THE WASTE ISOLATION PILOT PLANT - AN INTERNATIONAL CENTER OF EXCELLENCE FOR "TRAINING IN AND DEMONSTRATION OF WASTE DISPOSAL TECHNOLOGIES"

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP) site, which is managed and operated by the United States (U.S.) Department of Energy (USDOE) Carlsbad Field Office (CBFO) and located in the State of New Mexico, presently hosts an underground research laboratory (URL) and the world's first certified and operating deep geological repository for safe disposition of long-lived radioactive materials (LLRMs). Both the URL and the repository are situated approximately 650 meters (m) below the ground surface in a 250-million-year-old, 600-m-thick, undisturbed, bedded salt formation, and they have been in operation since 1982 and 1999, respectively.

Following the May 1998 U.S. Environmental Protection Agency (USEPA) certification and the March 23, 1999 resolution of all legal challenges, the WIPP repository opened on March 26, 1999. By November 15, 2002, 1,370 shipments of contact-handled (CH) transuranic radioactive waste (TRUW)[a] from across the USA had been safely disposed at the WIPP site. When filled to its legal capacity, the WIPP repository will contain 175,586 cubic meters (m^3) of TRUW that may include: up to 17 metric tons (MT) of plutonium with a half-life in excess of 24,000 years; and waste containers with external surface dose rates of up to 10 sieverts per hour (Sv/h). In other words*, the TRUW emplaced in the WIPP repository is both long-lived and highly radioactive*.

Founded on long-standing CBFO collaborations with international and national radioactive waste management organizations, since 2001, WIPP serves as the Center of Excellence in Rock Salt for the International Atomic Energy Agency's (IAEA's) International Network of Centers on "*Training in and Demonstration of Waste Disposal Technologies in Underground Research Facilities*" (the IAEA Network). The primary objective for the IAEA Network is to foster collaborative projects among IAEA Member States that:

1. Supplement national efforts and promote public confidence in waste disposal schemes;
2. Contribute to the resolution of key technical issues; and
3. Encourage the transfer and preservation of knowledge and technologies.

Hence, 132 IAEA Member States now have the opportunity to timely, cost-effective training of staff and demonstration of waste disposal technologies at the underground and surface-based laboratories managed by the current eight members of the IAEA Network. In addition, collaborations with the CBFO provide access to unique, state-of-the-art scientific, engineering, socio-economic, and strategic planning and implementation data as well as lessons learned during the 24-year repository development process preceding the 1999 opening of WIPP. Indeed, *collaborations with the CBFO/WIPP provide access to:*

- *A URL for staff training and cost-effective waste-disposal-technology demonstrations; and*
- *Data, codes, models, and stratagems used to a) open the WIPP repository, b) safely operate the WIPP site in compliance with applicable regulations, and c) recertify WIPP at least every five years of operation.*

In other words, the WIPP repository is a globally, first-and-only-of its-kind facility that enhances the global nuclear safety culture and the nuclear renaissance by:

1. Providing a national solution to the TRUW legacy.
2. Serving as the proof-of-principle for safe deep geological disposal of LLRMs.
3. Providing opportunities for other waste management organizations to timely and cost-effectively access the data and experience of, as well as the facilities managed by, the CBFO.

INTRODUCTION

In the United States of America (USA), the accumulation of LLRMs from the nation's nuclear-weapons complex (NWC) started in the 1940s and was followed in the 1950s by a continuously increasing accumulation of LLRMs from a broad range of commercial and research applications. (1) One legacy of these activities is that the USDOE now faces the challenge to safely:

- Deactivate, decontaminate, and decommission more than 700 federally-managed facilities;
- Clean approximately 80 million m^3 of contaminated soil and 6.8 billion m^3 of contaminated groundwater;
- Dispose approximately 380,000 m^3 of highly radioactive waste (HLW), 220,000 m^3 of TRUW (includes both existing and projected TRUW, but does not account for any volume reduction due to treatment/repackaging), and 3,300,000 m^3 of low-level radioactive waste (LLW) from the NWC; and
- Site, develop, operate, and decommission/close deep geological repositories for safe disposal of spent nuclear fuel (SNF) and other HLW from the nation's NWC and nuclear power plants. (2)

This legacy is significant in terms of the volumes, efforts, time, and cost involved, and the many sophisticated solutions that are required. Although several USDOE as well as other federal and state organizations are involved in and contribute to the mitigation of the nation's SNF, HLW, and TRUW legacies, this paper focuses on the national solution to the TRUW legacy, i.e., *the WIPP repository* (Fig. 1). The WIPP program *serves to enhance both the global nuclear safety culture and a nuclear renaissance by physically demonstrating that LLRMs can be safely transported long distances and disposed in a carefully sited and designed deep geological repository*.

Fig. 1. The U.S. map (left) shows the locations of the WIPP, its TRUW "feeder" (circles and squares) sites and TRUW transportation routes. The schematic (right) shows the WIPP Disposal System.

One cornerstone to the successful certification of the WIPP TRUW repository was international collaborations and reviews. Furthermore, since October 2001, the WIPP URL serves as the Center of Excellence in Rock Salt for the IAEA Network. Hence, the emphasis below is on the following select components of the CBFO's mission: (a) the main objectives, designs, and locations of the large-scale *in situ* tests conducted and the instrumentation used in support of the 1996 WIPP Compliance Certification Application (CCA) (3); and (b) the CBFO's approach/logic for building the main codes and models used in the WIPP post-closure safety/performance assessments (PAs) that lead to the 1998 certification of the WIPP repository. Specifically, provided below are: concise background descriptions of: the CBFO mission, including the status in November 2002; and the WIPP Disposal System (Fig. 1), followed by (a) an overview of the WIPP Test program, instrumentation, and codes and models deemed to be cornerstones to the certification of the WIPP repository, and (b) a summary of the potential benefits to the CBFO and others of collaborating with the CBFO. Clearly, there is more recent WIPP information. However, for the following main reasons, the above emphasis was deemed optimal for providing the 132 IAEA Member States *a road map* for identifying the tests, codes and models successfully used by the CBFO to certify and open the WIPP LLRM repository of particular interest and value to their respective program:

- Most IAEA Member States are in a very early stage of repository siting, design, and development;
- The current database is too large for presentation in a single paper (the site characterization, repository-design, and code and model development programs at the WIPP site began in earnest in 1975);
- Only the data, codes, and models used in the CCA have been subjected to regulator review and approval (by March 26, 2004, the CBFO should have another set of regulator-reviewed and -approved databases, codes, and models, because, by law (4,5), the USEPA must recertify the WIPP repository every five years of operation);
- The described databases include information that pertain to both TRUW and HLW disposal; and
- *Access to the current databases is available through collaborations with the CBFO.*

BACKGROUND

In order to fully appreciate and understand the application(s) of the WIPP information provided below, the following WIPP conditions should be recognized:

1. *Compliance with applicable regulations for post-closure repository performance is measured at the horizontal and vertical boundaries of the WIPP Disposal System shown to the right in Fig. 1.* (6,7)
2. The geologic setting provides virtually all radionuclide containment and isolation throughout the 10,000-year regulatory period. Specifically, the disposal concept at WIPP primarily relies upon:
   - The inherent rheologic (creep) behavior of salt to encapsulate the materials emplaced in the WIPP repository into a virtually impermeable monolith within 300 years;
   - The ability to design and emplace appropriate seals; and
   - The flow and transport characteristics of the repository-host rock and overlying formations within the WIPP Disposal System (Fig 1) to keep the release of radioisotopes below the regulatory limits after closure in the event the integrity of the natural system is breached by human intrusion(s). (3)
3. The large-scale *in situ* tests conducted in the URL between 1983 and 1995 were designed to establish the information required to design, construct, operate, and decommission a safe repository for TRUW and HLW. (8,9)
4. Pursuant to the applicable disposal regulations, (6,7) which also apply to the safe disposal of SNF and HLW at any other site than the Yucca Mountain site, the post-closure PAs must address the following two Safety Cases:
   - The maximum annual effective dose during the first 10,000 years after termination of disposal operations to an individual living at the Disposal System boundaries, when the repository is only affected by reasonably likely natural events; and
   - The cumulative amount of radionuclide releases beyond the Disposal System boundaries during the 10,000-year regulatory period when the repository is affected by both reasonably likely natural events and inadvertent human intrusions with a probability of occurrence equal to or greater than one chance in 10,000 during 10,000 years (10^{-8}).
5. The codes, models, parameters, and parameter values used in the CCA to model the safe post-closure performance of the WIPP repository satisfied: (a) very strict USEPA, USDOE, and Sandia National Laboratories (SNL) quality assurance (QA) and quality control (QC) requirements; (b) one international and six domestic peer reviews; and (c) reviews by National Academy of Sciences (NAS), State, and local oversight groups, other affected and interested parties, and the cognizant radioactive waste management regulator, the USEPA. By law, (4) any modification to these codes, models, parameters and parameter values as well as any new code and/or model used in support of future recertifications of the WIPP repository will experience a similarly stringent review.

