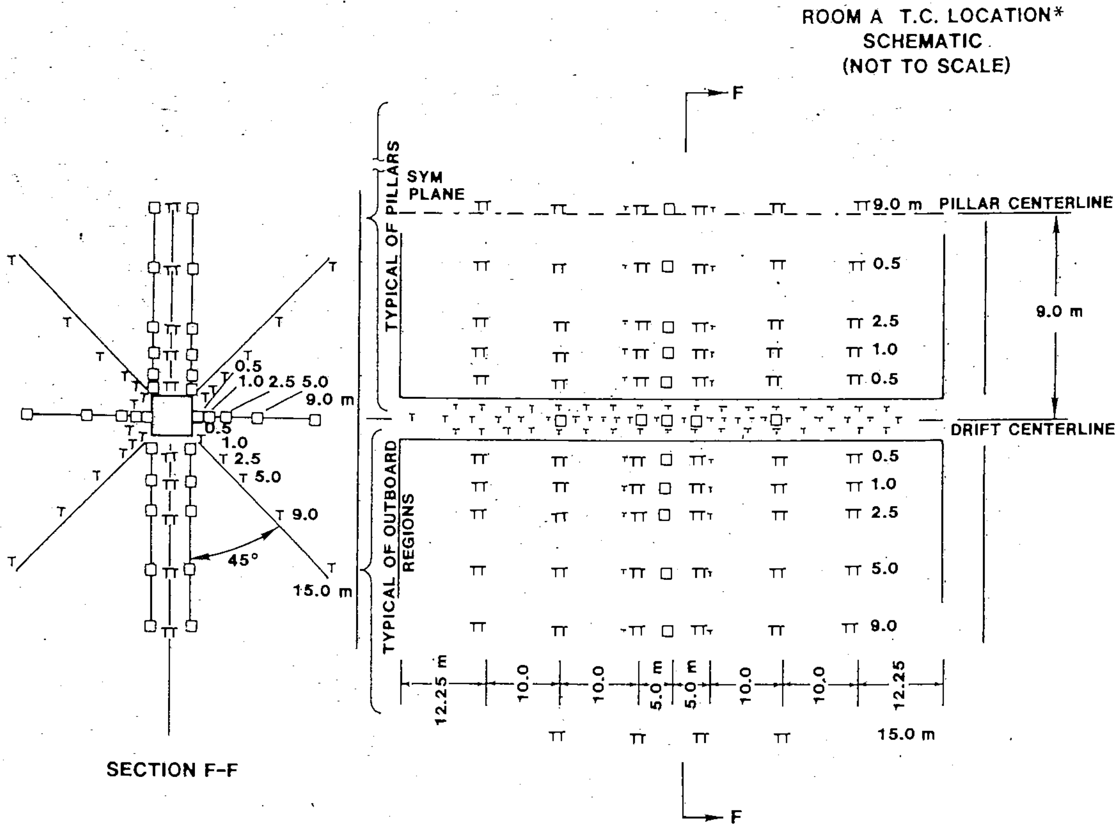


Fig. 9. Plan and Elevation Cross-Sectional View of a Representative Portion of the Thermocouple Emplacements for the 18-W/m^2 Test, All Symbols are Thermocouples

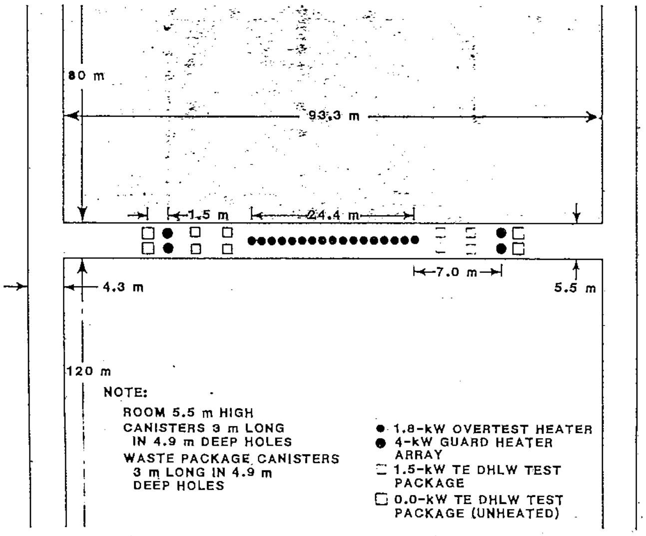


Fig. 10. Plan View Schematic of Heater Emplacements for the Overtest

of self-contained and interchangeable segments of a cylindrical shell backed by insulation. Appropriate radiative heat-transfer barriers may also be included in the final heater. The individual segments are assembled on a framework around the pillar so that each can be readily emplaced, removed, or replaced during the test.

