R-995

**BOREHOLE PLUGGING BY COMPACTION PROCESS
FINAL REPORT**

R. Fernandez, Project Manager

**Part 1. Engineering Analysis
by
C. McGowan and E. Nolan**

**Part 2. Reliability and Quality Assurance
by
R. Morey and A. Palty**

Prepared for
Office of Waste Isolation
Union Carbide Corporation
Nuclear Division
Oak Ridge, Tennessee 37830

The Charles Stark Draper Laboratory, Inc.

Cambridge, Massachusetts 02139

This informal document contains information which is preliminary and may be fragmentary or of limited scope. The assumptions, views, and conclusions expressed in this document are those of the author and are not to be interpreted as those of Union Carbide Corporation, Nuclear Division, or USERDA.

MASTER

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. Y-OWI-Sub-7087-1		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle BOREHOLE PLUGGING BY COMPACTION PROCESS				5. Report Date August 1976	
				6. Performing Organization Code	
7. Author(s) C. McGowan, E. Nolan, R. Morey, A. Palty				8. Performing Organization Report No. R-995	
9. Performing Organization Name and Address The Charles Stark Draper Laboratory, Inc. Cambridge, Massachusetts 02139				10. Work Unit No.	
				11. Contract or Grant No. Subcontract 7087	
12. Sponsoring Agency Name and Address Office of Waste Isolation Union Carbide Corporation Nuclear Division Oak Ridge, Tennessee 37830				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
<p>16. Abstract</p> <p>This report documents the requirements of an overall program to preserve the integrity of a repository formation. The repository is intended to be in stable earth stratum used as a safe and permanent storage area for nuclear waste material. These wastes represent an environmental hazard for a period of up to 200,000 years.</p> <p>The report presents an engineering analysis, a reliability and quality-assurance program, and a development program for borehole plugging by compaction process, using natural earthen materials.</p> <p>The report is presented in two parts. Part 1 provides the engineering analysis of downhole compaction methods and related instrumentation along with a recommended development plan from concept through a pilot in situ experiment. Part 2 provides a reliability and quality-assurance program from laboratory testing of materials through an in situ experiment.</p>					
17. Key Words Suggested by Author Deephole Compaction Compaction Tooling Quality-Control Program for Compaction				18. Distribution Statement MASTER	
19. Security Classif. (of this report) UNCLASSIFIED		20. Security Classif. (of this page) UNCLASSIFIED		21. No. of Pages 195	
				22. Price	

R-995

BOREHOLE PLUGGING BY COMPACTION PROCESS

FINAL REPORT

R. Fernandez, Project Manager

Part 1. Engineering Analysis

by

C. McGowan and E. Nolan

Part 2. Reliability and Quality Assurance

by

R. Morey and A. Palty

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration (ERDA), nor any of their employees nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of the information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This informal document contains information which is preliminary and may be fragmentary or of limited scope. The assumptions, views, and conclusions expressed in this document are those of the author and are not to be interpreted as those of Union Carbide Corporation, Nuclear Division, or USERDA.

Approved

W. G. Denhard
W. G. Denhard
Department Head
Air Force Programs Department

The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FOREWORD

The work was performed by The Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts under contract to the Office of Waste Isolation, Union Carbide Corporation, Nuclear Division, Oak Ridge, Tennessee on Subcontract No. 7087. This report completes all requirements of the contract.

This program was executed under the direction of Dr. W. C. McClain and Dr. George Brunton, both of Union Carbide Corporation.

As a contributor to this report, the assistance of T. Reed, CSDL, is gratefully acknowledged.

For review and comment on this report, the following are acknowledged.

Dr. C. Ladd, MIT

Dr. R. T. Martin, MIT

Dr. A. E. Z. Wissa, Ardaman Associations, Inc., Florida

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
INTRODUCTION.....	1
PART I - ENGINEERING ANALYSIS.....	3
1 SUMMARY AND CONCLUSIONS.....	5
1.1 Design Concepts.....	6
1.2 Development Program.....	7
2 INTRODUCTION.....	8
2.1 General Considerations.....	8
2.1.1 Adequate Quality Assurance.....	9
2.1.2 Permeability.....	9
2.1.3 Strength and Deformation.....	11
2.1.4 Hole Diameter.....	11
2.1.5 Diameter Variations.....	11
2.1.6 Hole Depth.....	11
2.1.7 Hole Deviation from Vertical.....	12
2.1.8 Hole Condition.....	12
2.1.9 Temperature.....	12
2.1.10 Drill Rig Interfaces and Power Sources..	12
2.2 Statement of Work.....	12
3 BOREHOLE PLUGGING.....	14
3.1 System Requirements.....	15
3.1.1 Hole Definition.....	17
3.1.2 Casing.....	17
3.1.3 Hole Diameter, Variation and Depth.....	17
3.1.4 Hole Size Variations.....	17
3.1.5 Other Considerations.....	18
3.2 Quality Assurance.....	18
3.3 Quality Control.....	18

Table of Contents (Cont.)

<u>Section</u>	<u>Page</u>
3.4 Natural Material.....	19
3.4.1 Stratification.....	19
3.4.2 Confirmation of Stratification.....	20
3.4.3 Procurement of Natural Materials.....	20
3.4.4 Material Processing and Storage.....	20
3.5 Surface Equipment.....	21
3.5.1 Surface System.....	21
3.5.2 Power System.....	21
3.5.3 Air Compressor.....	21
3.5.4 Control System.....	21
3.5.5 Equipment.....	22
3.5.6 Service Life.....	22
4 PROCESS VERIFICATION.....	23
4.1 Material Selection.....	23
4.1.1 Material Types.....	24
4.1.2 Identification of Characteristics.....	24
4.1.3 Chemical and Physical Analysis.....	24
4.2 Mass Balance.....	25
4.2.1 Weights.....	25
4.2.2 Hole Diameter.....	25
4.2.3 Stratification.....	25
4.2.4 Yielding of Sidewall.....	25
4.3 Indirect Testing.....	26
4.4 Borehole Formation.....	26
4.5 Lab Test Data Requirements.....	27
5 LAB TEST EQUIPMENT.....	29
5.1 Static Compaction.....	29
5.2 Impact Compaction.....	29
5.3 Vibratory Compaction.....	29
5.4 Roller Compaction.....	30
5.5 Air or Steam Gun Compaction.....	30
5.6 Test Molds.....	31
5.7 Materials Under Consideration.....	31
5.8 Performance Verification of Test Equipment.....	32

Table of Contents (Cont.)

<u>Section</u>		<u>Page</u>
6	COMPACTION METHODS.....	33
6.1	Static Compaction.....	34
6.2	Impact Compaction.....	42
6.3	Roller Compaction.....	48
6.4	Vibratory Compaction.....	54
6.5	Air/Steam Gun Compaction.....	57
6.6	Compaction Comparison Matrix.....	58
6.7	Explanation of Table 6-7 Column Headings.....	61
7	MATERIAL SUPPLY SYSTEM.....	62
7.1	Lowering Fill Material to Compactor.....	62
7.2	Preventing Degradation of Fill Material.....	63
7.2.1	Segregation of Mixture.....	63
7.2.2	Moisture Losses.....	63
7.3	Metering Proper Amount of Material to Working Face.....	63
7.3.1	Monitor, Metering.....	63
7.4	General Considerations.....	64
7.5	Gravity or Pneumatic Delivery.....	64
7.6	Conveyor or Screw Delivery.....	67
7.7	Batch or Bucket Delivery.....	67
7.8	Material Delivery System Comparison Matrix.....	70
8	IN-PROCESS QUALITY CONTROL.....	72
8.1	Instrumentation.....	73
8.2	In-Process Monitor.....	74
9	DEVELOPMENT PROGRAM.....	76
9.1	Reliability and Quality Assurance.....	77
9.2	Material and Mixture Parameters.....	77
9.3	Compactor and Component Development.....	78
9.4	System Verification.....	79
9.5	General Technology Roadmap.....	79

Table of Contents (Cont.)

<u>Section</u>	<u>Page</u>
9.6 Reference Technology Program.....	80
9.6.1 Task 1 - Borehole Investigation.....	80
9.6.2 Task 2 - Process Verification.....	82
9.6.3 Task 3 - Component Development.....	82
9.6.4 Task 4 - System Demonstration.....	83
9.6.5 Task 5 - Design and Fabrication.....	83
9.6.6 Task 6 - Fabrication.....	84
9.6.7 Task 7 - Reliability and Quality Assurance.....	84
LIST OF REFERENCES.....	92
 PART II - RELIABILITY AND QUALITY ASSURANCE.....	 93
1 RELIABILITY AND QUALITY ASSURANCE OVERVIEW.....	95
1.1 Summary.....	95
2 TASK DEFINITION.....	97
3 PROPOSED PROGRAM ORGANIZATION.....	100
3.1 Reliability and Quality Assurance: Management, Documentation and Traceability.....	 100
3.1.1 Organization.....	101
3.1.2 Quality System.....	104
3.1.3 Integrated Data System.....	105
3.1.4 Configuration Management.....	107
3.1.5 Contractor Interface.....	107
3.1.6 In-Process Monitoring.....	108
3.1.7 Post-Seal Monitoring.....	108
3.1.8 Reliability and Statistical Analysis.....	108
3.1.9 Other R&QA Activities.....	109
4 DEVELOPMENT OF TESTS AND TEST EQUIPMENT.....	111
4.1 Process Verification.....	111
4.1.1 Laboratory Test Equipment.....	111
4.1.2 Materials.....	112
4.1.3 Performance Verification of Test Equipment.....	 116

TABLE OF CONTENTS (Cont.)

<u>Section</u>	<u>Page</u>
4.2 Borehole Logging.....	120
4.2.1 Assessment of Logging Data.....	121
4.3 Field Permeability Testing.....	121
5 PROCESS AND EQUIPMENT QUALITY.....	125
5.1 Surface Equipment.....	125
5.2 Power Supply.....	125
5.3 Natural Material Supply.....	127
5.4 Compaction Methods.....	127
5.5 Material Feed.....	129
5.6 Process Limits Based on Material Type.....	129
6 IN-PROCESS QUALITY-ASSURANCE AND LABORATORY TESTS.....	135
6.1 In-Process Quality Assurance.....	135
6.1.1 Continuing Tests.....	135
6.1.2 No In-Process Monitoring.....	135
6.1.3 In-Process Monitoring.....	137
6.1.4 Probe-Type In-Process Monitoring.....	137
6.1.5 Periodic In-Process Monitoring Integrated with Equipment.....	138
6.1.6 In-Process Monitoring of Other Parameters.....	139
6.1.7 Above-Ground Environmental Protection, Work Safety, and Monitoring.....	139
6.1.8 In-Process Monitoring for Simulation and Pilot Tests (and Field Operation).....	140
6.2 Laboratory Tests.....	141
6.2.1 Proposed Laboratory Tests.....	141
7 DECISION POINTS BASED ON EVALUATION OF PROCESS ALTERNATIVES.....	150
7.1 Decision Points.....	150
7.2 R&QA Subtasks.....	150
7.3 Subsystem Interactions and Final Design Review.....	151
7.4 Life Cycle Projections.....	152
7.4.1 Reliability Analysis.....	152
7.4.2 Effectivity.....	153
7.4.3 Cost Estimate.....	153
7.4.4 Failure Mode and Effects Analysis.....	154

TABLE OF CONTENTS (Cont.)

<u>Section</u>	<u>Page</u>
8	PROCESS/EQUIPMENT DEVELOPMENT AND ENGINEERING VERIFICATION.....
	156
8.1	Option 1: Off-the-Shelf.....
	156
8.2	Option 2: Modification of State-of-the-Art.....
	158
8.3	Option 3: Redesign.....
	158
8.4	Option 4: New Design (Invention).....
	158
8.5	Final Evaluations and Experiments.....
	159
8.6	Trade-off Design Review.....
	159
8.7	Implementation.....
	159
9	SYSTEM VERIFICATION.....
	162
9.1	Laboratory Mockup Equipment.....
	162
9.1.1	Quality Plan.....
	162
9.1.2	Test Procedures and Laboratory Tests.....
	163
9.2	Simulation Tests.....
	163
9.2.1	Site and Test Support.....
	163
9.2.2	Test Program.....
	163
9.2.3	Data System.....
	164
9.2.4	Analysis of Test Results.....
	164
9.3	Modification of Designs (Based on 9.2) and Procurement and Verification of Prototype Equipment.....
	165
9.3.1	Quality-Assurance Plans and Activities.....
	165
9.3.2	Acceptance.....
	165
9.3.3	Possible Simulation Retest.....
	165
9.3.4	Contractor Interface.....
	165
9.4	Instrumentation and Pilot Test(s) of Prototype System.....
	166
9.4.1	Conditions for Test and Field Qualification.....
	166
9.4.2	Test Site Preparation.....
	167
9.4.3	Test Program.....
	168
9.4.4	Product Evaluation.....
	169

TABLE OF CONTENTS (Cont.)

<u>Section</u>	<u>Page</u>
9.5 Specifications and Procedures for Field Qualification (or for Final Product).....	170
9.5.1 Procedures.....	171
9.5.2 Final Report.....	171
9.5.3 Contractor Interface.....	171
10 FIELD QUALIFICATION.....	172
10.1 Field Qualification.....	172
11 FIELD OPERATION.....	173
11.1 Natural Material Control.....	173
11.2 Borehole Conditions.....	174
11.3 Instrumentation and Data Analysis.....	174
11.4 Equipment Monitoring, Failure Analysis, Corrective Action.....	174
11.5 Feed and Compaction Monitoring.....	174
11.6 Sealed Borehole Acceptance.....	175
11.7 Work-in-Progress and Final Reports.....	175
12 PRODUCT LIFE MONITORING.....	176
12.1 Monitoring Requirements.....	176
12.2 Contingency Plans.....	176
 <u>Appendix</u>	
A BOREHOLE LOGGING.....	177
B BOREHOLE GRAVITY GRADIOMETER.....	181
LIST OF REFERENCES.....	183
BIBLIOGRAPHY.....	184

LIST OF ILLUSTRATIONS

PART 1

<u>Figure</u>	<u>Page</u>
6-1 "Drill collar" static compactor.....	38
6-2 Hydraulic static compactor.....	40
6-3 Combination static and impact compactor.....	41
6-4 Simple surface-powered impact compactor, cable held and operated.....	44
6-5 "String" impact compactor.....	45
6-6 Percussion drill hammer compactor.....	46
6-7 Modified rockdrill, smooth cone rollers.....	51
6-8 Roller compactor, surface-driven.....	52
6-9 Roller compactor, downhole gearbox.....	53
6-10 Vibratory compactors.....	56
7-1 Gravity and pneumatic delivery systems.....	66
7-2 Bucket delivery system.....	69
9-1 Technology roadmap downhole compaction.....	85

PART 2

4-1 Technology roadmap, downhole compaction.....	113
4-2 Technology roadmap, development of tests and test equipment.....	115
5-1 Technology roadmap, surface equipment.....	126
5-2 Technology roadmap, compaction methods.....	128
5-3 Technology roadmap, process and equipment quality.....	130
6-1 Technology roadmap, in-process quality assurance and laboratory tests.....	136
8-1 Technology roadmap, process/equipment development and engineering verification; system verification.....	157

LIST OF TABLES

PART 1

<u>Table</u>	<u>Page</u>
2-1 Basic assumptions.....	10
3-1 System and equipment requirements summary.....	16
6-1 Typical permeability data by various compaction methods.....	35
6-2 Static compaction, advantages and disadvantages.....	43
6-3 Impact compaction, advantages and disadvantages.....	49
6-4 Roller compaction, advantages and disadvantages.....	54
6-5 Vibratory compaction, advantages and disadvantages.....	55
6-6 Air/steam gun compaction, advantages and disadvantages.....	59
6-7 Comparison of downhole compaction systems.....	60
7-1 Gravity or pneumatic delivery, advantages and disadvantages.....	65
7-2 Conveyor or screw delivery, advantages and disadvantages.....	67
7-3 Batch and bucket delivery, advantages and disadvantages.....	70
7-4 Relative comparison matrix of downhole delivery system schemes.....	71
9-1 Estimated development schedule.....	81

PART 2

3-1 R&QA manpower estimate.....	102
---------------------------------	-----

INTRODUCTION

This report presents an engineering analysis, a reliability and quality-assurance program, and a development program for borehole plugging by compaction process, using natural earthen materials. The report is presented in two parts.

Part 1 provides the engineering analysis of downhole compaction methods and related instrumentation along with a recommended development plan from concept through a pilot in situ experiment.

Part 2 provides a reliability and quality-assurance program from lab testing of materials through an in situ experiment.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

PART 1

ENGINEERING ANALYSIS

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SECTION 1

SUMMARY AND CONCLUSIONS

Part 1 of this report provides the engineering analysis of downhole compaction methods and related instrumentation along with a recommended development plan from concept through a pilot in situ experiment.

The assumption that duplicating the natural virgin formations with natural earthen material provides the only reliable long-term answer to plugging manmade boreholes forms the basis for this study. It is impossible to duplicate the natural virgin formations but it is possible to compact natural earthen materials to achieve equal or better permeability characteristics. The prime requirement in maintaining the integrity of a repository is to prevent the intrusion of water. Preliminary experiments have proven that it is possible to compact natural earthen material to sufficiently low permeability characteristics to exclude water. Other mechanical characteristics of the plug material will not equal the natural virgin formation but these are not as important.

An analysis of various possible compactions methods, as suggested in the MIT study,^{(1)*} was performed. These methods (five) covered the basic means to perform downhole compaction and no other methods have been discovered. The methods of compaction are for downhole operation using conventional surface drill rig equipment interface. The commercial market was surveyed for possible equipment for downhole operations or for potential modification. Where commercial equipment does not exist, concepts are outlined and their potential discussed.

This study shows that it is feasible to develop downhole compactors. Of the five basic methods, two must be eliminated due to the lack of quality control over the compaction operation. From the remaining three, two are recommended for future development. They are static and impact compaction. Roller compaction is not recommended because of its limited effectiveness in some soils.

* Superscript numerals refer to similarly numbered references in the Part 1 List of References.

Static and impact compactors have proven effective with certain combinations of tested materials. The design and development of each method of tooling can range from very simple to complex. Sections 6-1 and 6-2 outline the tooling development range potential and specific advantages and disadvantages.

In conjunction with the compactor design, the means to supply fill material downhole was also reviewed. From the three possible methods of supply, only one should be developed. This supply delivery system is called the batch or bucket system and is covered in Section 7-3. The other two methods must be eliminated due to the lack of sufficient control over the fill material delivery or the compaction operation.

Many aspects of a total program, starting with material selection through tooling and finally as an in situ experiment, were reviewed. A graphical display of the various functions is shown in a technology roadmap, Figure 9-1.

1.1 Design Concepts

Preliminary studies indicated natural earthen material can be compacted to desired limits, therefore no attempt was made to duplicate this work. Using data from these studies and by scaling it up to a normal 8-inch-diameter borehole, input energy levels for equipment requirements were generated. Using this information, various mechanical design concepts were developed. The concepts range from using standard hardware to complete tooling development.

Tooling for the recommended compaction methods can be built up using state-of-the-art equipment with minor changes for environmental reasons.

For each of the concepts developed, a brief summary is given for the various considerations involved in each, in terms of development requirements, availability of hardware, procedure of operation, possible critical experiments, and preliminary conclusions.

In the elimination process to the two proposed methods, static and impact, the total system was reviewed. This review covered mechanical feasibility of the compactor, necessary R&D, the material feed system, quality-control features, and the range of effectiveness with various soil types.

In operation for all concepts, the fill material is transported downhole to be compacted at a constant rate and as the buildup continues, the compactor is slowly raised to remain in a limited range of

the working face. Built-in measurement equipment will monitor all necessary parameters. These measurements will be multiplexed to surface recording equipment. Two means of recording would be used. The first is paper printout for field engineer evaluation at the site. The second is magnetic tape for a computer comparison between planned goals and the as-built configuration.

Basically no commercial equipment was found suitable for a compaction program. Limited oil-well equipment could be used as a basic starting point, but refinement and instrumentation would still be an R&D task.

1.2 Development Program

The development program leading to a field-qualified compaction system is described by four main tasks associated with future development efforts.

Task 1 Reliability and quality assurance.

Task 2 Materials and mixture parameters.

Task 3 Compactor and component development.

Task 4 System verification.

These tasks are summarized in Section 9 and then further detailed in an R&D program schedule and manning plan (Table 9-1). This plan, as outlined, is for an impact compactor system, a batch delivery system, the necessary testing of materials, instrumentation development, and full quality control. The program will run 3 years from start to the start of a pilot in situ experiment. The quality control and assurance plans are covered in Part 2.

The program plan does not cover any materials and supplies for either the test equipment or downhole equipment, support equipment or its manning, special monitor equipment for the pilot in situ borehole, or for any monitoring period after the the plug is formed.

The technology road map (Figure 9-1) shows the multitude of series/parallel options which have been considered and could be undertaken simultaneously or singularly. The recommended path has been indicated after careful review of all pertinent data. Within the confines of this path, other options must still be decided, depending on the combination of the amount of technical risk permitted, schedule, or funding available for execution of the program.

SECTION 2

INTRODUCTION

2.1 General Considerations

The object of this report is to document the requirements of an overall program to preserve the integrity of a repository formation. The repository is intended to be in stable earth stratum used as a safe and permanent storage area for nuclear waste material. These wastes represent an environmental hazard for a period of up to 200,000 years.

Specifically, for a repository, the prime requirement is to keep water from flowing through the stratum. The goal, ideally, is to plug manmade boreholes by duplicating the permeability and strength of the strata.

There are two general types of borehole wall construction, water permeable and impermeable. The only criterion for the hole fill material in water-permeable strata is bulk fill that will offer long-term support for impervious layers of fill. This report will place primary emphasis on the seal section of impermeable fill.

The natural stratum, as formed by nature, has withstood weathering for tens of millions of years as proven by geological history. Design of the seal plug integrity must equal the natural formation permeability and be of sufficient strength to prevent deformation. The required goal of 200,000 years is not an extrapolation upwards. If the requirements of the plug permeability are off, in the worst case by a factor of 10, the resulting margin of error is still five times better than the program requirements of 200,000 years.

Only natural earthen materials are considered. The final configuration of the material used depends on the methods used for installation and the final configuration of the plug. The material and method of installation, however, must be closely controlled.

Alternate methods of compaction are reviewed and an outline of an R&D program to develop those methods towards an in situ pilot program is furnished.

Evaluation of these methods for logical technical reasons and/or inadequacy is detailed. Recommendations are made of commercial tooling available and specific tooling which requires development.

From earlier studies, compaction of earthen materials can form an adequate plug. However, the downhole operation will put severe constraints on the method due to the small diameter, depth, type of material, and supply.

Details of quality control during actual plugging operations are outlined. This includes a study of hole configuration, material supply, and control of installation and machinery necessary. The unprecedented level of quality assurance, which this program requires, will be obtained from many inputs.

The purpose of the study is to review the alternatives for a Research and Development program to lead toward a pilot in situ program. Natural earthen materials and compaction methods are considered. Effort is made to adequately document the various factors, considerations, and rationale that support a reliable method of hole plugging.

Table 2-1 lists the basic assumptions and goals to which the overall study is addressed.

2.1.1 Adequate Quality Assurance

The required life span of a repository makes it mandatory that a complete quality-control and assurance program be used, covering all aspects of the development and plugging operations in the waste isolation program.

2.1.2 Permeability

The prime requirement is to keep water from flowing through the repository stratum. Only certain stratum (shale, etc.) act as seals, while other stratum will allow free flow of water. In this program the sealing stratum must be resealed at least as good as that particular stratum type is capable of, or to 0.1 μ D (mix) permeability, which lab studies show can be achieved with various sample materials.

Table 2-1. Basic assumptions.