The CBFO Mission

The USDOE is responsible for the development and operation of a deep geological repository for safe disposal of TRUW at the WIPP site. In December 1993, the USDOE established the CBFO (initially called the Carlsbad Area Office) to accomplish this mission. On March 26, 1999, the CBFO opened a regulator-certified deep geological repository for safe disposal of LLRMs at the WIPP site in the State of New Mexico. The opening of the WIPP repository was preceded by 24 years of site characterization, repository design and construction, and code- and model-development activities that culminated with the May 18, 1998, favorable USEPA Certification Decision (10) and the March 23, 1999, successful resolution of the legal challenges blocking the opening of WIPP. (11) By

November 2002, 1,370 shipments of CH-TRUW[a] have been safely received from the following five TRUW sites (indicated by squares in Fig. 1): Los Alamos National Laboratory (LANL), Idaho National Engineering and Environmental Laboratory (INEEL), Rocky Flats Environmental Technology Site (RFETS), Hanford, and Savannah River Site (SRS) and disposed at the WIPP site.

The WIPP Disposal System

The WIPP site is located on an arid, generally flat plain covered with sand, caliche, and desert bushes in the southeastern portion of New Mexico. Geologically, the WIPP site is located in the Delaware Basin, which covers over 33,000 km^2 and is filled with sedimentary rocks to depths of 7,300 m. The stratigraphic column at the WIPP site comprises about 4,575 m of Paleozoic sedimentary rocks on top of the Precambrian basement. (3) Pursuant to the applicable law, the horizontal surface area set aside from public use for the WIPP Disposal System measures 6.4 kilometers (km) by 6.4 km. (5) The resulting WIPP Disposal System is shown to the right in Fig. 1. As shown in Fig 2, the WIPP repository (and the URL) is situated 650 m below the ground surface in the lower half of the Salado Formation; a 600-m-thick, 250-million-year-old, laterally extensive, virtually impermeable, *bedded rock salt* formation. The development of the repository is staged and, by November 2002, Panels 1 and 2 had been excavated and used for TRUW disposal.

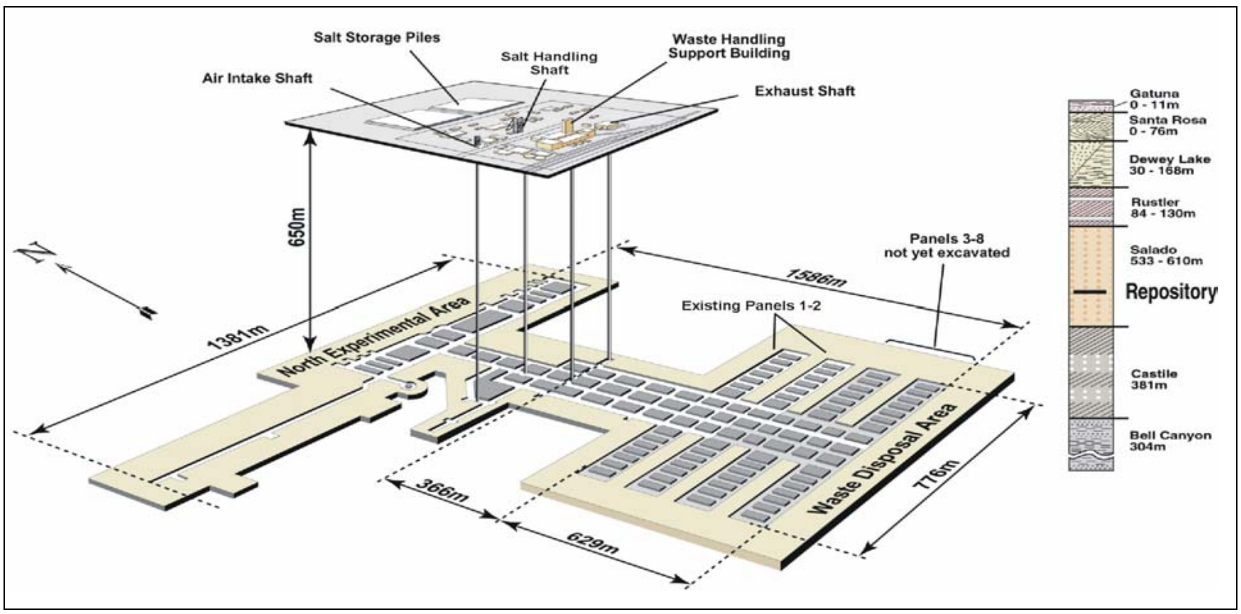

Fig. 2 Schematic illustration of surface facilities and subsurface facilities/openings at the WIPP site.

The IAEA Network

The IAEA Network was established in October 2001 to provide an opportunity for the 132 IAEA Member States to benefit from timely, cost-effective training of staff and demonstration of waste disposal technologies in *existing* underground research facilities (and associated surface-based laboratories). The primary objective for the IAEA Network is to foster collaborative projects among IAEA Member States that:

- Supplement national efforts and promote public confidence in waste disposal schemes;
- Contribute to the resolution of key technical issues; and
- Encourage the transfer and preservation of knowledge and technologies.

At the end of October 2002, the IAEA Network includes the following members (in alphabetical order) and their respective research laboratories:

1. Lawrence Berkeley National Laboratory (LBNL), USA, providing access to its research facilities.
2. Natioanale Genossenschaft für die Lagerung Radioaktiver Abfalle (NAGRA), Switzerland, providing access to the Grimsel URL in *granitic/igneous rocks*.
3. NAGRA, Switzerland providing access to the Mont Terri URL in *argillaceous rocks*.
4. Ontario Power Group (OPG), Canada, providing access to the Lac du Bonnet URL in *granitic/igneous rocks*.
5. Studiecentrum voor Kernenergie/Centre d’Étude de l’Énergie Nucléaire (SCK/CEN), Belgium, providing access to the HADES URL in *clay.*
6. University of Wales, United Kingdom, providing access to its Geotechnical Research Center.
7. USDOE CBFO, USA, providing access to the WIPP URL (the North Experimental Area) in *bedded salt*.
8. USDOE Office of Civilian Radioactive Waste Management (OCRWM), USA, providing access to the Yucca Mountain URL (the Exploratory Studies Facility) in *volcanic tuff*.

