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Waste Isolation Pilot Plant (WIPP) Borehole Plugging Program Description January 1, 1979

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Sandia Laboratories

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WASTE ISOLATION PILOT PLANT (WIPP)

BOREHOLE PLUGGING PROGRAM

DESCRIPTION

January 1, 1979

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WASTE ISOLATION PILOT PLANT (WIPP)

BOREHOLE PLUGGING PROGRAM (BHP)

DESCRIPTION

January 1, 1979

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I. General Discussion

Decommissioning of waste repositories will require reasonable assurance that public health and safety will not be affected during or subsequent to such actions. Inherently this implies that the emplaced wastes will not be expected to reach the biosphere, given realistic and rational release scenarios, in quantities that represent a health hazard to the human population. To expect absolute assurance that no radioactivity will ever reach the biosphere is unreasonable; to expect that all reasonable precautions will be taken to minimize the release to accepted safe levels should be a requirement for decommissioning of the repositiory. The borehole plugging program herein described is one facet of the latter requirement.

Preventing release of waste radionuclides via man-made penetrations is the basic premise for the borehole plugging program which, in turn, requires that fluid migration into and out of the repository be minimized and controlled. Thus the overall effort is directed at the understanding and control of fluid circulation near the plug. The requirements for a successful solution involve the following considerations:

> For a man-made penetration into a repository formation, what is the potential for and consequence of waste egress via this pathway; in what manner does the penetration compromise the integrity of the formation and for what duration?

Clearly, this is a complicated, difficult question which is site specific and cannot have an absolute universal answer. This program will address the issues involved for WIPP and attempt to quantify plugging techniques that protect the public interest and safety.

The salient issues in the above question are:

1. What is the potential for egress?
2. How is the formation integrity compromised?
3. For what duration is the formation integrity compromised?
4. What is the consequence of egress?

The WIPP BHP Program will attempt to provide answers to each of the above issues and will be site specific to the proposed southeastern New Mexico (SENM) WIPP site. Extrapolation of results to other geologic strata must be done carefully and thoughtfully.

1. The potential for egress depends on many factors. For purposes of the BHP program, the assumption is that, in the long term, some radionuclides will be in a location (i.e., at a borehole/media interface) to be transported via solution in brine either through the plug material, the formation rock near the plug/media interface, or along the interface itself. The issue here then is to address techniques for the following:

   A. Minimization of fluid presence at the waste horizon.
   B. Determination of flow rates under the assumption that fluids have reached these horizons through the well-bore.
   C. Control of possible gas releases.
   D. Determination of leach and transport rates of radionuclides at the determined flow rates.

2. The effect of a well-bore on formation integrity represents the major thrust of this program since the capability to preclude egress depends directly on how closely the formation was restored to its undisturbed state. The determination of the formation material properties prior to well-bore introduction, and the restoration of these properties are the primary goals to be achieved in the BHP. The issues to be addressed are as follows:

   A. What are the undisturbed media fluid migration rates and pathways?
   B. How do migration rates and paths through and around plugged well bores compare to the natural values?
   C. Can the well bore migration rates be made comparable to or less than the natural rates, and what is the impact of possible unresolvable differences?

D. What are the consequences to public health and safety for:

   1. natural migration rates?

   2. achievable well bore rates?

3. The validity period for the established well-bore rates is a more difficult issue. Clearly real-time proof over geologic lifetimes cannot be demonstrated, but geochemical techniques may be used to demonstrate long-term stability of plug materials in a given environment and these techniques will be utilized and expanded in an ongoing WIPP program to assess the long-term issues for WIPP and to provide a technology basis for the multi-media, multi-barrier Generic Borehole Plugging Program being directed by the Office of Nuclear Waste Isolation (ONWI).

4. The consequence of egress to the biosphere must consider the time-dependent nature of the nuclides, migration time and mechanism to and through a well-bore pathway, sorption/desorption mechanisms during transport and, finally, the decayed nuclide source strength and method of introduction into the ecosystem upon arrival at the biosphere. This problem is being addressed in the risk and consequence analysis portion of the Sandia WIPP program. For the BHP program, it is sufficient to evaluate whether fluid ingress and subsequent egress through the well-bore pathway is easier or more difficult than through the native material pathway on the basis of criteria received from the WIPP Consequence Analysis Program. There are indications from the WIPP Consequence Analysis Program that even the worst case of an unplugged well bore does not represent a significant impact on the public well-being. Further efforts to better quantify this consequence will continue concurrently with the BHP program.

II. Objectives

The preceding discussion leads to the formulation of the following objectives to be addressed in the WIPP BHP program.

- o Assess impact of leakage through man-made penetrations relative to natural migration pathways by determining potential effects on public health and safety utilizing consequence analysis and site specific data to specify acceptable well bore leakage critera.

- o Develop materials, techniques and instrumentation to determine the adequacy of plug designs in keeping well bore leakage comparable to that along natural migration pathways.

- o Use geochemical techniques to evaluate long-term plug design adequacy.

- o Evaluate impact of plug failure at various lifetimes with corresponding consequence analysis.

- o Provide acceptable plug design and installation procedures as the final product for application to the WIPP, including evaluation and development of a multi-layered, multi-purpose plug design.

III. Rationale For Plan Organization

The overall plan developed here is the result of workshop meetings, private comments, published critiques, and the WIPP schedule. A general overview of the why's and how's leading to the plan is presented here.

Commencement of WIPP construction may include a requirement that a BHP technology program is underway and that favorable results can be expected to isolate the repository when the future decommissioning date is reached. With construction scheduled to begin early in 1981, results must be obtained in the short term to support the feasibility of isolating the repository. To meet this initial requirement, cement-type materials will be used in the immediate program since this technology is already well established and there are no fundamental reasons to suggest that cementitious materials will not be adequate for the long term; however, this is not to preclude the use of alternate materials both for the plug itself or as an interlayered attenuating (sorptive) material in the long term. Subsequent development of the program will include materials similar to those found in the WIPP strata specifically, including multi-layer, multi-purpose plug designs.

While the use of natural materials may seem more satisfying in permitting restoration of the media with the least possible discontinuity and while some initial laboratory results are encouraging (Martin 1975), field demonstration techniques have not been adequately developed. Therefore, parallel paths for the long-term analysis of plug materials will be taken, one addressing the identification and use of natural plug materials, their emplacement and adequacy, and one addressing the long-term geochemical stability and suitability of grouts. In this way, the long-term stability of grout, if demonstrable, would provide a solution or at least a choice of techniques for the long term.

Thus, the program development evolves into two basic activity time frames (1) short-term efforts, involving current technology, and (2) identification and development of long-term efforts involving potential technology. For clarity these are arbitrarily defined as follows, recognizing that precise time delineations are neither possible nor required.

Short term: 1-2 years (e.g., to 1980) real time in which effects valid for 10-60 years can be predicted.

Long term: 2-30 years (e.g., to 2000) real time in which it may be possible to predict effects valid for geologic times.

The initial thrust of the program will be to exploit the short-term issues with the immediate goal of satisfying WIPP construction schedule requirements, and evolving into a definition and solution leading to the satisfaction of the long-term issues.

The primary test beds will be well bores, nominally 6-8" in diameter in which emplacement and testing techniques will be developed with subsequent adaptation to shafts with diameters on the order of feet. A fundamental issue to be assessed is the extent of the disturbed zone in the proximity of the well-bore or shaft wall and how this is affected by the technique utilized in creating this well bore, i.e., drilling, coring, or blasting, and the subsequent effect on appropriate plugging efforts. Specific attention will be given to the influence of these effects on methods used to construct the WIPP repository.

IV. ISSUES TO BE ADDRESSED

The first step in a BHP program is the identification of the issues, evident or perceived, which must be addressed to assure an adequate borehole plug for both the short- and long-term. The program must evaluate the importance of each issue so that efforts and resources will be appropriately distributed. The testing program must be directed toward resolving these issues thereby establishing credibility within both the scientific and lay communities regarding the capability for providing competent plugs.

A tentative summary of potentially important issues (without consideration of relative importance) is given in Table I and represents the basis from which the program will develop. Note that the last item, consequence analysis, falls outside the realm of the other physical plug characteristics in the list and hence will be addressed as a separate element in the program. Work in this area is underway to support the WIPP project, and results obtained will be utilized to support the BHP program.

All of these issues will be addressed to assure that the phasing of laboratory and field programs is appropriate to support a schedule commensurate with WIPP program needs.

To accomplish the objectives of the program, specific delegation of tasks must be done to insure a coordinated effort. The general assignment of these tasks is as follows:

1. Quantitative Assessment of Current Technology: Formal collection of existing technology data will be done by ONWI subcontractors.
2. Consequence Analysis: Site specific data will be provided by Sandia for integration into the WIPP consequence assessment program and for determination of acceptable migration rates. Sandia consequence analysis will be coordinated with WISAP studies as appropriate.
3. Materials: Grout recipes will be developed and distributed by Sandia. Laboratory testing will be done as a joint effort between Sandia and ONWI. The geochemical program will be initiated by ONWI with support from Sandia. The alternate materials program will be

developed by ONWI with field test beds provided by Sandia. Specific plug design will be a Sandia effort with calculations coordinated with any ONWI contractors. Grout recipes and plug seepage criteria will be provided by Sandia.