Assumptions	Minimum	Maximum
Adequate quality assurance	200,000 years	---
Permeability	0.1 μD^*	Or less than strata permeability, whichever is larger.
Strength and deformation	Hold 300-foot of water per 1-foot section.	Sufficient to maintain permeability over 200,000 years.
Hole diameter (inches)	8	24
Diameter variation	-	Increase of 100% in 3 feet (cohesionless soil)
Depth (feet)	-	10,000
Deviation from vertical (degrees)	-	5
Hole condition	-	Open and dry
Temperature	-	120°C
Drill rig interface	Conventional equipment -	
Power source	Conventional mobile electrical power -	

*A unit of porous permeability equal to the permeability of a medium, through which the rate of flow of a fluid having 1-centipoise viscosity under a pressure gradient of 1 atmosphere per centimeter would be 1 cubic centimeter/second per square centimeter of cross section.

2.1.3 Strength and Deformation

The critical parameter of the plug seal is permeability. Strength and deformation characteristics are only important to maintain the integrity of the permeability characteristic of the plug. Throughout this report, the terms permeability, strength, and deformation are used relative to this definition (unless otherwise stated). Maintaining the required permeability of the plug material throughout the borehole requires sufficient strength, adhesion, and deformation characteristics to prevent motion. Relative motion, either by settlement or shearing, will allow the plug seal material to relax with resultant increase in permeability. Conversely, the clay areas may be lightly compacted so that any small intrusion of water will not cause sufficient swelling to damage the adjacent plug formation.

2.1.4 Hole Diameter

The minimum and maximum hole diameters have been selected to be 8 and 24 inches, respectively. The 8-inch diameter is selected to be the trade-off minimum, where tool design and related equipment would not be a major design problem starting from scratch. The hole is generally drilled with large diameters at the surface, with a reduction in size as the hole progresses in depth.

Holes of much larger diameter (up to 20 feet or more) could be filled using more conventional compaction equipment (Section 3.1.3).

2.1.5 Diameter Variations

The boreholes through seal-type strata (shale, etc.) will be smooth and true to the drill-bit diameter. However, in cohesionless soil strata (sand, etc.), the diameter may be greater than the drill-bit diameter due to collapse or washing action during the drilling or cleaning operation. During the plugging operation, it will be difficult to obtain full compaction in these areas without special tooling. Because of the characteristics of cohesionless strata, the permeability would not be critical and the plugging operation would only be necessary for the mechanical strength and deformation requirements.

2.1.6 Hole Depth

The depth for boreholes requiring plugging was assumed to be up to 10,000 feet. Holes of this depth will not exist in most cases, while

it may be possible some may exceed this. Holes that extend deep enough so that the downhole temperature exceeds 95°C create problems in the moisture control of the plugging material.

2.1.7 Hole Deviation from Vertical

Hole deviation from the vertical is restricted to 5 degrees. The common straight hole drilling techniques are well within this tolerance.

2.1.8 Hole Condition

The basic assumption of the hole being open and dry is to allow the insertion of the necessary equipment for plugging without the complication of packers and seals.

2.1.9 Temperature

Temperature of the hole will vary from the surface temperature up to 120°C at the bottom of a 10,000-foot hole. The moisture in fill materials delivered to a depth of 10,000 feet at 120°C would turn to steam. This would require the fill material to be delivered in a humidity-controlled environment.

2.1.10 Drill Rig Interfaces and Power Sources

Drill-rig-interface and power-source requirements will be selected to meet the operating characteristics of the total operating system.

2.2 Statement of Work

Task 1 - Problem Definition

The primary intent of this task was to direct and limit the scope of the program. This was accomplished by recording all assumptions including, but not restricted to, those relating to purpose, requirements, environments, material types, and operational constraints, e.g., only clean dry boreholes will be considered for plugging. The concepts were discussed and agreed upon at a meeting held on 19 May 1976 at ORNL. The attendees were: G. Brunton, ORNL; R. Fernandez, Program Director, CSDL; R. T. Martin, MIT; W. McClain, Program Director, ORNL; and E. Nolan, CSDL.

Task 2 - Quality Assurance

The conceptual development of specific laboratory and field tests necessary for an adequate quality-assurance program is included in this task. This task addresses the broader problem of general hole plug adequacy as well as the specific tests required for compacted-earth verification.

Task 3 - Definition of Compaction Methods

There is more than one possible method of downhole earth compaction. This task investigated and defined these methods for the purpose of selecting one for further development.

The results of this subtask are presented in this report. They include the recommended method, as well as all factors utilized in arriving at this selection. Included is the recommended program necessary to develop both the compaction technique and the off-site quality-assurance program.

Task 4 - Definition of In Situ Tests

This task outlines an R&D program leading to an in situ experiment for verification of the compacted-earth technique. This is presented as a roadmap diagram. Also included is an estimate of costs for the R&D program along with specific test methods and data requirements for both in situ quality assurance and operational quality control.

SECTION 3

BOREHOLE PLUGGING

Five methods of mechanically replacing the various soil strata in existing oil and gas well exploration boreholes or as yet undrilled test boreholes used to survey the proposed repository site area are evaluated for reliability and mechanical feasibility. Since the exact sites and soil materials are unknown, all natural earthen materials and mixture ratios must be considered candidates. This study will concentrate, not on specific materials, but on general characteristics of materials. Material selection and a proper series of tests must be conducted in the future, once the site strata is known.

The MIT report⁽¹⁾ shows that low permeabilities can be obtained by mechanical compaction of various common soil materials. However, the energy input requirements for these tested soil samples vary greatly and with the possible introduction of many more materials and mixtures, this range may increase.

The mechanical methods covered are basically the five mentioned in the MIT report:⁽¹⁾ No alternative methods were found.

- (1) Static pressure compaction.
- (2) Impact compaction.
- (3) Vibratory settlement compaction.
- (4) Roller compaction.
- (5) Air gun compaction.

The advantages and disadvantages of each are considered. Some methods are limited for various reasons and others are limited to certain types of materials, both of which are discussed later.

In conjunction with compaction methods, the following related requirements are covered.

- (1) Quality-assurance program.
- (2) In-process quality control.
- (3) Surface equipment.
- (4) Bulk material storage and testing.

All requirements outline the major areas of concern and provide a starting point for future study and development. Any final detail work must result from both these future studies and from development of prototype machinery, in scale or full size. When the actual soil types are known, in-depth testing for the best method of compaction obtainable, permeability, optimum mix and water content ratios, and input energy requirements may be determined. Then a scale up to full-size hole and equipment forces must be completed with quality-control and monitor-equipment correlation. At this point, full-scale equipment and hole-size molds may be required to fully correlate input energy and permeability results from the scale change.

3.1 System Requirements

The design of an integrated in situ system to fill and compact boreholes with any natural earthen materials can be divided into four major areas:

- (1) Hole definition.
- (2) Compaction method to achieve permeability and deformation requirements of the original hole strata with sufficient mechanical strength to prevent movement.
- (3) Downhole material feed system.
- (4) Instrumentation, reliability, and quality assurance of the plug formation system.

Related system and equipment requirements are noted in Table 3-1.

Some specific system requirements identified for the four major areas are:

- (1) Restraints and assumptions established in Table 2-1.
- (2) Compact natural earthen material into an open borehole, duplicating original strata permeability or $0.1 \mu D$, whichever is greater.

Table 3-1. System and equipment requirements summary.

Conventional drill rig, capable of handling drill string up to 24-inch-diameter hole to a depth of 10,000 feet.

Compacting device, located downhole, capable of providing mechanical forces to the fill material.

Material supply, storage, batch mixing, and handling facilities.

Surface to downhole, fill material transfer equipment.

Control system, downhole monitor and sensing equipment, including closed electronic servo-loop control of fill-material transfer equipment.

Primary electrical mobile power unit and auxillary, as required, to give continuous operational capabilities.

Pneumatic equipment as required.

Reliability and process control, facilities for testing and sampling of materials.

- (3) Conventional drill rig and power sources, and operating crew as required.
- (4) Mobile power sources including electrical, pneumatic, etc., (sites may be remote from commercial services).
- (5) Automatic control system capable of controlling a compacting and material feed system in producing a plug that meets a preset criteria.
- (6) Instrumentation system giving quality-control data on the compaction process on site.
- (7) Contingency plans should be made for recovery of downhole equipment in event of loss of equipment in the hole.
- (8) A life-cost-cycle study should be made for the service life on the operating systems to support an adequate production rate.
- (9) Adequate work safety to meet OSHA standards and environmental protection planning.
- (10) Verification and planned calibration and maintenance of all systems on a predetermined basis.

3.1.1 Hole Definition

The holes may vary in diameter and/or depth, may deviate from vertical, and may be located in various types of strata.

Identification of the hole will be the responsibility of Office of Waste Isolation (OWI).

Constraints placed on the hole are listed in Table 2-1.

A further definition of an adequate logged hole is required.

3.1.2 Casing

Holes with casings have not been considered.

3.1.3 Hole Diameter, Variation and Depth

The diameter of the hole must be a minimum of 8 inches. The 8-inch diameter is selected to be the trade-off minimum, where tool design and related equipment would not be a major design problem starting from scratch. The maximum diameter of 24 inches is limited by design constraints on the compacting equipment.

In the future, a study should be made into the possibility of redrilling the holes to a diameter of 20 feet or more. This larger diameter will allow for the use of conventional compacting equipment, ease of quality control and assurance of the compacted plug, and availability of sidewalls for sample measurement of the surrounding stratum.

Although this method of operation will require large-bore drilling, use of temporary casing, and much more plug material, a study may show that it is more cost effective over development of small-bore hole tooling and operation. ⁽²⁾

3.1.4 Hole Size Variations

Hole size variations will be determined by adequate caliper logging. ^(3,4) Allowable variations of up to 100 percent over 3 feet are reasonable. Adequate knowledge of hole variations in determining volume is a prerequisite.

Quality control of the logging should be regulated to ensure that all the fill material compacted is in the correct location with respect to the surrounding strata.

Obviously, any errors in logging will seriously affect production times in that compaction equipment would have to be withdrawn and logging equipment installed for verification checks.

3.1.5 Other Considerations

In sealing stratum such as shale (a cohesive material), the hole diameter will be smooth and true. In a nonsealing stratum such as sand (a cohesionless material), the hole diameter may vary due to collapse or washing action from the drilling or cleaning operation.⁽⁵⁾

If the walls of the hole are covered with drilling mud, it must be removed by mechanical means. No chemicals will be used within the borehole, as chemicals may contaminate the hole and the surrounding material. The presence of any foreign material or substance may have detrimental long-term effects on the fill.

A hole of 10,000 feet, depending on the earth temperature gradient, can cause problems in the quality control of the fill material moisture content. If the ambient temperature exceeds 95°C, humidity control of the downhole material bin must be considered.

3.2 Quality Assurance

Quality-assurance plans are developed in total as shown in Part 2. This plan provides for intelligent assessment of the decisions that lead to the selection of equipment, materials, and processes for borehole plugging to meet the criteria of permeability, strength, and deformation.

3.3 Quality Control

Quality control is of primary importance during the filling of the borehole. Permeability and stress/strain characteristics of the compacted plug should be obtained on a completely automatic basis.

Several methods of instrumentation for obtaining this information on compaction for quality control are considered, accelerometer, plate bearing, nuclear density gage, and core sampling.

The various types of tests may or may not be applicable to the method of compaction being used. Individual or combination use of these devices in conjunction with a microprocessor could provide stress/strain characteristics on a continuous basis.

The measurement of the output characteristics of an accelerometer, mounted on an impact foot, would be correlated to the stress/strain and permeability characteristics of the plug. Similarly, a bearing plate test could provide the same information.

Nuclear density testing will furnish only density,^(3,4) which can be correlated by prior lab test to provide permeability on a periodic basis.

Core sampling will not provide an automatic continuous non-interruptive output sampling.⁽⁶⁾ This is a type of destructive sampling and probably should not be used except on a predetermined basis in in situ test holes only for correlation of data. Its value as a monitor tool is still doubtful because of the release of internal stress during the sampling process.

3.4 Natural Material

Natural material type, quality, and quantity will be dictated by the results of the borehole logging data. Logging shall be used to confirm the strata. From this, a geological map will be created and the materials required to plug the borehole will be selected.

A predictable compaction rate of volume and material requirements must be made available prior to the start of construction. This will ensure proper material acquisition and readiness, and an integrated production sequence with the most cost-effective program.

The natural material operation can be divided into several pertinent areas.

- (1) Confirmation of strata.
- (2) Procurement.
- (3) Material processing.

3.4.1 Stratification

Logging of open boreholes will provide a description of the significant properties of the sub-surface material. From these data and other measurements, a map defining the complex strata can be generated. This map, showing the geological profiles, will establish volumes and types of required fill.

The logging will be done under the direction of OWI. Quality control in the logging sequence must be a highly visible portion of the operation. As an example, conventional caliper logging of a hole determines the diameter to approximately 0.1 inch, which for an 8-inch hole would introduce a 2.5 percent error in volume.

It is an assumption of this report that adequate borehole logs are available.

From the stratification information, the fill material will be inserted in the borehole to be compatible with or to exceed the permeability and be of sufficient strength to maintain the stability of the adjacent stratum and the plug.

3.4.2 Confirmation of Stratification

The definition of the strata will be accomplished by an independent logging system or geological surveys. Analysis of this data will provide a basis for the determination of types and quantities of materials required. Specifications for the various types of material can then be written. A geological profile map, showing each stratum can then be made to assist in preproduction planning. Discontinuous layers, if detected through adjacent boreholes, may be neglected in developing the geological map. Scheduling of material delivery into the hole to match the existing stratum can be achieved.

3.4.3 Procurement of Natural Materials

Locating the necessary suppliers or on-site procurement may be possible. In either case, delivery to the site and safeguarding against possible contamination is required. Bulk transport delivery involves the handling of the material from the supplier to the site. This is an advantage over delivery in sacks by reducing the labor and lessening the chances of contamination. Dust-free tanks with pneumatic handling systems are commercially available and can be tailored to the specific use. Quality-assurance testing of all material received is required.

3.4.4 Material Processing and Storage

Material processing is the mining, milling, and grinding of the natural materials to the proper specifications as interpreted from the specification derived from the logging analysis. Quality control of the mixed material prior to downhole compaction is required to verify specifications set for optimum moisture content, granular size, and additional tests to be prescribed. Additionally, as new and different material mixes are required to match the downhole formations, means must be available to continually supply this material on a basis so as not to interrupt construction.

The mixing of more than one material and adjusting the moisture content of the materials, to obtain the finished product, will have to be considered an R&D task. There is no adequate commercial equipment available to perform this function. The completely mixed material must be stored in sealed humidity-controlled tanks while awaiting delivery downhole.

3.5 Surface Equipment

To support a borehole compacting program, the following subsystems are required.

- (1) Surface system.
- (2) Power system.
- (3) Air compressor.
- (4) Control system.

3.5.1 Surface System

Drilling rig capable of supporting a drill string of 8 to 24 inches in diameter at a depth of 10,000 feet. Design compatibility with a downhole compaction and material delivery system. Design considerations include temperature, gas vapors, mud, and water.

3.5.2 Power System

A main and auxillary electrical generating system capable of supporting all systems with adequate reserves.

3.5.3 Air Compressor

An air compressor with a capacity necessary to support operating requirements and free of oil contamination.

3.5.4 Control System

A closed-loop automatic control system designed to compact fill compatible with adjacent materials. This system will monitor all parameters and provide adequate readouts for visual observation. Provide for automatic shut down in case of failure and give audio warnings when a malfunction occurs.

All equipment and facilities will be considered to be in the mobile category and self contained.

3.5.5 Equipment

Of the several downhole compaction configurations proposed there are many common operational considerations.

- (1) Surface power systems.
- (2) Drill rig control.
- (3) Insertion of compaction system.
- (4) Insertion of material feed system.
- (5) Instrumentation and control.
- (6) Material storage and bulk mixing.
- (7) Operating personnel.
- (8) Safety.
- (9) Calibration and planned maintenance.

Compaction system designs investigated included static, impact, vibration, roller, and air/steam gun.

The designs investigated for a downhole material delivery system included gravity, conveyor, screw, bucket, and pneumatic.

3.5.6 Service Life

Based on the assumptions of fill rates in the order of 4 to 8 feet per hour, a Mean Time Between Failure (MTBF) of 2000 hours would be consistent with good production. With redundant units, servicing and repair of equipment would be scheduled on a production maintenance basis.

The mechanical component life cycle should be predictable. In any new design or equipment purchased, the harsh environmental conditions should be considered (temperature range up to 120°C).

SECTION 4

PROCESS VERIFICATION

Process verification will be an extended test program, using full quality-control functions, which must commence as soon as the potential test site is selected. Preliminary testing on typical expected soil materials as noted in the MIT studies⁽¹⁾, using quality control to establish testing equipment, methods, and procedures can start immediately. The lab test program will require extremely detailed recording and analysis of test operations and results. The test program and resultant construction plans for a specific site borehole will be dependent on accurate logging data and specific soil properties on the various strata.

The test verification program is required to address three major areas:

- (1) Material selection.
 - (a) Material types.
 - (b) Identification of characteristics.
 - (c) Chemical and physical analysis.
- (2) Mass balance.
 - (a) Weights.
 - (b) Hole diameter.
 - (c) Stratification.
 - (d) Yielding of sidewall.
- (3) Indirect testing - correlation of indirect with direct measurement.

4.1 Material Selection

The MIT study proved that the source from where natural earthen material is obtained has a direct effect on the physical characteristic

(permeability) results after compaction. Careful attention must be paid to the source and condition of the various materials. Then as plugging requirements for a particular stratum are known, the proper material may be selected which can match or exceed the required specifications.

The prime requirement for the plug is the permeability measurement, but during these tests and the selection of materials, it must be kept in mind that the mechanical characteristics are also important. The strength and deformation characteristics must also be achieved in compaction without causing harm to the borehole sidewall. To achieve the permeability level without having to use too much input energy, other natural materials (e.g., clay) may be added as well as molding water content adjustments. The maintenance of quality-control records during these tests will allow later selection of the proper materials and mixtures to meet necessary plug parameters.

4.1.1 Material Types

Only natural earthen materials will be used in the plugging operation. The reason for this is that geological history has proven that natural materials have the strength and permeability to effectively seal and protect lower formations for tens of millions of years. No manmade material has survived more than a few thousands of years.

Geological charts and past drilling history in site areas will allow the start of a search for basic natural materials. Some of the materials have been used in the MIT study. As borehole logging data on specific holes becomes available, additional materials may have to be located.

4.1.2 Identification of Characteristics

As the basic materials become available, extensive testing must be done using the recommended compaction methods in lab equipment. The result of careful testing of various materials and mixtures will give sample plugs which must be tested for all pertinent characteristics. See Part 2.

4.1.3 Chemical and Physical Analysis

To ensure proper matching of fill material to plug formation, and for future plug requirements, the exact material parameter must be

known. This can only be done by a complete chemical and physical analysis. This may have to be done twice; once as incoming raw material and again after processing, to ensure no harmful effects were introduced during processing.

4.2 Mass Balance

In the plugging operation, the amount of material used in a particular borehole will change according to many variables. The series of lab tests will give detail information as to how much loose dry material of any given type is necessary to form a plug section (by volume) to various mechanical parameters and permeabilities. The variables are as follows.

4.2.1 Weights

The bulk material will be controlled as dry loose material. The tests with various mixtures to required parameters will give the necessary dry-weight-volume to plug-weight-volume ratio.

4.2.2 Hole Diameter

In order to determine the volumes of plug fill material required, the hole diameter and variations must be known accurately. An error of 0.1 inch in the diameter will introduce a 2.5 percent error in volume. This points out that in a seal strata formation, where permeability is important, the volume of material placed in an assumed known section can not be a criterion for density and permeability results.

4.2.3 Stratification

The types of strata formations and their depth must also be known to establish necessary material types and quantity.

4.2.4 Yielding of Sidewall

The borehole sidewall constraints or yielding will also have an effect on the volume of fill material. The test compaction molds should be designed to each sidewall yield strength. If this is done, then the material volume ratio should be a direct result of the tests. Care must also be exercised to ensure optimum input energy is used for specific material and plug characteristics. This is so that the sidewall structure is not damaged by overcompaction.

4.3 Indirect Testing

For in-process monitoring of the downhole plug, instruments must be calibrated to ensure that the proper characteristics are achieved. The recommended compaction methods, static and impact, require at least three methods of quality-control in-process monitoring. These will be accelerometer, bearing plate tester, and nuclear gage. None of these instruments directly measures the most important parameter, permeability. The accelerometer and bearing plate tester, used in impact and static compactors respectively, will give continuous strength and stress/strain measurements with each compaction operation. The nuclear gage will give density measurements at selected intervals. These indirect measurements must be correlated to permeability measurements for each material mixture.

Therefore, during the test program where direct plug characteristics can be monitored, the required instruments must be calibrated to produce a reliable indirect measurement. This indirect measurement must be correlated to the direct measurements. These indirect measurements will be used for quality control during the compaction operation.

4.4 Borehole Formation

For the purposes of this report, an adequate logging of the specific boreholes is assumed. In order to complete the above related tasks, the logging data must furnish the following minimum basic information.

- (1) Hole depth.
- (2) Hole diameter.
- (3) Strata material analysis. (For each stratum)
 - (a) Chemical and physical analysis.
 - (b) Permeability (local and remote).
 - (c) Deformation characteristics.
 - (d) Shear strength.
 - (e) Stratum depth and thickness.
 - (f) Stratum sidewall yield (modulus).
- (4) Type and analysis of drill mud used, if any.
- (5) If and where cement or grout used.
- (6) Local gravity (check for local voids or fluid reservoirs).
Potential problem areas.

- (7) Possible pressure testing for strata fractures.
- (8) General hole conditions (wet or dry mud).
- (9) Water flow and quantity, if any.

4.5 Lab Test Data Requirements

As previously stated, all testing must be done under full quality control. All parameters⁽⁷⁾ of the test program must be recorded and the results matched to specific formation requirements. Following is a list of the natural material and test parameters which must be recorded. This list, as studies advance, may have to be expanded.

- (1) Natural material (each).
 - (a) Complete chemical and physical analysis.
 - (b) Exact location of origin.
 - (c) History of processing.
 - (d) Condition prior to mix.
 - (e) Past history of existence in natural formations and what, if any, potential for change when mixed with other materials.
- (2) Mix ratio of different natural materials.
- (3) Moisture content.
- (4) Mold used and its parameters (sidewall yield).
- (5) Method of compaction.
 - (a) Type of compaction (static, impact, etc.).
 - (b) Energy input (force, rate, lift, etc.).
- (6) Permeability.
- (7) Density.
- (8) Swell.
- (9) Shrinkage.
- (10) Shear strength.
- (11) Lateral stress.
- (12) Indirect monitor equipment characteristics.

Careful comparison between borehole logging data, past geological studies of the typical formations, and the lab test results must be made. From these comparisons, an operation process chart for filling the particular hole can be made. This chart will detail each operation of the plugging operation, and necessary check points.

All of the process verification must be closely monitored by experienced quality-control personnel for exacting control of all parameters. This includes recording and verifying original logging data, natural material source and processing, laboratory testing, cross comparison of all data, operation process charts, in-hole quality control, and certification of all equipment used in any of the operations. The quality-assurance and quality-control function will be a very large-scale operation and will require extensive control over the entire operation. However, it is a mandatory function which will be the only means to ensure each operation is done properly. The only way to ensure the necessary 200,000-year life expectancy is to have a tight quality-control program.

SECTION 5

LAB TEST EQUIPMENT

Dynamic standard test equipment is available for lab compaction testing by static, impact, and vibratory methods. Some equipment is listed in Reference 1. However, from the report, the limits of these particular commercial units were reached. With a minimum of design, the capacities of these units can be increased to reach any necessary lab testing requirements, particularly if in future testing, larger molds are desired. However, because of the unlimited field of materials which may ultimately be tested, effort was not extended into any design considerations of lab equipment in this study.

5.1 Static Compaction

Static compaction can be achieved by two means. The basic concept is to apply a known static load for a known period. This can be done simply by adding weights to the pressure foot or by using a hydraulic ram. The hydraulic ram system would be the most universal.