OVERVIEW OF THE WIPP TEST PROGRAM, INSTRUMENTATION, AND CODES AND MODELS

The CBFO has designed and conducted a broad range of tests designed to obtain the information required to design, operate, and decommission/close a safe deep geological repository in bedded salt. For example, between 1983 and 1995, the WIPP URL was used to study the effects of both HLW and TRUW emplacement in bedded salt. (3,8,9,12). *The WIPP in situ experiments were frequently preceded and/or augmented by laboratory experiments and always by numerical modeling*. In general, where the scale and reality of underground testing did not add to the understanding of and confidence in the process being evaluated, the tests were done in above ground facilities where the experimental parameters were more easily controlled. For example, rock mechanics testing on core, backfill compaction, gas generation, and chemical studies of magnesium oxide (MgO) (backfill) were more efficiently and cost effectively carried out in existing off site test facilities and laboratories. Furthermore, restrictions at the WIPP prior to operation required that experiments with radioactive isotopes and radioactive waste be conducted off site. Consequently, batch sorption and flow through retardation studies with the actinide isotopes were conducted at several national laboratory locations, such as SNL and LANL. The modeling was conducted initially to guide the experiments. As experimental data were acquired, they were used to adjust the model concept as required. This iteration was repeated until there was satisfactory agreement between experimental observation and model prediction. Although a large number of laboratory-based tests were supplementing the larger-scale *in situ* field tests, *the emphasis below is on the large-scale in situ field tests*. Additional information on all aspects of the WIPP Test Program is available in the CCA (3) and through collaborations with the CBFO and its main contractors. (8,9,12)

The WIPP Test Program

The primary purpose of past and current WIPP Test Program is to develop an adequate understanding of the physical processes involved in the designing, constructing, operating, decommissioning and closing a safe deep geological repository for LLRMs in the Salado Formation rock salt at the WIPP site, including the development and use of codes and models supporting the adequate prediction of post-closure repository behavior for at least 10,000 years. Specifically, the focus of the WIPP Test Program is on:

1. Room stability, including the disturbed rock zone/excavation disturbed zone (DRZ/EDZ), and creep closure at ambient and elevated temperatures.
2. Seal performance.
3. Flow and transport characteristics of a) the Salado Formation (repository host rock) and b) the overlying Rustler Formation (hosts the site’s highest-hydraulic conductivity units) (Fig. 2).

Summarized below are descriptions of the objectives, designs, and locations of the following three groups of *in situ* tests conducted in the URL between 1983 and 1995 for establishing the effectiveness of containing and isolating LLRMs in a salt repository followed by concise descriptions of the *hydrologic testing*, *instrumentation*, and *codes and models* used in support of the CCA:

1. Thermal/Structural Interactions (TSI) Tests.
2. Plugging and Sealing (P&S) Tests.
3. Waste Package Performance (WPP) Tests.

Fig. 3 shows the locations and Fig. 4 shows the main instruments used in the aforementioned tests. (3,8,9,12)

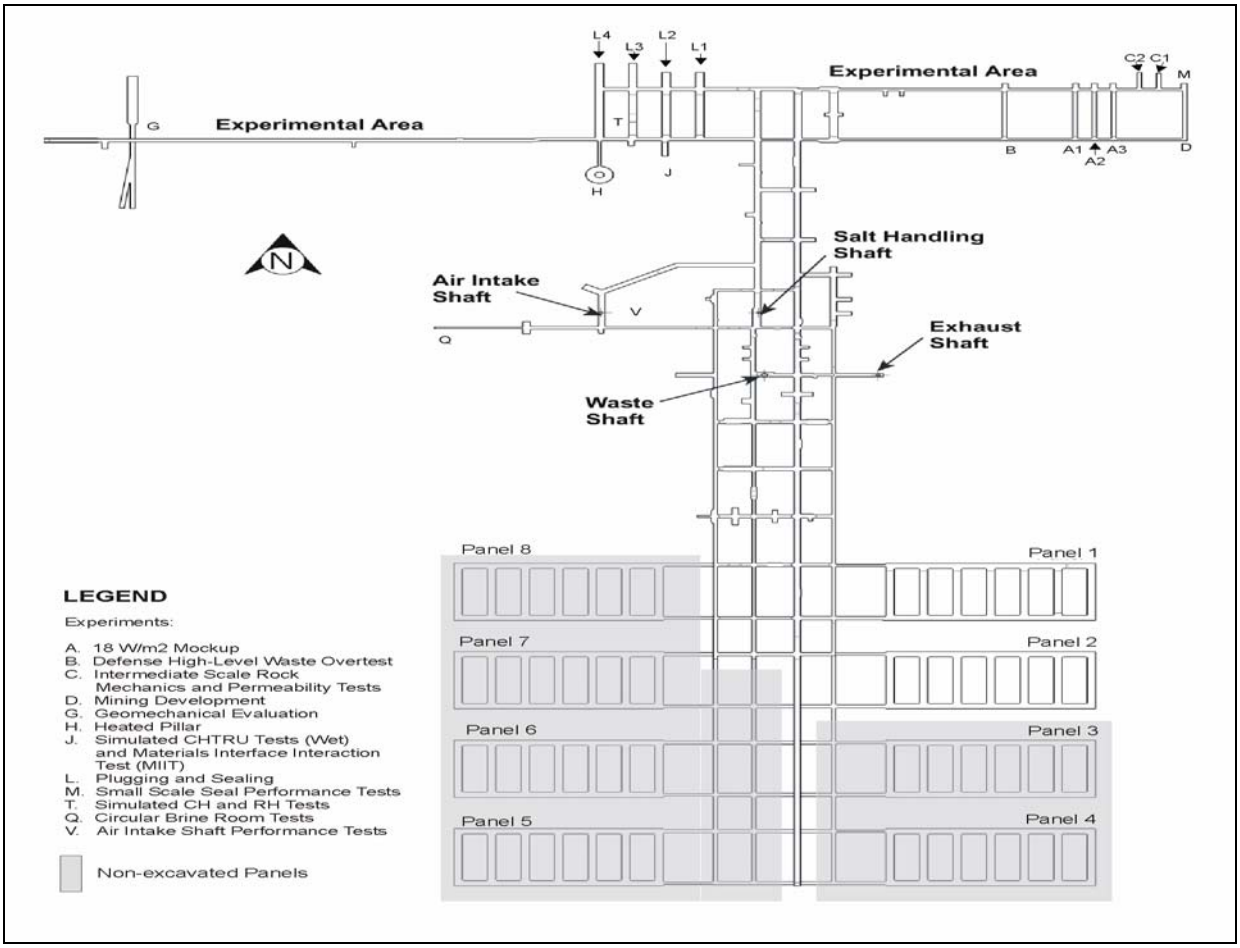

Fig. 3 Layout of underground facilities and locations of large-scale in situ tests.

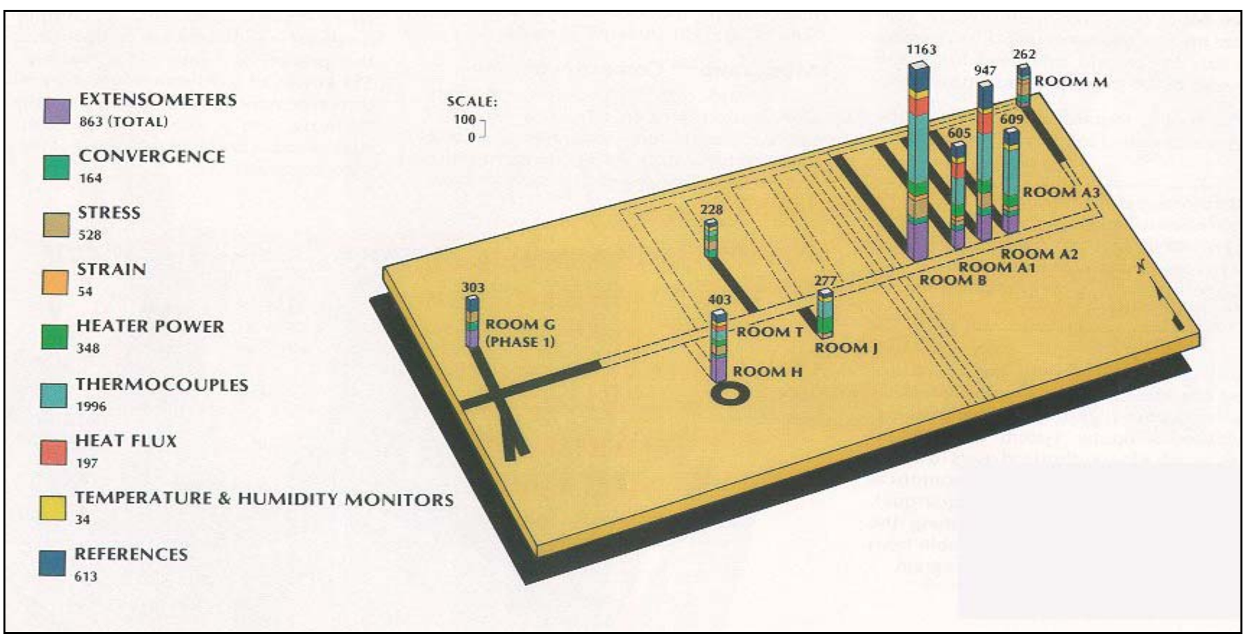

Fig. 4. Instrument distribution in the North Experimental Area.