5. Instrumentation: Requirements and development will be accomplished by Sandia.

6. Field Testing: Requirements will be provided by Sandia.

7. Quality Assurance: Plan development and implementation will be a joint effort between Sandia and ONWI.

TABLE I POTENTIALLY SIGNIFICANT ISSUES

- Field Activities
  - Material availability
  - Mixing
  - Emplacement
- Curing Interactions
- Plug Permeability
- Peripheral Region Permeability
- Host Rock Properties
- Plug/Rock Interface integrity
  - Bonding
  - Strength
  - Leakage
- Plug/Rock Compatibility
  - Thermal
    - Expansion
    - Stability
    - Conductivity
  - Mechanical
    - Modulii (Elastic)
    - Expansivity
    - Unconfined Compressive Strength
  - Chemical
    - Thermodynamic Stability
    - Resistance to Electrolytic Degradation
- Geochemical Stability
- Alternate Materials
  - As plugging fillers
  - As barrier filters (adsorbers)
- Consequence Analysis

V. PROGRAM ELEMENTS

At our present state of knowledge, several program elements have been identified for which activity is required. These elements include activities which are pertinent to both WIPP specific concerns as well as more generic studies for BHP. The appropriate responsiblities for some of these activities will be resolved as the WIPP BHP program is integrated into the ONWI generic program for BHP.

A. Quantitative Assessment of Current Technology

In addition to surveys and summarization of all pertinent efforts in BHP, a concerted effort will be made to quantify and document the related industry and DOE efforts at borehole plugging. These include data from gas storage fields, in-situ permeability tests, etc. Emphasis should be placed on determining how effective the methods are and organizing the data into a presentable form so that its applicability to nuclear waste repositories is apparent. Useful historical data may be gained from plugs which have been emplaced for long enough times to infer information about plug behavior.

Specifically, additional information may be obtained by analyzing plugged boreholes used for potash exploration near the WIPP site. These holes were plugged and subsequently intercepted as mines were developed. Since numerous holes are typically required for ore horizon definition, good statistics may be available on plug integrity and plug adequacy provided by the emplacing time technology, permitting updating and comparison to now current cementing techniques. Information contained in the "Status Report" on current technology presently being prepared for ONWI will be the basis for this program element.

B. Consequence Assessment

Development of analytic consequence assessment codes to address the results of water flow in boreholes or gas migration out of the repository will be valuable in determining what is meant by an "adequate" plug. Preliminary work in this area for the WIPP specific environment would indicate that an absolute seal is not required (Brannen, 1978). Moreover, even the most conservative assumptions about establishment of direct flow between the Rustler aquifers (Appendix C, Figure C3) and the disposal horizon does not lead to radionuclide concentrations at potential discharge points which exceed present maximum permissible concentration standards. The goal should be to utilize consequence analysis to determine acceptable leakage criteria and to develop a plug to meet this criteria. Then the added protection of the plug in providing repository isolation could be evaluated.

One possible variation on the concept of the borehole plug is to deliberately cause it to be more permeable than the native rock, thus designing it to be a path of least resistance to radionuclide migration. In this way, long-term radionuclide migration resulting from the possible decomposition of the waste form matrix, would tend to concentrate in selected well bore pathways from which samples could be taken and the effective regional migration predicted. That is, specific well bores could be designed to be a known weak link, a fuse as it were, which would provide early-time warning of possible impending problems and permit corrective action to be taken if required. A consequence analysis model of this scenario should be included in the overall consequence assessment. Additional work incorporating the potential for dissolution caused by fluid intrusion will be integrated into these assessments.

Conclusions from the consequence assessment at the WIPP site may not, however, be generally applicable to other sites and different media. The local hydrologic environment and nuclide migration potential must be considered before similar conclusions are made for other potential repositories.

C. Test Program

A general testing program will be implemented based on the integration of field and laboratory programs. The principal initial activities will be directed toward determining which of the issues in Table I are in fact significant and on the application of current technology (cementitious grouts and conventional/near-term instrumentation) to boreholes near the WIPP site. Candidate drill holes will be selected from:

- o industry holes near the WIPP site,
- o previously drilled WIPP holes,
- o new drill holes, if necessary.

Holes within the WIPP site will not be used in the testing program. Extension of the test program to long-term issues will proceed as the program evolves and is discussed in each subsection.

The thrust of the program will be to form a suitable mix of calculational modeling based on site-specific data, laboratory testing of appropriate grouts leading to a plug design, supportive instrumentation development, and plug emplacement field testing and experiments utilizing available techniques to provide a credible data base to support the borehole plugging technology.

These concepts are expanded in the following sections.

C.1. Environment Definition

Determination of the plug environment will be required to permit development of the plug design models and realistic consequence analysis scenarios. Site specific data must be obtained as the first step in this process, and the various items of interest include:

Hole conditions - This requires characterization and documentation of wall surface conditions, and the degree and extent of disturbance caused by drilling or stress relief. These data will be provided by extensive logging of potential holes. It will be sufficient to utilize state-of-the-art logging techniques to make a satisfactory assessment. Any special hole treatment or preparation necessary before plug emplacement will depend on this evaluation and become a part of the plugging quality assurance procedures.

Host Rock Properties - The host rock also will be characterized in terms of permeability, thermo/mechanical properties, and geochemical properties. In addition, it may be desirable to develop techniques to determine the local in situ stress state so that plug emplacement will not hydrofracture the borehole wall. Well bore core samples will be gathered whenever needed.

A supporting experiment is:

<u>Media Quantification Experiment</u> - a dedicated area in a potash mine where facilities will be provided for investigations including the determination of in-situ permeability, local stress states, and chemical and thermal reactions between the media and the plug. These parameters can be investigated over a larger range not possible in a well bore. The resulting data will be used to calibrate and judge the adequacy of similar data obtained from boreholes.

C.1.1. Media Quantification Experiment (MQE)

Objectives:

To evaluate plug/media interactions not practical in deep vertical boreholes

Test Bed:

A dedicated location in existing mine workings.

Rationale:

Determination of media properties within a borehole is inherently more difficult than in a dedicated region in a mine, and this experiment is required to support, supplement and calibrate those efforts which cannot be carried out within the borehole.

Discussion:

Knowledge of media parameters is an important facet in interpreting borehole test results. In many cases, sufficient data may not be obtainable from deep boreholes. Some anticipated studies in the mine include media permeability in situ, calibration of developmental instrumentation, in situ stress measurements, definition of fracture region and healing around boreholes, and depth to surface fluid and gas migration paths and rates. Sandia is currently negotiating for a dedicated experiment area in a mine to conduct WIPP related investigations and space within this area would be available for the MQE. Sandia has also developed a permeability program in support of the WIPP which will provide helpful data to be integrated into the BHP program.

Schedule:

Some Impact. A dedicated area is in the negotiation stage and implementation of the in-mine experiments are contingent on the outcome of these negotiations.

C.2. Materials

The materials portion of the Borehole Plugging Program encompasses both short- and long-term aspects of materials research. This involves both laboratory and supporting field efforts for the near term and an initial laboratory development effort for the long term. These aspects are:

- o Short Term: Current Technology
  - Grout development and analysis of plug/host rock properties
  - Industrial assistance
  - Plug design
- o Long Term: Advanced Technology
  - Geochemical program
  - Alternate materials

C.2.1. Short Term: Current Technology

1. Grout Development and Plug/Host Rock Properties

For the short-term goals, these items are being addressed specifically by the Waterways Experiment Station (WES) at Vicksburg, MI, under Sandia sponsorship (Gulick 1978). Specific tasks demanded by the BHP program will be phased into the ongoing research program as required by the field-test program. Additional support from other laboratories will be requested through ONWI as necessary. The following list of tasks is underway or planned in the WES program along with the supportive field efforts:

(a) Continued evaluation of all candidate grout specimens which are included in long-term exposure tests, samples of lab-development mixtures and field samples, as well as cores from ERDA #10 field plugging operation. Nondestructive testing methods such as measurement of weight change, sonic velocity, and dynamic modulus of elasticity are the prime techniques in these evaluations.

(b) Testing and evaluation of cements, pozzalans, (flyash), expansive additives and admixtures to determine properties and improve grout mixtures.

(c) Permeability studies of grout samples, particularly grout/rock interfaces.

(d) Investigation of chemical, mineralogical and microstructural characteristics of reaction zone between cement plug and wall rock.

(e) Analysis of volume and length changes of grout specimens both in the long-term exposure studies and at early age under pressures and temperatures simulating down hole plug conditions.

(f) Feasibility investigation for developing accelerated aging techniques by curing specimens at elevated temperatures and/or pressures.

(g) Studies of the densification of grouts under pressures and temperatures comparable to the expected field conditions.

(h) Determinations of thermal properties of cement grouts including conductivity and expansion.

The program will be conducted with appropriate quality controls and will be responsive to the general quality assurance program.

The supporting and parallel associated field effort will:

(j) Obtain samples of materials and grout mixtures used for field tests. When possible, obtain samples of grouts during pumping.

(k) Perform tests on materials and proposed grout mixtures using actual cements from cementing contractor's current stocks in the field lab at the site.

(l) Obtain cores of plugs and plug/rock interfaces as required.