Instruments will be installed to measure vertical and horizontal drift closures, deformations of, and stresses (pressures) in the salt pillar and around the drift up to 15.2 m into the salt. Thermocouples will be installed to measure temperatures of the salt around the drift and pillar. Deformation and fracture of the pillar will be monitored by acoustic-emission triangulation. Fractures will also be monitored by visual observations of the pillar surface at designated locations. Measurements will continue for at least 3 yr.

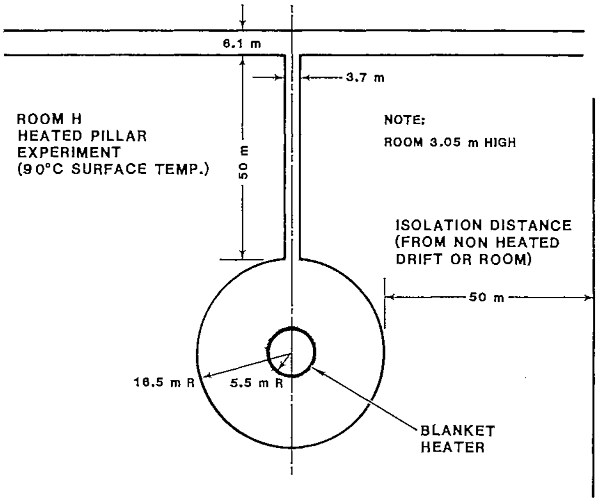


Fig. 11. Plan View Schematic of Heated Axisymmetric Pillar Test

Excavation of the annular room is planned in stages. First, a pilot drift of crude dimensional tolerances is excavated approximately along the annular room axis. Second, this pilot drift is slashed with conventional methods to full extent on the outer wall and the pillar of the annular room. Third, final excavation of the inner wall of the room to final pillar dimensions is excavated to the proper tolerances using special care. During excavation, expendable extensometers and stressmeters will be placed in the pillar region.

Geomechanical Evaluation: The general configuration and construct in phases of the test are shown in Fig. 12. Development is in four phases. In Phase 1, a main drift 460 m long and 3 m high by 6.1 m wide is driven. Phase 2 begins 1 yr after the main drift with the driving of a crossdrift 238.5 m long and 3 m high by 6 m wide. In Phase 2 also, a 61-m length of the main drift is widened to 9.1 m. Phase 3 will begin immediately after Phase 2 with the development of the wedge pillar that starts 27.4 m in the crossdrift and is driven at a 7.5° angle to the crossdrift. Phase 4 starts 1 yr after completion of Phase 2 and involves widening a 91.4-m section of the crossdrift to 12.2 m.

Instruments and gages planned for this test are grouped into six major stations; three stations are associated with the long 2D drifts, two stations with the 3D intersection, and one station with the wedge pillar. These stations are designated A through F, and are shown on drawings as section stations. Instruments and gages include individual anchor bolts (single point extensometers) for manually measuring horizontal and vertical salt displacements around the drifts, coupled with multipoint extensometers for remote measurement of these displacements; temporary and permanent manual floor-to-ceiling closure stations; temporary and permanent manual rib-to-rib closure stations; remote-reading vertical and horizontal closure gages; stress gages and pressure cells. The prompt installation of temporary closure stations is also critical in this test for early measurements. Thermocouples are not required for this room temperature experiment. A typical instrument station is shown in Fig. 13.

The wedge pillar has inclinometer holes in addition to typical instruments and gages. This pillar will also be instrumented with geophones for detecting acoustic emissions during pillar failure.