The TSI Tests were designed and conducted to address: (a) the stability of the excavated rooms during repository operations and possible waste retrieval; and (b) the long-term deformation of the disposal room. In other words, the TSI Tests addressed the mechanical behavior of rock salt as influenced by excavation effects, stress, and thermal loading and interactions induced by waste emplacement. The goal was to develop and validate predictive modeling and calculation techniques for design and PAs of bedded salt repositories. The TSI Tests included the following seven major tests (shown in Fig.3):

1. The 18-Watt/square meter (W/m^2) defense HLW (DHLW) Mockup in Rooms A-1, A-2 and A-3.
2. The DHLW Overtest in Room B.
3. The Geomechanical Evaluation in Room G.
4. The Heated Axisymmetric Pillar Test in Room H.
5. The *In Situ* Stress Determination by Hydraulic Fracturing in the Room G entry.
6. The Ambient Temperature Tests in Room D.
7. The Scale Effect Tests in Rooms Q and C.

Following are the main objectives and designs of these tests:

- ***The 18 W/m² DHLW Mockup Tests*** were conducted to determine: (a) rates of salt creep and room closure; (b) effects of heat transfer to the host rock; (c) validity of predictive methods and techniques; and to (d) demonstrate the suitability of a reference DHLW disposal room. Hence, the Mockup Tests were designed to provide information on the effects of heat on room closure, structural stability, and waste encapsulation, using the exact thermal and structural matches of the Reference Repository Configuration for DHLW in bedded salt within the limitation of presenting the fields of a large array of rooms with a three-room configuration. Room A2 (Fig. 3) was an exact match of the thermal and structural configuration, including the canister size, heat load, and spacing, and it contained 28 0.47-kilowatt (kW) heaters in two rows guarded by two 1.41 kW heaters at each end. A single row of 1.41-kW heaters in each of Rooms A1 and A3 provided the thermal and structural boundary conditions on Room A2 that would be experienced by an interior room in a large array of rooms. In addition to the main objectives defined for this test, it also provided valuable data on the effects of excavating adjacent rooms (*mine-by experiment*).
- ***The DHLW Overtest*** was an accelerated version of the Mockup Tests and it was designed and conducted to: (a) determine room closure rate and heat transfer at elevated temperatures; (b) validate predictive techniques; and (c) evaluate long-term effects of heat and room closure. The geometry of Room B (Fig. 3) was the same as the disposal rooms of the reference repository design, i.e., 5.5-m-high, 5.5-m-wide, and 93.3-m-long. However, only one row of 17 1.8-kW heater canisters was emplaced at 1.5-m-spacing in the floor along the centerline of the room, whereas 24 0.47-kW heater canisters were placed in two rows of boreholes spaced 3.44-m apart in Room A2. The canister/salt interface temperature was about 250 degrees centigrade (^{o}C). The Overtest used about four times the reference thermal load to drive the room to failure more quickly to provide additional information on the creep constitutive model verification and structural data on canister response and room failure mechanisms. Installed instruments at the Overtest and the Mockup test measured vertical and horizontal room closures, and deformation of and stresses (pressures) in the salt mass. Upon completion of the field test, the DHLW canisters were recovered by overcoring and retained for corrosion analysis in the laboratory.
- ***The Geomechanical Evaluation Test*** was designed and conducted to determine: (a) effects of room geometry on the creep deformation of drifts for two-dimensional (2-D) analysis; (b) validity of the theoretically developed models in predicting the response of different-sized openings; (c) response of 3-D drift intersection and the validity of using 2-D modeling techniques; (d) failure mode of a large volume of salt under high stress; (e) techniques for developing underground drift designs; and (f) *in-situ* stress by hydrofracturing techniques. However, only the first phase of the test was implemented due to financial constraints and mission changes. The first activity in phase one consisted of drilling long boreholes in advance of the mining face. These holes were hydrofractured at different distances from the mining face using tracer fluids that fluoresced in ultraviolet light. Pressure required to fracture the rock and careful observation as mining proceeded through the fractured area allowed both *in situ* stress levels and orientation to be determined in width. To provide a full-scale, 2-D geometry to match the 2-D aspects of the calculation model being used at that time, Room G (Fig. 3) was excavated at the end of a long drift to isolate it from effects of other openings. Room G had several instrument stations consisting of anchored bolts placed in the invert, ribs/walls, and ceiling/roof to obtain measurements of displacements of the salt and drift closure; and pressure cells that provided a measure of stress distribution.

- ***The Heated Axisymmetric Pillar Experiment*** was conducted to determine: (a) validity of the models and computer codes in predicting the response of heated rock-salt mass; (b) behavior of room and pillar in response to (accelerated) creep; (c) mechanical properties and failure modes of salt and other constituents in the testing envelope; and to (d) compare actual 3-D response to 2-D models, and *in-situ* data from laboratory-model pillar tests and from other salt mines to assist in model evaluation. Room H (Fig. 3) was constructed to provide as good a match as possible between the 2-D modeling capability and the excavation geometry. Except for the necessary, 50-m-long, access drift, the concentric annular room around the 190-m^3 central cylindrical pillar of salt conformed to the 2-D, axisymmetric geometry, which can be modeled by 2-D codes without resorting to any geometric abstractions or approximations. Thermocouples measured the temperature of the salt surrounding the annulus and pillar. Deformation and pillar fractures were monitored visually. After acquiring creep information on the pillar and room at ambient temperature for one year, the pillar was covered with an insulating blanket and heated with strip heaters to about 70^{o}C. This heating continued until one year before decommissioning to allow a one-year cool down period. Ten years of active data were acquired from this test. Installed instruments measured vertical and horizontal room closure, deformation of the salt mass bordering the room; and stresses in the rock mass bordering the room.
- ***The In Situ Stress Determination by Hydraulic Fracturing in the Room G entry*** is described above under the Geomechanical Evaluation Test.
- ***The Ambient Temperature Room Test*** was conducted in Room D (Fig. 3). This room was the earliest room excavated in the experimental complex and was used to test gage installation techniques and obtain rock mechanics data at ambient temperature. The room was the same geometry as the heated Room B and was therefore a useful baseline against which to compare the accelerated creep experienced in Room B.
- ***The Scale Effect Tests*** were conducted to resolve the debate over whether the scale of excavations could be responsible for some of the discrepancies between observation and model calculations. Two cylindrical boreholes of different dimensions were instrumented and observed. One borehole, 30-m-long and about 1-m in diameter, was constructed between Rooms C-1 and C-2 (Fig. 3) after a pre-emplaced array of stress and extensometer gages was recording baseline data. The other test was conducted in conjunction with a 100-m-long, 3-m-diameter boring, Room Q (Fig. 3), and implemented primarily to conduct a large-scale brine-seepage test. Structural behavior of both test results was accurately predicted by the model, eliminating scale effect as a source of concern in the calculations.

The primary objectives of the ***P&S Tests*** were to: (a) develop candidate materials and structural systems for long-term plug/seals at WIPP; (b) evaluate materials and emplacement techniques for adequate sealing of boreholes, shafts, and drifts; (c) develop assessment techniques for predicting long-term performance with field and full-sized tests; (d) evaluate host rock permeability and other properties related to plug/seal interactions; (e) demonstrate plug/seal performance with field and full-sized *in situ* tests; and (f) develop a design basis and criteria for the plugs and seals at WIPP. The following two groups of tests were conducted:

1. "*Characterization of the Formation Tests*", including permeability (underground areas), gas flow (underground areas), moisture transport and release (Rooms A1, B, and Q, and Air Intake Shaft (AIS) (Fig. 3) performance.
2. Developing and evaluating seals ("*Seal Tests*"), including plug test matrix (Rooms L1 and L2 [Fig. 3]), borehole plug (underground and surface), small-scale seal performance (Room M [Fig. 3]), and backfill design and emplacement.