(m) Prepare specimens for shipment to the lab for additional testing and inclusion in the long-term exposure and mineralogic/thermodynamic studies.

(n) Implement an effective and practical quality control and quality assurance program for the laboratory testing and supervision of the field cementing operations.

2. Industrial Assistance

The need for a cementing industry representative, knowledgeable about available materials, emplacement techniques, and industry capabilities will be evaluated. Clearly, having a representative with hands-on knowledge available as a consultant could preclude possible false starts with the field effort and provide assistance in the development of quality control procedures.

3. Plug Design

Plug design capability will be developed as a part of the materials program, with the short-term goal of selecting suitable cementitious plug mixes, performing calculational analysis of candidate designs using material and well bore in situ properties, and comparing performance to the consequence assessment plug criteria. As this design capability develops, expansion to consideration of the long-term geochemical suitability of cementitious materials and identification of alternate plug materials and designs will occur.

C.2.2. Long Term: Advanced Technology

1. Geochemical Program

For the long-term goals of establishing cementitious material suitability, the development of a formal geochemical program will be required. While the capability to determine the suitability and stability of cementitious materials over geological time periods may theoretically now exist, an organized, well-defined program is not available. Estimates of the time to establish a viable program are one to two years, with actual results following this. Hence, this capability is considered a long-term goal which can be started now but will not provide answers during the current field test series.

Some representative initial tasks envisioned in the grout suitability portion of the program are listed below. Similar studies relating to natural material candidates will be defined as the program evolves.

(a) Grout Mineral Phase Analysis

Identify minerals present in grouts by optical examination of 30 thin sections by a petrographic microscope and x-ray diffraction. Identify zones of chemical reactions taking place during curing. Mapping of selected samples for microprobe quantitative analysis.

(b) Grout Microprobe Analysis

Identification and quantitative chemical analysis of cement components for characterization of phases which have and have not reached chemical equilibrium during curing. Depiction of "frozen" reaction zones and chemical analysis at 70 A resolution to enable formulation of possible future reactions involving phases in grout and host rock.

(c) Grout and/or Host Rock Thermodynamic Analysis

Calorimetry performed on phases for which basic thermodynamic functions (G_o, S_o, H_o) are not known, so that numerical assessment may be made of reaction potential involving phases in grouts and host rocks, catalyzed by brines.

(d) Grout/Host Rock Reaction Product Analysis

Identification of phases likely to form as a result of postulated reactions involving phases in grout and host rock. Further identification of reaction products likely to have undesirable properties in a grout plug (lower molar volume than reactants, higher permeability, greater solubility in most probable brine solutions, etc.).

The geochemical program will be carried out under the auspices of ONWI with coordination and design support provided by Sandia, Waterways Experiment Station (WES), and other laboratories as appropriate.

2. Alternate Materials

The use of non-cementitious materials as well bore plug and/or filter material is necessarily deferred as a future goal of the BHP program since a formalized technology in this field does not exist. The use of natural material as plugs may in the long-term mitigate the "geologic time" suitability objection to grouts, but the technology to emplace these materials has not been demonstrated. More appropriately, perhaps, natural materials could be used as filters or adsorbers of radionuclides if their introduction to the well bore occurred. The ultimate evolution of the plug design could be a composite of cementitious materials as fluid barriers and natural materials as radionuclide barriers, thus providing a multi-media, multi-barrier path to the biosphere.

The alternate materials program is not fully developed at this time and will be expanded within the ONWI Generic Borehole Program. Provision to incorporate a small-scale field test of possible alternate material candidates is included in the Field Test Program as the Salt Plug Experiment (SPE), and a modest effort to support the Field Test Program will be conducted by Sandia.

C.3. Instrumentation

The fundamental purpose of the instrumentation program is to provide the capability to acquire the laboratory and field test data. Preliminary analysis of instrumentation needs and availability is described in the following sections.

C.3.1 Short-Term Needs

Near-term needs, by definition, will utilize so-called "off-the-shelf" instruments; those which are available with "current technology." This, of course, does not preclude a measure of adaptation to the constraints of the particular BHP test. In fact, nearly all proposed instruments will demand some modification in their specific applications. However, for the near-term, such redesign will be modest. The envisioned applications are described below:

1. Environment. The characterization of borehole conditions and the quantification of the surrounding media will generally utilize

standard well-logging apparatus. However, in two important areas of concern, a development effort is underway to provide suitable instrumentation as follows:

a. In Situ Stress - The modification of the local stress field by the drilling and subsequent relaxation of the borehole needs to be determined. Through modeling, an approximation of the fracturing and increased permeability caused by the stress relief can be ascertained. Then, upon emplacement of the plug, any restoration of the stress field and the consequent healing of the fractures may require monitoring. Sandia is developing extensometers and borehole stress gages which may be acceptable for these purposes. These may be placed either in the main borehole or in nearby satellite holes.

b. Fracture Delineation - In this case, a refinement of logging tools used by the oil and gas industry to determine the fracture content of the host rock is needed. Acoustic techniques may prove valuable in this context.

2. Plug Assessment. As noted above, the principal focus of the BHP Instrumentation Program will be to obtain data to certify the integrity and performance of actual emplaced plugs. The near-term effort will be keyed to the three field tests planned for FY79 and FY80.

The basic objectives of these tests, beyond gaining field experience in the mechanics of hole preparation and plug emplacement, is to evaluate the quality of the plug. Thus the first demand on the instrumentation is to answer when, where, and how much fluid penetration occurs. The second question is why, and this entails a more sophisticated analysis, probably culminating in plug removal by coring.

Current instrumentation techniques under consideration are:

a. Water Level Indicator (in clear hole above plug)
b. Electrical Conductivity Probe (of fluid above plug)
c. Electrical Resistivity Probe (of plug and host rock)
d. Tracer Detection (gaseous and/or radioactive)
e. Pressure and Temperature (PT) Monitoring (natural or man-made sources)
f. Acoustic Probe (impedance mismatch)
g. Inductance Probe (of plug and host rock)

Table II shows the estimated time scale for significant events in the development of the instrumentation listed under Section B.

TABLE II

Near-Term Instrumentation Availability

Item	Design Phase	Fabrication	Lab Check	Fielding
a. Water Level	10/78	12/78	2/79	4/79
b. Fluid Conductivity	10/78	12/78	2/79	4/79
c. Plug Resistivity	9/78	10/78	12/78	3/79
d1. Tracer (gas)	10/78	12/78	2/79	4/79
d2. Tracer (RA/gas) space resolved	3/79	6/79	9/79	12/79
e. PT Monitor	12/78	2/79	3/79	4/79
f. Acoustic Probe	3/79	6/79	6/79	12/79
g. Induction Probe	12/78	2/79	4/79	5/79

A few points are worth noting. Items a, b, c, d1 and e will be ready for incorporation into the field test plugs described elsewhere in this program document. Items d2 and f will probably be developed by subcontractors to SLA. The space resolved tracer detection system referred to in d2 involves in concept a detector able to pinpoint tracer gas leakage paths on a fractional-inch scale rather than bulk volume sampling as in d1. This system is not available now but the tracer gas canister associated with d2 can be emplaced on the d1 schedule. The space resolving sensing system is intended for later development. Thus, bulk volume tracer gas detection can be included in the three scheduled field tests.

3. Laboratory. While the major thrust of the instrumentation effort involves field activities, more specifically quantification of the plug and its environs, attention must be paid to ancillary activities. The laboratory assessment of candidate plug material performance will generally utilize standard apparatus such as universal testing machines. One exception to this is:

(a) Test Cell Facility

Large Volume High Pressure Test Cell - A cylindrical chamber will be identified (or designed) to accept large (0.5 m diam x 1.0 m long) rock core samples. The permeability under radial stress of prototype plugs may be tested in such an arrangement. Interface and host-rock fracture conditions are also accessible to test. Development of this facility is essential for evaluating bench scale samples and initial design will commence in FY79.

4. Miscellaneous Concerns. This category includes the following items:

a. Power supplies (possibly remote)
b. Cabling (including gas/fluid blocking)
c. Recording (possibly unattended)
d. Packaging (against the down-hole environment)
e. Installation (drill stem, wire line, etc.)
f. Calibration, Quality Assurance and Life Testing

With regard to these concerns, the following comments are pertinent:

a. Remote power supplies will not be needed until Table II, items d2, and f are fielded and should be integrated into their design.
b. Cabling capable of withstanding the downhole environment will be emplaced whenever necessary. This type cable is available and routinely used in the oil and gas industry for short in-well bore times such as during logging operations but not for long-term emplacement as is necessary in the planned field tests. Once specific experiment requirements are defined, the cable must be ordered since this is a six-month lead time item.
c. Recording facilities that permit unattended operation are in hand.

d. Packaging requirements are an inherent part of the design of any downhole instrument or sensor. Sandia will utilize experience gained in harsh environments in other projects such as the in situ fossil fuel extraction programs and at the Nevada Test Site.

e. Installation will entail close cooperation and coordination with the contract drillers and with the appropriate fielding organizations at Sandia.

f. Calibration of the sensor elements will proceed according to established laboratory practice. Life-testing will be approached via magnifications of the anticipated environment. While the QA requirements have not been completely identified, all Sandia laboratory instrument calibrations are traceable ultimately to National Bureau of Standards (NBS), and proper records will be maintained.