5.2 Impact Compaction

Impact dynamic compaction can be achieved by two means, also. The basic concept is to apply an impact load by gravity or force drop. The gravity drop has no reaction force while the force drop has a small reaction force.

5.3 Vibratory Compaction

Vibratory compaction can be achieved by two means. The basic concept is to apply a vibration or shaking force through the material. Vibration input is done by using an electromechanical oscillator on the material to allow soil particles to realign into a denser formation. In a test lab, this is usually accomplished by using a vibration table, but in the field it must be done by using a vibrating rod. Power is

introduced either by electronic oscillators, electromechanical source, or by explosive charges. One other method is the use of water-jet aggravation which is not recommended. All these means have a lesser effect in forming a dense stratum and are limited to use in cohesionless soil materials (sand, gravel, etc.).⁽⁸⁾

5.4 Roller Compaction

Roller compaction is the main means of compacting soils in the field. The basic concept is to simply apply a kneading action to the soil by rolling a weighted wheel across shallow layers of soil. The roller face can have a smooth surface or a knobbed face depending on the soil characteristics. Standard lab equipment is not available. The development of a roller test station, however, would not be difficult. The main problem, even in an 8-inch-diameter hole, is the small roller diameter which could be used and a drive mechanism for the rollers themselves. Again, note that the effectiveness of a roller and the texture of the roller face is dependent on the particular soil characteristics. The roller effectiveness can be improved by use of a vibrator on the rollers. Roller compaction would give the best compaction and mechanical adhesion at the borehole sidewall interface due to the roller action and kneading near the plug outside diameter. The roller compaction system would give less reaction force than static, but more than impact.⁽⁹⁾

5.5 Air or Steam Gun Compaction

Air or steam gun compaction was investigated in the MIT study.⁽¹⁾ The basic concept is to accelerate soil particles with an air stream so that they impinge the working face of the plug. The densification of the applied soil is dependent on the impact force and adhesion qualities of the material. It is not believed that laboratory testing equipment of this type is available commercially. MIT developed their own test equipment which fired preformed and compacted pellets in which the moisture content was closely controlled and acceleration was accomplished by air.

In a system designed for bulk production, the supply of pellets of loose soil material with a closely controlled moisture content may be difficult. With this in mind, it may be possible to use steam to control the moisture control of the soil as it is accelerated.

Development of equipment to run laboratory tests would not be too difficult. The main problems with this method would be in the downhole operation and the lack of quality control. These problems would be control of the nozzle face to the working face, supplying large volumes of air or steam downhole (pipe losses very large), and material losses by being blown back out of the hole with the exhausting air or steam. Generally, this method is not acceptable.

5.6 Test Molds

In all testing, no matter which method of compaction is used, the size of the mold and its sidewall stiffness must be controlled. The mold size will be determined by the capacity of the testing apparatus for the particular method of compaction. When the final method or methods of compaction are selected, it will be advisable that all the necessary molds be a common size for ease of comparison and for limiting accessory inventory.

The sidewall properties of the molds will have to vary in stiffness to approximate the borehole conditions. The borehole sidewall stiffness or elasticity will vary with strata formations. The permeability achieved with a known energy input in a firm confining sidewall will not be repeated in an area of a less confining sidewall strata or vice versa. This effect on density and resultant permeability showed up in the MIT studies where the different mold sidewalls changed thickness only slightly.

5.7 Materials Under Consideration

Whereas the main objective of the plugging operation is to fill the borehole, replacing each stratum with similar natural earth material to achieve similar permeability and mechanical strength to prevent motion, the material selection is wide open. This study did not concentrate on specific materials, but on general characteristics such as cohesive and cohesionless. In this study, no type of compaction has been dropped because of material types or characteristics. However, from the range of materials used in the MIT study and from the results shown, it will be possible to replace the soil strata using a mechanical compaction process and obtaining necessary mechanical strength and permeability.

Once the site is selected and the general materials are known, the necessary testing and material source selection process can begin. Then, the final refinements and perhaps an expanded selection of materials (as the boreholes are drilled or old holes are logged accurately) can be made.

From the generally available geological data now on file covering proposed site areas, an expanded testing program can start immediately. This also covers the selection and development of the necessary laboratory and field equipment and a full quality-control program.

In general, the only required changes will be in the input energy requirements and the size of the material lift to meet permeability, strength, and deformation requirements. These parameters will vary from material to material and the particular compaction method.

5.8 Performance Verification of Test Equipment

The quality assurance for the successful plugging of a borehole will only result from a good quality-control program. Only the detail recording of all data in the testing program, to establish reliability and repeatability, will give the assurance required to meet the program requirements. This quality control includes the complete control over all natural materials, mixtures, tests, methods, and comparison to the strata data from the boreholes. This resultant data bank will eventually expand so that as the changes between holes at a given test site are done only a minimum amount of testing will be required. At this point in time, only batch samples of the new fill material may have to be tested to verify repeatability. Refer to additional information in Part 2.

SECTION 6

COMPACTION METHODS

(14) The process of densifying, i.e., compacting, soil is the oldest and most important method of soil stabilization. Compaction alone will often solve a particular soil problem and is usually the most economical of the techniques available.

In compacting any particular soil, the engineer can vary moisture content, amount of compaction, and type of compaction. As will be pointed out later in this section, the compaction characteristics of the soil can also be varied by means of chemical additives. A considerable amount is known about the effect of moisture content and amount of compaction on the properties of the compacted soil; unfortunately, less is known about the effects of types of compaction.

The most desirable combination of the placement variables depends on the particular soil and the particular set of properties desired. Varying each of these placement conditions of the soil has an effect on such properties as (1) permeability, (2) compressibility and swellability, and (3) strength and stress-strain characteristics.

Compaction is the process of condensing a volume of material into a higher density form by transient loads without the extrusion of water. The process of compacting soil particles is accomplished by forcing the individual particles to rearrange their orientation so that there are little or no air voids between particles.⁽¹⁰⁾ In nature, this is accomplished over a long time space by consolidation which involves water extrusion and then as the strata build up, by the tremendous weight and heat caused by the succeeding formations.

In the case of replacing the natural soil strata in boreholes, the process can be accomplished by mechanical means only. There are various methods by which this can be accomplished. However, in working in a deep small-diameter borehole, the generally practiced means are not possible. MIT has made a study of various means to successfully

compact some common soil materials.⁽¹⁾ The report shows clearly that the basic natural materials can be compacted to required permeability, sufficient to seal boreholes (see Table 6-1).

Permeability of a clay soil is a function of molding water content, dry density, and type of compaction. For a given type of compaction, density increases at a decreasing rate with an increasing energy input. Permeability decreases as density increases.

By alternating compaction methods to obtain the best results for a particular material, and by using natural additives (e.g., clay), the resultant plug closely simulates the pertinent properties of natural strata.

There is no equipment on the commercial market for downhole compaction. However, there is equipment used in the drilling industry which may be modified. Another reason for modification of commercial equipment is that no provisions are made for quality control. The equipment is listed in the area covering the specific method of compaction.

Studies have shown the importance of the material selection and source, as well as the moisture content, and type of compaction in reaching the desired parameters. These factors and the soil characteristics also dictate the method of compaction. Table 6-1, condensed from the MIT study, shows a relative comparison of materials, methods, and input energy required in the laboratory tests with resultant permeability values (the most important characteristic requirement in borehole plugging).

Before any field operations can be started, extensive laboratory tests must be done by the methods selected, on the particular soil types found at the borehole, and with fill material from selected sources. Throughout the testing program, the exact method of compaction for the soil characteristics and resultant parameters will dictate the particular energy input requirements.

6.1 Static Compaction

Static compaction is the process of compressing the material into the required density by applying a known static force. In field operations this can be accomplished by two basic means. The first and simplest is by the use of commercial drilling weight collars. The second method is by use of a hydraulic ram.

Table 6-1. Typical permeability data by various compaction methods.*

	Dry Density pcf	Water Content (%)	Permeability in Micro- Darcey (μD)	(Input Force/ Energy MIT Test (lb/in. ²)	Input-Force/Energy		
					8 Inch dia.	12 Inch dia.	24 Inch dia.
<u>STATIC COMPACTION</u> (1.2-Inch Dia. Tamper, 3.5-Inch Long Sample)							
Montmorillonite (MT)	69	7	0.09	100	5000	11,310	45,400
Sodium Chloride	103	--	--	6500	278k	629k	2580k
Ninnescah Shale (Core)	125.7	12.5	0.1	4000	171k	387k	1588k
Ninnescah Outcrop	125.7	12	0.12	4000	171k	387k	1588k
Dewey Shale Outcrop	120.7	10.7	4.4	4000	171k	387k	1588k
Conasauga Shale Outcrop	129	11.4	1.7	4000	171k	387k	1588k
65% Sand + 35% MT	110	2.0	0.11	1000	43k	97k	397k
80% Dewey Lake + 20% MT	119	15	0.25	1000	43k	97k	397k
80% Gypsum + 20% MT	99	18.6	0.74	1000	43k	97k	397k
					(lb-ft)	(lb-ft)	(lb-ft)
<u>IMPACT</u> (1.2-Inch Dia. Tamper, 3.5-Inch Sample)							
Ninnescah Outcrop	126.1	11.2	0.09	6750	256k	578k	2,371k
Ninnescah Core	130.6	11.4	0.18	2250	85.3k	193k	790k
Dewey (DL) Core	132.8	10.2	0.13	2250	85.3k	193k	790k
Dewey (DL) Core	136.7	6.5	0.19	2250	85.3k	193k	790k
80% DL + 20% MT	126.0	12.0	0.10	1125	48k	109k	447k
80% Gypsum + 20% MT	105	24.0	0.06	379	17k	37k	150k

Table 6-1. Typical compaction data by various compaction methods. (Cont.)

	Dry Density pcf	Water Content (%)	Permeability in micro-Darcey (μ D)	Input Energy in MIT Studies
<u>PNEUMATIC</u> Dewey	141.7	7.5	0.08	50 lb, 5.5 inches, 1/4-inch dia. 5 blows/3 tsps./83 lb/in. ²
<u>KNEADING</u> 100% Ninnescah Core 90% Ninnescah and 10% MT	101 103.4	19.1 21.7	627.0 1.8	5 layers, 25 blows, with 40 lb on 0.5 inch dia.
<u>AIR GUN</u>	119	22	---	2-gram pellet, 40 lb/in. ² , 500 cm ³ air

For reference only. Permeability (μ D) is the standard for comparison.

*Scaled to typical borehole sizes.

In the laboratory test program, a hydraulic ram was used with input pressures ranging from 100 to 6500 lb/in.² (see Table 6-1). The range of pressure reflects the reaction force from various soil types, and before any field operations can be conducted, an exhaustive testing program on the particular soils must be conducted. As low as 100-lb/in.² input energy was used for clay, while shale and salt required 4000 and 6500 lb/in.² respectively to get satisfactory permeability levels.

In static compaction using collar weights⁽¹¹⁾ (see Figure 6-1), the equipment is commercially available. Because of the weights required (Table 6-1), plugging operations would be limited to a 12-inch-diameter borehole maximum. Using an 8-inch-diameter hole as a standard, the required weight would be 171,000 pounds for a working face pressure of 6000 lb/in.² This would require 2000 feet of 8-inch outside by 3.5-inch inside diameter drill collar weights. Various sizes of collars are available so the dimensions can be changed slightly with a corresponding change in length. As an example, using this method on a 24-inch diameter hole, a 1,588,000-pound load would be required. This would be more than most drill rigs can handle.

Standard drilling equipment can handle weights of this magnitude for up to 12-inch-diameter holes, so the use of standard collars is practical except for three problems which must be resolved. The first is material supply. Any kind of downhole operation for material supply would be in two stages. The first, from surface to the top of the collar section, and then the 2000-foot feed through the collar section. The second problem is the setdown rate of the drill string and collar assembly. Any impact from this amount of weight would overcompact the plug and possibly cause fracturing of the hole sidewall. This also would be a potential problem if, for example, a shale strata was directly above a clay formation. The shale would compress the clay to the high limit where any swelling of the clay would damage the sidewall strata. Experiments would have to be conducted to evaluate this type of situation and just how the force is applied, and at what rate.

The third problem is how a hole less than 2000-feet deep should be handled. The only possible solution would be to add surface-mounted weights as the sections of drill collars are removed. This would require a second, more standard, source of weights.

Figure 6-1. "Drill collar" static compactor.

The previously mentioned magnitude of weights would be for a salt or shale type material. In a clay strata as shown in Table 6-1, the static weight would be approximately 5000 pounds. The problem is how to limit the weight. As an example, for a 100-lb/in.² load at the working face, only 5000 pounds would be required. A drill string of 6-inch diameter and 5000-foot length will weigh approximately 60,000 pounds. In this case, the drill string would have to be hung from a force gage and when set down, lowered only enough so the force gage still has a weight load of 55,000 pounds. See Figure 6-1 for weighted static compaction sketches.

A second static compaction method would be through the use of a hydraulic ram. No commercial equipment for this application is available.

The design and development of a hydraulic assembly for this task would not be too difficult. The entire unit should be located at the bottom of the hole for ease in handling. If a 6-inch-diameter ram is used, a working pressure of up to 10,000 lb/in.² would be required. Working with this pressure, the lines must be short and not something to be assembled and disassembled working in a drill string. The problems to be overcome with this method would be the supply of material around or through a minimum of a 7-inch overall diameter ram assembly and the clamping of the string assembly to counteract the resultant upward push.

The supply of materials past the ram could be solved if a ring of rams about 2-inch-diameter each were used. However, the smaller rams would require a higher pressure of up to 16,000 lb/in.² (see Figure 6-2).

Travel time for a 6-inch ram to travel 3 feet (maximum) using a 6 gal/min pump would be 45 seconds. Depending on the size of a given lift and the amount of clearance required under the ram foot for material spreading, a lift compression cycle time of 1 minute is reasonable. If a hold pressure is maintained (as in previous tests) for 1 minute, then a cycle time of 2 minutes would be required.

The hydraulic ram type instrument assembly would be the easiest to handle and the most versatile to adapt to the various soil material types. The hydraulic pressures can be monitored and controlled remotely to adjust the pressure as required. See Figures 6-2 and 6-3.

Figure 6-2. Hydraulic static compactor.

Figure 6-3. Combination static and impact compactor.

The major problem relative to a hydraulic system is clamping the working string to give a 300,000-pound (min) anchor. The surface unit and the string itself cannot hold this load. A possible solution is the use of a packer type unit just above the hydraulic assembly. If the packer is about 40 feet long, inflated to 125 lb/in.² and can maintain a sidewall friction coefficient of 0.2, it can act as an anchor. Possibly, commercial packers working in series could also do the job.

In both methods of static compaction, the in-process monitoring is not difficult. The monitoring of weight and pressure is no problem and can be handled using commercial items and minor electronic design. The depth of the hole and working face can be monitored from the surface. The travel of a hydraulic ram can be monitored also, using a commercial or custom Linear Variable Differential Transformer (LVDT).

Through the use of bearing force of the compactor and the monitoring equipment, the entire unit can act as a monitoring tool. It would act as one large bearing plate tester (California Bearing Ratio Test) with each applied load. This test would give a direct reading of deformation (stress/strain), which can be correlated in lab tests to strength and permeability. Another method of monitoring is to have a nuclear gage, to monitor density, built into the working face. This can be correlated through lab tests to permeability, strength, and deformation requirements.

If the prior borehole logging accuracy is sufficient, the hole depth and material usage will give verification between the various methods.

Table 6-2 lists advantages and disadvantages of the static compaction system.

6.2 Impact Compaction

Impact compaction is the process of densification using a falling or driven weight traveling a known distance to impact on the working surface. There are various methods by which the process can be accomplished. Between the various methods of compaction, the impact compaction process is probably the most versatile. It is possible to perform impact compaction from the surface or at the bottom of the borehole. In the laboratory (Reference 1), satisfactory compaction of all tested materials was accomplished using both a dropweight, kneading, and pneumatic compactors. See Table 6-1.

Table 6-2. Static compaction, advantages and disadvantages.

Advantages	Disadvantages
<p>Relatively simple method.</p> <p>Basic hardware is state-of-the-art.</p> <p>Good quality control on plug continually during construction.</p> <p>Little or no wear.</p>	<p>Limited to 12-inch diameter (maximum) because of force and reaction.</p> <p>To change input force, weights must be added or removed in weight collar system.</p> <p>Material feed problem in weight collar system (poor quality control).</p> <p>Hydraulic system anchor.</p> <p>Possible oil contamination in hydraulic system.</p>

The simplest approach to using impact compaction would be to have a guided weight at the bottom of the borehole, connected by cable to the drill tower. The cable can then be lifted and dropped by the use of a winch or small walking type beam mechanism. The typical input energy used in lab testing of a 3.5-inch sample of shale was approximately 2250 pound-feet. This same force scaled to an 8-inch-diameter hole would be about 85,000 pound-feet. If a weighted cylinder of 300 pounds was used downhole, the drop distance, by varying the lift height and number of blows per lift, can be varied to get wide range of input energy. Testing will give a weight and drop so an optimum compaction system can be developed. See Figures 6-4 and 6-5.

Another method is the development of a drop hammer assembly for downhole use. There are commercial impact drills⁽¹²⁾ for downhole operations which are covered later. Figure 6-6 shows a possible drop hammer which could be developed. In Figure 6-3, it is shown as a combination tool also incorporating a hydraulic ram static compactor.

In this proposed concept, the weight is the center mass which is raised by a linear travel motor. The motor winding is a fixed coil and the mass acts somewhat like a solenoid plunger. Electrical power would lift the weight to the desired height (variable) and when the power is cut, the hammer weight falls. Although a few vendors produce small linear motors, none are sized to lift 300 pounds. However, one

Figure 6-4. Simple surface-powered impact compactor, cable held and operated.

Figure 6-5. "String" impact compactor.

Figure 6-6. Percussion drill hammer compactor.

firm believes it would be possible and if approached in a development program could develop one. The firm is "Polynoid Linear Motors" (Skinner Polynoid Division, 95 Edgewood Ave., New Britain, Conn. 06050 Phone (203) 225-6421) and in their standard line, they have a 3-phase, 460-volt, 60-Hertz, 7.6-ampere, 11.8-inch travel, and 54-pound stall force. In this application, the motor would have to be at least six times larger. Another inherent problem is the self heating of the motor. Therefore, heatsinking or cooling would have to be researched.

There is, on the market, an air-driven percussion drill. The vendor is "TRW Mission Manufacturing Company, a Division of TRW Inc., P.O. Box 40402, Houston, Texas 77040. The range of standard drills is from 3 to 10 inches in diameter. The 3-inch-diameter unit has a kinetic energy range of 158 to 263 foot-pounds/blow and a frequency of 1100 to 1400 blows per minute, depending on air pressure. The 6-inch model has a range of 530 to 1050 foot-pounds per blow and a frequency of 950 to 1250 blows per minute, depending on air pressure. A representative of Mission claimed a normal working depth of 2000 feet and they have been used to 5000 feet. The limiting factor, as far as depth is concerned, is the supply of air. However, the air supply they require is not only for power but chip removal. (See Figure 6-6).

In order to use this type unit it would have to be redesigned to limit and control the number and force of the blows by changing air pressure. At the pressure and rates needed, without chip removal, the working depth could be greatly increased.

One disadvantage of the air hammer assembly is that at the end of the required blows per lift, the unit must be raised clear of the working face for the application of the next lift. An alternative to this is to have the air supply lift the piston and foot assembly such that there is room for the fill material to pass by and spread across the working face.

A development program will be required for each of these assemblies for holding, foot design, material feed, and monitoring the input energy as well as the soil density during the compaction.

In each of the methods, LVDT sensors can monitor travel and count the number of blows. For a density measurement, two methods could be used. First, a bearing plate tester using the tool and load cells previously mentioned (Section 6.1), and second, an

accelerometer could be mounted on the impact foot. Testing with various soils and sidewall constraints would have to be conducted to evaluate and document hammer deacceleration versus density. The accelerometer on the hammerhead would give a direct reading, with each blow, of the stress/strain characteristics of the plug. This could be correlated to soil permeability, and deformation characteristics during the testing program. Also a nuclear gage could be built in for a third monitor system.

Figure 6-3 is a proposed assembly in which static and impact sets of tooling are combined. A unit of this type would be a complete tooling development program. The unit would be fairly complicated, compared to current drilling practices, on tooling complexity.

A filling rate, as proposed in the MIT study,⁽¹⁾ of 1 foot per hour using 0.2-inch lifts and 5 blows per lift can be obtained. Filling rate must be set by various material characteristics, coupled with input energy established from a testing program, for desired permeability requirements.

It may be possible to use larger lifts and greater input energy to increase filling rates. This can only be determined by an expanded test program with increased capacity testing apparatus.

Except for possible overheating problems with the linear motor, the impact compaction methods may be a continuous process where small lifts of natural earthen material are fed to the face with each blow.

Because of the available energy input through impaction methods, without a vertical reaction force, tooling can be hung from a cable or smaller diameter drill pipe. In either case, power and signal cables can be fed down beside the cable or pipe from a drum storage reel. This would greatly ease the handling problem.

An automatic takeup system could be built in using the LVDT data (as the working face moves up, the assembly is lifted a known increment).

Table 6-3 lists advantages and disadvantages of the impact compaction system.

6.3 Roller Compaction

Roller compaction is the process of densification using a heavy weighted roller to kneed and compress the soil. Although this is the

Table 6-3. Impact compaction, advantages and disadvantages.

Advantage	Disadvantage
<p>Various methods to monitor energy input from commercial hardware.</p> <p>Wide range of input energy without vertical reaction force.</p> <p>Range of input energy provides good quality control during construction.</p> <p>Units can range from very simple surface-controlled to downhole units.</p> <p>Compaction foot can be rotated during lift cycle to cover material feed opening.</p> <p>May be used for continuous feed and operation. (No idle time as in static operation.)</p> <p>No possibility of oil contamination.</p> <p>Automatic or semiautomatic take-up during construction.</p> <p>Good quality control.</p>	<p>Reciprocating part wear.</p> <p>Electric motor type may have development and heating problems. Weight (armature) must be good electrical conductor (aluminum, copper, or silver).</p> <p>Without care, overcompaction can cause damage to sidewalls.</p>

most common method of soil compaction in the field, nothing exists on the commercial market for downhole construction to the best of our knowledge.

A roller compactor requires the rotation of the roller assembly within the hole, as well as the rotation of the rollers themselves. Without the rollers being driven, they would just slide around due to the weight and small roller diameter required. This sliding or plowing of the fill material would not give any compaction. Because of the hole diameter (8 inches), motors of sufficient size would not fit. A solution would be to have a gearbox with the input shaft driven from the surface. The output shafts would have to be concentric and driven at different speeds. With the use of a gearbox there are various problems which must be overcome. The foremost is getting a sufficient gearbox in this diameter hole and having clearance for material feed. The next is clamping the gearbox to the sidewall to prevent rotation (a packer type unit could be used). The rotating drive shaft from the surface may also be a problem. If the drive shaft can be maintained in tension, it may not be necessary to have spacers to hold concentricity. Shaft spacers would create material delivery system problems.

For a roller tool to work in the small diameter, it is proposed that a three-cone rock drill be modified. The modification will consist in replacing the knobbed cones with smooth rollers. The cones would have to be cut as gears so that the center shaft drives the rollers. This feature of exposed gears on the inner diameter is bad from a wear standpoint. Frequent changes of the roller assembly and roller drive shaft would be required (see Figures 6-7 and 6-8).

The roller section must be weighted and variable, depending on the soil type. As the plug is built up, the unit must be advanced some reasonable distance before the packers need to be released, and the entire unit lifted for the next section. The weight and travel with buildup would have to be an automatic servo loop.

Another alternative (other than a gearbox) is to use a triple pipe string. This method would be difficult to handle, but is feasible (see Figure 6-9).