The P&S Tests provided the technical basis for an adequate and defensible design for sealing the WIPP repository after decontamination and decommissioning. The long-term sealing strategy utilized the reconsolidation of crushed salt, eventually resulting in a seal that approaches the density, permeability, and strength of the intact host salt. To assure isolation and prevent fluid intrusion in the time frame before crushed salt reconsolidation is completed, bentonite clay, concrete, and asphalt plugs supplement the primary salt plug. Testing involved both laboratory studies and intermediate-scale (meter diameter holes) *in situ* testing of these materials. Emplacement evaluations and fluid flow studies provided guidance on the design of the WIPP seal system. Characterization of the DRZ/EDZ, which surrounds the excavations and any emplaced plugs, was accomplished by gas flow testing. Following is a summary of the primary objectives, designs, and locations for the main "*Characterization of the Formation Tests*":

- The primary objective of the *Permeability Tests* was to determine the natural potential of the Salado and Rustler formations (Fig. 2) to restrict the fluid flow. More than 50 12-cm-diameter horizontal boreholes were drilled into pillars or wall rock from locations ranging throughout the underground facility and more than 50 surface boreholes were used to assess the transmissivity of the Culebra Dolomite unit of the Rustler Formation, which is the highest hydraulic conductivity unit at the site. Permeability was inferred from calculations based on measured pressure variations and flow rates with time.

- The primary objectives of the *Gas Tests* were to provide information on (a) extent and flow parameters of the DRZ/EDZ; (b) interaction between the seal and the formation; and (c) resultant hydraulic (or fluid) conductivity of any gas-bearing layer in the vicinity of the seal. Several long (about 65 m) horizontal and inclined boreholes were subjected to gas testing in Room M (Fig. 3) and several other locations in the URL.
- The primary objectives of the *Moisture Transport and Release Tests* were to: (a) characterize and model the movement of naturally occurring moisture in the host rock; (b) evaluate the quantity, rates, and composition of moisture release to openings in the repository horizon as a function of temperature and time; and (c) compare *in-situ* measurements with laboratory studies and model predictions. Although the salt at the repository horizon does not contain any circulating groundwater/brine/liquid, it does contain an average of 1 percent (%) by weight of liquids. Moisture transport and release rates were measured from within the heated boreholes in Rooms A1 and B (Fig. 3). A flowing nitrogen system continuously swept the cumulative quantities of moisture by means of condensation and desiccant apparatus. Pore pressure and moisture releases were also measured in the surrounding rock.
- The AIS was the fourth and last shaft to be constructed at the WIPP site (Figs. 2 and 3). A raise-boring machine drilled the 6.1-m-diameter, 659-m-long shaft from the repository horizon to the surface. This was the only shaft made available for experimental measurements. The primary objectives of the *AIS Performance Tests* were to: (a) determine complete history of shaft creep closure in the Salado Formation; (b) support model development for long-term predictions of the shaft; (c) quantify near-field permeability in the Salado and Rustler formations; (d) determine the effects of shaft construction on the development of the DRZ/EDZ; (e) assess the impact of the DRZ/EDZ on seal design technology development; (f) acquire data supporting the modeling of hydrologic communication between units in the lined section (approximately upper 100 m) of the shaft; (g) quantify the amount of brine inflow at selected depths in the Salado Formation for model development; and (h) determine net inflow of fluids to the shaft from all sources. These objectives were achieved with the following four main groups of tests:

  1. Structural response tests.
  2. Near-field permeability tests in the Salado and Rustler formations.
  3. Near-field hydrologic monitoring in the Salado and Rustler formations.
  4. Moisture movement and inflow tests in the Salado Formation.

  The *Structural Response Tests* monitored the creep closure behavior of the Salado Formation at five stations by means of radial closure measurements and ultrasonic sensors. At three locations, these closure measurements were augmented by extensometer and thermocouple measurements for evaluating ground displacements, 15.2 m into the salt surrounding the AIS.

  The *Near-Field Permeability Tests* were performed at 11 stations along the AIS; eight in the upper concrete-lined portion, including the Rustler Formation, and three in the unlined Salado Formation portion (Fig. 2). Multi-packer systems were set in 11.8-m-deep, sub-horizontal boreholes and pressure-pulse tests were conducted to provide profiles of rock permeability as a function of distance from the shaft wall into the surrounding rock. Three to four discrete intervals in each hole were isolated and tested.

  The *Near-Field Hydrologic Monitoring Tests* used the same holes as those used in the aforementioned permeability tests after this test was completed. Packers were set between 7.3 m and 9 m into the holes and pressure transducers located at the concrete lining and rock interface and at the "bottom" of the hole below the deepest set packer.
  The Moisture Movement and Inflow Tests were conducted in the Salado Formation (Fig. 2) at four stations at different depths. Ten-degree downward sloping boreholes, 10-cm in diameter and 7.7-m-deep, were used to collect brine. The humidity in the AIS was also measured.

Following is a summary of the primary objectives, designs, and locations for the main "*Seal Tests*":

- The primary objectives of the *Plug Test Matrix*, conducted in Rooms L1 and L2 (Fig. 3), were to determine: (a) interactions and long-term geochemical stability of candidate seal materials in various salt conditions; (b) emplacement techniques applicable to each candidate plug material; and to provide (c) *in-situ* cured samples for future laboratory investigations. Grout, concrete, and salt mixtures were emplaced in boreholes in Rooms L1 and L2. The tests conducted in Room L1 were conducted at ambient temperature while the tests conducted in Room L2 were conducted at elevated temperatures.
- The primary objectives of the *Borehole Plug Tests* were to determine: (a) performance of seals in deep boreholes; (b) interaction of the borehole seals with the host rock; and to evaluate (c) deep-borehole seal emplacement techniques and procedures; and (d) stability and durability of recovered borehole seals materials. In the first of these tests, conducted in September 1979, one 20-cm-diameter, 2-m-long freshwater grout plug was placed about 1,370 m below the ground surface in an anhydrite layer in the Castile Formation (Fig. 2). A differential pressure of 12.4 megaPascals (MPa) was applied from below the plug.
- The primary objectives of the *Small-Scale Seal Performance Tests*, conducted in Room M (Fig. 4), were to determine: (a) *in-situ* fluid flow performance for various seal systems; (b) *in-situ* mechanical performance of the host rock and seal materials; and to assess (c) seal emplacement techniques; and (d) the development of numerical predictive capabilities. One series of tests consisted of seals of natural materials. Seals formed of compacted crushed salt; bentonite and salt/bentonite mixtures were tested in both horizontal and vertical holes. The holes were instrumented with strain and stress gages. After a period of time to allow for some salt creep consolidation, brine was introduced behind the seals to observe the flow rates and to examine the beneficial aspects of including bentonite in the seal matrix. A second test series utilized seals of engineered materials. Concrete seals were emplaced in numerous boreholes varying in diameters from 15 cm to 91.4 cm. Different cement formulations were tested to evaluate the interface bond and chemical compatibility. Some expanding cement was tested. Both vertical and horizon holes were utilized. Flow tests showed decreasing permeability of the seal with time as the salt creep closed the micro fractures in the salt surrounding the seal. Temperature of the concrete and stress on the interface were measured during the test and the bonding at the interface and chemical alteration of the concrete were examined on post-test core specimens.
- The primary objective of the *Backfill Design and Emplacement Tests* was to establish the behavior of backfills based on crushed salt and salt/bentonite mixtures. These tests were conducted as a component of several of the seals tests described above augmented by laboratory tests. Blocks of pre-compacted salt were used to fabricate the small-scale seals in order to reduce the time required for natural salt creep to achieve a near-natural state density. Moisture content was varied to determine the optimum amount for salt re-consolidation. Crushed salt backfill was eliminated from the WIPP design, but the experiments prove valuable for modeling the salt portions of the shaft seals.