For the acoustic-emission experiment, a network of geophones and piezoelectric transducers with their own recording system will be installed in the wedge pillar section. Frequency response of the sensors ranges from 10 kHz to 1 MHz. Sensors will be emplaced about 0.5 m into the salt in a 3D network surrounding the area of anticipated failure. Spacing, which is controlled by the configuration of the experimental zone being investigated, should be roughly half the dimensions of the zone. For the wedge pillar, the density of sensors will increase toward the tip to provide adequate accuracy in locating emission sources.

In Situ Stress: A long (182-m), 100-mm-dia borehole was drilled along the Room G entry drift west from the existing SPDV area. Several hydrofrac tests were dye-marked along the length,of the deep borehole. The fractures will be exposed and studied during drift excavation. Instruments include a modified hydrofrac tool for a 100-mm-dia borehole, high-resolution caliper gages, a borehole viewer, an impression packer, a portable recorder, and pressure cells.

Direct Shear of a Clay Seam: A 1x1-m block in a wall or floor containing a representative clay seam will be isolated by cutting around it in place in one of the drifts. Flatjacks will be installed in slots cut around the block so that shear and normal stresses can be applied. Displacements of the seam will be measured as a function of applied stress. Other direct shear measurement techniques will be evaluated for possible application.

Pretest Calculations

In the development of all of the above tests, many calculations were used to aid in concept definition, test design, room geometry adjustment, and gage selection. To handle a large number of complex