To monitor the soil during construction, two methods could be used; either the bearing plate test, using the assembly, or a nuclear gage as outlined in Section 6.1. In either case, the roller section would have to be stopped so as not to interfere with the unit's operation. An aid in achieving compaction would be to add a vibrator unit to the assembly. This is a standard procedure in normal roller compaction.

There are no tests on roller compaction which can be related to this type program. In general construction, 60- and 80-ton units (200 to 400 lb/in.²) make numerous passes over the compaction area until core samples show the desired density has been achieved. As a result, extensive testing must be performed to determine if this concept is feasible. Also, the method of compaction and its success is highly dependent on the material characteristics and the roller configuration. On some materials, a smooth-faced roller is not effective. Cohesionless soils generally compact with a smooth roller, while plastic or clay soils require a knobbed (sheepsfoot) faced roller.

The units, as outlined in Figures 6-8 and 6-9, can be continuous operation up to the point of either packing or travel limit. The rate of construction is impossible to determine at this time because it is unknown what size lift can be worked. The rate of rotation can be controlled from the surface rig.

Figure 6-7. Modified rockdrill, smooth cone rollers.

Figure 6-8. Roller compactor, surface-driven.

Figure 6-9. Roller compactor, downhole gearbox.

Table 6-4 lists advantages and disadvantages of the roller compaction system.

Table 6-4. Roller compaction, advantages and disadvantages.

Advantages	Disadvantages
Continuous construction.	Quality control more difficult.
Simple material supply to working face.	Method not proven (needs test program) for downhole operation.
In general construction, a proven method.	No standard equipment.
Built-in scraper keeps roller clean (except sheepsfoot or textured rollers).	Tooling development and test required.
Uses less total force.	Double or triple pipe string difficult to handle.
Utilizes standard drill equipment and surface drive.	Different materials may require different roller face configuration.
Would compact near wall to give better adhesion mechanically.	
Low reaction forces.	

6.4 Vibratory Compaction

Vibratory compaction⁽¹³⁾ is the process of shaking the soil particles into best-fit configuration so that few voids exist between particles. Vibratory compaction has been done by various means such as explosion, shake tables, mechanical vibrators, and water jetting. From past experience, vibration is limited to cohesionless soils such as sand or gravel.

The only commercial downhole vibration compactor is a gravel or sand water-jetted process made by B & W, Incorporated, 19706 South Normandie Avenue, Torrance, California 90502. This unit is used to line the outside annulus of perforated pipe in water, oil, and gas wells. It would not be too useful in plugging a borehole to meet the program requirements.

To develop a vibrator, two methods may be used. The first would be an electromechanical device where electric motors swing weight masses, causing the vibration. The second method would be limited to use of an electronic oscillator.

Because of the space limits, the development of the electromechanical unit may be very difficult. The motors and weights may fit, but there would be little or no space left for material supply.

The electronic oscillator type could be developed to fit in the required size and still leave room for material feed. See Figure 6-10.

In operation, the soil material is fed in the middle of the hole between two or three vibrating rods. The rods, to be effective, will extend 6 to 8 inches down into the compacting soil. A sensor, on the side of the assembly, is used as a level monitor. As the soil level builds up, the assembly is lifted to maintain a set distance. When desired, the vibrator can be shut off and stress/strain measurements can be taken by a bearing plate tester or a nuclear gage, possibly used as discussed in Section 6.1.

Before development, experiments to determine energy requirements and results must be completed to determine if such a unit would be worthwhile. The process would be limited in use to specific soil which responds to the vibration. However, in a sand-type soil, this method would be continuous and completely automatic.

Table 6-5 lists advantages and disadvantages of the vibratory compaction system.

Table 6-5. Vibratory compaction, advantages and disadvantages.

Advantages	Disadvantages
Tooling would be relatively simple.	Quality control difficult.
Adaptable to fully automatic operation.	Limited basically to cohesionless soil.
Can be cable-operated system.	Not proven by testing.
Few wearable parts.	No commercial equipment available.
Low reaction force.	
Light equipment downhole.

Figure 6-10. Vibratory compactors.

6.5 Air/Steam Gun Compaction

Air or steam gun compaction is the process of densification using an air or steam jet to impinge the soil particles against the working face. The MIT study⁽¹⁾ performed limited testing in this area by forming soil into pellets and using air pressure to accelerate the pellets for impaction on the working face. The process was done in two stages. First a pellet must be formed and then it must be installed in an air gun for firing. This process would be too slow and complicated for downhole operations.

Another method is to feed a dry material mix to a mixing chamber located just before a nozzle. In the mixing chamber, a moist-air or steam jet, under high pressure, is fed in to drive the material through the nozzle and against the working face. This method of compaction requires a higher moisture content of the soil in order to achieve compaction. Therefore, moist air or steam must be used. If the soil mixture had the moisture content added at the surface, there is danger of sticking and plugging of the feed lines.

The studies performed indicate that the distance from the nozzle tip to the working face is very critical. It must be maintained between 1 and 2 feet, but this would have to be determined after future studies and experimentation. Also, in an 8-inch-diameter hole, the nozzle would have to be oscillated to cover the entire working face to get an even buildup. In an area of enlargement of the hole diameter, there may be a problem reaching the outer parameters unless built-in features detected the enlargement and the oscillation range was increased. With this method there are many problems.

While this type of composition has been used above ground, i.e., gunite[®], it has not been developed for small-hole application. A Waltham, Massachusetts firm, Foster Miller Associates, has just developed a similar piece of equipment for lining large-diameter boreholes (9 to 16 feet) with a quick-set concrete. The dry-mix material is mixed with water and air and pumped down the borehole to a revolving nozzle to form a 4- to 6-inch concrete coating on the sidewall. The system is automatic and works from the surface down. Foster Miller Associates is a firm specializing in mining-equipment development and production.

A second problem is the amount of air/steam required. This is a two-phase problem; the first is getting sufficient air/steam downhole to give the required energy. The next is that the soil particles, if loose, can be washed to the surface with the exhausting air stream. The pressure losses due to friction and turbulence are very large when trying to move large volumes of air. As stated in Section 6.2, impact hammers using large volumes of air are basically limited to 2000-foot depths.

The delivery of materials in an air stream, in a dry condition, eliminates potential sticking and jamming problems. However, this system would require two and maybe three pipes from the surface (and difficult design). This would complicate handling. The delivery of bulk material at intervals and mixing with moisture and air downhole would eliminate one pipe string. Material mix would in all possibilities have to be done at the surface and not downhole.

The quality control in this method would be more difficult to handle. The mixing and moisture content control, which is critical would be very difficult to monitor. To monitor stress/strain or density, the system would have to be shut down while measurements are taken. The stress/strain measurements could be taken by a bearing plate tester or a nuclear gage for density monitoring as stated in Section 6.1. Another in-process monitor problem is maintaining the critical dimension from nozzle to working face. The spraying of damp soil particles will cause coatings to stick to all possible monitors and give faulty readings.

Table 6-6 lists advantages and disadvantages of the air/steam gun compaction system.

6.6 Compaction Comparison Matrix

The five basic compaction schemes (static, impact, vibration, roller, and air or steam gun), for which conceptual designs have been presented, were selected as potential methods to achieve program goals. All of the schemes presented are technically feasible and could be developed through future testing to produce a satisfactory mechanically sealed borehole. However, the amount of research and development, as well as mechanical limits due to various soil properties, cause a considerable degree of risk which the program must consider. Any rating at this stage must be based on engineering

Table 6-6. Air/steam gun compaction, advantages and disadvantages.

Advantages	Disadvantages
<p>Possibly the fastest method of construction.</p> <p>Large air flow will give self cleaning of feed tubes using a dry mix.</p>	<p>Quality control impossible on material.</p> <p>Extensive development and research still required to prove concept and quality of compaction.</p> <p>Extensive tooling development and design.</p> <p>Multiple pipe string required.</p> <p>In-process quality control appears to be difficult.</p> <p>Large air and/or steam supply required.</p> <p>Must shut down operation to monitor density or other parameters.</p> <p>Steam, if used, complicates handling problems greatly.</p>

judgement and must, of necessity, be subjective. Table 6-7 rates the various methods with development and end potential in mind. The scheme judged to require the least effort or to yield the best properties was assigned the number one (1). All other schemes were rated relative to this scheme within each vertical column. The "Sum" column is a total relative number combining all parameters for an overall program risk factor.

In conclusion, to pursue only one line of development could prove to be a time- and money-consuming mistake. Based upon the overall evaluation, it is strongly recommended that static and impact schemes be further studied for design and development. The test data on lab studies show that they cover the best range of materials and are feasible for downhole construction.

For a static compactor, the hydraulic (air or oil) system would be the most practicable for all the stated reasons. The impact compactor, both the cable and drop hammer systems, should be developed. The reason both should be started is the design and development of a linear motor is questionable. However this problem can be resolved easily by working

Table 6-7. Comparison of downhole compaction systems.*

Basic System		Compaction Energy (X3)**	Research & Development (X5)**	Product Properties		Material		Quality Control (X10)**	Sum (including weighting factor)
				Simplicity Mechanical Handling (X2)**	Material Supply Handling	Contaminate Reaction	Limits Cohesive or Cohesionless		
Static	Collar Weight	1	1	1	7	1	2	2	40
	Hydraulic Rams	1	2	2	1	2	2	1	32
Impact	Cable Weight	1	1	1	1	1	1	2	33
	Drop Hammer	1	3	1	1	1	1	1	33
	Percussion	2	3	1	3	1	1	1	38
Roller	Surface Drive	1	3	4	2	1	3	2	52
	Gear Box	1	4	3	2	2	3	3	66
Vibratory	Electro/Mech.	4	4	3	1	1	3	3	73
	Electronic	4	3	3	1	1	3	3	68
Air or Steam Gun		4	5	3	8	3	3	5	107

* The lower the number, the higher the desirability.

**Weighting given to complexity.

with the linear motor people listed in Section 6.2. If the motor question can be resolved quickly we would recommend the development of both instruments into one single unit as described in Figure 6-3. This unit gives all the best features in one unit and would work with just about all materials.

The roller system which is the most widely used method in the field would be good to develop in lab models so that a better comparison with necessary typical materials can be made.

6.7 Explanation of Table 6-7 Column Headings

- (1) Basic System—lists the potential compaction systems as discussed earlier.
- (2) Compaction Energy—is the relative complexity involved in downhole, surface, and reaction forces or energy problems.
- (3) Research and Development—is the relative complexity involved in the design, and construction of the downhole compaction and monitor equipment.
- (4) Simplicity Mechanical Handling—is the relative handling problem associated with installing, operating, and removal of the downhole compaction system.
- (5) Material Supply Handling—is the relative problems associated with downhole feeding and metering of fill material.
- (6) Contamination Reaction—is the relative risk from either oil or excess water content contamination of the fill material.
- (7) Limits (Cohesive or Cohesionless)—is the relative risk due to mechanical compaction limits due to soil characteristics.
- (8) Quality Control—is a factor covering the potential risk and limits of adequate quality control of the process and as-built plug.

SECTION 7

MATERIAL SUPPLY SYSTEM

A material supply system for a downhole compaction system consists of three functions:

- (1) Lowering fill material to compactor.
- (2) Preventing degradation of fill material.
 - (a) Segregation of mixture.
 - (b) Moisture losses.
- (3) Metering proper amount of material to working face.
 - (a) Monitor, metering.

No commercial equipment exists that can function as a material supply system for a deep downhole compaction system. Commercial equipment and current processes can, however, be applied without major development to build a supply system. Whatever method is used must maintain control over the above functions to strict quality-control requirements.

7.1 Lowering Fill Material to Compactor

The system to transport fill material down as much as 10,000 feet must be reliable. The material being handled will be basically dry (~10% moisture) and small grain sized (0.5 centimeter maximum). The rate of feed will be relatively small in 8-inch-diameter holes, but must be at a constant rate except during testing or servicing periods. Also the type of material will change as downhole formations change. The timing for changing material input at the top before it is required downhole may place the wrong material either too soon or too late. This misplacement of material would happen if the construction rate changed.

The system must also be such that a pause in compaction, for testing or breakdown, will not cause a jam.

7.2 Preventing Degradation of Fill Material

The supply system must be capable of handling the fill material without any degradation or loss of quality control. The degradation of material consists of two main areas.

7.2.1 Segregation of Mixture

The fill material may consist of a mixture of two or more materials and some water content. During transport, consideration must be given to maintaining the mixture balance. Since the mixtures are basically dry and will consist of different density components and size particles, separation is possible. If separation occurs, the quality control of the plug will be lost.

7.2.2 Moisture Losses

Moisture control in the fill material is very critical for good quality control. This component can separate from the mix by handling, air-flow characteristics, and in deep holes, from the subsurface heat. Consideration to each must be given and in the case of temperatures above 95°C, special humidity-control precautions must be taken.

7.3 Metering Proper Amount of Material to Working Face

Each method of compaction requires a limited amount of fill material to be deposited at the working face. Too little or too much material, at any given time, will cause loss of quality control. Therefore, the metering, either from the surface or downhole, is as important to quality control as the compaction process itself.

7.3.1 Monitor, Metering

As stated, the correct amount of fill material at any given time is critical to the compaction quality control. This makes it mandatory that a means of monitoring the lift amount be incorporated into the supply system.

The impact and static compaction system can use the LVDT as a means to monitor the lift size. The other methods must have the monitor in the supply system. The monitor in the static and impact systems should be considered a backup system for quality-control purposes rather than the prime system.

7.4 General Considerations

Material supply, in this section, is limited to the transportation from the surface preparation area to the compaction area. Whatever method of compaction is used, the transportation down the hole will be a major area of concern. The major problem in any method of compaction will be the metering, at the working face, of the right amount of material in its proper mixture. Working in a borehole, 8 inches in diameter and up to 10,000 feet deep, will require a metered volume of material ranging from 5 to 150 cubic inches every minute or so, depending on the compaction method. The material must be furnished as a single shot for static, impact, or vibratory compaction, and as a steady flow for roller, air gun, and maybe vibratory compaction.

Except for air/steam gun compaction, where the moisture may be added either on the surface or downhole, it will be best to completely mix the fill material on the surface. By mixing on the surface, samples of the batch may be taken for lab tests to fulfill quality-control functions.

The transportation downhole is limited to three basic types of delivery.

- (1) Gravity or pneumatic delivery through smooth-bore pipe.
- (2) Conveyor or screw delivery.
- (3) Batch or bucket delivery.

Each system has unique problems because of the characteristics of the various materials and the method of compaction. The main objective is to have a simple trouble-free system. Any jamming of the delivery system will cause long work delays (pulling pipe and perhaps the compacting tooling) to clear the jam.

Also, the working reserves of any feed system must be limited within the borehole so that changes in fill materials can be made. This is very important where strata may be relatively narrow.

7.5 Gravity or Pneumatic Delivery

Gravity and pneumatic systems, while similar in concept, have unique characteristics and are only suited to dry materials.

A gravity system would work with the roller or vibratory compaction system, where a cohesionless soil (sand or gravel) is metered at the surface and allowed to fall directly to the working face. Any material

used in compaction has been conditioned (mixed) for its optimum compacting qualities. The free fall of any material in a small confining pipe will jam and compact into a sealing plug within the pipe if any obstruction is present. Therefore, if a hopper or reservoir bin were at the bottom of a pipe, the impact force from free fall would cause compaction within the bin and thus jam the entire system. If the material were dropped in dry mixed condition and water were added downhole, another problem exists. In a long free fall of dry materials, the mixed components would separate due to density and size variations and air turbulence so that quality control would be lost. See Figure 7-1.

A pneumatic system uses an air stream to force the fill material down the hole. This method has the same problems as gravity feed. Any obstructions will cause a jam, and the accelerated particles hitting the jam will compact, thus causing failure. Also, separation of the mixture will tend to take place. Only during conditions of careful metering and continuous operation can the feed system be expected to work successfully.

Table 7-1 lists the advantages and disadvantages of the gravity and pneumatic delivery systems.

Table 7-1. Gravity or pneumatic delivery, advantages and disadvantages.

Advantages	Disadvantages
<p>Simplicity on downhole end in gravity system, no design problem.</p> <p>Uses standard hardware in gravity system.</p>	<p>Both systems subject to jamming.</p> <p>Both require pipe string.</p> <p>Both systems subject to separation of mixture and lost quality control.</p> <p>System cannot be stopped until all material used.</p> <p>A jam requires pulling system from hole.</p> <p>Limited to roller, vibration, and air/steam gun operation.</p> <p>In air/steam gun operation, feed system will consist of at least two pipe strings.</p> <p>In air/steam gun operation, special downhole mix and accelerator chamber must be designed. Timing, so material jam cannot take place, must develop.</p> <p>In temperature zones above 95°C humidity-control system must be developed</p> <p>Poor quality control in both methods.</p>

Figure 7-1. Gravity and pneumatic delivery systems.

7.6 Conveyor or Screw Delivery

In a conveyor or screw delivery system, a mechanical belt or lead screw is used to force feed the material at a controlled rate. Both systems control the rate of delivery and eliminate the separation of material mix. In fact, the screw type will tend to continue the mixing process. Both systems, for a 10,000-foot vertical delivery, would be extremely difficult to design into the small diameters required, and also difficult to handle in the borehole installation and removal.

The mechanical design for the endless belt to be approximately in 50- to 100-foot sections, with transfer points and drive coupling, would be too complicated to consider. The screw feed system, although adaptable to section assembly, has three major problems. The first is time-consuming assembly and disassembly handling when working on the string. The second is the possibility of jamming if the system is stopped, due to the soil-compacting characteristics. The third is that wear and tear on the system would mean a short life span of components (pipe and screw).

Table 7-2 lists the advantages and disadvantages of a conveyor or screw delivery system.

Table 7-2. Conveyor or screw delivery, advantages and disadvantages.

Advantages	Disadvantages
Positive feed.	Subject to jamming.
Better quality control than gravity or pneumatic system.	Cannot stop until all material used, restart difficult.
Less subject to segregation of materials than gravity or pneumatic.	Long vertical drop requires large development program.
	Difficult handling job on site.
	Poor quality control.

7.7 Batch or Bucket Delivery

The batch or bucket delivery system would be a fairly simple and positive means of achieving material delivery. This method uses a cable-held bucket which fits either within the borehole or the outer

pipe string. The bucket is filled with a large volume of fill material (mixed to the proper consistency) and then lowered to the receiving bin mounted above the compacting tooling assembly. During the lift and lower operations, the bucket is guided by the compactor assembly pipe and cable system. Upon reaching the reservoir bin at the compactor assembly, the material is transferred. An alternate method would be to feed the material directly from the bucket to the working face, but then time is lost during refill. However, this time could be spent in taking quality-control measurements.

Another method of emptying the refill bucket would be through the use of air or hydraulic ram pushers from the bin top. This would give positive transfer to the downhole bin.

A typical circular storage bin, 7-inch OD by 3-inch ID by 30 feet long, at the compactor, would hold approximately 9000 cubic inches of material. Using a maximum lift of 150 cubic inches (3-inch lift in an 8-inch bore), 60 lifts can be compacted between refills. If a compaction rate of 5 feet an hour is accomplished, the refilling operation can be made once every 3 hours. This method allows control of material change in small increments to match strata changes. There is little or no separation of the mix during feed, thus quality control would be good.

The mechanical handling is simple and separate from the working string assembly. Both the feed bucket and reservoir bin would require a feed mechanism, such as a screw and vibrator, to prevent jamming, but this is a relatively simple task. See Figure 7-2. Any phase of the compaction or feed operation can be stopped immediately without restart problems.

The feed and metering screw on the downhole reservoir bin can be driven at various speeds to increase or decrease the lift volume to match material or compaction requirements. Level detectors can also be used to monitor lift sizes and reservoir bin levels.

Also load cells on the downhole bin supports would give another method of monitoring the metered lift size to give redundant quality control on this operation.

In the deep-hole situation, where temperatures exceed 95°C and moisture control becomes a problem, a special downhole bin with humidity control could be used. This would be a sealed bin, except for the bottom feed pipe, to lock in moisture. If additional moisture is needed, a water system could be attached to the bin to add water (steam) as needed.

Figure 7-2. Bucket delivery system.

Table 7-3 lists advantages and disadvantages of the batch and bucket delivery systems.

Table 7-3. Batch and bucket delivery, advantages and disadvantages.

Advantages	Disadvantages
<p>Independent cable lift operation.</p> <p>Most components commercially available.</p> <p>No material separation.</p> <p>No pipe handling.</p> <p>Transfer downhole can be automatic.</p> <p>Bucket and reservoir bin can be altered to any reasonable size.</p> <p>Because of small quantity of material being handled at any given time, interruptions or breakdowns not a major problem.</p> <p>Variable lift sizes can be made downhole.</p> <p>Refills can be done on schedule or varied to suit other operations.</p> <p>Good quality control over material and metering.</p> <p>Possible sealed container for high-temperature operation for moisture control.</p>	<p>Unless compactor power and signal cables are protected and held straight, bucket could cause damage during refill operation.</p> <p>Must have open hole for clearance to get large volumes in a refill bucket.</p>

7.8 Material Delivery System Comparison Matrix

The three basic delivery schemes (gravity, conveyor, and batch), for which design reviews have been presented, were selected as potential schemes to meet program goals. All of the schemes presented are technically feasible and could be developed through future design and testing to meet the compaction requirements. However, the amount of research and development, and timing, as well as mechanical limits due to various soil properties, cause a considerable degree of risk. Any rating at this stage must be based on engineering judgement and must, of necessity, be subjective. Table 7-4 rates the various schemes with ease of handling, development, and soil quality control

Table 7-4. Relative comparison matrix of downhole delivery system schemes.*

Method	Needed		Product Properties			Sum (including weighting factor)
	Metered Batch	R&D (X2)**	Simplicity (Handling) Mechanical (X3)**	Quality Control (X5)**	Material Limits	
Gravity	2	1	2	3	3	28
Pneumatic	2	2	3	3	3	33
Conveyor	3	4	5	2	2	38
Screw	3	3	5	2	2	36
Batch/ Bucket	1	2	1	1	1	14

* The lower the number, the higher the desirability.

**Weighting factor.

in mind. The scheme judged to require the least effort or to yield the best quality control was assigned the number one (1). All other schemes were rated relative to this scheme within each vertical column. The "Sum" column is a total relative number combining all parameters for an overall program risk factor.

In conclusion, the batch method appears to be the area for further development. However, in an air or steam jet method, the pneumatic system would most likely be the better solution. Based on the overall evaluation and program requirements, the delivery system will have to be continually developed to best match the particular compaction scheme.

Quality control over the fill material and metering is extremely important. If the material is out of control in mixture or quantity, the resultant plug will not meet program requirements.

SECTION 8

IN-PROCESS QUALITY CONTROL

After all lab testing, to prove the various materials and methods for program goals, has been completed and the required tooling has been built, the field operations can commence. Only by applying an equal, or better, quality-control program (than was used on the laboratory studies) to the field operations can any assurance of meeting program goals be expected.

During the construction phase, there are only two possible courses of action.

The first is to rely on laboratory experiment results for soil-mixture performance, with various input-energy levels, for the particular method of compaction. Then, in the field, duplicate these energy-input levels without any other monitoring of results obtained downhole. This method of construction would create a filled borehole of completely unknown conditions. Due to the serious nature of the stored material, this method of operation would be unacceptable.

The second, and necessary, method of construction is to have a full-scale quality-control program. During construction, every possible parameter should be monitored and recorded. Any variation from pre-planned or expected results would receive a full review by management and responsible engineer before operations continue (see Part 2).

At scheduled intervals during construction, a series of independent plug quality tests should be conducted to verify that the in-process monitors are performing as expected. These tests should be conducted while the compacting equipment is out of the hole for service or calibration.

The in-process quality-control function can be covered by three basic operations, with a continuous cross check to ensure desired performance.

The three operations and the following descriptions are the basic requirements which, as the program continues, will be expanded.