As indicated above, at WIPP, the waste packages essentially serve to contain the waste during transport, handling, and disposal. In other words, they are neither required nor expected to provide any long-term containment or isolation of the waste. However, a number of ***WPP Tests*** were conducted in the WIPP URL to evaluate the short-term (5 to 50 years) integrity of the waste package for both CH- and RH-TRUW. The primary objectives of these tests were to: (a) assess the durability of waste packages in near-reference and overtest conditions; (b) determine the confinement integrity of waste packages; (c) evaluate the effectiveness of engineered barriers for waste confinement; and (d) evaluate predictive models and techniques for assessing long-term performance. A secondary objective was to develop an understanding of the conditions that might be faced during the operational period of WIPP in the event that *retrieval* was required. Additionally, because bedded salt was still being considered for disposal of DHLW and civilian HLW in the mid-1980s, *in-situ* experiments were conducted in the following areas to evaluate possible HLW canister materials and to examine leaching of several nations candidate glass waste forms:

1. Simulated DHLW Technology Experiments.
2. Materials Interface Interactions (MII) Tests.
3. Simulated CH- and RH-TRUW Technology Tests.

However, interest and funding for HLW experiments at WIPP diminished in 1987 when the USDOE was directed by the U.S. Congress to focus its HLW-repository siting program on tuff (the Yucca Mountain site in the State of Nevada) and abandoned the candidate salt (the Deaf Smith Canyon site in the State of Texas) and basalt (the Hanford Reservation site in the State of Washington) repository sites. (13) Following is a summary of the primary objectives, designs, and locations for the main ***WPP Tests***:

- The primary objectives of the *Simulated DHLW Technology Experiments*, conducted in Rooms A1 and B (Fig. 3), were to evaluate: (a) performance and confinement integrity of the simulated DHLW packages in a thermal environment; (b) interactions of waste canisters, backfill materials, and host rock at near near-reference and overtest conditions; (c) testing procedures for application to future radioactive tests; and to (d) compare *in-situ* test results with laboratory and analytical studies; and (e) develop a technical basis for evaluating the concept of safe disposal of HLW in salt. Eighteen full-size (0.6 to 0.79-m diameter and 3.0-m long) simulated DHLW packages were installed vertically into the floor/inverts of Rooms A1 and B: six in Room A1 and 12 in Room B (Fig. 3). Eight of the 12 DHLW packages in Room B contained 1,000-W heaters. The remaining 10 DHLW packages in Rooms A1 and B contained 470-W heaters. The primary purpose of these tests was to evaluate alternative canister materials and backfill materials in a heated, corrosive salt environment under normal and overtest conditions. The tested canister materials comprised 304L stainless steel, mild steel, and TiCode-12 and four of the overtest canisters in Room B contained simulated DHLW glass waste. The tested backfill materials comprised crushed salt, low-density bentonite/sand mixture, and entrapped air. Canister surface temperatures ranged between 90^{o}C and 200^{o}C. The only aspect not simulated in these tests was the radiation field. Only a few canisters from the most severe environment were recovered before funding constraints terminated the DHLW studies.
- The primary objectives of the *MII Tests*, conducted in Room J (Fig. 3), were to: (a) determine the performance of non-radioactive Defense Waste Production Facility (DWPF) glass under anticipated and accelerated geochemical conditions; (b) effects of waste-package components and backfills on waste glass durability; (c) degradation mechanisms that are associated with the surface interactions of glass and waste-package materials; (d) evaluate relative performance of other U.S. and foreign waste glasses under anticipated and accelerated geochemical conditions; and (e) develop a standardized *in situ* database to compare with existing laboratory information for the international community. The primary purpose of the tests was to test glass leaching and secondarily to test corrosion of the potential canister materials. The tests addressed multiple emplacements of various U.S. and international (Belgium, Canada, France, Germany, Japan, Sweden, and United Kingdom) glass waste forms (non-radioactive) in contact with several candidate canister materials, rock salt and brine, all heated and maintained at 90^{o}C. Fifty boreholes, each about 10-cm in diameter and 1.2 and 2.1-m-deep were used. The waste-package materials investigated in the MII Tests included 980 waste form samples of 15 different compositions, including 16 different glasses and 11 different metals. In addition, 278 canister or overpack metals and 587 salt and backfill geologic specimens were involved. Periodic removal of duplicate test specimens allowed for determination of the corrosion and leaching as function of time. Intermediate sampling and analysis occurred at one-half, one, two and five years occurred. The MII Tests also used extensive periodic sampling of the brine in which the samples were immersed to determine the chemistry of the test environment.
- The primary objectives of the *Simulated CH- and RH-TRUW Technology Tests*, conducted in Rooms J and T (Fig. 3), were to evaluate: (a) Corrosion and deformation of TRUW containers in both nominal and accelerated thermal test environments; (b) Confinement integrity of TRUW containers in the WIPP underground conditions; (c) Effectiveness of engineered barriers for waste confinement; and (d) Performance of RH-TRUW containers emplaced horizontally in unlined boreholes. The simulated CH- and RH-TRUW tests in Rooms J and T evaluated the durability, corrosion behavior, and crushing of containers. Drums in Rooms T and J were tested under "normal" and worst-case ("overtest") repository conditions, respectively. The stress and strain on the drums in Rooms J and T was measured, as was room closure, by remotely read instruments. The initial plan was to recover the drums after about five years. The purpose was to determine the condition of the drums at a time when recovery might be performed. However, these plans were changed and a "post-closure" drum-removal test was conducted in another portion of the North Experimental Area in April 1992.

  A total of 174 208-liter standard oil drums filled with simulated CH-TRUW were emplaced in Room J (Fig. 4): some were immersed in the purposely filled brine pool, others were covered by one or two types of backfill (salt and salt/bentonite); and some were subjected to humid air only. In the Room J "over-test", the drums were immersed in the brine pool, which was heated to about 40^{o}C. Other drums were emplaced in a salt and in a salt/bentonite backfill into which some brine was wicked. The purpose was to examine corrosion under "worst-case" conditions. Tests to study radionuclide migration, using non-radioactive chemical tracers, were also conducted in Room J, both in the surrounding salt and in the marker bed located about 0.3 m below the floor/invert of Room J.

A total of 240 simulated CH-TRUW drums and eight simulated RH-TRUW containers were emplaced in Room T (Fig. 3). One-hundred-twenty drums were covered by salt backfill and 120 drums were covered with salt/bentonite backfill. In the backfilled portions of the rooms, the ceiling, floor and one wall were allowed to creep in and apply pressure to the backfill and ultimately to the drums. Eight full-size RH-TRUW canisters were emplaced into boreholes in the side of a design validation test room. The canisters were heated with 120-W heaters to impart about twice the maximum heating expected from the RH-TRUW. Four of the holes were backfilled with a mixture of 70% bentonite and 30% silica sand. The other four holes were not backfilled. The experiment was monitored with hole-closure, temperature and pressure gages. After five years, the canisters were to be recovered for evaluation. However, the recovery did not take place due to budget constraints.