C.3.2. Long-Term Needs

Long-term instrumentation development will be addressed as requirements are defined and schedules become firm.

C.4. Field Test Matrix

The field program consists of three basic well-bore field tests:

- Bell Canyon Test (BCT) - A minimum length plug placed to isolate brine water in lower strata (Bell Canyon) formations from the WIPP repository horizon. Existing deep holes near the WIPP site that will be plugged before final decommissioning of the WIPP provide the impetus for conducting this test.
- Shallow Hole Test (SHT) - A test to assess the ability of plugs to prevent water flow from water bearing strata above the repository to the salt level. This test will be performed in conjunction with nearby mine workings.
- Diagnostic Test Hole (DTH) - A new drill hole through the upper water bearing formations designed to allow detailed diagnosis of individual plugs in a single well bore by using an open central casing which permits instrumentation access over the full strata range.

?.4.1 Current Technology Well Bore Tests

A discussion of the tentative plan for this series as well as some supporting experiments follows:

1. Bell Canyon Test (BCT)

Objectives:

- o Assess properties of an existing BHP
- o Assess condition of borehole walls and peripheral region permeability
- o Demonstrate capability for working in existing industry-like holes
- o Evaluate isolation between Bell Canyon water sources and evaporite layers

Test Bed:

An existing hole which penetrates into the Bell Canyon formation, selected from candidate list. (Figure 1)

Rationale:

Construction of a minimum length cement plug which can withstand the approximately 2000 psi hydrostatic pressure level present in the Bell Canyon Formation essentially assures that, at least in the short term, cement plugs can be emplaced to hold off high-pressure hydrostatic heads. Thus, the isolation of the upper aquifers with head differentials of approximately 200 feet (approximately 90 psi) is easily within the current cement technology capability. This plug will serve a dual purpose: it is designed to provide a real-time seal, thus providing data on its mechanical plugging capability; it will simultaneously allow confirmation of planned seepage around or through the plug, thereby providing migration rate data for the underlying brine and tracer gases.

Discussion:

This test constitutes a worst case scenario for WIPP in terms of a hostile plug environment (approximately 2000 psi on plug at depth), risk to the WIPP Horizon in terms of possible dissolutioning, and demonstrates techniques for working at depths on the order of 4000'. Coring any existing plug may permit laboratory analysis of bond strength, permeability of plug, nature of bond and transition region, aging of plug in situ, and may lead to conclusions as to the adequacy

BELL CANYON TEST (BCT): Establish Capability to Isolate High Pressure Zones with Minimum Length Plugs

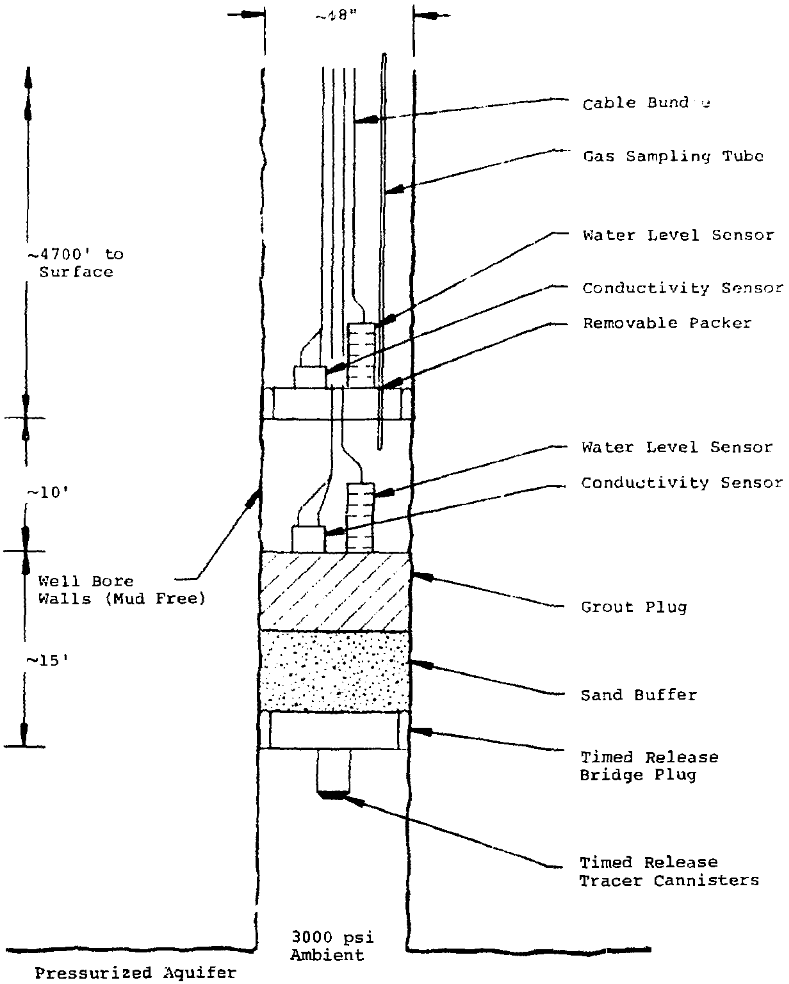


Figure 1

of the technology base when the plug was poured. Emplacing of the replugs will utilize state-of-the-art technology and provide for active instrumentation to monitor the plug performance in real time. Successive plug removal and replugging operations provide the opportunity to certify new plug design technology, to remove existing instrumentation penetrations, if required, and provides for permanent plugging and abandonment.

The initial plug will be designed to be of minimum length capable of withstanding the existing pressure differential. Design will require assumptions and testing of bond shear strength, permeability of flow paths at the plug location and calculations of migration times for comparison to observed times. There will be a seepage rate either around or through the plug which is a requirement for a successful experiment. The arrival time of the seepage will determine whether the assumptions are acceptable for a permanent installation; early arrival indicating that the leak paths were not adequately characterized; late arrival indicating the initial assumptions were conservative.

Planned hardwire instrumentation includes:

1. Monitoring of liquid level at plug top.
2. Monitoring of liquid conductivity at plug top to determine source of flow, i.e., either from upper aquifers or from Bell Canyon flow around plug.
3. Tracer gas release at timed intervals below plug will be detected at plug top for determination of migration rates.

There is an inherent risk in an experiment of this type in that the design is deliberately selected to be the minimum required to accomplish the objective. Clearly, when overdesigns are permitted, success of the plug is assured in the short term as evidenced by oil field practices. However, in this test, the goal is to predict the minimum acceptable plug length, install this plug, and monitor the seepage results for comparison to predictions. Due to the deliberate marginal safe design criteria, emplacement and casing difficulties are anticipated in the efforts and may have to be repeated. This is part of the test and should not be construed as a failure. Follow-on tests within the well bore will allow for changes of variables (i.e., plug length, material, etc.) to permit evaluation in conjunction with the WIPP permeability program of design isolation capability.

Schedule Impact:

Minimal schedule impacts - need to select and acquire borehole, prepare instrumentation and install. Projected time required 6-8 months from approval to first plug installation.

Information Anticipated:

- Well bore preparation and analysis
- Plug emplacement technique
- Quality assurance procedure analysis
- Existing plug integrity assessment
- Analysis of borehole and peripheral region permeability
- Assess plug and formation composite competence
- Provide samples for laboratory analysis for long-term stability

Conclusions Anticipated:

Successful stemming of the high pressure region will:

- Permit updating and validation of modeling capability
- Assess the suitability of cement plugs for withstanding high pressure source flows in the short term
- Permit evaluation of the surgical-like plug emplacement techniques required.

2. Shallow Hole Test (SHT)

Objectives:

- o Assess effectiveness of overlying aquifer isolation
- o Provide plug/rock samples at salt horizon
- o Provide a test bed with access above and below the plug

Test Bed:

Existing or new hole into the Salado penetrating a mine working (Figure 2)

Rationale:

An evaluation of the effectiveness of cement plugs in isolation fluid flow will be obtained from the Bell Canyon Test. Using these results, evidence that the overlying aquifers in the WIPP strata can be isolated one from the other and also from the salt strata will be the goals of this experiment.

Detailed experimental design is being deferred pending analysis of existing plugs. The outcome of these results will be used to determine whether or not the Shallow Hole Test should be conducted or combined with the Diagnostic Test Hole.