- (1) Tooling performance.
- (2) Plug (as-formed) measurements.
- (3) Material, as supplied, and plug material sample measurements in lab.

The continuous cross checking is to ensure that the desired characteristics of the hole plug are achieved. This is to guarantee that the placement and physical characteristics of the plug meet or exceed the requirements for the particular strata being rebuilt.

8.1 Instrumentation

During the design and development of the downhole compactor, equipment will have to be designed in to monitor pertinent operations. Using present electronic concepts, it will be simple to have a multiplexer-type circuit located in the downhole assembly. This circuit will receive input signals from any number of sensors and then send these signals, in a serial sequence, to the surface. The advantage of this type of instrumentation is that only a few wires are needed, regardless of number of sensors. At this time, it appears that all necessary sensors are commercially available. The commercial units may need to be modified for the environmental conditions but this is a relatively simple task. A tentative listing of sensor types which can be used follows.

- (1) Load cells—to measure weights lifted or applied loads.
- (2) Accelerometers—on impact foot to measure energy input and soil compaction through deacceleration.
- (3) Pressure transducers—to measure hydraulic pressure, air, steam, water, and environment.
- (4) Resolver—to measure rotation of hammer or foot.
- (5) Bulk bin level detectors—to measure level of reserve material in bin.
- (6) Linear variable differential transformers (LVDT)—to monitor linear travel of any downhole equipment and distance to working force.
- (7) Nuclear gage density detector—to measure plug density during formation.

- (8) Counters—to record number of blows for a drop hammer or number of feed-screw revolutions.
- (9) Temperature sensors.

The surface monitoring equipment and processing will consist of an on-line microcomputer. The following additional inputs can be mixed with the downhole data so a complete printout gives a full quality-control report at all times. The surface-monitored data shall include at least the following.

- (1) Time and date.
- (2) Material, by key punch in code.
- (3) Desired density, inputted code for comparison to downhole date.
- (4) Time from last material feed to next required load.
- (5) Any other work parameter, by keypunch input as desired.

All of these data signals can be printed out on a paper printer at the surface station or processed on microcomputers as well as being recorded on magnetic tape. Any critical measurements can have built-in limits so that if the system drifts out of specification, the particular operation will be noted and corrective action taken.

All of the equipment shall have a scheduled calibration check at set intervals to guarantee proper performance.

8.2 In-Process Monitor

At intervals during plugging construction, other special test measurements (such as bearing plate) should be made to complement continual operation monitoring. Prior correlation must be developed between all test method measurements and soil characteristics. Certain properties, in some strata, may not be as important as in others. In a sand or gravel stratum, compaction is required to obtain a stable and high-friction plug which will not move with time. Permeability, in this case, is not important.

If, however, the plug is in a low-permeability stratum, then the measurements should be related to permeability. Basically, in all compaction methods, except impact and static, the compaction process must be stopped and the measurements taken.

It is possible to develop direct correlation between relevant plug properties (permeability, deformation) characteristics and one or more of the following.

- (1) Accelerometer on impact-tool foot. The accelerometer output will give a measurement of input power and a deacceleration measurement which can be traced to soil stress/strain characteristics. The use of an accelerometer on the impact foot provides a readout of plug formation with each and every blow. This feature provides extremely tight quality control over impact compaction. Also, in the proposed impact methods, most have hydraulic rams to raise or lower the hammerhead. Therefore, the rams can also be used with the impact head to provide California Bearing Ratio Test (CBRT) measurement. Both of these methods provide good quality control over the plugging operations.
- (2) The bearing ratio test (CBRT) method is usable on all methods of compaction. This unit would consist of a plate, driven with a known power, where the force is measured through strain gages or load cells, to give stress/strain characteristics. The CBRT is adaptable to impact, static, and roller compaction methods and could be used at intervals on the other two compaction methods. This is a standard soil test, and after correlation with the tooling and materials, will provide a good quality control.
- (3) Nuclear gage measurement^(3,4) is usable on all methods of compaction. This system would use a small transmitter and receiver section to monitor plug density. The unit may require design changes, such as a flat foot or wiper system to smooth the plug surface. This is required if accurate measurements are to be obtained.
- (4) Core samples for lab tests are the most common and reliable test methods. However, this requires pulling the work string or having provisions for a small core tube to pass the compactor. This method should be restricted to pilot in situ testing. Its use for permeability measurement is presently doubtful.

Experiments and development of each of these methods are required to ensure the quality of each for the particular soils and should be checked during in situ pilot program.

Outlines and plans for a quality-control program are contained in Part 2.

SECTION 9

DEVELOPMENT PROGRAM

The development program to validate a compaction system as a process for borehole plugging is derived from the technology roadmap, Figure 9-1, and the concepts described in Sections 6 through 8. In overview, the required development effort is basically applied engineering of existing state-of-the-art technology with exact design limits and methods dependent on future material testing. The individual methods of compaction have limits with respect to the soil characteristics such that it is possible that one compactor design may not be sufficient. A review of the earth formation in prospective site locations should be completed to exclude methods, if possible, or to determine if more than one is required. The ideal approach is to have one instrument with a wide controlled range to cover all prospective materials and mixes. The combined instrument concept shown in Figure 6-3 may be feasible as such a unit.

The development of in-process downhole monitoring equipment and calibration to the various material mixtures and resultant formations will be one of the most demanding tasks.

This study has been addressed to downhole compaction in clean open boreholes, but holes in other than ideal conditions will complicate the design, development, and mostly the field downhole construction operation.

A flexible development program is intended to permit options from the low-cost short-time-schedule high-technical-risk end of the spectrum to the high-cost long-time-schedule low-technical-risk end.

Realistically, the actual development program is expected to fall between the low-cost to moderate-cost approach. The low-cost high-technical-risk approach is the bold confident one of design and fabrication of a compaction system having no component development feedback, prior to system demonstrations in the laboratory, to separate

the postulated from the real development problems. The risk involved in this approach is that of system failure due to multiple component failures that are difficult to isolate. This, then, has the effect of starting over with component development tests as building blocks to successful system demonstration. The payoff, however, is one in which at least limited success is achieved and clearly defined component modifications are identified for subsequent successful system demonstration.

On the high end of the cost spectrum is the conservative approach of comprehensive design and analysis supported by step-by-step mechanism and component tests. A moderate cost approach, which should minimize the cost-to-technical-risk ratio, is to construct a development program that is methodical, with logic constraints that are technical rather than schedular. This approach defines the critical data required from one logic block to initiate the next one, etc.

The main development efforts are:

- Task 1 Reliability and Quality Assurance
- Task 2 Material and Mix Parameters
- Task 3 Compactor and Component Development
- Task 4 System Verification

9.1 Reliability and Quality Assurance

Due to the serious nature and long time span of the repositories, the reliability and quality-assurance program is probably the most important part of the overall effort. A team of R&QA personnel should be present, monitoring all aspects of the program. It should start during the planning of borehole logging and continue through downhole construction and after, to monitor performance. The R&QA function (detailed in Part 2) is the major task on borehole plugging and after careful review will, in fact, eliminate some of the proposed methods of compaction and material supply.

9.2 Material and Mixture Parameters

Detailed studies of the earth formations and expected material requirements in the proposed site areas must be made. Then, closely controlled testing of suitable fill materials and mixtures must be conducted. The nature of the fill material and mix ratios will also

determine which method of compaction will be required to achieve the proper input energy. Standard laboratory test equipment for some proposed methods exist but are limited in range of input energy. Some modification of standard equipment may be required, while other equipment must be designed. The MIT study provides a good foundation on material testing. However quality control was lacking, and now, in future testing, must be emphasized.

Molds for all testing methods should be standardized and the side-wall constraint of molds should reflect the various borehole formation characteristics.

The testing of materials will continue throughout the entire program, covering tooling development, system laboratory test, and monitoring of each fill batch during the borehole construction program. All operations must be quality controlled and a data bank built for performance and comparison to the various natural formations.

9.3 Compactor and Component Development

The mechanical hardware for downhole plugging construction of boreholes does not exist. However, the basic components for downhole construction, material transport, and monitoring are all state-of-the-art and can be redesigned and modified to accomplish the task. The first requirement is to better define the materials to be covered, the final realistic plug mechanical properties, and the input energy required to meet these goals. A general tabulation of these parameters, along with compactor system limits, will allow the preliminary design of laboratory and engineering model systems.

The complexity of a compactor system will depend on the requirement of fitting it into an 8-inch diameter borehole. If a larger diameter borehole is encountered, the scale-up of the equipment will be relatively simple.

The downhole measurement and monitoring of the plug quality is the greatest unknown. There are various methods listed, and their development will require constant testing and calibration, working with the material test personnel.

The monitored parameters, mechanical and electrical, can be electronically processed downhole to a multiplexed signal requiring a minimum of electrical leads, using existing hardware. The surface station will require a decoding system with both magnetic-tape recording and instant printout. The printout enables the field engineer

to have complete control and instant knowledge if out-of-specification conditions exist. This feature will allow corrections to be made, thus precluding the possibility of a redrill of the hole to remove out-of-specification areas.

Basic system concept prototypes, can be built for the laboratory, and tested, before engineering model prototypes are built, to verify intended designs.

9.4 System Verification

As the system and an engineering model are developed, laboratory testing must be done with intended mixtures to verify that scale-up and design limits meet or exceed earlier lab testing equipment parameters. The test setup should have the same capacity and range intended for use in the final field system.

As part of this test program (in an in situ test), portions of these test sections should be performed in a deliberately poor-quality manner (but with good quality control). These controlled poor-quality plug areas will provide valuable data for control limits and for effect on adjacent plug areas.

When the engineering model system is complete, a series of in situ experiments, in shallow boreholes, should be planned. These tests should include all materials, monitors, and instrumentation possible, as well as extra monitors which can only be used during a test and not in the repository site. This series of tests will give the quality assurance necessary for extrapolation to the required 200,000-year life of the repository.

9.5 General Technology Roadmap

The technology roadmap, as shown in Figure 9-1, specifies the options available to develop a borehole compaction system, along with the supporting test and design concepts. This roadmap is intended to visually delineate a set of technology paths that logically lead to an operational field system. The various options, or combinations of options, to be taken, must be selected after careful review of the materials and conditions expected in the general area of the proposed storage site. Each method or option has advantages and disadvantages which must be weighed against the potential risk in develop-

ment and final performance, i.e., the safety of the repository. As an example, two potential paths are described.

- (1) A complete investigation of technology paths, covering all possible earthen materials, methods of compaction, delivery, and monitoring with full quality assurance and control. This would result in a long-term high-cost low-risk production system. All component and system tests are required, and all paths are performed in series-parallel, as one hinges on the completion of another to reach a decision point.
- (2) An investigation of one method of compaction compared to limited material testing without in-process monitoring or quality control. This would result in a short-term low-cost high-risk production system. It could result in the immediate use of a standard drill string and collar weights for a simple static compactor.

These are obviously the extremes, and the realistic course lies somewhere in between. After a review of the method limits and expected formation characteristics in the proposed site areas, the proper path or paths can be selected.

9.6 Reference Technology Program

This section combines previous results and condenses the options into one which lends itself to an early field system with the most reasonable cost and technology risk, while maintaining assurance that the performance and plug-quality options remain flexible. The concept chosen for development schedule and costing is an impact compactor using a bucket delivery system. Table 9-1 presents an estimated development schedule.

9.6.1 Task 1 - Borehole Investigation

This task is to determine the essential parameters of the borehole and surrounding formation by survey and test of candidate boreholes to update requirements.

Subtask 1.1 Material Requirements.—This task is to define the specific materials by formations and location.

Table 9-1. Estimated development schedule.

		Man-Months per Month	Year									Man-Months Total*
			1			2			3			
			3	6	9	3	6	9	3	6	9	
<u>Task 1</u>	<u>Borehole Investigation</u>											
1.1	Material Requirements	2	←	→								18
1.2	Mechanical Parameters	3	←	→								36
<u>Task 2</u>	<u>Process Verification</u>											
2.1	Material Selection	1		←	→							9
2.2	Test Equipment (Impact)	2		←	→							18
2.3	Testing	3			←	→						18
<u>Task 3</u>	<u>Component Development</u>											
3.1	Compactor Assembly (Impact)	3	→	→	→							27
3.2	Delivery System (Bucket)	2	→	→								18
3.3	In-Process Monitors (Accelerometer)	3	→	→	→							27
<u>Task 4</u>	<u>System Demonstration</u>											
4.1	Laboratory Simulation	3	←	→	←	→	←	→				54
4.2	System Field Operation	6							←	→		54
<u>Task 5</u>	<u>Design and Fabrication</u>											
5.1	Preliminary Design (Impact)	2	→									12
5.2	Detail Design, Engineering Model	4		←	→							24
5.3	Field System Design	3			←	→						18
<u>Task 6</u>	<u>Fabrication</u>											
6.1	Engineering Model	3		←	→							18
6.2	Field System	2			←	→						18
<u>Task 7</u>	<u>Reliability and Quality Assurance</u>											
7.1	Complete Program (see Part 2)	8	←	→	←	→	←	→	←	→		220
<u>Task 8</u>	<u>Program Management</u>											
8.1	Minimum Requirements, High- Quality Plug	3	→	→	→							27
8.2	Preliminary Design Review	2	←	→								8
8.3	System Design Review (Engineering Model)	2		←	→							12
8.4	System Design Review (Field System)	3			←	→						27

*Total 56 man-years.

Subtask 1.2 Mechanical Parameters.—This task is to determine the mechanical properties of the various formations and determine essential parameters that affect the plug quality. The MIT study has established the necessary mechanical parameters required for compacted earth plugs (permeability, deformation, and strength), with permeability being the most important. The object of this task is to define where exactly in the borehole the necessary plug must act as a seal (extreme high quality) and where the plug may be less stringent in quality due to surrounding soil characteristics.

9.6.2 Task 2 - Process Verification

This task is to verify, through a test program, that selected materials, mix ratios, and methods assure a high-quality plug to achieve the design objective.

Subtask 2.1 Material Selection—Select and verify that natural materials from selected sources meet or exceed minimum plug requirements for a high-quality plug.

Subtask 2.2 Test Equipment—Develop or modify lab test equipment to duplicate scaled-down compaction methods, mixing methods, and simulated borehole formation molds to verify quality plug formation.

Subtask 2.3 Testing—Conduct high-quality controlled testing to verify material input energy and methods to form a plug capable of meeting or exceeding the minimum plug requirements.

9.6.3 Task 3 - Component Development

The purpose of this task is to modify or develop required tooling for compaction, delivery, and in-process monitoring of the downhole construction of a high-quality plug. The full-scale tooling must match or exceed the parameters obtained with the lab test equipment.

Subtask 3.1 Compactor Assembly—Develop the downhole power head containing necessary support, material metering, and monitors to ensure a high-quality plug meeting or exceeding minimum requirements established during lab testing.

Subtask 3.2 Delivery System—Develop a delivery system which will transport the required material mix from surface preparation stations to the compactor assembly in a uniform and controlled condition.

Subtask 3.3 In-Process Monitors—Develop a monitoring system to control all parameters of the compacting tool, delivery system, energy inputs, and plug quality during downhole construction. This is to ensure that a high-quality plug is formed to meet or exceed minimum requirements.

9.6.4 Task 4 - System Demonstration

The basic object of this task is to demonstrate the performance of the compaction system in a lab environment and then to provide a field operation of the compaction system. From the tests of a plugged system prove that it meets the requirements of no water penetration for a period of 200,000 years.

Subtask 4.1 Laboratory Simulation—Demonstrate an engineering model system in a controlled laboratory environment to verify that minimum program requirements are met and a high-quality plug is formed.

Subtask 4.2 System Field Operation—Demonstrate a full-scale operation of all field equipment. At the conclusion of this task, the system should be ready for production and field use in borehole plugging construction.

9.6.5 Task 5 - Design and Fabrication

This task is the design and analysis effort necessary to provide the preliminary design of the compaction system to support the component tests, the laboratory demonstration, field demonstration, and associated design changes to correct development problems.

Subtask 5.1 Preliminary Design (Impact)—Provide the design and analysis effort for a complete compaction system and all associated components to meet program requirements. This task ends in a preliminary design review.

Subtask 5.2 Detail Design, Engineering Model—Provide the detail design and drawing for fabrication of an engineering model compaction system. This task ends in a design review.

Subtask 5.3 Field System Design—Combine the results of the above two to detail design and drawings for a field operational system and add the design and integration of the above-ground equipment. This task ends in a design review.

9.6.6 Task 6 - Fabrication

This task covers the fabrication of the two systems.

Subtask 6.1 Engineering Model—Fabricate an engineering model to demonstrate, in a lab environment, the compaction system. Long-lead-item procurement for engineering-model and field-model systems must be ordered prior to design review.

Subtask 6.2 Field System—Fabricate the field system and incorporate engineering-model adjustments and all support equipment for surface operations.

9.6.7 Task 7 - Reliability and Quality Assurance

This task covers the complete monitoring and control over the entire program. This must start at Task 1 (Borehole Investigation) and follow through to completion of all operations. See Part 2 for breakdown.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Figure 9-1. Technology roadmap downhole compaction
(Sheet 2 of 6).

Figure 9-1. Technology roadmap downhole compaction (Sheet 3 of 6).

Figure 9-1. Technology roadmap downhole compaction (Sheet 4 of 6).

Figure 9-1. Technology roadmap downhole compaction (Sheet 5 of 6).

SECTION 9

Figure 9-1. Technology roadmap downhole compaction
(Sheet 6 of 6).

PART 1

LIST OF REFERENCES

1. Martin, R. T., Feasibility of Sealing Boreholes with Compacted Natural Earthen Material, MIT Research Report 75-28, Cambridge, Mass., June 1975.
2. Meehan, R. L., "The Uselessness of Elephants in Compacting Fill," Can. Geotech. J. 4(3), 358-360 (1967). (Repeated passes by elephants ineffective for compaction because they step in their old tracks.)
3. Schlumberger, Log Interpretation: Volume I - Principles, 1972; Volume II - Applications, 1974; Schlumberger Limited, New York.
4. Schlumberger, Log Interpretation Charts, Schlumberger Limited, New York, 1972.
5. Brantley, J. E., History of Oil Well Drillings, Gulf Publishing Co.
6. Harding, J., L. Rubin, and W. Still, Drilling and Preparation of Reusable, Long Range, Horizontal Bore Holes in Rock and in Gouge, Volume I, #FHWA-RD-75-95, Foster-Miller Associates.
7. Alva-Hurtado, J. and H. Einstein, A Review of Equipment Available for In Situ Testing of Soil, MIT, 1975.
8. Jumikis, Theoretical Soil Mechanics, TA 710.J947.
9. Lambe, T. W., and R. V. Whitman, Soil Mechanics, John Wiley, New York, 1969.
10. Terzaghi and Peck, Soil Mechanics in Engineering Practice, TA 710.T334.
11. Composite Catalog of Oil Field Equipment and Services, World Oil, Houston, Texas.
12. Mission, TRW, Operation and Maintenance Manual #105, Percussion Drilling Equipment, 1975.
13. D'Appolonia, Elio, Loose Sands - Their Compaction by Vibroflotation.
14. Foundation Engineering, edited by G. A. Leonards, McGraw-Hill, New York (Chapter 4, T. W. Lambe).

PART 2

RELIABILITY AND QUALITY ASSURANCE

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

SECTION 1

RELIABILITY AND QUALITY ASSURANCE OVERVIEW

1.1 Summary

Part 2 of this report defines the reliability and quality assurance (R&QA) tasks required for any borehole sealing program. Specific examples are given for compaction of natural earthen material.

Systems and subsystems, as determined by an engineering evaluation, have been analyzed for the R&QA component.

In R&QA management, the initial task will be the generation of quality operating procedures which will describe the methods of controlling and recording the phases and operations of the project. An integrated data system is proposed for the accumulation and evaluation of the data so as to facilitate analysis. Configuration management will assure documentation and traceability and can be used as an input and recording system. The interface and control of different contractors and organizations are discussed with respect to reliability aspects. An important segment of the R&QA management effort is reliability analysis, which is the application of engineering knowledge and mathematics to the review of design concepts, development design, or the actual hardware, so as to be able to define fault or failure events, their probabilities of occurrence, cause and effect, and correction.

In the test equipment development section, the equipment and laboratory tests are defined. This includes laboratory test equipment and procedures, materials and processes, and also criteria for correlation with field data. Calibration and verification of equipment is discussed, as is the evaluation and calibration of instrumentation to control and monitor the compacting process. Suggested methods for monitoring are briefly discussed. Borehole logging is a major problem and the various methods are outlined and discussed, and the use of a gradiometric device is outlined. The problems of permeability testing are discussed.

The process and equipment quality are discussed with reference to surface equipment, power supply, natural material supply, compaction methods, material feed, and the process limits based on material type.

A major effort in any R&QA program is in-process quality assurance and laboratory testing, and the ramifications are outlined.

R&QA inputs are essential for decision points in the evaluation of engineering options, i.e., for material feed, compaction, etc., and are discussed. This includes type of instrumentation and extent of in-process and post-process monitoring programs. Reliability analyses and an effectivity analysis are proposed, as is life cycle cost and a failure mode and effects analysis.

Process equipment development and engineering verification is discussed with respect to both state-of-the-art and development options.

System verification is discussed with reference to laboratory mock-up equipment, simulation tests, design modification, instrumentation and pilot testing, and the procedures for field qualification.

Part 2 concludes with a discussion of field qualification and field operation, and finally product life monitoring.

Part 2 defines the areas of quality assurance and emphasizes establishment of definite baselines of quality controls and process definition.

SECTION 2

TASK DEFINITION

The extensive nature of this recommended R&QA function is not unique to the compaction process. Any hole-plugging method must have an integral quality-assurance program and an intensive on-site quality-control operation.

Part 2 covers the R&QA aspects of specifically compacting a natural earthen plug into a borehole with minimum long-term disturbance to the surrounding material formation, but can be used as a basis for controlling a borehole filling operation using any type of material, artificial or natural.

The R&QA function is to evaluate all the different engineering options that are possible when compacting earth, participate in the decisions as to which options to use, and to set up controls in the operation to ensure that the following criteria are met.

- (1) Permeability of the composite to be 0.1 micro Darcy or that of the adjoining formation, whichever is greater.
- (2) Adhesion of packed plug to the formation to provide a bond strength that will withstand 300 feet of differential water head across a 1-foot length.
- (3) Durability—the permeability and adhesion criteria must apply for 200,000 years.

To ensure that these criteria are met, laboratory and field tests are necessary to fully define and document the processes selected.

A method tolerant of a wide range of materials offers a quality-control (QC) advantage, as would be a material that is compatible with more than one formation.

As it is not possible to monitor the final product for even a fraction of the required life, it is essential to ensure that the final plugged system is reliable, through careful monitoring and control of the project in all phases.

The waste isolation process is to be carried out in areas that have been geologically stable for at least 5,000,000 years, and if one can reproduce the structure that is present, then one can assume the area will be stable for 5,200,000 years.

Surveillance during the program performance is the only way that quality can be guaranteed. The overall duration of the program is assumed to be 3 years, up to and including field testing with an engineering model. It is essential that R&QA be involved in the preliminary laboratory borehole logging and sampling tests, and field testing to define the requirements for on-site monitoring and assist in the design of specialized instrumentation. R&QA will also be required to monitor and control the subcontractor's procedures throughout the program life.

It is proposed that an R&QA organization with expertise in innovative quality-control techniques such as CSDL be used for technical consultation and to monitor and control on-site operations. This program, which is detailed herein, can be adjusted up or down depending on the progress of the project. This close monitoring is essential to ensure success and to dispel unfavorable popular reaction regarding waste disposal.