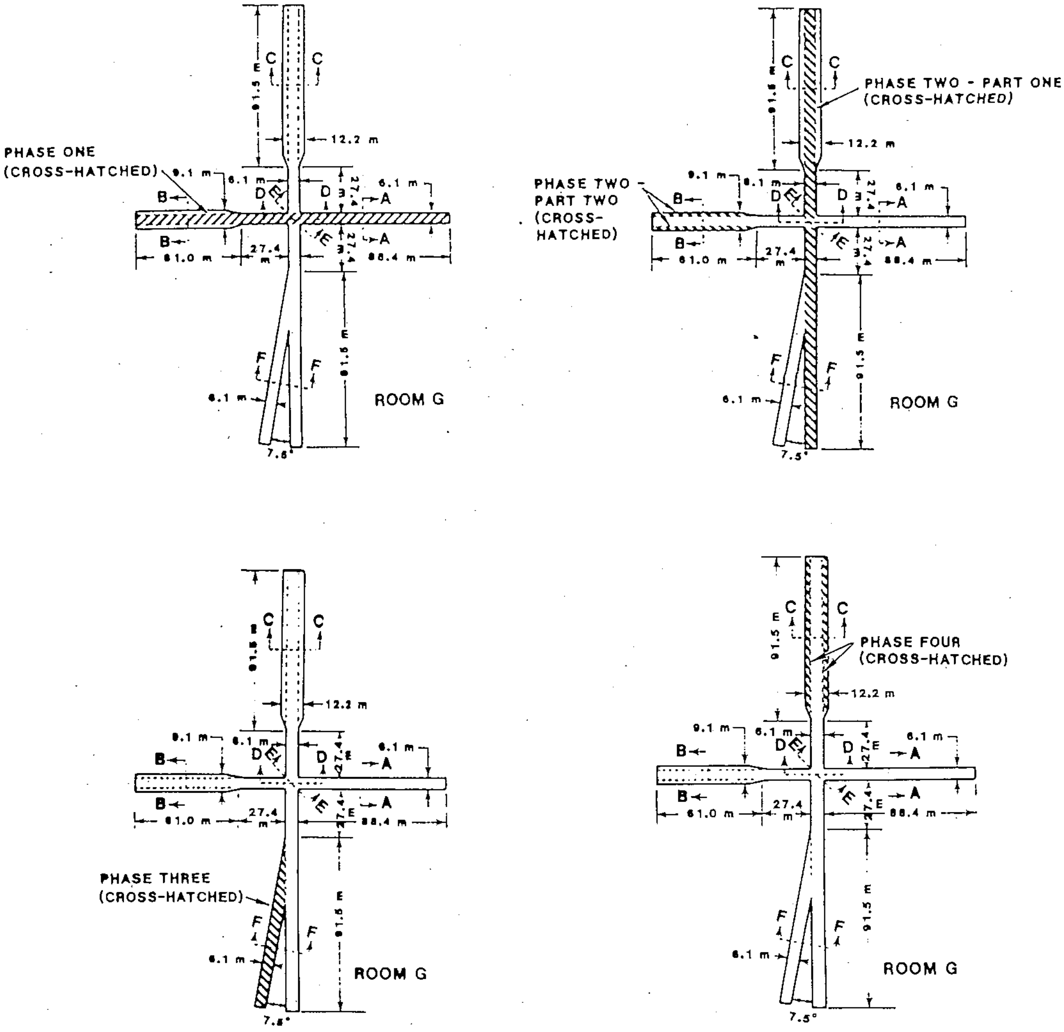


Fig. 12. Construction Phases of the Geomechanical Evaluation Test

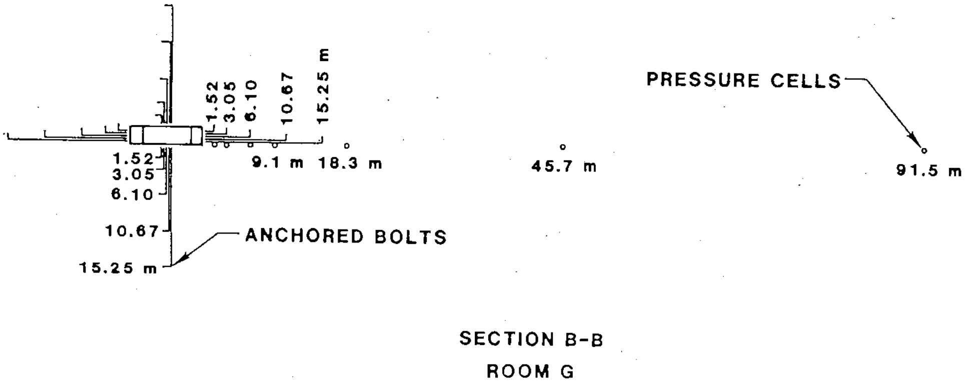


Fig. 13. Schematic of Instrument Station B-B Gage Emplacements

calculations that naturally use definition of many parameters required applying some discipline to the system. Consequently, calculations were categorized as (1) parametric study, (2) scoping, (3) reference and (4) comparative analyses. Only the first two categories are completed, except for a few reference calculations.

By definition, parametric study calculations are where parameter values, room geometry, or stratigraphic details are arbitrarily chosen by the analyst to gain knowledge of generic behavior. Considerable freedom is permitted in these calculations.

Scoping calculations, on the other hand, have several constraints: the stratigraphy, material parameters, constitutive model and boundary conditions are prescribed to a temporarily fixed set of reference conditions.[4] Thus, between infrequent updates of the reference conditions, all scoping calculations are related to a common basis. In scoping calculations, test geometry is also as near to actual as possible. Some changes may occur as the test develops. Enforced use of reference conditions is necessary if one expects rational correlation between calculations for test design.

Reference calculations are those in which the as-built test or room geometry and as-built stratigraphy are used in conjunction with the reference material parameters. The reference stratigraphy updates will have the actual stratigraphy based on up-to-date information from the field.

As the field data become available, comparative analyses will be done; typically discrepancies can be anticipated between calculated and measured results. This is the nature of such R&D. These comparative analyses and evaluations, and through an iterative process, eventually a final analysis will indicate the source of the discrepancy; the technology base will be modified accordingly. The culmination of the comparison is then improved analytical capability and verified computer codes for prediction and design.

Presently, many scoping calculations are complete for each TSI test for currently understood conditions and geometries. Typical results are shown in Fig. 14 where the thermal fields calculated at 3 yr for Room B (overtest) are given. The calculation is 2D and assumes a planar ideal heat source equivalent to the canister heaters. An example of room-displacement calculational results is given in Fig. 15 for Room G, Geomechanical Evaluation. These calculations are 2D and made by using a finite element, dynamic relaxation code and the reference conditions. Even though the example does not involve added heat, the codes used can solve the complete thermal/structural problem. The last example is the calculated stress contours[22] at three different times for the Room H, Heated Pillar test, in Fig. 16.