Procedure Outline:

(Phase I)

1) Select or drill hole typical of potash exploration
2) Inspect and diagnose borehole wall condition and peripheral region permeability
3) Plug hole with appropriate material and emplace tracers
4) Emplace upper instrumentation

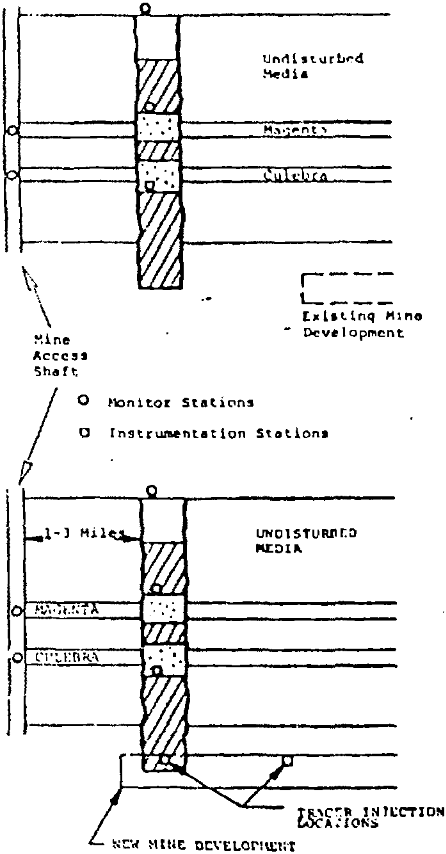
(Phase II)

5) Advance mine to bottom of borehole (perhaps at various levels)
6) Collect lab samples
7) Emplace tracer gas injection equipment and instrumentation
8) Tracer pressurize plug bottom
9) Monitor upward or downward flow migration

Discussion:

Utilizing a potash exploration hole provides the opportunity to gain access to the borehole bottom for additional testing. This borehole

SHT - Shallow Hole Test: Establish Adequacy of Plugs in Isolating Aquifers



PHASE I

1. Utilize Existing or Drill Potash Exploration Hole
2. Plug Salt and Aquifers with Best Technique
3. Instrument and Monitor Flow Communication

PHASE II
6-12 months after Phase I

1. Mine back to Borehole Bottom
2. Conduct Tracer Injection Tests at Borehole Bottom and in Undisturbed Media. Monitor Gas Arrival at Appropriate Locations (e.g., Access Shaft or at Surface)
3. Core Plugs for Laboratory Study
4. Permanent Re-plug for Abandonment if required

FIGURE 2

will be drilled, instrumented, plugged, and monitored for flow communication during Phase I. During Phase II, (6-12 months) access to the plug bottom will be achieved by mining to the plug region where coring and active testing such as tracer gas injection of the plug and native undisturbed media can be done. Laboratory analysis of the plug integrity will be accomplished during this phase. Replugging can be done during this phase if required. As an adjunct, already mined-through existing potash exploration holes can be used to develop tracer pressurization techniques and quantify the technology utilized when these plugs were poured.

A decision on whether to conduct the Shallow Hole Test will be made when the preliminary results of the Bell Canyon Test are obtained. Clearly, if the BCT is successful in withstanding the high-pressure head, proof at the lower pressure heads associated with the upper aquifers is redundant. Additionally, this test permits access only at the top and bottom (salt) strata, with no intermediate strata access. It may be desirable to conduct the Diagnostic Test Hole (DTH) in lieu of the SHT, modified as necessary to achieve the objectives of both experiments.

Schedule:

Significant Impact. Acquisition of suitable holes will be dependent on mine operators acceptance of experiment and agreement to cooperate. Phase II will be tied to mining schedule, and timing of access to plug bottom may be unpredictable. Cost and contract problems are anticipated.

Information Anticipated:

- Evaluation of emplacement technique
- Quality assurance procedure analysis
- Analysis of plug and peripheral region permeability
- Assess component plug and upper formation competence
- Provide samples for laboratory analysis of long-term effect between plug and host rock

3. <u>Diagnostic Test Hole (DTH)</u>

<u>Objectives:</u>

- o Provide a full length sample of plug/rock interfaces in upper formations
- o Provide a test bed for continuous monitoring of in situ plug performance

<u>Test Bed:</u>

All Supra-Salado rocks (Figure 3)

<u>Rationale:</u>

Whereas the SHT provides access at the top and bottom only of the well-bore, this test permits access at all strata levels, thus providing a more comprehensive test bed facility. The design of such a test is more complicated than the SHT and requires more preparation time, but the potential data return is much greater. The lack of an adequate capability to conduct the overcoring operation may preclude the initial plug installation.

<u>Procedure Outline:</u>

(Phase I)

1) Drill nominal 8" diameter borehole to Salado
2) Inspect and quantify well bore
3) Emplace tracers and instrumentation as appropriate
4) Plug hole with best technique and monitor

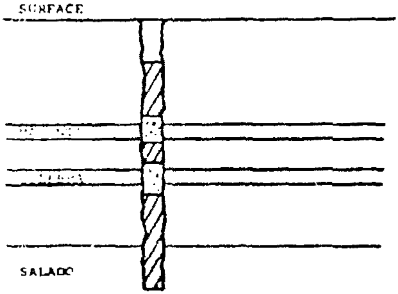
(Phase II)

1) Overcore plug to 24"-36" diameter
2) Recover samples for laboratory analysis
3) Install new plug with open internal casing
4) Utilize open casing to conduct on-going plug/peripheral testing at various levels

<u>Discussion:</u>

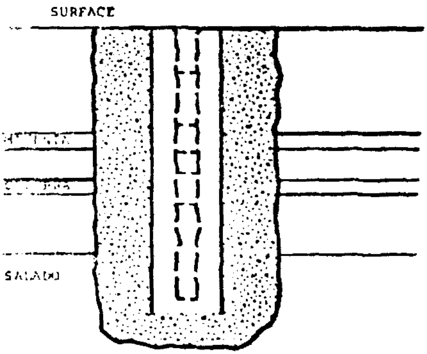
This test will provide flexibility within the test program to conduct sample removal, tracer injection, and active monitoring at any selected location in the borehole. The initial phase of this test sequence is to emplace a plug in a new drill hole (8") which reaches into the top of the Salado. After sufficient time for curing and stability, the entire plug would be overcored at a nominal 24". The

DTH - Diagnostic Test Hole: Provide in-situ test bed for SHORT and LONG term analysis



PHASE I

1. Drill Nominal 8" Borehole to Salado
2. Plug with Best Techniques
3. Instrument and Monitor for Aqueous Incursion



PHASE II
6-12 MOS AFTER PHASE I

1. **Overcore 8" Plugged Hole to 24"-36"**
2. **Emplace Plug with Internal Casing to Provide Diagnostic Test Bed for On-going Program**
3. **Instrument and Monitor**

Figure 3

large plug/rock sample could then be used for laboratory analysis. The second phase would consist of an appropriate plug in the 24" diameter hole. This plug would also contain a centralized casing (8") which would allow instrumentation access. Future activities would consist of penetration, tracer injection, pressurization, and instrumentation at selected locations.

The capability to overcore an existing full-length plug may not exist or may be prohibitively expensive, in which case the initial phase may be deleted and a single 24" - 36" cased hole drilled instead. The experimental impact is the non-availability of the full-length plug, which may be significant. A final decison as to the trade-offs invol ·d in the SHT and DTH will be made at a later date.

Schedule impact:

Most significant. Complexity of drilling a new hole and plugging entails considerable cost. Second-phase activities may stress the current over-covering state-of-the-art and add considerably to overall expense.

Information Anticipated:

- o Well-bore characterization and data on emplacement techniques
- o In situ coring and stabilization of emplaced plug
- o Provides samples for extensive laboratory analysis of plug, interface and surrounding rock
- o Testing and analysis of interactions at any level within plugged region can be conducted over long-term (approximately 20 years) periods.

C.4.2. Potential Technology; In-Mine Tests

The program described thus far relies on current technology to accomplish the BHP goals. This approach, although likely to be sufficient, is not meant to preclude developing alternate technologies. For this long-term program, consideration will be given to the following specific elements:

- Alternate Plug Materials.

  The ultimate objective in the BHP is to identify, test, and qualify appropriate material for use in plugging well bores. Cementitious material may meet all the requirements, but alternative approaches should be investigated also. Thus the objective of the alternate plug material development is to:

  - Identify suitable non-cementitious material for use as plug materials.
  - Encourage the design of multilayer, multipurpose plug designs to provide a multibarrier egress path.
  - Utilize materials which may behave in identical fashion to the surrounding media and provide additional confidence in long-term plugging.

- Advanced Instrumentation.

  Instrumentation development is recognized as a necessary part of field testing, and provision for advanced techniques is included in the program to permit development as required.

To provide for developmental efforts in support of long-term programs, two field environment tests are included.

- Salt Plug Experiment (SPE) - This experiment is designed to provide for in situ testing of alternate materials for potential application to BHP. Techniques for emplacing and evaluating these materials will be emphasized both in the field and laboratory programs.
- Advanced Instrumentation Development (AID) - Space will be provided within the in situ mine environment to permit testing and development of advanced instrumentation systems for possible future application to the long-term monitoring of bore hole integrity.

A discussion of the tentative plan for these two program elements follows:

1. Salt Plug Experiment (SPE)

Objectives:

- Provide for testing and emplacing of alternate native-like plug materials in salt formations
- Enhance development of long-term alternates to cements

Test Bed:

A dedicated location in an existing mine workings

Rationale:

The development of alternate plugging materials and emplacement techniques is a long-term goal of the BHP. This experiment provides the initial opportunity to develop this capability with anticipated extension to a later time well bore plugging test.

Discussion:

These tests will provide for evaluation of techniques for alternate plug materials, in the event a need for such methods is desirable for specific formations in the long-term. Recognizing that native material may represent a viable solution to the effects of man-made penetrations and that the salt horizon provides the most protection from the standpoint of repository integrity, it is prudent to establish a program to specifically address plugging salt penetrations with salt. If in fact suitable techniques for emplacing salt or salt-like grouts can be developed which provide adequate isolation, then it can be concluded that the man-made penetrations in the salt are not weak links in the repository integrity. Existing laboratory analysis (Martin, 1975) indicates that such techniques may be available on a laboratory basis, and this experiment will provide for development and testing in situ. It represents a first step in the field for addressing a long-term vital alternative in the borehole plugging program.