SECTION 3 TASK SUMMARY
R&QA MANAGEMENT, DOCUMENTATION AND TRACEABILITY

Section	Subject Matter
3.1.2	Quality System - QOP's
3.1.3	Integrated Data System
3.1.4	Configuration Management, including reporting
3.1.5	Contractor Interface, including agreements and audits of development production and operation
3.1.6	In-process Monitoring
3.1.7	Post-seal Monitoring
3.1.8	Reliability and Statistical Analyses
3.1.9	Other R&QA activities, as defined in QOP's (Section 3.1.2)
	(1) Laboratory testing for material acceptance
	(2) Laboratory testing for field sample and survey evaluation
	(3) Laboratory testing to investigate compaction or other processes
	(4) Equipment and process capability investigation
	(5) Preparation of specifications
	(6) Presentation and analysis of data for design reviews and project management decisions
	(7) Instrumentation design, calibration, capability
	(8) Operate non-conforming material/process disposition system, including Material Review Boards, and provide continuing data reporting on defects and corrective action.

SECTION 3

PROPOSED PROGRAM ORGANIZATION

3.1 Reliability and Quality Assurance: Management, Documentation, and Traceability

The objectives of the borehole sealing project imply the need for a R&QA management and information system, because of the potentially serious consequences of a failure or defect and consequently the stringent quality requirements imposed. One reason for such a system is the complex relationship of the development, qualification, and field operation phases, since each phase affects succeeding ones and its reliability must be analyzed and documented. Again, there is the need to provide for, monitor, and document interactions between different development organizations, contractors, and project management in order to assure that project requirements are satisfied. The national importance and visibility of the overall program, of which the borehole sealing project is part, necessitate that comprehensive, fully traceable data and reliability analyses are available. These demonstrate that all technical, safety, and environmental concerns have been adequately investigated and satisfied to a high confidence level.

The type of R&QA system proposed has seen extensive and successful application in many space and military programs, providing quality monitoring and corrective action during successive program phases. To be effective, it requires early inception in the program, in order to ensure that test and operational data can be recovered to analyze future problems, satisfy investigations or inquiries, or substantiate the basis for decisions made in the course of the program.

If the system is adequately designed to satisfy the needs of the project over its duration, it lends itself well to an initial low-key effort, e.g., during a laboratory test phase and the analysis of test results. With all system building blocks provided for, a scale-up of activities can then readily take place as project needs dictate.

The objectives of the system are essentially as follows:

- (1) Control of quality and of implementation of design decisions by an integrated data system.
- (2) Assurance that design intent is met.
- (3) Evaluation of data and reports to project management.
- (4) Monitoring of quality and performance.
- (5) Recommendations for corrective action to project management.

The following paragraphs describe the principal tasks of the R&QA Management and Information System. The organization required to implement it, initially on a smaller scale, is described in Section 3.1.1 ahead of the principal tasks, since it sets the conditions for the functioning of the system.

3.1.1 Organization

The responsibility for design and implementation of the R&QA Management and Information System will be assigned to a reliability and quality-assurance project engineer. During early phases of the project he may operate alone or with a skeleton team, drawing assistance and services as required from his parent organization. Manpower is projected to increase as the effort progresses, particularly during qualification and field operation, and to some degree during equipment and process capability evaluation (Table 3-1).

The organizational activities fall into several divisions, representing areas of responsibility (to be staffed as project work load increases).

(1) Statistical Function

- (a) Integrated data system.
- (b) Analysis of field data, base.
- (c) Reliability analysis.
- (d) Failure mode and effects analysis (FMEA).
- (e) Post-sealing, monitoring; data analysis.
- (f) Summary data reports.

Table 3-1. R&QA manpower estimate.

	Man-Months per Month	Year									Man-Months Total*
		1			2			3			
		3	6	9	3	6	9	3	6	9	
1. R&QA Management	2	←————→			←————→						48
2. Development of Tests and Equipment	2	←————→									24
3. Process and Equipment Quality	2	←————→									24
4. In-Process R&QA	2				←————→						24
5. Decision Points	1				←————→						12
6. Development and Engineering Verification	1				←————→						12
7. System Verification	2				←————→						12
8. Field Qualification	1				←————→						6
9. Field Operation	2				←-----→						24
10. Product Life Monitor	1							←-----→			18

* Total 17 man-years.

(2) Materials, Process and Equipment

- (a) Materials test procedures.
- (b) Materials test evaluation.
- (c) Processing equipment evaluation.
- (d) Materials and equipment specifications.
- (e) Process evaluation, capability, specifications.

(3) Test and Instrumentation

- (a) Laboratory test equipment and specifications.
- (b) Instrumentation development evaluation.
- (c) Instrumentation capability and specifications.
- (d) On-site instrumentation and test operation.
- (e) Instrument and equipment calibration.

(4) Contractor Interface

- (a) Interpretation and negotiation of specifications.
- (b) Monitoring of contractor task quality.
- (c) Control of critical contractor activities by negotiated agreement.
- (d) Periodic reports and recommendations for correction action.

(5) Site Activities

- (a) Site inspection and monitoring.
- (b) On-site test and quality evaluation during field test operation.
- (c) Post-seal audit or monitoring of sites.

The key to the successful operation of the system is the early and continuing involvement of the R&QA project engineer and his team in design, test, and operational activities. This ensures that the system responds to the existing and evolving needs of the project and that reliability and quality requirements are satisfied in each phase of the project.

A suggested manpower loading for the R&QA team is shown in Table 3-1. This is a minimum loading for a program to design, build, and field test a pilot engineering model of a downhole compaction system. This pilot

hole operation would include natural material supply, compaction, and quality-assurance verification. This would be an 8-man-month/month operation for a 2-year period and, depending on the magnitude of changes and problems, at least a 2-man-month/month operation for the third year, but most likely at a 4-man-month/month level.

Materials and services (including computer analysis) have not been included pending project decisions on the specific program tasks to be implemented and on the extent of conditions to be investigated and defined.

3.1.2 Quality System

The quality system will be defined in a series of Quality Operating Procedures (QOP), which shall describe the methods of controlling and recording the phases and operations of the project. This will include, but shall not be restricted to, the following.

- (1) Laboratory tests for material acceptance.
- (2) Laboratory tests for field sample and survey evaluation.
- (3) Laboratory tests to investigate compaction or other processes.
- (4) Equipment and process capability.
- (5) Establishment of specifications (material, equipment, instrumentation, etc.).
- (6) Design reviews, and process/equipment evaluation.
- (7) Instrumentation design and calibration.
- (8) In-process control and monitoring recording system.
- (9) Configuration management (including change control).
- (10) Contractor review of planning, control, and performance.
- (11) Audit of development, production, and operation.
- (12) Failure or nonconforming material/process reporting, disposition and corrective action.
- (13) Definition and procedure for establishing on-site monitoring system or network for on-going data logging or audit after boreholes have been sealed.

(14) Troubleshooting test and corrective procedures in the event of accidental disturbances of seepage.

(15) Integrated data, progress and failure-reporting system.

3.1.3 Integrated Data System

The integrated data system provides for the storage and retrieval of the extensive information required by the project. The type of data system proposed is similar to the ones used in space and military programs to ensure traceability and supply the data base for technical decisions on reliability analyses, including failure analyses (e.g., FMEA). Basically, the system must supply answers to the following questions.

- (1) What is the design intent?
- (2) What were the changes at different times and/or for different boreholes?
- (3) How well was design intent fulfilled (as-built configuration under specific conditions)?
- (4) What were the defects, problems, failures?
- (5) How were they corrected in-process and prevented on succeeding units?

It is planned that the system will be computerized. It will not store all project information, since the projected volume of information is large. However, critical data will be stored, and access lists and retrieval methods provided for information such as extensive laboratory test data.

In general, critical information and summary information will be stored in computerized form (tape, cards, etc.). Noncritical and very voluminous information will be keyed to provide ready search and retrieval by means of computerized access lists. The objective of the integrated data system is to provide any anticipated information needs during the project and after its completion, either through direct retrieval of computerized data or through rapid access to stored hard copy. In order to provide for unforeseen volume increase in data storage required or in post-seal product life monitoring, a method for purging or summarizing selected information needs to be provided over the life of the data system (as specified by the project management).

The input to the system is dictated by project requirements, and no comprehensive estimate has been made at this stage of the project. Key information is anticipated to include the following.

- (1) Summary data and access lists for borehole logging, geological information, laboratory feasibility studies.
- (2) Summary data and access lists for development data, equipment and instrumentation evaluations, process capability of equipment/instrumentation.
- (3) Specifications access or detailed requirements for materials, equipment, instrumentation.
- (4) Traceability information for test conditions, sites, materials, equipment, instrumentation (including, for instance, type and source of compactor and its performance characteristics).
- (5) Test and operational data for analysis of process effectiveness (quality of sealing, in-process monitoring).
- (6) Deviations from process or design, identifying equipment, test, or site to which this applies.
- (7) Modifications in process or design, traceable to the specific applications.
- (8) Acceptance information (or access list) for completed tasks, equipment and operations.
- (9) Environmental and safety information summary/access lists.
- (10) Post-seal monitoring data summaries and access lists.
- (11) Reliability analysis summaries and access lists.
- (12) Failure analysis summaries/access lists and corrective action summaries/access lists.
- (13) Status (progress or completion) of project tasks or operations.

The data system needs to be designed to facilitate the ready retrieval of the specific desired information and the preparation of summary or detailed reports to project management. For example, specific outputs are required by reliability analysis (process capability, operational data, measurement against process parameter limits, cost evaluation, etc.).

3.1.4 Configuration Management

The integrated data system represents a part of overall configuration management. The latter assures the documentation of design decisions, design and process changes (via a change control system), and traceability as to time, location, and particular as-built systems (including sealing boreholes) affected by such decisions and changes. Although the data system relating to tests and field results serves as a basis for changes incorporated in the configuration control system, the latter can operate as an independent input and reporting activity. As in other critical projects, for instance military or space, configuration control effectively records and traces planned and actual build and performance and presents a real-life, and if necessary real-time, display to program management. Display or reporting must be flexible enough to permit overview at a higher system level or a detailed report, for example, of plug material properties or borehole profiles for a given location.

The integrated data and the configuration control systems provide an on-going and necessary information base for program planning (e.g., on a PERT basis), for mathematical modelling, and for reliability and fault-tree analyses. Because of the need to have realistic and workable systems, successful experience with similar systems of significant complexity is required for their design, documentation, and implementation.

3.1.5 Contractor Interface

An aspect of the overall R&QA system that should be emphasized is the interface with, and control, of different contractors and organizations assigned to specific tasks of the project in development and production. In particular, a given contractor's methods, equipment, and test procedures need to be defined, evaluated against project requirements, and documented. Implementation of such an agreed-on design and documentation package, exemplified by the Class 1 agreements negotiated and monitored in some government projects, will then be verified by periodic audit. This method ensures a high degree of confidence that design and process intent of project decisions are fully satisfied and that proposed or required changes are reviewed and decided through systematic channels. In view of the interaction with many, often competitive, contractors, it has been found that such a system operates most effectively when designed and implemented by an independent third party, which may be an integral part of the project design and development effort, but which is not influenced by production or operation interests.

3.1.6 In-Process Monitoring

Another task of the R&QA activity is the in-process monitoring of the effectiveness of the process. This has been discussed in succeeding sections relating to instrumentation and process verification. It is of particular interest because it supplies data to assess actual field performance on the final product, as opposed to laboratory data and pilot tests.

3.1.7 Post-Seal Monitoring

Post-seal monitoring of the area containing sealed boreholes is desirable to assess changes in the soil environment (e.g., hydrostatic head, pore pressure), degradation, and external effects (temperature infiltration, etc.). Depending on the instrumentation approach selected, the extent and type of such monitoring will be dictated by the overall project requirements. Some aspects of such instrumentation are discussed in the succeeding sections. It appears advantageous if at least some boreholes or test holes selected on some detection pattern or AQL basis are instrumented for a specified period. Such data will be incorporated in the integrated data system and will be used in the reliability and fault-tree analyses, in order to provide continuing assurance that integrity of seal and other safety requirements are satisfied. (Fault-tree analysis and FMEA (failure mode and effects analysis) have been proven to be effective management tools in anticipating problems of design or operation and in analyzing failures or malfunctions which have occurred.)

3.1.8 Reliability and Statistical Analysis

The reliability analysis aspects of the project are described in following sections of this report, particularly Section 7.1. This represents a significant R&QA task, interfacing as required with design, safety, and environmental analyses.

As a part of the data and test analysis, a significant task is the evaluation of the significance and reliability of laboratory and field testing. On-going statistical analysis will be used to provide this and to assess the confidence limits in scaling up from laboratory to field tests. Of special interest is the correlation of laboratory data with general geological engineering data, since the basis for an effective sealed borehole necessary assumes integrity of the plug

or seal with the surrounding strata. Further, pilot test programs (pilot holes) need to be designed and the results evaluated against theory, laboratory, and field results, and the project requirements over the life specified.

3.1.9 Other R&QA Activities

Other activities relating to the reliability and quality assurance function are required for the successful accomplishment of the project. However, their scope is essentially evident from the description of the Quality Operating Procedures, listed in Section 3.1.2, and are represented by tasks 3.1.9 in the Task Summary preceding Section 3.

SECTION 4. TASK SUMMARY
DEVELOPMENT OF TESTS AND TEST EQUIPMENT

Section	Subject Matter
4.1.	<u>Process Verification</u>
4.1.1	Laboratory Test Equipment
4.1.1.1	Specimen and Equipment Types
4.1.1.2	Test procedures for Laboratory Testing
4.1.2	Materials
4.1.2.1	Procedures (specifications, data recording, and transmittal
4.1.2.2	Correlation with Field Data
4.1.3	Performance Verification of Test Equipment
4.1.3.1	Calibration
4.1.3.2	Process Capability (of equipment against standards; standards specifications)
4.1.3.3	Compaction Effectiveness
4.1.3.3.1	Analysis Based on Records and Sampling (equipment operating records and sampling)
4.1.3.3.2	Accelerometer on Equipment (correlation study with laboratory tests and in-situ conditions)
4.1.3.3.3	Sensors in Plug and Surrounding Area
4.1.3.3.4	Periodic In-Process Monitoring, Integrated With Equipment
	(1) Feasibility
	(2) Design specifications and correlation
4.1.3.4	Periodic Monitoring of Other Parameters
	(a) Methods for measuring depth, material changes, temperature (heat), moisture, pressure, string weight, face-to-string characteristics.
	(b) Design of methods and verification.
4.1.3.5	Environmental Quality Monitoring
	(a) Select and verify instrumentation for dust, water contamination, hydrostatic effects, etc.
	(b) Design and verification of methods.
4.2	<u>Borehole Logging</u>
4.2.1	Assessment of Logging Data (analysis of supplied logging data)
4.3	<u>Field Permeability Testing</u> (development verification of permeability methods)
	(Appendix: A. EVALUATION OF BOREHOLE LOGGING METHODS B. GRADIOMETRIC METHODS)

SECTION 4

DEVELOPMENT OF TESTS AND TEST EQUIPMENT

4.1 Process Verification

The general task (see Figures 4-1 and 4-2) addresses itself to the definition and calibration of test equipment and the laboratory tests required to map the direction of the specific development and evaluation tasks described in following sections. Much of the work outlined is a continuation and refinement of the investigations reported in the concept feasibility phase.

Testing, calibration, and materials cannot be treated as independent subsystems but have major interactions and must be so regarded, e.g., Montmorillonite, no load but compacted shale needs a load.

4.1.1 Laboratory Test Equipment

4.1.1.1 Specimen and Equipment Types

Definition of Specimens: The type and size of specimen need to be analyzed on the basis of available laboratory and field data, so as to assure a high degree of correlation with the actual borehole system. Section thickness; effect of disturbance in sampling from existing strata; pressure and water saturation; orientation of specimen constituents, e.g., orientation of alumina-silica platelets in clay, will be established, or else be determined as an insignificant variable.

The optimum specimen type will dictate the configuration of test equipment such as molds, presses, hydrostatic subsystem, and compaction equipment. The exact type of measurement devices or instrumentation will then be defined for permeability, plasticity index, shear strength, and void volume.

4.1.1.2 Test Procedures for Laboratory Testing

Based on a test program, procedures will be prepared to define:

- (1) Initial material.
- (2) Attrition methods (grinding, crushing, etc.)

- (3) Soil classification, e.g., sieving, Atterberg limits, compressibility, permeability, stress-strain deformation and strength.
- (4) Measures to preserve water content.
- (5) Storage (e.g., at controlled RH and temperature).
- (6) Stress maintenance in samples cored in situ.
- (7) Chemical, x-ray diffraction, or other analysis to verify specimen constituents.
- (8) Mixing of different basic materials.
- (9) Addition of water, as required.
- (10) Transfer to laboratory test equipment to avoid change in specimen conditions.

4.1.2 Materials

4.1.2.1 Procedures

Quality-assurance procedures and specifications will be prepared to document the following.

- (1) Material type (e.g., Montmorillonite, shale core, etc.).
- (2) Origin.
- (3) Method of sampling or preparation.
- (4) Geological, crystallographic, or chemical identity.
- (5) Date and source for all of the above.
- (6) Correlation with previous laboratory tests.

An overall quality-assurance document shall assure the correct data entries, recording, and transmittal of this information to ensure traceability of all materials or specimens throughout the program.

4.1.2.2 Correlation with Field Data

It may be necessary to use specimens for correlation to logging data or other field tests, and this will require the establishment of characteristics correlatable to such tests. For example, it will then be necessary to determine:

- (1) Radioactivity characteristics, e.g., gamma ray.
- (2) Neutron activation tests.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

Figure 4-2. Technology roadmap, development of tests and test equipment.

- (3) Response to sonic excitation or sonic transmission.
- (4) Sensitivity to gradiometric, magnetic, or electrical resistivity measurements.

The criteria as to when such characteristics shall be obtained and the procedures to determine them shall be developed as part of this material characterization phase.

4.1.3 Performance Verification of Test Equipment

4.1.3.1 Calibration

Laboratory test equipment shall be inspected and calibrated to equipment specifications, for instance:

- (1) Dimensions.
- (2) Materials of construction.
- (3) Operating parameters (e.g., pressure against dead-weight tester).

4.1.3.2 Process Capability

In order to verify that equipment is capable of test results within acceptable error limits, repeatability and process capability shall be demonstrated, using standard materials of known or established characteristics. Such standard materials (specimens) shall be defined and specified over the range of materials expected in borehole strata and in plug or fill construction.

Standard materials shall similarly be specified for the determination of plug or plug-to-cored-hole physical characteristics. These shall include measurements of:

- (1) Permeability.
- (2) Pore pressure.
- (3) Lateral stress (axial where anticipated).
- (4) Consolidation.
- (5) Settling or creep.
- (6) Aging effects due to temperature, stress increase, leaching of residual ions, etc.

4.1.3.3 Compaction Effectiveness

In addition, verification procedures shall be determined for logging or in situ test characteristics described in Section 4.1.2, such as radioactivity or sonic transmission.

A major process verification task is the evaluation and calibration of instrumentation to determine the effectiveness of compaction. Methods available to assess this appear as follows.

- (1) Accelerometer on impacting foot (energy input to equipment) or California Bearing Test on foot or roller.
- (2) Calibration of compacting method against laboratory samples and tight control of process variables in the field.
- (3) Incorporation of sensors in face or body of plug or fill at spaced intervals downhole to monitor characteristics of seal or fill.
- (4) Layer analysis from the face: instrumentation capable of assessing compacted layer structure, attached to support structure of compacting head.

As a first step, instrumentation for these different approaches shall be investigated and developed as an integral part of the compactor process (Reference Part 1, Section 8.1). Since the physical characteristics of the compacted plug or fill are a critical variable of borehole sealing, the measuring and/or monitoring of the compaction process constitutes a major R&QA task. Principles and approaches underlying the different methods proposed are, therefore, discussed in some detail in this section. Instrumentation is required both in hole and in formation during pilot hole operation for quality-control checks.

4.1.3.3.1. Analysis Based on Records and Sampling

This approach is essentially similar to 4.1.3.3.2, except that accelerometer instrumentation of a compactor foot is not a necessary part of the method. What is envisaged is a compacting method other than weight or force impact, e.g., roller, air gun, or other processes. Obviously, the method can also apply to direct impact. If direct energy input measurements to the compacting agent working on the face is not possible, then the following program is required to assure reliability.

- (1) Calibration of power source.
- (2) Calibration of power transmission.
- (3) In-process monitoring of both.
- (4) Extensive correlation of compaction versus the above process variables, as well as the material and borehole characteristics.

Without measurements at the face, the range of the compaction attained will be significantly wider and will be evaluated against the plug and fill requirements specified (based on the concept feasibility, engineering analysis, and field test data).

4.1.3.3.2 Accelerometer on Equipment

Accelerometers as transducers mounted on the foot of a compactor can be used to measure the energy input to the compactor. A correlation study is required to determine:

- (1) Energy absorbed by compaction versus energy input.
- (2) Energy input versus consolidation of a lift or layer.
- (3) Effect of the different materials compacted.
- (4) Effect of lateral and axial constraints, that is, amount of borehole fill below the face, closeness to borehole wall, and energy absorption of different strata constituting the wall.

Laboratory tests are needed to establish the degree of compaction, e.g., by void and permeability measurements and accelerometer response. Further, it may be necessary to investigate and predict additional compaction which may be caused by the overburden of additional fill on top of an existing plug or sealing layer, particularly with regard to additional lateral stresses imposed on the borehole walls and changes in water retention in plug and borehole walls due to increased pressure or stress. Stringent controls are essential at this stage.

Obviously, this method permits no assessment of the structure of plug or fill below the face, except by correlation with laboratory data. In order to obtain confirmation of the validity of such data, it will be necessary to verify this on cored samples obtained in situ from field tests (pilot borehole sealing).

4.1.3.3.3 Sensors in Plug and Surrounding Area

The implantation of sensors in the different layers of plug and fill and/or surrounding strata appears desirable, in order to permit monitoring of the sealing process. If the overall constraints of the program do not permit this in a high percentage of the holes, it would be of great value in some Acceptable Quality Level (AQL) sample of holes (Reference 1, Section 11). As previously outlined, long-life monitoring is unfeasible. If an area has been stable for 5,000,000 years, then

one has to show that one is conforming to the geology of the area, and the area would then be stable for at least 5,200,000 years which would then meet the program requirements.

To this effect, implantation of electrodes, induction or magnetic sensors, radioactive sources and detectors, low-level sonic emitters/detectors need investigation, development, and field verification. The resistivity method, particularly, may offer a good way of assessing and predicting infiltration of water. Piezoelectric devices, or devices which set off a signal (perhaps sonic) at a given pressure or strain would also permit compaction measurement as the plug or fill layers are built up. Other devices are outlined in Part 2.

4.1.3.3.4 Periodic In-Process Monitoring, Integrated With Equipment

At the least, such measurements should be investigated on a pilot test basis and correlated with other process monitoring and laboratory analysis.

Layer analysis from the face appears a promising approach for investigation. The evaluation of this, when the string has been removed, is covered in another part of this report (see Section 4.2.2 and Appendix B), for instance, by gradiometry.

In-process monitoring will be achieved by mounting a movable instrumentation package on the support structure of a compactor assembly. Periodically, compacting can stop and the measuring head be lowered on the face.

A safety factor could be established during the pilot-hole drilling program. This would be to deliberately compact so that permeability at the interface of the plug/formation system is inadequate. A test to failure could be made. Quality-control data would then be studied on this hole and on better holes. The safety limit could then be determined.

One approach would consist of focused (perhaps spherical) electrodes designed to allow conductance through the lift or layer being built up or just completed. Other approaches would consist of lowering a small downward-viewing gradiometer or neutron sources/detectors. The last approach may be particularly successful if tagged isotopes or absorbants can be incorporated in the plugging material.

- (1) Feasibility needs first to be evaluated, that is, the detection limits of instruments, the constraints of the process on the instrumentation design, the capability with respect to different materials, compaction methods, bore-hole walls, and surrounding strata.

- (2) Design specifications of instrumentation and data analysis will be based on correlation with laboratory samples and field testing. The result of this phase will be a verified design specification, measurement procedures and analytical correlation.