Data Acquisition/Recording

As a consequence of the large scope of the TSI tests, considerable quantities of data will be generated from the approximately 2000 data channels. A suitable, automated data acquisition/recording system is essential to the field effort.

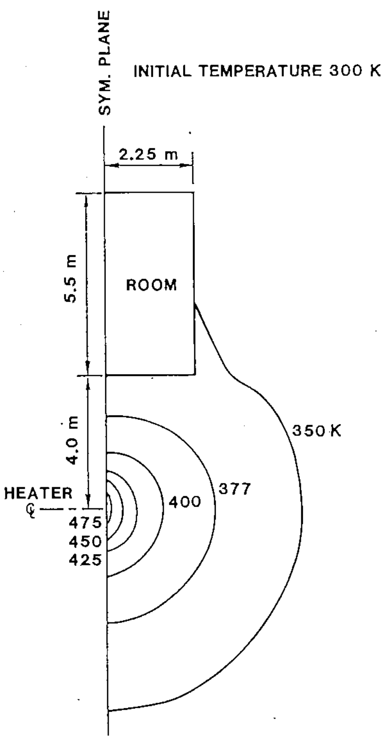


Fig. 14. Expected Temperature Contours (in K) for the Overtest at 3 Yr

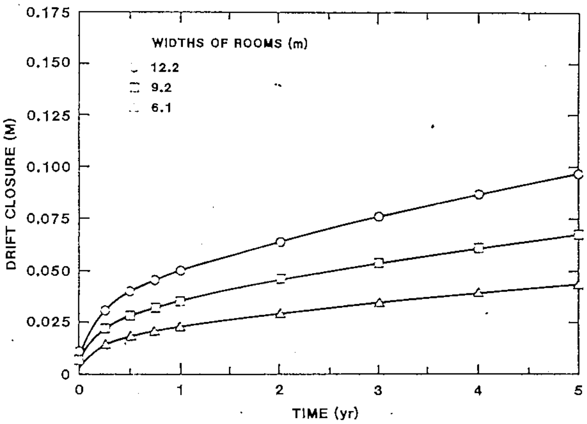


Fig. 15. Calculated Vertical Closure at the Centerline of the Drifts in the Geomechanical Evaluation as a Function of Time

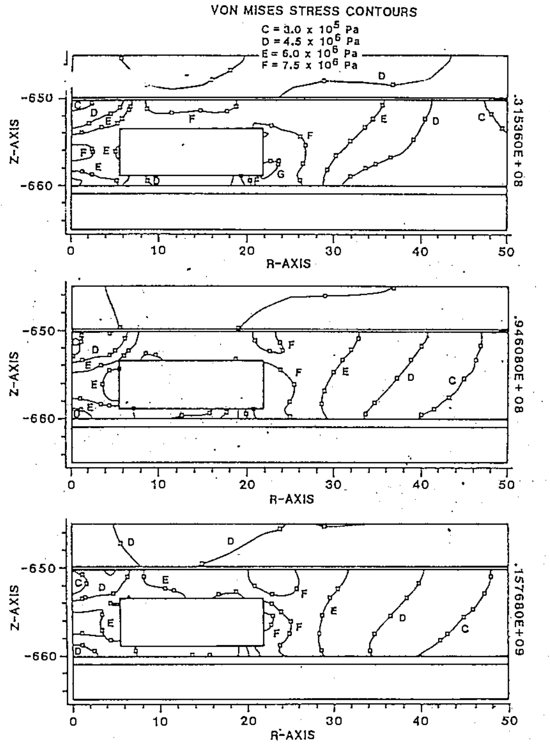


Fig. 16. Plots of Effective Stress in Area of Pillar and Drift at 1 Yr (Top), 3 Yr (Center), and 5 Yr (Bottom) For Case 4 (after reference 22)

The MODCOMP system, shown schematically in Fig. 17, consists of underground equipment sheds in alcoves near each TSI test room. Equipment housed in the buildings consists of scanners, voltmeters, calibration electronics, and power supplies. Instrument outputs in the test room are scanned periodically and transmitted by cable to the surface trailer housing the computer system for *recording* and real-time processing. Data can be transmitted to Sandia National Laboratories by means of telelinks or data tapes. Intermediate processing of data produces data files ready for analysis.