Hydrologic Testing

Natural processes are not expected to breach the WIPP repository while the waste is hazardous. Human intrusion however, could introduce radioactive isotopes into boreholes and the "transmissive units" of the Rustler Formation (Fig. 2). Consequently, it is necessary to understand the hydrologic system and the transport processes in that system, in order to predict the movement and concentration of radioactivity with adequate assurance to satisfy the regulatory requirements. As hydrologic studies of the WIPP site progressed, it became clear that the transport mechanisms were more complex than first anticipated. Extensive pumping tests and large-scale, chemical-tracer tests were conducted to clarify the hydrologic transport mechanisms involved. Laboratory tests, not discussed here, were also useful in elucidating the transport behavior. Hydrologic studies were also conducted in the Salado Formation salt beds even though salt is a very low permeability rock. These tests were performed in order to understand and quantify the issue of brine seepage into repository rooms. This seepage is one possible source of water (brine) that could interact with the waste and lead to the generation of significant amounts of gas, an important aspect of long-term repository safety/performance. The tests also provided permeability values for modeling the movement of gas and brine outward from the waste rooms. Following are summaries of the main surface- and subsurface-based tests:

- ***Surface-based testing:*** More than 50 deep boreholes have been drilled and tested to assess and evaluate the hydrologic system at the WIPP site. These tests permitted determination of the transmissivity field over the site region and also identified the physical transport mechanisms that occurred in the aquifers. Initial studies examined three potential aquifers overlying the Salado Formation but, ultimately, only the Culebra Dolomite Unit of the Rustler Formation (Fig. 2) merited detailed hydrologic study. All holes were subjected to slug tests and draw down tests to obtain local estimates of Culebra Dolomite Unit transmissivities. In regions that could sustain long-term pumping, long-term pumping tests were used to interrogate much larger intervals, frequently for a distance out to as much as 1,000 m. These locations were usually also the location of non-radioactive, chemical tracer studies in which tracers were injected into three or more satellite holes and periodically sampled from the pumping hole. One such location, pad H-19, used six injection holes at different distances and azimuths with injections occurring at different horizons within the Culebra Dolomite Unit.
- ***Subsurface-based testing of the Salado Formation:*** The very low permeability of the Salado Formation salt (Fig. 2) could not be accurately assessed from the surface due to the special techniques and precision required. Pressure decay testing proved to be the most appropriate method to arrive at the salt permeability. The extremely low flows involved required careful attention to tubing and fittings to ensure leakage did not compromise the test. Specially designed packer configurations utilizing guard packers provided confidence that leaks around the primary packers were not compromising the test results. Pure halite had permeability of less than 10^{-22} meter square (m^2), about the limit of the testing capability to measure. Some clay-rich salt had permeability as high as 10^{-18} m^2. Tests were conducted in boreholes at depth ranging from five to 50 m. Inclined holes were used to test the anhydrite interbeds above and below the waste emplacement horizon.

Instrumentation

The large strains and displacements encountered in the WIPP salt in combination with the elevated temperatures used and the corrosive environments hosting the tests were all conducive to instrument failure over the time span of the experiment, which could be as long as ten years or more. Furthermore, salt creep and lack of access to high temperature rooms prevented the replacement of many instruments/gages. Hence, the test designs at WIPP included redundancy of instruments (and heaters) to assure adequate measurements even if instrument- (and heater-) failures occurred. Several of the experiments, where the test geometry allowed, were instrumented before excavation and were monitored while the subsequent excavation for the experiment took place. This was particularly important to capture the very early time transient creep. Remote, electronic measurement was the principal data recording technique but, wherever possible, these data were substantiated by strategically located manual measurements. Documentation of gages, their specifications and calibrations, their location and other experiment related information was a high priority because they would ultimately be subjected to critical QA examination by the WIPP regulator. Pre-test modeling predicted the strain and displacements and temperatures to be expected in the WIPP experiments. This information was used to acquire and place the instruments. Redundancy was built into the plan. The principal gages used in the WIPP experiments are summarized in Fig. 4.

Extensometers proved to be the most useful measurement for detailing the creep of the salt. Because of the large strains, wire-extensometers were the principal type used. Rod-extensometers were used in a few instances where precise measurement of small strains was desired. Most extensometers were multi-point with four additional anchors between the collar of the installation hole and the deepest anchor at 15.24 m. Teflon sleeves covered the wires of the extensometers where they were subject to salt accumulation due to the brine seepage. Convergence measurements provided direct information on the changing dimensions of the excavated openings. Because the dimensions of the excavations were a critical parameter in the modeling, the experimental rooms were excavated to tight tolerances to compare to later observations. To put all these relative movements on an absolute basis, a high precision laser survey was brought underground from a benchmark on the surface. Extensometers and convergence gages proved to be more useful than the large number of stress gages used due to the creep of the salt around the stress gages, which compromised the stress value. Interpretation of the stress gage readings required de-convolution through numerical modeling techniques. Thermocouples were used in large numbers to acquire good spatial information on the thermal field for the heated rooms. This information was critical because salt creep rate is very temperature dependent.

In addition to the type of instrumentation described above for the TSI testing, the small-scale seal tests employed fluid pressure testing to determine the leak rates around and through the various seals. Gas pressure changes in a known volume behind the seal were used to determine the leak rate and tracers in pressurized liquid were used to determine the path of leakage. Periodic measurements evaluated the effectiveness of the progressive creep closure around the seal in healing the interface between the seal and the rock and in healing the DRZ/EDZ. At termination of the active phase of the experiment, cores taken through the salt-seal interface were examined in the laboratory for chemical interactions and bond strength. Furthermore, in addition to the standard rock mechanics instrumentation described above, selected waste packages were instrumented with strain gages to record the deformation of the package as creep of the salt imposed increasing stress on the surface of the package. Waste package experiments involving elevated temperature, such as the MII Tests and the simulated CH-TRUW, RH-TRUW, and DHLW Technology Experiments, used a large number of thermocouples and thermistors to detail the thermal environment. The DHLW Technology Experiment also employed stress and strain gages to record the conditions to which the waste packages were subjected.

Hydrologic testing in the Culebra Dolomite Unit of the Rustler Formation (Fig. 2) utilized conventional electronic instrumentation to record water levels and pressure fluctuations. These measurements, which were obtained over long periods of time, in a very saline environment, put a premium on gage longevity. Drill stem tests and slug tests were used to determine aquifer characteristics close to the borehole. Some drill-stem tests utilized a multiple packer configuration to assure the test interval was adequately isolated from the open portions of the borehole. Long-term (30 to 60 days) pumping test were used to interrogate the aquifer over much greater distances, often a 1000 m or more. Brine density and chemistry varied significantly over the site area. These parameters were established by borehole sampling with subsequent laboratory analysis. Non-sorbing tracer tests were used to provide better definition of the hydrologic system and of the transport mechanisms. Multiple tracers injected in up to six satellite holes were detected through frequent sampling of the pumping well and analysis of samples in the laboratory. Radioactive tracers were not employed due to the prohibitions of using radioactive material at the WIPP site during the site characterization period.

Hydraulic testing in the Salado Formation presented unique problems due to the very low permeabilities that exist in the salt. Measurements were conducted in boreholes 10- to 30-m long. Guarded packer systems were designed and used to assure a tight borehole seal and provide the ability to determine how much packer leakage, if any, was occurring. Measurements were conducted in both the halite and the anhydrite interbeds. Both pressure build-up and pressure decay measurements were used to calculate the permeability. The pressures used in the testing were quite high, often approaching 15 MPa, and the change in pressure could be quite small. This required pressure transducers that could resolve a small fraction of the peak range. Because the volumes of fluid flow were so small, even miniscule leaks in the tubing and coupling could confuse the measurements and had to be eliminated. For studies in conjunction with brine seepage (Q-Room [Fig. 3]), permanent emplaced resistivity grids tracked the movement of the brine through the DRZ/EDZ from the walls into the floor of the experimental drift. These measurements were accompanied by pore pressure gages that followed the changes in inter-crystalline brine pressure as the drift was excavated and the DRZ/EDZ formed.