4.1.3.4 Periodic Monitoring of Other Parameters

During the compaction process, other parameters will be measured. It is probable that the seal section of the plug will be at the formation with the limiting low permeability so that the method of measuring should be as accurate as the program permits. Certain formations need to be more critically determined than other formations and will be determined by the geology of the area. The temperature should be continuously checked to allow thermodynamic analysis for the likelihood of phase changes to undesirable structures. Pressure could be monitored for indications of problems that arise in process.

4.1.3.5 Environmental Quality Monitoring

Above-ground environmental quality must be monitored, both to ensure that no deleterious effects occur to the environment and to assuage fears of changes in properties of materials used for plugging. It would be desirable to monitor dust, humidity, and water levels. Methods of test will be designed and verified, and procedures written for field operation.

4.2 Borehole Logging

An imposed ground rule in this study is that the borehole is clean and adequately logged. While borehole logging is beyond the scope of this program, it is the key to the overall program and cannot be overlooked. As outlined in Appendix A, it is proposed, as an R&QA function, to monitor and control this operation. The success of an earthen compact system is closely related to the degree of knowledge of the properties of the formations present. The laboratory test program can only be as successful as the data supplied from downhole. Well logging for information on formation properties and hole concentricity presents problems, and an evaluation of various techniques and applicability at various test sites is proposed. It is further proposed to investigate the feasibility of utilizing a gravity gradiometer for a more accurate determination of the surrounding formations.

In a similar manner, techniques have been developed for measurement of porosity and water saturation. However, permeability can only be estimated from empirical relationships and these estimates have only order-of-magnitude accuracy. As is further outlined, a developmental program is proposed to develop more accurate measurements of in situ permeability.

The two areas to be covered by R&QA in this area are (1) the assessment of logging data for completeness and accuracy and (2) development of in situ techniques for permeability data.

4.2.1 Assessment of Logging Data

The results of the borehole logging will be assessed and compared to the known geology of the area.

4.3 Field Permeability Testing

As none of the logging techniques outlined in Appendix A is completely adequate for determining permeability, it is proposed that an effort be expended to develop a technique for measurement using rate of pore water pressure dissipation. It must be remembered that there are infinitesimal quantities of water involved, so that any ordinary field methods are not applicable.

One method could be the use of a radiation method using water-soluble isotope dispersion. A feasibility program could be established during the pilot hole operation. Dispersion would take place with flow, and by overcoring and examination, rates of flow could be established.

As outlined in Reference 2, the low permeability required suggested that an evaluation for unsteady flow conditions would be appropriate and probably would lead to simpler instrumentation. One scheme for determining permeability through excess pore pressure dissipation is to expand a long cylindrical membrane in the soil by means of internal pressure. The soil in the vicinity of the membrane will yield, and excess pore pressures develop. The solution to this plane-strain problem could be obtained using plasticity theory. It gives a logarithmic distribution of excess pore pressure that decays radially away from the membrane. The pore pressures thus derived, could be used as the initial conditions in the Finite Element computer program, CONSOL, and the pore pressure dissipation obtained at different distances away from the membrane at different times.

It is suggested:

- (1) Should the pore pressures be measured near the membrane at different times after expansion and compared with the results of computations similar to the ones performed, permeability can be approximated.
- (2) During consolidation, the soil in contact with the membrane undergoes negligible displacement. This means that if a rigid cylinder were used instead of a flexible membrane, results would not have changed.
- (3) The geometry of the membrane need not be restricted to a long cylinder. A sphere will cause no additional difficulties. More complicated geometries, such as short cylinder or any other surface of revolution, can also be used at some greater expense in numerical computations.
- (4) To use this type of device, the distribution of excess pore pressure is believed to be the weakest link in the analysis. The same applies to other devices which require that excess pore pressures develop in the soil when it reaches a plastic state, e.g., by penetration. The reasons are (1) the difficulty associated with obtaining plasticity solutions, and (2) the limited accuracy of plasticity theory in modelling real soil behavior.

It is proposed that laboratory testing as outlined in Section 6 be initially carried out to develop a standardized procedure to be followed by field testing. Correlation with other permeability testing methods is essential. It is stressed, however, that in situ tests are a prime requirement for a successful process.

SECTION 5 TASK SUMMARY
PROCESS AND EQUIPMENT QUALITY

Section	Subject Matter
5.1	<u>Surface Equipment</u> <ul style="list-style-type: none">(1) Receiving, classification, separation, grinding, measuring equipment, storage.(2) Environmental quality equipment, e.g., cooling towers, precipitators, air analysis instrumentation, etc.
5.2	<u>Power Supply</u> <ul style="list-style-type: none">(1) Specification of power limits (type) and safety margin.(2) Transmission to:<ul style="list-style-type: none">(a) Surface equipment(b) Downhole feed(c) Compaction equipment(d) String mount equipment(e) Instrumentation and test equipment(3) Fail safe and redundant requirements for power needs.(4) Reliability assessment of power.(5) Environmental protection and quality measurement.
5.3	<u>Natural Material Supply</u> <ul style="list-style-type: none">(1) Bill of materials for specific sites.(2) Incoming material traceability and tests.(3) Tests of procedures for material preparation (e.g., grinding).(4) Storage procedures and in-storage tests.(5) Pre-use verification of characteristics.
5.4	<u>Compaction Methods</u> <ul style="list-style-type: none">(1) Specification of equipment for different methods selected (static, impact, vibration, roller, air/steam gun, etc.).(2) Process capability tests of equipment (including limitation).

SECTION 5 TASK SUMMARY
PROCESS AND EQUIPMENT QUALITY (Cont.)

Section	Subject Matter
	(3) Limits for requirements of power, feed rate, material of process, ion waste disposition (e.g., air stream, steam, heat, etc.).
	(4) Limits of compaction on laboratory or acceptance testing.
	(5) Design and qualify in-process equipment monitors.
	(6) Effectivity analysis.
5.5	<u>Material Feed</u>
	(1) Specification of equipment for different methods selected (gravity, conveyor, screw, bucket, pneumatic, etc.).
	(2) Process capability, including limitations.
	(3) Limits for requirements: power, rate, materials, borehole size and orientation, waste disposition (including protection of environment from dust).
	(4) Compaction capability with feed parameter variations.
	(5) Design and qualify in-process feed monitors.
	(6) Design test corrective equipment for jamming, stall, etc.
	(7) Effectivity analysis.
5.6	<u>Process Limits Based on Material Type</u>
	(1) Material preparation based on hole logging.
	(2) Feed/compaction analysis for different material requirements.
	(3) Material mix, density, water content limits based on this section and project requirements.
	(4) Plug parameter limits (permeability, density, etc.) verification.
	(5) Evaluate best compromise for predicted materials, methods and borehole lithology.

SECTION 5

PROCESS AND EQUIPMENT QUALITY

Process and equipment quality are essential for any borehole filling project, and are not specific to compacted earth. Although some areas of this section are specifically oriented towards compacting natural earth, they can be extended to all operations.

5.1 Surface Equipment

The specifications and requirements for the surface equipment (see Figure 5-1) need to be established. This would include all classification, separation, grinding, measuring, and storage equipment. Where alternate methods are available, i.e., in grinding, hammer, core, roll crushers, etc., the optimum procedure for the selected material will be developed. Tradeoff studies will be performed to determine if standardized equipment can be used in all localities. A list of equipment needed for each site will be established and minimum acceptable limits established. Equipment qualification procedures will also be established. In a similar manner as that for laboratory test equipment, all items shall be periodically inspected and calibrated to ensure correct and efficient operation.

5.2 Power Supply

Due to the remoteness of most proposed sites, on-site power generation equipment will most probably be required. The minimum power requirements will be established for each location and a listing of preferred sources established. This will ensure that a known and verified supply will be used, and if alternate equipment is indicated, it also will necessitate a qualification test prior to use. This qualification test will be established. Transmission lines to operating equipment will be evaluated and, if necessary for reliability of the finished product, fail safe and redundant features will be installed. (Particular care must be taken for transmission lines extending down borehole to the compaction head and instrumentation package.)

Figure 5-1. Technology roadmap, surface equipment.

5.3 Natural Material Supply

For each particular location, a list of required natural materials will be established. A chart will be developed showing various strata formations in the borehole and the required fill material to be used in that area. A positive identification scheme will be established in that each particular fill material will be stored separately and characteristics established. The water content will be monitored at predetermined intervals and compared to the required value.

The required fill material will have traceability as to place of origin either from on-site or externally. In those cases where a fill material is to be used which does not correspond to a formation, e.g., montmorillonite clay, a similar set of characteristics and properties will be established and procedures established for monitoring of water content.

Specifications for the sampling of bulk material will be established per an ASTM, or better, specification to ensure that the sample is representative of the whole.

5.4 Compaction Methods

Various compaction methods (see Figure 5-2) are available as outlined in Section 6 of Part 1, and for a particular borehole and fill material one method may be more desirable than other schemes. The major schemes for compaction are:

- (1) Static
- (2) Impact
- (3) Vibration
- (4) Roller
- (5) Air/steam gun

The components of each group, i.e.,

- (a) Power/Input
- (b) Materials
- (c) Power
- (d) Rate
- (e) Monitor
- (f) Design

Figure 5-2. Technology roadmap, compaction methods.

will have been established and a decision made as to optimum choice with reliability and quality-assurance conditions an integral part of the decision making process.

Due to costs, the optimum choice can only be made as a result of laboratory tests and pilot plant operation. These tests must be constantly monitored and controlled to ensure that they are representative of any borehole that can be encountered at any location. A representative range of formation characteristics must be utilized. This problem is discussed further in Section 5.6.

5.5 Material Feed

A problem area that requires intensive investigation is the supply of soil to the face of the borehole. As is detailed in Part 1, choices for evaluation are:

- (1) Gravity
- (2) Conveyor
- (3) Screw
- (4) Bucket
- (5) Pneumatic

Again, each method must be carefully analyzed as detailed in Section 5.6. The simplest solution may not necessarily be the most reliable system and the system has to be reliable in both:

- (1) Maintenance and life.
- (2) Ability to deliver the required amount of material at the required time.

For a 10,000-foot hole, the former may be the more difficult to attain.

For all methods, an assessment has to be made as to effects on the original properties of moving the material down the hole.

5.6 Process Limits Based on Material Type (see Figure 5-3)

For each location a set of standard operating documents will be generated. The variations in the process will be determined by the properties of the formations in the borehole and the subsequent choice of fill material. Careful correlation has to be made with laboratory tests and on-site verification tests.

Figure 5-3. Technology roadmap, process and equipment quality.

The critical parameter is permeability. The permeability of the constructed composite must be 0.1 micro Darcy or that of the adjoining formation, whichever is greater. Permeability tests are made under constant head flow, and the laboratory hydraulic gradient, generally 800 to 1100, is greatly in excess of the field gradient in the order of 1. Correlation will be made from measurements with different gradients to determine if there is a detectability gradient below which there is zero flow for the chosen fill material. The flow rate may be nonlinear with respect to gradient (Reference 3). The most likely suspect area in the composite for permeation is at the junction between plug and formation. As detailed in Section 6, intensive laboratory tests are planned to determine the interface shearing force and the related permeability. The required compacting force is then derived for each combination of plug material and formation.

For each process variable that is determined to be critical, e.g., water content of fill material, compacting force, etc., operational limits will be established. These limits must be achievable within cost and process effectiveness requirements. Within each operating document the allowable limits will be specified. The task of the R&QA site representative would be to ensure that those limits are maintained at all times. The total time to fill a particular borehole will probably be in the order of months, and caution must be taken against degradation of instrumentation, e.g., loss of calibration in that time span. The material used must be sampled and constantly checked to ensure that the material is satisfactory for construction.

The equipment used in the process, e.g., grinding, must be checked to ensure that normal wear and tear has not degraded its performance during the operating period so as to exceed the preset limits. All monitoring equipment must be standardized and calibrated at regular intervals to ensure against erroneous results.

If different fill material is required when a new formation is reached, then the operating procedures must be checked.

This activity would be a prime function of R&QA during the process to ensure that a reliable and quality end product is achieved.

The limits in the process would thus be based on:

- (1) Material preparation based on hole logging. When the results of logging for a hole in a particular location are known, then the fill material can be procured. This may be on site or off site, based on the particular formation, its properties, and the availability of required material. As there may not be an equivalent material to the formation readily available, an extraneous material may be necessary. In all cases the material must be crushed or ground to the required fineness and safely stored.
- (2) Feed/compaction analysis for different material requirements. Due to the differences that are likely to be present in the properties of the formation and the selected fill material, limits must be established for rate of feed and degree of compaction. Both these variables will have been previously determined by laboratory tests and verified by pilot plant or in situ tests. R&QA must verify that these limits are understood and enforced.
- (3) Material mix, density, water content limits based on above and project requirements. As has been noted, a particular fill material may have to be modified by the addition of montmorillonite or other materials. If this is necessary, the mix must be closely monitored, the resultant density measured, and the necessary water added to meet the required limits mandated by laboratory and verification in situ tests. As the material may have to be stored for months, periodically samples have to be taken to insure product uniformity.

- (4) Plug parameter limits verification (permeability, density, etc.). For each different fill material and formation there will be optimal processing limits set to achieve the required properties in the region of their interface. In this zone the formation may be cracked due to stress changes from drilling or due to stress increases during compaction of the plug. The plug material may also be of lower quality in this zone due to the vertical compaction effort not being carried to the boundary of the hole. Another problem area is that the test results in the laboratory may not be equivalent to the in situ tests due to the lower lateral restraint provided by the formation walls compared to laboratory molds. All laboratory tests thus have to be carefully correlated to take these problem areas into account. Results from in situ tests must be examined carefully and process limits established so that no possibility of failure can occur in this zone. This is probably the most important area for control in the whole process.
- (5) Evaluate best compromise for predicted materials methods and borehole lithology. The results from the above evaluations must be combined into the best compromise. The relative importance of the permeability, durability, and strength of the plug/formation system must be combined to ensure optimum properties. If compromises are required, then this must be weighted against the overall requirements of the program. R&QA must ensure that no degradation to marginal levels be allowed to occur.

SECTION 6 TASK SUMMARY

IN-PROCESS QUALITY-ASSURANCE AND LABORATORY TESTS

Section	Subject Matter
6.1	In-Process Quality Assurance ⁽¹⁾
6.1.1	Continuing Material Analyses and Laboratory Tests
6.1.2	No In-Process Monitoring
6.1.2.1	Laboratory verification of energy input instrumentation only
6.1.2.1.1	Specifications and procedures for 6.1.2.1
6.1.2.2	Laboratory verification of energy input and feed rate
6.1.2.2.1	Parameters for specifications and procedures for 6.1.2.2
6.1.2.3	Reliability analysis of 6.1.1.1 and 6.1.1.2
6.1.2.4	Reporting system for data
6.1.3	In-Process Density Monitoring ⁽²⁾
6.1.3.1	Laboratory verification of 4.1.3.3.1 concept
6.1.3.2	Parameters for procedure and specifications, including calibration
6.1.3.3	Reporting system for data and reliability analysis
6.1.4	Probe-Type In-Process Monitoring ⁽³⁾
6.1.4.1	Laboratory verification at 4.1.3.3.3 concepts
6.1.4.2	Evaluation and selection of alternatives
6.1.4.3	Optimization of probe method
6.1.4.4	Parameters for procedures and specifications
6.1.4.5	Reliability analysis
6.1.5	Periodic In-Process Monitoring Integrated with Equipment
6.1.5.1	Laboratory verification of 4.1.3.3.4 concepts
6.1.5.2	Evaluation and selection of alternatives
6.1.5.3	Optimization of method
6.1.5.4	Parameters for procedures and specifications
6.1.5.5	Reliability analysis
6.1.6	In-Process Monitoring of Other Parameters
	Laboratory verification of 4.1.3.4 concepts
	Selection of methods
	Optimization of method
	Reliability analysis

SECTION 6 TASK SUMMARY
IN-PROCESS QUALITY-ASSURANCE AND LABORATORY TESTS (Cont.)

Section	Subject Matter
6.1.7	Environmental Quality Monitoring
	Verification in field of simulation of concepts of 4.1.3.5
	Optimization of methods
	Procedures and specifications
	Continued monitoring, reporting and analysis
6.1.8	In-Process Monitoring for Simulation and Pilot Tests (and field operation)
6.1.8.1	Design review to select systems and methods
6.1.8.2	Procedures and specifications - preparation
6.1.8.3	Schedules for calibration, maintenance, etc.
6.1.8.4	Monitoring program, equipment, operation
6.1.8.5	Data reporting and reliability analysis
6.2	Laboratory Testing Methods ⁽¹⁾
	Optimization of methods of 4.1.1 and 4.1.2
	Procedures and specifications
	Calibration and maintenance program
	Sampling and test schedule procedures

-
- (1) Method and instrumentation development in Sections 4 and 5, particularly 4.1.3.3.2.
- (2) See 4.1.3.3.1 and 5.4
- (3) See 4.1.3.3.3

SECTION 6

IN-PROCESS QUALITY-ASSURANCE AND LABORATORY TESTS

6.1 In-Process Quality Assurance

The in-process quality-assurance tasks (see Figure 6-1) are based on the development task results of Sections 4.1 and 4.2, and the quality evaluations of Section 5. As such, several of the approaches or general schemes in Sections 6.1.1 through 6.1.5 may be discarded during the development phase, Section 4, or the process of equipment quality phase, Section 5, for reasons of effectiveness, feasibility, or cost. Since no judgement as to their applicability is made in the subject report, all of these approaches are shown as tasks.

The major task in this phase is quality control to ensure conformance to design criteria. From the controls, quality assurance is then established.

6.1.1 Continuing Tests

Throughout the process, analyses of materials will be performed in accordance with a sampling test plan. In addition, samples of materials will be laboratory tested in accordance with a periodic test plan, in order to determine characteristics such as permeability, Atterberg limits, etc.

6.1.2 No In-Process Monitoring

The approach assumes no direct monitoring of process parameters, except energy input (at borehole entry, power source or transmission) and feed rate, supplemented, of course, by the continuing tests of Section 6.1.1.

This would be an extremely high-risk and low-reliability program. An example would be filling a hole with cement by pumping in grouts with zero in-process monitoring. This type of monitoring is not recommended.

Figure 6-1. Technology roadmap, in-process quality assurance and laboratory tests.

6.1.3 In-Process Monitoring

As shown in the development phase of Section 4.1.3.3.2, this method utilizes accelerometers or similar sensors mounted on the foot of an impactor, or other compacting device. For some compaction methods, e.g., by roller, it may be more advantageous to record torque/time resistance or other parameters. In static compaction, stress-strain characteristics will be measured on every lift. In either case, the common feature of these monitoring methods is the direct measurement of energy input to the densification tool. It is understood that this approach is complemented by the continuing tests of Section 6.1.1. The following tasks are required.

- 6.1.3.1 Laboratory verification of the instrumentation developed in Section 4.1.3.3.2, including correlation of energy input measurements to laboratory density and permeability results.
- 6.1.3.2 Determine parameters and limits required for specifications and procedures, including initial and periodic calibration of instrumentation.
- 6.1.3.3 Determine the requirements for a data reporting system within the integrated data system of Section 3.2, including parameter upper and lower limits based on a reliability analysis and taking the process limits of Section 5.6 into account.

6.1.4 Probe-Type In-Process Monitoring

This approach relies on sensors in the plug (or fill) and/or surrounding strata (a discussion of possible methods appears in Section 4.1.3.3.3). The greatest difficulty is that of identifying and calibrating possible sensors and correlating their performance with laboratory test results relating to plug effectiveness. Holes will be instrumented for pilot holes for correlation purposes and will only be monitored for a predetermined length of time. In full operation, boreholes will not be instrumented.

In the qualification of such instrumentation, several cautionary conditions deserve consideration. The nature of the sensory measurement poses its own requirements. For instance, a number of electrical resistivity methods rely on the presence of a conducting coupling agent such as mud and on a minimum water content in the conduction path (e.g., through a number of strata). Moreover, probes imbedded in a soil medium

are subject to environmental effects such as corrosion. These effects and protective measures must be evaluated. When the development phase of Section 4.1.3.3.3 has determined feasible methods, then the following tasks are needed for the in-process monitoring system:

- 6.1.4.1 Laboratory verification of the Section 4.1.3.3.3 design concepts, including correlation with laboratory density and permeability results. It is postulated that the specific method(s) selected will need confirmation in the system verification program (Section 9).
- 6.1.4.2 Evaluation and selection of most practical alternatives, considering effectivity of methods, project constraints as to boreholes to be instrumented, feasibility in build operation, and costs.
- 6.1.4.3 Optimization of probe method(s), including design modifications for producibility.
- 6.1.4.4 Determination of parameters to be monitored and of parameter limits as a function of compaction method, materials, etc. (see Section 5.6); basis for specifications and procedures.
- 6.1.4.5 Reliability analysis of selected method(s), which may require reevaluation of Section 6.1.4.2, and design of data reporting system to fit the integrated data system of Section 3.2.

6.1.5 Periodic In-Process Monitoring Integrated with Equipment

The concept, outlined in Section 4.1.3.3.4, relies on a gravity gradiometer radioactive source/detector or other measuring device lowered periodically from the string support structure to the face (to measure just-compacted plug layers). The concept needs comprehensive evaluation of feasibility, but has the potential of providing significant assurance of the plug quality. Tasks are as follows:

- 6.1.5.1 Laboratory verification of Section 4.1.3.3.4 design concepts, including correlation with plug quality sampling tests, and probable in situ test during the Section 9 phase.
- 6.1.5.2 Evaluation and selection of alternatives, including operational feasibility, costs of operation pauses for measurement, and overall instrumentation costs.
- 6.1.5.3 Optimization of method selected.

6.1.5.4 Determination of parameters, including the limits defined in Section 5.6, for specifications and procedures.

6.1.5.5 Reliability analysis (may require reevaluation in Section 6.1.5.2); data system to be part of integrated data system (Section 3.2).

6.1.6 In-Process Monitoring of Other Parameters

Methods will be developed for measuring depth, temperature, string weight, pressure, etc. Off-the-shelf equipment will be utilized as much as possible and initial laboratory tests will be run to verify that the concepts are feasible. Once laboratory tests confirm the concepts, then particular methods can be selected and optimized. It is essential that any instrumentation be integrated with the design of the downhole equipment, rather than added on as an after thought. Before any method can be considered complete, it will be necessary to run a reliability analysis of the process. This would include both hardware problems, (1) the ability to accurately give data and the reliability of the process, (2) are all the controlling parameters identified. Only then can the process be released for full-scale operation.

An essential monitor to be developed is a downhole humidity sensor. At the bottom of a 10,000-foot hole it is estimated that the temperature will be 120°C. At temperatures greater than 90°C, to preclude drying out of water from fill material, a packer and superheated steam will most likely be required. Adding water to a clay and mixing downhole is not a feasible operation and accordingly an accurate assessment of the downhole environment must be continuously monitored.

6.1.7 Above-Ground Environmental Protection, Work Safety, and Monitoring

The borehole sealing project management must ensure that operations at any location will have minimum environmental impact. There must be a high degree of confidence that all proposed alternative procedures at any given site be extensively studied to determine the environmental effect. The study should preferably be carried out by a group not influenced by production or operation interests and a logical choice would be an R&QA group. This group would have the power to veto any proposal that has major environmental effects. If mining is to be carried out in the vicinity, e.g., outcrop material, there must be assurance that there will be no adverse effects and that a plan is developed to reclaim the area. Although the environmental impact

assessment and plan is not strictly an R&QA function, it is a logical choice as they are involved in assuring that the plug material is ecologically equivalent to the surrounding formation so that no long-term degradation can occur in the vicinity.

An extension to the problem of environmental quality is the impact on the borehole plugging operation. The changes in the environment above ground, but primarily underground, may affect the operation being followed and inject unallowable variances in the final product. Monitoring techniques must be set up to measure particle count, relative humidity, water seepage, etc.

The monitoring equipment will be set up in the field, and optimized for efficiency and reliability. Procedures and specifications will be written and schedules allotted for the reporting of data. R&QA will continuously analyze the data for possible impact on the process.