Information Anticipated:

- Salt plug emplacement technique development
- Testing and analysis of in situ salt plugs
- Laboratory salt plug samples for further testing

Schedule:

Comments in MQE schedule apply.

2. <u>Advanced Instrumentation Development (AID)</u>

<u>Objectives:</u>

o Provide capability for evaluating advanced instrumentation

<u>Test Bed:</u>

A dedicated location in an existing mine workings

<u>Rationale:</u>

This test will be conducted in conjunction with other ongoing in-mine experiments on a not-to-interfere basis, to provide an in situ test bed for developing instrumentation systems.

<u>Discussion:</u>

This experiment provides the opportunity to test and evaluate advanced instrumentation equipment and associated sensors.

<u>Information Anticipated:</u>

o Performance of advanced systems in in-situ conditions

o Field experience with such systems

<u>Schedule:</u>

Comments in MQE schedule apply.

D. <u>Summary</u>

The BHP Program described herein is designed to address in a reasonable and scientific manner the concerns associated with this subject in the past, with the intent of establishing a quantitative data base on borehole plugging techniques. To accomplish this goal, the tests and experiments described attempt to provide a mix of borehole (with limited access) and in-mine (with relatively unlimited access) environments in which assessment of the various issues involved can be undertaken. The end result of the program should lead to a better understanding of which issues are significant and which are not, thereby, permitting emplacement of plugs that satisfy the criteria developed in the program.

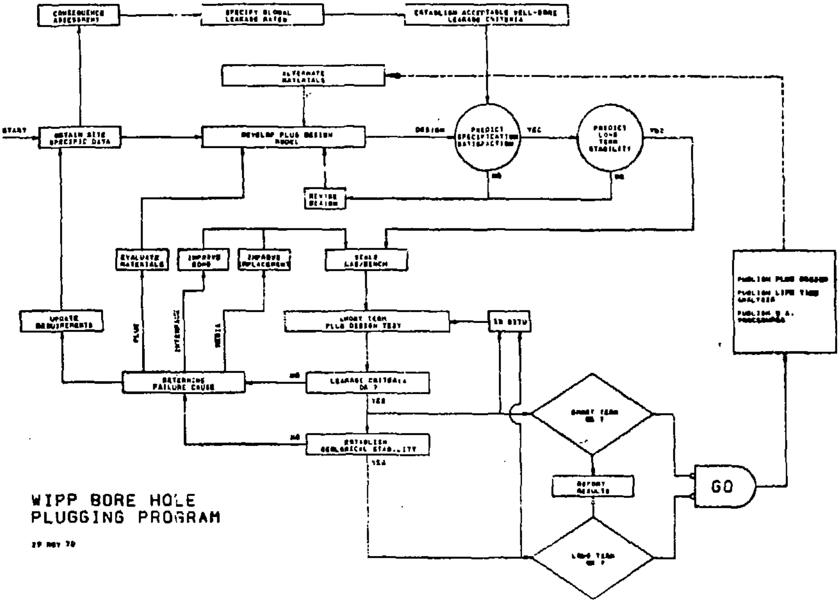
The Bell Canyon Test provides the opportunity to instrument and analyze a plug in a high pressure region. The Shallow Hole Test permits application of best techniques for plugging and then access to both the top and bottom of the plug for further analysis. The Diagnostic Test Hole permits recovery of bench scale size samples for analysis and establishes an in-borehole laboratory in which to conduct testing and analysis in all strata from the surface into the salt horizon. The additional in mine experiments provide the opportunity to investigate in more detail specific effects on plugs in the salt region and allows evaluation of instrumentation systems.

The logic diagram of Figure 4 is designed to reflect the overall goals and interconnections of the various aspects of the borehole plugging program. Site specific data permits plug design modeling and consequence analysis. Following this, laboratory testing and refinements lead eventually to field tests and in situ data recovery. Successful short-term results expand through geochemical techniques to evaluate the long-term results. Finally, when both short- and long-term tests have been completed, a suitable plug design is evolved, leading to the final result that repository isolation can be achieved.

VI. QUALITY ASSURANCE

A quality assurance program for the WIPP borehole plugging effort will be developed by Sandia Laboratories. This plan will be based on applicable federal regulations for nuclear installations. Effort will be devoted to categorization of activities so that the appropriate structure and format is applied to program elements based on their respective impact on public safety. As requirements specific to waste repositories are developed, they will be incorporated into the Quality Assurance Plan.

The borehole plugging phase of the WIPP program will have a unique relation with respect to quality assurance interface. Although the basic plan will be developed by Sandia, this plan must be compatible and integrated into both the general WIPP quality assurance plan developed by the WIPP project office/DOE and the ONWI quality assurance plan. A significant initial effort on the coordination of these activities will be necessary to expedite the implementation of the QA plan and to minimize any deleterious impact on the technical program. A proposed framework from which to build an acceptable QA Program is shown in Figure 5.



START
DESIGN
EVALUATE MATERIALS
FAILURE CAUSE
GO
WIPP BORE HOLE
PLUGGING PROGRAM

Figure 4

PROPOSED WIPP BOREHOLE PLUGGING QUALITY ASSURANCE ORGANIZATION

To insure that the work done in this program will satisfy regulatory standards with regard to nuclear facilities if required, a Quality Assurance Program will be initiated. This program must be compatible with the QA plans of both the WIPP Project Office (DOE/WPO) and ONWI. To accomplish this, Sandia will assume responsibility for the development of the plan utilizing Sandia-selected personnel working under the guidelines set forth by DOE/WPO and any regulatory requirements. Transfer of the developed plan will be made to ONWI for integration into the Generic Borehole Plugging Program and DOE/WPO for integration into the operating contractor's program for WIPP.

The overall responsibility for the WIPP BHP QA PLAN will be retained by Sandia. During the development of the plan, interagency liaison will be maintained with all waste management organizations for appropriate inputs.

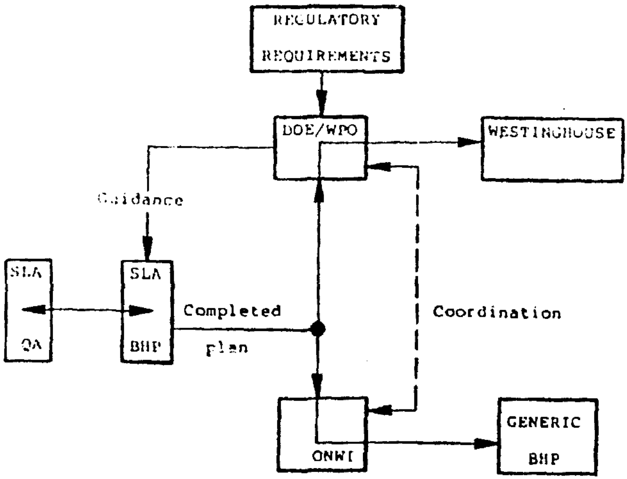


Figure 5

III SCHEDULE

REPORTS AND PROGRAMS

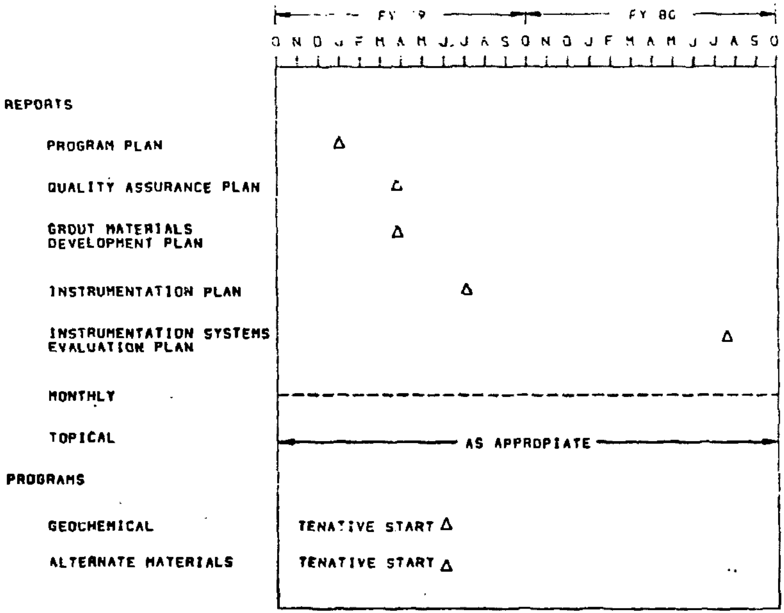


Figure 6

VII SCHEDULE

FIELD TEST

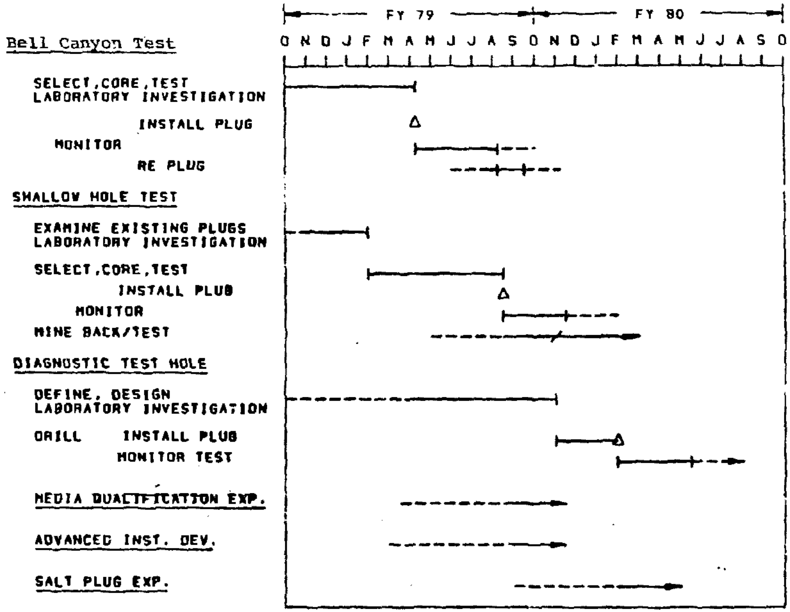


Figure 7

VIII Reports

Reports will be provided in accordance with the Uniform Contractor Reporting System (UCRS) as follows:

Program Plan

1. Logic Network
   Level 3 WBS (Subtask Level)
2. Work Breakdown Structure Dictionary
   Level 3 WBS (Subtask Level)
3. Milestone Log and Milestone Schedule Plan
4. Cost Plan
   Level 2 WBS (Task Level)
5. Manpower Plan
   Level 2 WBS (Task Level)

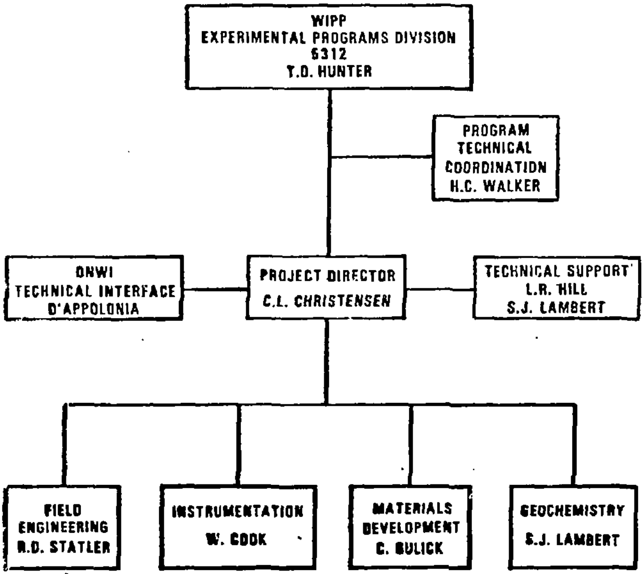
Technical Progress Reports

1. Quarterly
2. Topical

Monthly Status Report

1. Contract Management Summary Report
2. Project Status Report
3. Cost Management Report
   A. Level 2 WBS (Task Level)
   B. Cost Element
4. Milestone Schedule and Status Report

WIPP
BOREHOLE PLUGGING PROGRAM
ORGANIZATION



AUGUST 1978

Sandia Laboratories

APPENDIX

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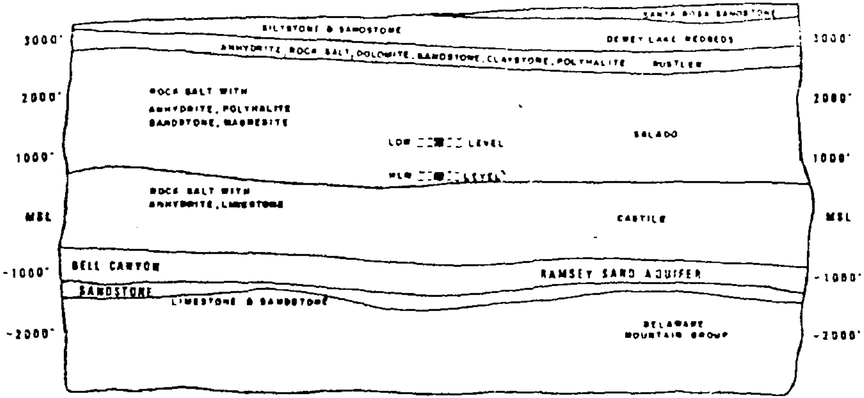
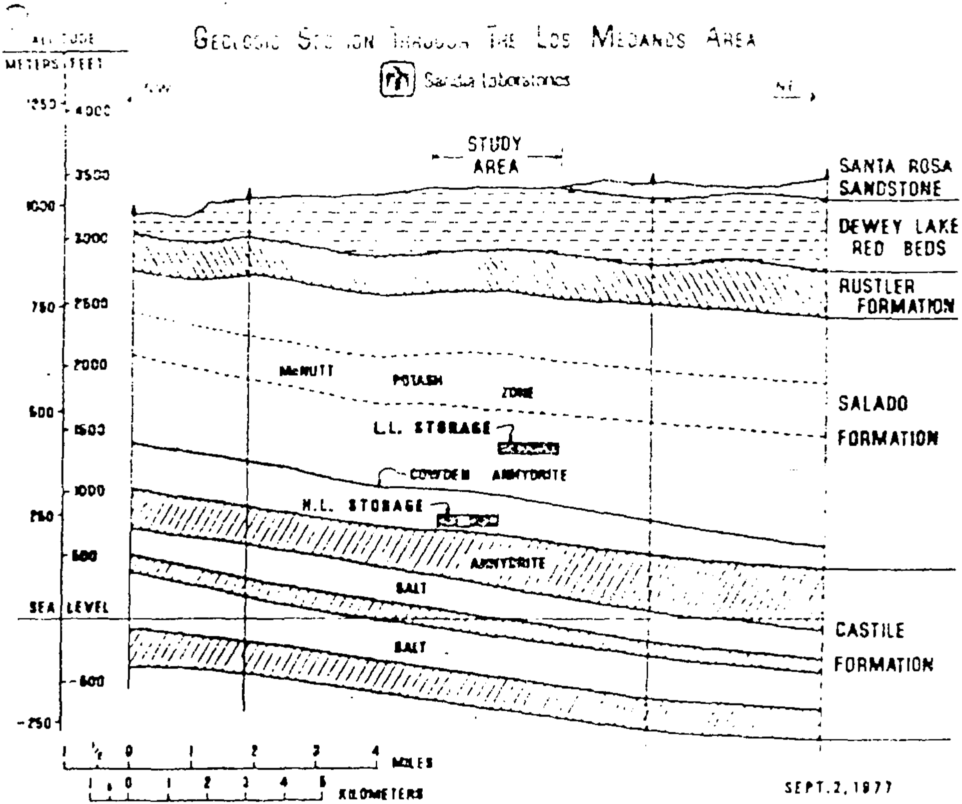


A GEOLOGICAL SECTION OF THE LOS MEDAÑOS AREA

C1


Geologic Section Through The Los Medanos Area
Sandia Laboratories
ALTITUDE
METERS FEET
1250 4000
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750 2500
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500
SEA LEVEL
-500
-250
STUDY AREA
SANTA ROSA SANDSTONE
DEWEY LAKE RED BEDS
RUSTLER FORMATION
McNUTT POTASH ZONE
SALADO FORMATION
L.L. STORAGE
COWDEN ANHYDRITE
H.L. STORAGE
ANHYDRITE
SALT
SALT
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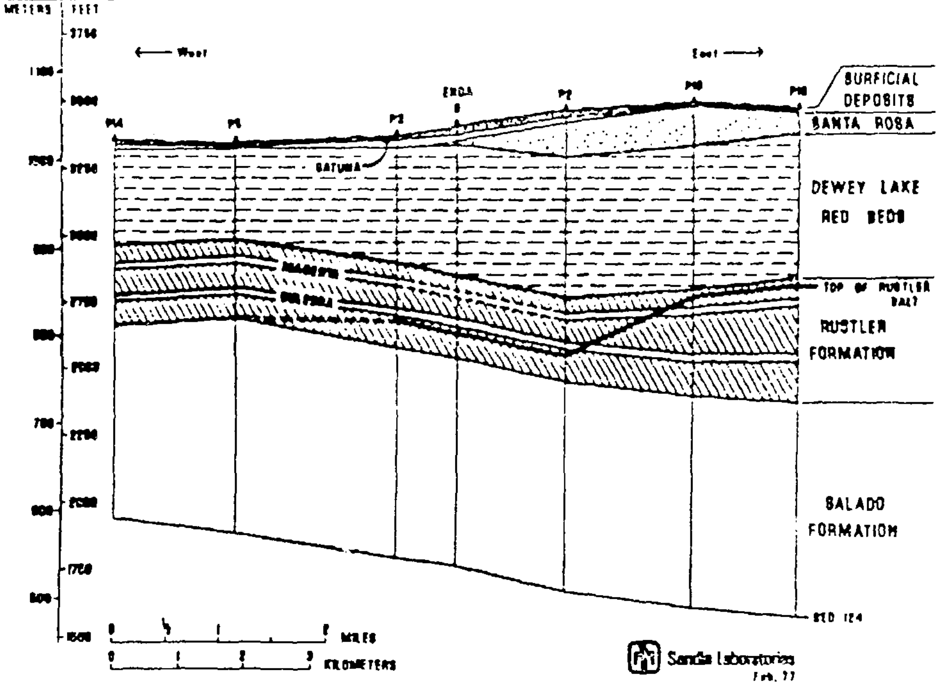
GEOLOGIC SECTION THROUGH THE LOS MEDAÑOS AREA