Codes and Models

As illustrated in Fig. 5, the WIPP PA comprises a complex, stochastic integration of stated assumptions, field and laboratory data, conceptual and numerical models, parameters and parameter ranges, operating experience, and *regulatory stringency requirements*. The radionuclide releases from different scenarios, i.e., combinations of features, events, and processes (FEPs), are computed by means of probability-based PAs. Pursuant to the USEPA's compliance criteria regulation, (7) the results of the PAs are presented in the form of *mean complementary cumulative distribution functions* (CCDFs). Furthermore, the number of CCDFs generated shall be large enough such that the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least 0.95 probability. Also, any certification and recertification application must contain information that demonstrates at least a 95% confidence-level of statistical confidence, and the mean of the population of CCDFs must meet the containment requirements defined in the disposal regulations. The PAs presented in the CCA involved and documented 54 codes and models and more than 1,800 parameters; however, *based on thorough sensitivity analyses, only 57 parameters were varied in the PA analyses.* (3)

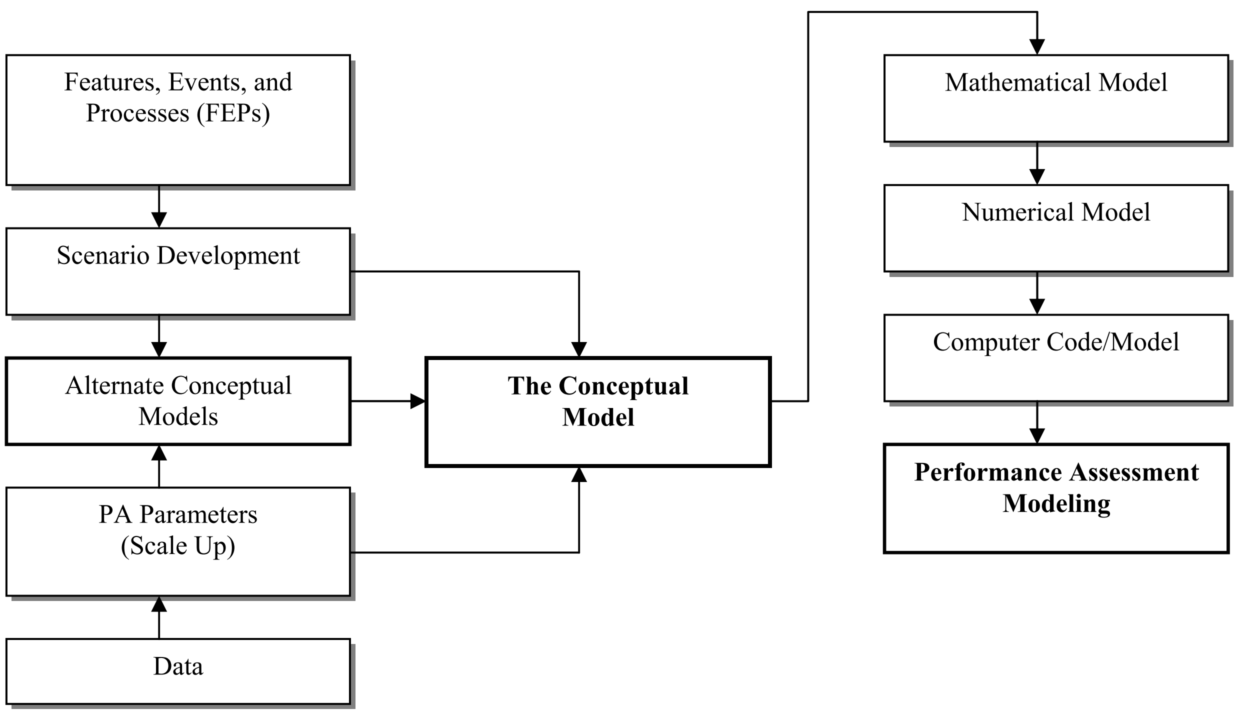

Fig. 5. Logic diagram for the progression of code and model development at WIPP.

SUMMARY

The preceding text outlines a roadmap for others to (a) identify components of the CBFO mission of potential benefit and (b) establish timely and cost-effective collaborations with the CBFO. Summarized below are the main benefits gained by the CBFO from its international collaborations and their potential applicability to other waste management organizations.

Since 1994, international collaborations and reviews have been integral cornerstones in the CBFO's successful strategy for accomplishing broad-based acceptance as well as the opening and operation of the world's first certified LLRM repository at the WIPP site. Four particularly important aspects of the CBFO's international programs have been:

- A long-standing "open door policy" for international and other national waste management organizations to access and comment on the intellectual knowledge and facilities vested in the CBFO and its main contractors;
- Contributions enhancing the global nuclear safety culture by showcasing that
  (a) LLRMs can be safely transported long distances on public roads, and
- (b) LLRMS can be safely disposed in a carefully sited and designed deep geological repository; and
- The willingness and ability to honor international commitments and obligations.

Past international collaborations have also greatly contributed to the following CBFO benefits:

1. They enabled timely and cost-effectively *acquisition and implement* data and information supporting the continued safe operation (*periodic recertifications*) and closure of the WIPP disposal system.
2. They enabled project staff to *stay abreast* of technical, political, programmatic, and regulatory developments within the international waste management community, which also served as an insurance policy for *staff (institutional-memory) retention*.
3. They *fostered discussions* about CBFO activities of interest and benefit to other radioactive waste management organizations *leading to international collaborations and events in Carlsbad*.

Collaborations with the CBFO provide other waste management organizations the timely and cost-effective access to: (a) CBFO activities contributing to the successful siting, development, certification, and opening of an LLRM repository at the WIPP site, including state-of-the-art databases, codes, and models; and (b) the intellectual resources, including hands-on experience in all aspects of repository siting, design, development, licensing, and operation, and the facilities available through the CBFO and its main contractors. Due to the facts that host rock types, safety concerns, and regulatory approaches differ among nations and programs, *it is important that the impacts of significant differences among approaches used for the WIPP and those used or to be used for other projects are understood*. It is the CBFO's experience that these differences precipitate questions and issues. Radioactive waste management organizations that collaborate with the CBFO have access to regulatory-approved and -monitored conceptual and numerical models and can become familiar with the repository development and operational approaches used at the WIPP site. Effective international partnerships will advance the programmatic interests of all participants, though all participants need not have the same objectives or needs for the partnerships to be effective. Rather, participants may engage in an activity for many different reasons.

Notwithstanding these differences, collaboration with the CBFO provides a unique opportunity for other radioactive waste management organizations to (a) train employees in the design and implementation of a broad range of waste management activities and (b) conduct underground state-of-the-art experiments in an existing, well-maintained URL. For example, the WIPP site provides a unique opportunity for conducting underground experiments in rock salt, especially related to monitoring disposed LLRMs and engineered systems. Furthermore, the 25 years of site characterization and repository developments preceding the 1999 opening of WIPP have resulted in extensive databases and interpretative capabilities. The experience gained also includes:

- Successful planning, designing, and implementing of cost-effective site characterization programs involving and integrating state-of-the-art investigations, tests, and conceptual and numerical models;
- Successful demonstration of compliance with stringent and prescriptive radioactive (and hazardous) waste disposal regulations; and
- Successful planning, designing, and implementing of public, scientific, regulatory, institutional, and political acceptance programs.

The applicability of this experience among other radioactive waste management programs is predicated on the recognition that:

- All sites considered or proposed for deep geological disposal of LLRMs must be characterized for basic geological, (geo)chemical, and hydrological properties;
- All deep geological repositories must implement tunnel and/or shaft seals and other engineered barriers to contain and isolate the emplaced LLRMs;
- Most, if not all, candidate repository sites are evaluated in the context of formal risk, safety, or performance assessments; and
- *Whereas science and engineering largely govern the licensing of a LLRM repository, public and, in particular, local acceptance govern the schedule and cost for the siting, development, and opening of a LLRM repository*.

In closing, the CBFO would like to acknowledge that it is honored to be a member of the IAEA Network and takes pride in honoring international commitments that serve to enhance the global nuclear safety culture and a nuclear renaissance. Hence, the CBFO looks forward to supporting the IAEA Network by making the WIPP repository and related infrastructure, experts, and lessons learned available to the 132 IAEA Member States.

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Footnote

[a] Only TRUW from *defense-related activities* containing at least 3,700 becquerels of alpha-emitting, transuranic (atomic weight/number greater than ^{92}uranium) isotopes with half-lives greater than 20 years, per gram of waste, and not exceeding a canister surface dose rate of 10 Sv/h may be disposed at the WIPP site. (4,10) There are two activity-based TRUW categories: *contact handled* (CH) and *remote-handled* (RH), which may have canister surface dose rates of up to 0.002 Sv/h and between 0.002 Sv/h and 10 Sv/h, respectively. (4,10)