FIELDING OF TESTS

Even though actual fielding of tests is just beginning, many fielding activities will reflect earlier planning and organizational structures emplaced over the past 2 yr. While this process developed at the WIPP is probably not unique, it can be taken as an example of a reasonable system.

Organization

Two organizational structures will be examined: one is the major participant structure for the project, and the other is the structure for fielding the tests. Major participants are organized under the DOE as in Fig. 18, exclusive of subcontractors. Within the framework, Sandia is responsible for the overall WIPP R&D support to the DOE, and will carry out the WIPP TSI in situ tests as part of the R&D program.

Perhaps of even greater interest at this stage are the organizational details of the fielding operation. The organizational structure, shown in Fig. 19, highlights the important work areas. The

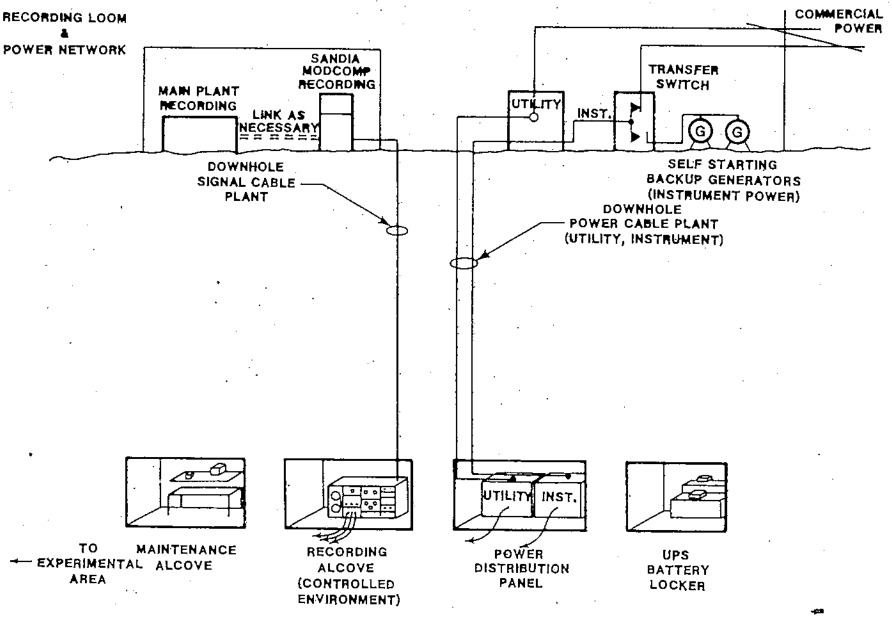


Fig. 17. Data Acquisition and Power System, WIPP Experimental Area (after reference 2)