EXPLANATION

LITHOLOGIC SYMBOLS

- Sandstone
- Mudstone; siltstone; silty and sandy shale.
- Shale
- Limestone
- Dolomite
- Cherty limestone and dolomite
- Shaly limestone
- Anhydrite (or gypsum)
- Interlaminated anhydrite-calcite
- Halite (rock salt)
- Granitic rocks

ERA	SYSTEM	SERIES	FORMATION	GRAPHIC LOG	APPROX. DEPTH TO CONTACT AT SITE	PRINCIPAL LITHOLOGY	APPROX THICKNESS (feet)
CENOZOIC	RECENT		Surficial sand			BLANKET SAND AND DUNE SAND. SOME ALLUVIUM INCLUDED	0-100
CENOZOIC	QUATERNARY	PLEISTOCENE (Kansan?)	Mescalero caliche & Gatuna Fm.		10 40	PALE REDDISH BROWN, FINE GRAINED FRIABLE SANDSTONE. CAPPED BY 5-10 FT. HARD, WHITE CRYSTALLINE CALICHE (LIMESTONE) CRUST	0-35
MESOZOIC	TRIASSIC	UPPER TRIAS.	Santa Rosa Sandstone		50	PALE RED TO GRAY, CROSS BEDDED, NON MARINE, MEDIUM TO COARSE GRAINED FRIABLE SANDSTONE. PINCHES OUT ACROSS SITE	0-250
PALEOZOIC	PERMIAN	OCHOAN	Dewey Lake Redbeds		540	UNIFORM DARK RED BROWN MARINE MUDSTONE AND SILTSTONE WITH INTERBEDDED VERY FINE GRAINED SANDSTONE. THINS WESTWARD	100-550
			Rustler	M C	850	GRAY GYPSIFEROUS ANHYDRITE WITH SILTSTONE INTERBEDS IN UPPER PART. REDDISH BROWN SILTSTONE OR VERY FINE SILTY SANDSTONE IN LOWER PART. HALITIC NEAR BASE. CONTAINS 2 DOLOMITE MARKER BEDS, MAGENTA (M) IN UPPER PART AND CULEBRA (C) IN LOWER PART. THICKENS EASTWARD DUE TO INCREASING CONTENT OF UNDISSOLVED ROCK SALT	275-425
			Salado (Upper member; McNutt member; Lower member)	CA	CH ZONE RH ZONE 2825	MAINLY ROCK SALT (85-90%) WITH MINOR INTERBEDDED ANHYDRITE, POLYHALITE AND CLAYEY TO SILTY CLASTICS. TRACE OF POTASH MINERALS IN MC NUTT ZONE. THE MINOR INTERBEDS ARE THIN AND OCCUR IN COMPLEXLY ALTERNATING SEQUENCES. THICKEST NON-HALITE BED IS THE COWDEN ANHYDRITE (CA) [illegible] THICK. MULTIPLE ANHYDRITE INTERBEDS ARE MOST COMMON IMMEDIATELY BELOW THE COWDEN AND IMMEDIATELY ABOVE BASE OF SALADO	1750-2000
			Castile (Anh III-IV; Hal II; Anh II; Hal I; Anh I)		4075±	THICK MASSIVE UNITS OF FINELY INTERLAMINATED ("VARVED") ANHYDRITE-CALCITE ALTERNATING WITH THICK HALITE (ROCK SALT) UNITS CONTAINING THINLY INTERBEDDED ANHYDRITE. TOP ANHYDRITE UNIT LACKS CALCITE INTERLAMINATIONS	1250±
		GUADALUPIAN	DELAWARE MOUNTAIN GROUP: Bell Canyon (Delaware sand)		5100±	MOSTLY LIGHT GRAY FINE GRAINED SANDSTONE WITH VARYING AMOUNT OF SILTY AND SHALY INTERBEDS AND IMPURITIES. CONTAINS CONSIDERABLE LIMESTONE INTERBEDS AND LIME RICH INTERVALS. TOP UNIT IS LAMAR LIMESTONE MEMBER, A PERSISTENT SHALY LIMESTONE OR LIMY SHALE	1000±
			DELAWARE MOUNTAIN GROUP: Cherry Canyon		6200±	MOSTLY GRAY TO BROWN, FINE TO VERY FINE GRAINED SANDSTONE SIMILAR TO BRUSHY CANYON, INTERBEDDED WITH SHALE, DOLOMITE AND SOME LIMESTONE	1100±
			DELAWARE MOUNTAIN GROUP: Brushy Canyon			PREDOMINANTLY FINE GRAINED, GRAY TO BROWN SANDSTONE INTERBEDDED WITH MINOR BROWN SHALE AND DOLOMITE	1000±

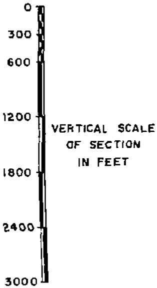
REFERENCES:

1. Anderson, 1978
2. Anderson, et al, 1972
3. Brokaw, et al, 1972

1. Jincerson, [illegible]
2. Anderson, et al, 1972
3. Brokaw, et al, 1972
4. Foster, 1974
5. Griswold, 1977
6. Meyer, 1966
7. Sipes, Williamson and Aycock, 1976

NOTE:

For complete citations, refer to Powers, et al., Chapter 4.



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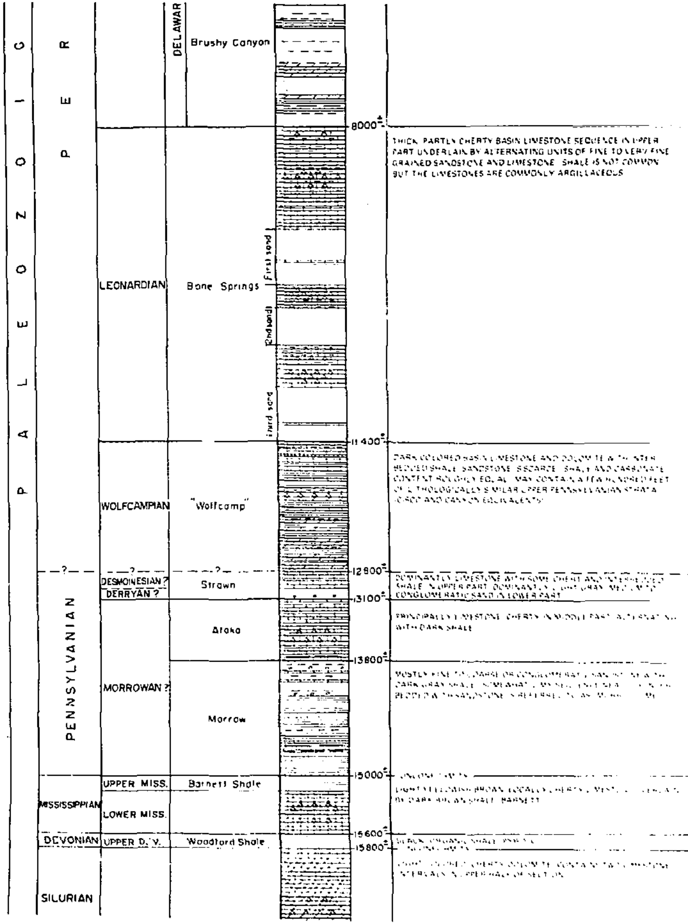

SITE GEOLOGIC COLUMN

3000 ft

SITE GEOLOGIC COLUMN

C4

PENNSYL	MORROWAN?	Morrow			MOSTLY FINE TO COARSE OR CONGLOMERATIC SANDSTONE WITH DARK GRAY SHALE. SOMEWHAT LIMY SEQUENCE NEAR TOP INTERBEDDED WITH SANDSTONE IS REFERRED TO AS "MORROW LIME"	1250
				15000±	(UNCONFORMITY)	
MISSISSIPPIAN	UPPER MISS.	Barnett Shale			LIGHT YELLOWISH BROWN, LOCALLY CHERTY LIMESTONE OVERLAIN BY DARK BROWN SHALE (BARNETT)	650±
	LOWER MISS.					
				15600±		
DEVONIAN	UPPER DEV.	Woodford Shale			BLACK ORGANIC SHALE, PYRITIC	175
				15800±	(UNCONFORMITY)	
SILURIAN					LIGHT COLORED CHERTY DOLOMITE. CONTAINS TWO LIMESTONE INTERVALS IN UPPER HALF OF SECTION	1150
				16900±		
ORDOVICIAN		MONTOYA GROUP			CHERTY LIMESTONE AND DOLOMITE	1300±
		SIMPSON GROUP			ALTERNATING BEDS OF LIMESTONE AND GRAY OR GREEN SHALE WITH MINOR SANDSTONE UNITS	
		ELLENBURGER GROUP			CHERTY DOLOMITE (INCLUDES BASAL SANDSTONE MEMBER)	
				18200±	(UNCONFORMITY)	
PRECAMBRIAN					IGNEOUS INTRUSIVE TERRANE (AGE 1.2-1.4 BILLION YEARS)	