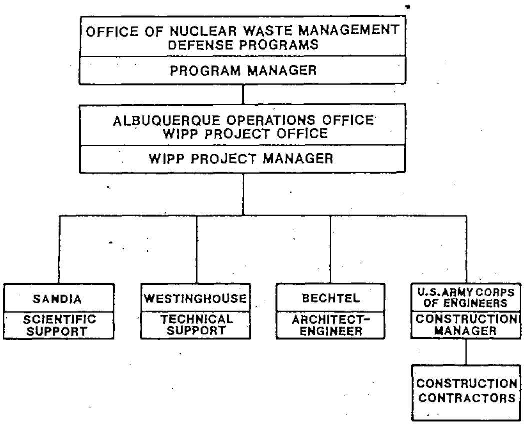


Fig. 18. Major Participants in the WIPP Project

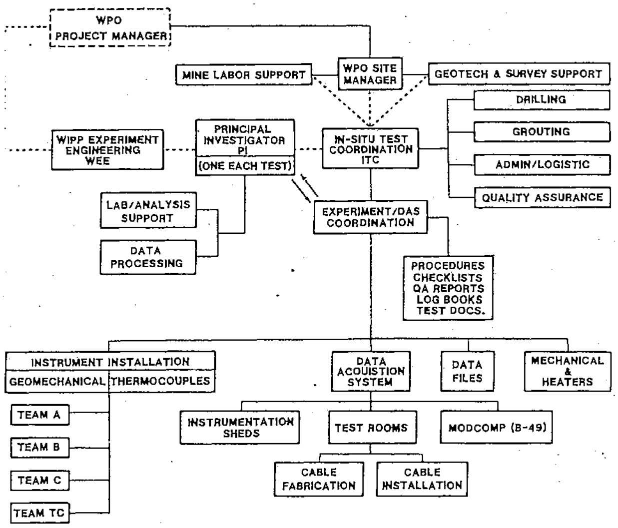


Fig. 19. Organization Structure for Fielding TSI Tests

experiment coordinator has direct charge of instrument installation teams, installation of large mechanical components, the data acquisition system from the underground test room to the MODCOMP computer trailer, and data files. The coordinator is responsible through a quality assurance system for paper traces of activities, procedures, logs, and checklists relating to the instrument calibrations, identification, and installation.

The principal investigator (PI) who has responsibility for technical development, implementation, and analysis of the test directly interfaces with the experiment coordinator during fielding. The PI is the link to the TSI R&D program analysts and the overall program.

An important individual, the in situ test coordinator, is the liaison between the PI, the experiment coordinator, and the WIPP Site management. In situ test coordination includes two essential support functions: coordination of routine support furnished through and from the site personnel, and direction of special technology support activities. Specific activities evolved from the unique requirements of fielding these TSI tests include drilling practice for large-diameter emplacement holes, grouting techniques for installing of instruments, and extraordinary handling methods for massive canisters. In addition, this support includes Sandia administrative activities and the quality assurance (QA) program that is indispensable to any radioactive waste isolation program.

Quality Assurance (QA) Program

Strict interpretation of the QA criteria would logically place the WIPP TSI in situ tests in the "minor" category, which requires minimal documentation. However, as a matter of policy, Sandia has chosen to treat the program and tests as "major," the next higher level, which requires extensive documentation. This means stricter control over records, documents, and procedures. In the TSI test development, consideration given to the day-to-day mechanics of assuring that the tests were planned well, are fielded as planned, and will be traceable for any significant aspect of the test. In practice, the daily QA tasks are many, but principal among them are several routine tasks. All test plans were checked several times to assure accuracy of dimensions and gage types and designations. This task extended to include the architects/engineer construction drawings. Individual gages required manufacturers' material and performance certifications, calibration records, installation records, and maintenance logs. Construction activities will require careful consideration to assure keeping appropriate records and to determine physical dimensions and deviations of each room and each instrument and canister borehole. QA during installation of instruments will require accurate correlation of gage, location, and appropriate marking. Extensive daily logs will be maintained by the DOE construction managers (Corps of Engineers), the experiment coordinator, and the PI. All these records become part of permanent files containing complete "as-built" configuration of the experiment and instrumentation systems.

Important to this process is a system control that prevents changes in test configuration during construction and fielding without approval. All changes require PI approval; major changes require the same organizational approvals as the test plans. Any changes are noted on a "red line" copy of the test plan, with appropriate approvals annotated.

QA also carries directly through the data handling process to assure proper data storage and documentation for analysis. Numerical codes used for analysis are QA-controlled to assure no undocumented changes.

CONCLUSIONS

The in situ tests have yet to be fielded, which prevents reaching conclusions on the adequacy of the planning and development of these tests at this time. However, we are far enough along in the process to make some preliminary statements that we believe will be factual even when the tests are completed.

1. In situ tests of this magnitude require extensive planning at an early stage to assure that they are well-conceived in attainable objectives, and that the interface problems are solved so the construction can accomplish the proper test configurations.

2. Because the tests are relevant to radioactive waste repository design, early and continuing peer review of the plans and development of the test goals and configurations are essential.

3. The quality level for data potentially significant to repository design must be assured even though the requirements of obtaining well-controlled data from large-scale underground tests may be a competing process with construction. Planning, preparation, and training consequently assume high priority in the effort.

4. Because of the potential importance of the data obtained to future repository design, special efforts are necessary to assure that recordkeeping methods are well established and properly maintained to the QA levels required.

In general, these tests and the underground response data they provide will aid in the advance toward the WIPP R&D program goal of developing validated technology for design and performance predictions for radioactive waste repositories in salt.

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