Environmental quality equipment in use at the site such as filtration equipment, dust precipitators, cooling towers, air analyzers, etc., will have schedules prepared for preventative maintenance.

A similar situation relates to work safety. All equipment must be inspected to ensure that as well as meeting performance standards, it must meet all safety considerations. The procedures for operating such equipment must take into account human factors and be essentially fail safe.

6.1.8 In-Process Monitoring for Simulation and Pilot Tests (and Field Operation)

The R&QA tasks of this phase are in support of the System Verification Tests of Section 9 and the subsequent Field Qualification (Section 10, if necessary) and Field Operation (Section 11). As such, they are based on the development phase (Section 4) and the in-process monitoring methods of Sections 6.1 through 6.7. They serve mainly to ensure full preparation for and support of engineering test and operational activities and are summarized below. As discussed in Section 9.4, System Verification Pilot Tests need to include pilot boreholes sealed with qualified plug material, but constructed or compacted inadequately. These inadequate plug/formation systems will then serve to determine permeability in the pilot test. This permeability will be compared to that predicted on the basis of laboratory tests. The pilot hole(s) sealed adequately in accordance with the process requirements of this

report will show no permeability as measurable in the field, at least in the plug region having low-permeability material, such as montmorillonite.

- 6.1.8.1 Design review to select systems and methods - this provides the final trade-off evaluation of the type and frequency of in-process monitoring.
- 6.1.8.2 Preparation of specifications and procedures for the alternative(s) selected.
- 6.1.8.3 Preparation of schedules for calibration and maintenance, and of repair procedures.
- 6.1.8.4 Design of the monitoring program, procurement and installation of the required instrumentation, and operation of the system. This subtask may be further subdivided, for example, to assign procurement and operation of the in-process monitoring to different organizations or contractors. However, there is an overall R&QA responsibility to ensure completion of this subtask(s) to satisfy project requirements (including schedules).
- 6.1.8.5 Design and install data reporting system to fit the requirements on the integrated data system (Section 3.2); provide for the operation of the system and the analysis of data (including reliability analysis).

6.2 Laboratory Tests

The starting point in establishing program requirements for any area under consideration is to run laboratory tests on samples. These samples which can be core samples, samples taken from wall of hole, outcrop material, etc., must be sufficient to fully identify the lithography. As it will be necessary to duplicate as nearly as possible in the laboratory all possible combinations of fill material and formation material, great care must be taken to ensure the validity of the samples. It is highly recommended that all samples be taken under cognizance of R&QA to verify the sampling technique and method. R&QA will develop a set of operating procedures to cover this task.

6.2.1 Proposed Laboratory Tests

The following laboratory tests are proposed.

- (1) Permeability
- (2) Standard Water Content

- (3) Specific Gravity
- (4) Atterberg Limits
- (5) Grain Size Distribution
- (6) Swell Pressure Tests
- (7) Shrinkage Tests
- (8) Plug/Formation Properties
- (9) Mineralogical Composition

In general, methods of testing will be evaluated and optimized with certain methods for full site usage and other tests for remote laboratory use. Procedures and specifications for each test will be established as will be the test schedule and sampling procedure. For repeatability, a calibration and maintenance program for test equipment will be established.

6.2.1.1 Permeability Tests

Permeability is a critical property to achieve a satisfactory plugged hole and is the controlling criterion.

The criterion is that the permeability of the constructed composite be equal to 0.1 micro Darcy or that of the surrounding stratum, whichever is greater, as an assurance that the quantity of water flowing will be below a safe minimum.

A standardized method of determining permeability under constant head flow will be used. Operating instructions will be written to cover variation from this standardized method by R&QA as needed. A hydraulic gradient will be developed so that the laboratory gradient will give comparable results compared to the field hydraulic gradient.

Permeability tests will also be run on the plug/formation system and are essential for the evaluation of the adequacy of the final product.

As there is a stress relief when samples are taken from underlying formations there will be a difference in permeability in situ compared to the laboratory. Tests will be run in the laboratory to determine what, if any, correlation will be made.

As the most likely source of premature failure in a borehole is at the plug/formation interface, the technique for preparing such laboratory specimens must approach actual on-site conditions.

6.2.1.2 Water Content

This useful relationship is the weight of water divided by the weight of solid in a soil element. The water content is obtained by weighing the natural material, drying, and then reweighing. For compaction, material may need to have water added during filling operations. Facilities must be available on site, i.e., a balance of sufficient accuracy and a controllable oven to ensure that the level of water in the sample can be rapidly determined. It is noted that mixing water into clay presents grave problems.

6.2.1.3 Specific Gravity

This is the unit weight divided by the unit weight of water. There may be a difference in these values for the same generic type of material, e.g., montmorillonite, obtained from different locations, but is not expected to be significant.

6.2.1.4 Atterberg Limits

These limits are based on the concept that a fine grained material can exist in any of four states, i.e., solid, semisolid, plastic, or liquid. The water contents at the boundaries between adjacent states are termed shrinkage limit, plastic limit, and liquid limit.

These tests are necessary laboratory tests for material identification and classification. Limits can thus be established for determining the suitability of use of certain fill materials.

R&QA must ensure the validity of laboratory testing and determine the need for on-site verification tests.

6.2.1.5 Grain Size Distribution

The distribution of grain sizes in a cohesionless soil is determined by sieving, however, the size of the soil in the finer fraction

i.e., portion which passes the 200 mesh (0.074-inch minimum opening) sieve, or of a cohesive soil is measured by the hydrometer test. A standard ASTM procedure, i.e., C136, would be used for sieving. A hydrometer test utilizing the motion of particles falling through a still liquid (a known weight of soil is placed in a cylinder, shaken, and allowed to settle). The unit weight of the suspension at given depths below the surface can be obtained by readings on a hydrometer which is periodically immersed in the fluid.

6.2.1.6 Swell Pressure Tests

The material to be used as a plug material such as a compacted clay shale may or may not be a highly expansive material and it is essential that the swell potential of the compacted candidate materials be determined, prior to use, by laboratory tests. It is recommended that the following tests be made.

6.2.1.6.1 Maximum Constant Volume Swell Pressure

In order to determine whether or not the stresses imposed on the surrounding formation due to swelling of the plug will be excessive, an estimate of the maximum value of swell pressure at constant volume for any given material as a function of its molding water content and initial (as compacted) dry density is required.

6.2.1.6.2 Prestressing

Residual stresses will undoubtedly be imposed on the plug and surrounding formation as a result of the compaction process. It is necessary to know to what extent additional stresses may result from swelling.

6.2.1.6.3 Admixtures

Once the swell potential of a given material is determined, it becomes necessary to know to what extent these properties can be modified through the use of natural earthen additives to suit the requirements of the system. A material exhibiting an excessively high swell potential may have that swell potential reduced by the addition of quartz sand. If it is desired that a material exhibiting a low swell potential have that potential increased, this may be

accomplished by adding montmorillonite. It is essential that the system be tailored by matching water content of plug and formation to obviate mass water transport. A tailored system will allow migration within ± 1 hole diameter.

6.2.1.6.4 Swelling and Swell Pressure

Any mechanism permitting expansion of the compacted plug will induce a decrease in observed swell pressure. It is therefore necessary to develop a relationship between amount of swell and swell pressure in order to determine what percentage of the maximum constant volume swell pressure can be anticipated in a downhole situation.

Testing that has been carried out (Reference 4) indicates that for the same material from different locations, i.e., core versus outcrop, there are differences in swell pressure. This indicates that if material is brought in from an external source, there are likely to be significant differences in swell pressure. Swelling also has a large effect on swell pressure and small amounts of swelling will result in large reductions in swell pressure. Any occurrence of swell pressure in a downhole situation will result in some expansion of the plug (or of the formation if its swell potential is greater than that of the plug) which will lower the magnitude of the swell pressure. The plug expansion can come about as a result of a number of different mechanisms. Material can swell into small cracks in the side of the hole left after drilling of the hole. Small cracks can be propagated due to an increase in stress. Some deformation of the formation will occur due to any increase in lateral stress.

All these problem areas must be fully assessed and R&QA inputs will be essential for assurance that reliability is not compromised. It must be emphasized that for swelling to occur, water must be available.

6.2.1.7 Shrinkage Tests

Any material exhibiting a large potential for swelling will also exhibit a similar potential for shrinkage. Excessive shrinkage of the plug material may cause prohibitive increases in permeability at the interface between plug and formation. For this reason, it is necessary to identify the shrinkage characteristics of material used as a plug.

Again it is emphasized that the controlling factor is water content of the formation relative to that of the plug. Redistribution of moisture within a system will occur.

Laboratory testing (Reference 4) has indicated that the volumetric stability tends to increase with decreasing molding water content. The result of using quartz sand as an admixture has the effect of reducing shrinkage as well as swell potential, whereas the effect of adding montmorillonite is to increase shrinkage as well as swell potential.

6.2.1.8 Plug/Formation Tests

In order to simulate actual borehole conditions, it is essential that tests be run utilizing a composite plug-formation system. The mechanical properties of plug and formation materials can be determined separately but the properties of the system consisting of plug and immediately adjacent shale formation need to be known so that an assessment of the process can be made.

It is mandatory that laboratory tests be carried out using either compacted shale to provide the simulated formation or a machined specimen. Preliminary experiments are planned to optimize a standard method. The method noted in Reference 4 will be standardized. In this method, the samples are confined to preclude leakage during permeability testing or failure during compaction. The simulated boreholes are plugged utilizing compacting techniques with sufficient material and pressures that the required overall density is achieved. The plugs can then be extruded out using a piston on the plug and restraining motion of the formation material.

It is proposed to use these laboratory tests to ascertain what conditioning of the wall is necessary and the problems involved in arriving at the correct water content and density of plug material. The need for a "mudded" or clean hole will be ascertained. An endeavor will be made to reproduce what is actually in the borehole and so determine if scraping of the walls is required.

The strength criterion of an adequate plug is that the adhesion of the placed plug to the formation will provide a bond strength that will withstand 300 feet of water head across a 1-foot length calculated for an 8-inch-diameter hole. This criterion is essentially that the average shearing resistance on the circumference of a 1-foot plug is greater than 22 lb/in.²

R&QA will control all plug-formation tests to ensure that testing is representative of actual conditions for both borehole formation and fill material.

6.2.1.9 Mineralogical Composition

It is proposed that X-ray diffraction analysis will be used for the identification and quantitative determination of mineral content, particularly for clay classification. Petrographic examination, scanning, and transmission electron microscopy will also be used for structure clarification.

Other techniques will be used as required, i.e., differential thermal analysis, infrared spectroscopy, analytical chemistry as needed for identification and pin pointing of potential problems in the use of certain materials.

SECTION 7 TASK SUMMARY
DECISION POINTS BASED ON EVALUATION OF PROCESS ALTERNATIVES
(2, 3 and 4)

Section	Subject Matter
7.1	<u>Decision Points</u> <ul style="list-style-type: none">7.1.1 Surface equipment.7.1.2 Power supply.7.1.3 Raw material supply.7.1.4 Compaction method.7.1.5 Material supply (including downhole), in-process quality assurance and environmental quality monitoring.
7.2	<u>R&QA Subtasks (for Section 7.1)*</u> <ul style="list-style-type: none">7.2.1 Analysis of test data, including validity of conclusions.7.2.2 Ensure sufficient process capability under predicted conditions.7.2.3 Verify feasibility of alternatives with scaled-up equipment.7.2.4 Analyze and predict reliability of subsystems and overall process system.7.2.5 Ensure in-process and final product monitoring over product life.7.2.6 Assist in trade-off analysis.<ul style="list-style-type: none">(a) Determine which methods are more effective for given conditions
7.3	<u>Subsystem Interactions and Final Design Review</u> <ul style="list-style-type: none">7.3.1 Subsystems selection for overall system.7.3.2 Determination of tasks to bring subsystems to final evaluation stage.7.3.3 Determine off-the-shelf procurement, new design, etc.7.3.4 R&QA support of Section 7.3.3 (as in Sections 7.2.1 - 7.2.6).7.3.5 R&QA analysis of different decision paths.7.3.6 Programs to implement decisions.<ul style="list-style-type: none">(a) Equipment/process specifications.(b) Test procedures.

SECTION 7 TASK SUMMARY
DECISION POINTS BASED ON EVALUATION OF PROCESS ALTERNATIVES
(2, 3 and 4). (Cont.)

Section	Subject Matter
7.4	<u>Life Cycle Projections</u>
7.4.1	Reliability Analysis.
7.4.2	Effectivity (of system, subsystems, material, etc.).
7.4.3	Cost Estimate (including cost consequences of deleting task or subtask).
7.4.4	Failure Mode and Effects Analysis.

* The subtasks apply to subsystems of Sections 7.1.1 through 7.1.5 and the overall system. Basis for analyses will include life-cycle predictions (Section 7.4).

SECTION 7

DECISION POINTS BASED ON EVALUATION OF PROCESS ALTERNATIVES

The evaluation of process alternatives will have provided sufficient data on process and equipment capability and the probability of satisfying the overall system requirements to permit the selection of the most promising options for the final development, test, and qualification.

7.1 Decision Points

Decision points require design and process reviews for each major task, i.e.:

- 7.1.1 Surface equipment.
- 7.1.2 Power supply.
- 7.1.3 Natural material supply.
- 7.1.4 Compaction method.
- 7.1.5 Material supply (downhole) in-process quality assurance (tests, instrumentation, data analysis).

The reviews will assess the alternatives tested against the criteria of best probability of satisfying overall objective, feasibility (to achieve planned project milestones), cost, and reliability.

7.2 R&QA Subtasks

The particular tasks of the R&QA activity include:

- 7.2.1 The analysis of test data and designs to verify the validity of the results and conclusions.
- 7.2.2 To ensure that process capability is sufficient to meet functional requirements under a variety of predicted conditions.

- 7.2.3 To verify the feasibility of the alternatives with scaled-up equipment (predict field performance).
- 7.2.4 To analyze and predict reliability of subsystems and the overall process reliability.
- 7.2.5 To ensure that in-process and final product monitoring is possible to measure ultimate product reliability over the required life.
- 7.2.6 To assist in trade-off between different methods and in determining the conditions under which particular methods are more effective.

Task 7.2.6 addresses itself also to the changes which different environments (location of site, structure of strata, etc.) may require as to equipment and process. Some changes may be readily accomplished, for instance, the substitution of materials to seal boreholes through different strata or possible pretreatment of boreholes or invaded zones. Others may be difficult on-site, such as the substitution of pneumatic downhole material delivery versus bucket delivery. Particularly in the latter case, a value analysis is desirable to weigh the cost and effect on reliability of such changes against the probable payoff.

7.3 Subsystem Interactions and Final Design Review

The review of each subsystem or major task will consider the interactions of the separate subsystems, since the optimum alternative for a given subsystem is not necessarily the best choice for the overall system. For example in dynamic impact compaction, the best compacted layer requires a large number of blows, however, control presents a different quality-control problem and the effect of the process on the borehole walls is both deleterious and variable. A final design review will start with the overall system objectives and evaluate the best alternatives selected by the prior evaluations subsystems. The particular R&QA task is the evaluation of interactions of subsystems and the effect on overall system and process reliability.

The final system review:

- 7.3.1 After identifying the subsystem alternatives to be implemented in final development, test and field qualification,
- 7.3.2 Determine the tasks needed to bring each subsystem to the final evaluation stage.

- 7.3.3 Review data on available equipment and decide on off-the-shelf procurement, modification of existing equipment or processes, or initial design and development.
- 7.3.4 R&QA tasks are of the same type as previously outlined in this section (Tasks 7.2.1 through 7.2.6).
- 7.3.5 An additional significant task is the prediction of success in following the different procurement or development paths: this analysis forms the basis of the final design review decisions, together with engineering evaluation, cost analysis, value analysis, and feasibility in field operation.

7.3.6 Programs to Implement Decisions

It is the task of project management, with the assistance of the R&QA function, to design the programs required to implement the review decisions. R&QA tasks consist of:

- 7.3.6.1 Detailed equipment/process specifications.
- 7.3.6.2 Test procedures for the procurement of existing or the development of to-be-designed hardware or subsystems, within the project guidelines.

Further implementation of the review decisions is described in Section 7.4.

7.4 Life Cycle Projections

R&QA development of product life cycle projections serves as a baseline for project decisions as to process alternative, type of instrumentation, and extent of in-process and post-process monitoring programs.

7.4.1 Reliability Analysis

As part of this overall task, reliability analysis will be performed at the completion of each project phase to assess:

- (1) The reliability of a given process path on the roadmap, of a plug material, and of the in-process data obtained.
- (2) The trade-off in reliability in selecting one process or type of equipment over others.
- (3) The final product reliability over the required product life (i.e., sealed borehole for 200,000 years).

It is not likely that the type of process and product can lend itself to a reliability block diagram or similar formal analysis. Rather, it is proposed that each phase be developed to the quality level required to result in the highest possible reliability. Confidence limits of these projections will, of course, become wider with increasing product life, since the time base of laboratory and field data is relatively small in comparison with total product life.

7.4.2 Effectivity

An effectivity analysis is required to determine the availability of material, equipment, and instrumentation in order to accomplish the schedule of the roadmap. This is mainly required for field operation, but may include at least estimates for the simulation testing, pilot test, and any additional field qualification not carried out at the pilot test stage:

7.4.2.1 Factors affecting the availability include:

- (1) Material availability and logistics.
- (2) Material preparation equipment (including spares) and process time.
- (3) Feed, power, and compaction equipment maintainability. (spares, projected operating time without failure).
- (4) Instrumentation: as item (3).
- (5) Inherent waiting times in-process, e.g., for test results on a sample.
- (6) Availability of personnel and surface rigs, e.g., drilling crews.

The effectivity analysis furnishes the basis for the equipment, material and personnel needs to complete operations within a time schedule, and permits the assessment of risk involved with different process roadmap paths or certain levels of spares.

7.4.3 Cost Estimate

The life cycle cost estimates translate the different roadmap paths, including instrumentation for in-process monitoring, into a common measurement. As such, they are used as one of the factors at decision points and trade-off evaluations.

The R&QA function, in addition to preparing costs for positive selection, needs also to evaluate the cost consequences of omitting a task or operation, in order to present all foreseeable consequences of different alternatives to design reviews. For instance, the decision of not instrumenting during compaction may lead to a defective borehole seal: the risk and cost of this needs to be assessed.

7.4.4 Failure Mode and Effects Analysis

In order to envisage the possible problems during and after borehole sealing, a failure mode and effects analysis (FMEA) of the sealing process and of the seal during product life appears desirable. This will be made during the pilot hole program when holes will be made under a wide range of conditions. The materials will not be altered but only the compacting process. This allows a clearer definition of the likely consequences of a given decision, and provides for the reliability and cost projections for the chosen process path compared to others. As discussed in Section 12, this appears particularly desirable in connection with product life monitoring. The particular fault-tree/FMEA approach will need to be defined during the initial development stages of the project, in order to base it on a clearer understanding of the various interactions to be expected.

SECTION 8 TASK SUMMARY
PROCESS/EQUIPMENT DEVELOPMENT AND ENGINEERING VERIFICATION

Section	Subject Matter
8.1	<u>Off-the-shelf</u> (Option 1).
8.2	<u>Modification of state-of-the-art</u> (Option 2).
8.3	<u>Redesign</u> (Option 3).
8.4	<u>New design</u> (Option 4).
8.5	<u>Trade-off evaluations and experiments.</u>
8.6	<u>Trade-off design review – R&QA subtasks:</u> Analysis and presentation of: <ul style="list-style-type: none">(1) Design evaluations.(2) Engineering and verifications of data.(3) Quality and reliability analyses (see Section 7.4).(4) Consequences of selections under anticipated field conditions; including effectivity and feasibility in field operation.
8.7	<u>Implementation of Section 8.6.</u> <ul style="list-style-type: none">(1) Documentation for implementation.

SECTION 8

PROCESS/EQUIPMENT DEVELOPMENT AND ENGINEERING VERIFICATION

This phase of the project is principally concerned with the equipment and instrumentation selected, although some further process development or modification may be part of it. The latter may include changes or treatment of raw materials, or preparation of borehole surfaces (including possible treatments to improve interface adhesion or permeability, i.e., strengthen the interface condition of borehole wall to plug or fill).

Four major paths or options are possible on the roadmap, Figure 8-1.

<u>Equipment/Process Status</u>	<u>Option</u>
State-of-the-Art	1. Off-the-shelf 2. Modification
Development	3. Redesign 4. New design

From a cost and time standpoint, Option 1 is the most desirable, followed by Option 2. The R&QA task to prepare procurement and evaluation has been outlined in Section 7. Final tasks, (Numbers 8.5 and 8.6) after the project decisions on specific subsystems or process modifications have been made, will depend on the roadmap of PERT diagram path selected as follows.

8.1 Option 1: Off-the-Shelf

- (1) Verification of compliance with specifications.
- (2) Process capability verification (through the range of anticipated variation of performance requirements under predicted conditions).
- (3) Functional test for acceptance or subsystem qualification.
- (4) Pilot test under field conditions as required.

Figure 8-1. Technology roadmap, process/equipment development and engineering verification; system verification.

- (5) Modifications of specifications, as required.
- (6) Negotiation with contractors to ensure acceptance of specifications.

8.2 Option 2: Modification of State-of-the-Art

- (1) Quality plan to provide test and inspection points during modification program.
- (2) Preparation of objectives and specifications.
- (3) Evaluation as to quality and reliability of modification or initiation, in-process and completion of program.
- (4) Design of instrumentation and procedures to determine critical parameters (critical experiments).
- (5) Verification of compliance to requirements, process capability and functional tests for subsystem qualifications.
- (6) Pilot tests under field conditions, as required.
- (7) Revision of specifications and/or procedures, as required.
- (8) Negotiation with contractors to ensure acceptance of specifications.

8.3 Option 3: Redesign

- (1) Determine adequacy of design directions with respect to quality.
- (2) Collaborate in preparation of redesign directives and program.
- (3) Other tasks as for Option 2.

8.4 Option 4: New Design (Invention)

- (1) Assist in preparation of work statement and program design.
- (2) Participate in design reviews during redesign and prototype testing.
- (3) Design and carry out prototype testing.
- (4) Other tasks as in Option 2, with the exception that functional and process capability steps will be more exhaustive to the degree that a new design departs from state-of-the-art equipment, instrumentation, or process.

8.5 Final Evaluations and Experiments

Trade-off evaluations and experiments designed to provide a data base for trade-off decisions will be conducted during different segments of this phase.

8.6 Trade-off Design Review

A final trade-off design review will provide for the selection of the optimum subsystem. The tasks of the R&QA activity are the analysis and presentation of:

- (1) Design evaluations.
- (2) Engineering verification data.
- (3) Quality and reliability analyses (see Section 7.4).
- (4) Advantages and disadvantages of the possible selection under the range of variation of anticipated field conditions.

As part of these analyses, effectivity of equipment and process (availability, maintainability, need for spares, logistics, etc.) will be evaluated. In addition, feasibility in field operations and costs attached to the different options needs to be analyzed.

It is of extreme importance to provide synergistic analysis of the whole system, in addition to subsystem evaluations, in order to ensure that interactions and bottleneck conditions have been properly analyzed and an optimum system determined.

8.7 Implementation

After project selection on the basis above, the R&QA function will prepare, as necessary, specifications and other documentation to implement the selection.

SECTION 9 TASK SUMMARY
SYSTEM VERIFICATION

Section	Subject Matter
9.1	<u>Laboratory Mockup Equipment (procure or modify)</u>
9.1.1	Quality Plan (for system simulation test)
9.1.2	Test Procedures and Laboratory Tests
9.2	<u>Simulation Tests</u>
9.2.1	Site and Test Support
9.2.2	Test Program (using breadboard equipment and instrumentation)
9.2.3	Data System (design and operation of)
9.2.4	Analysis of Test Results
9.3	<u>Modification of Designs (based on Task 9.2) and Procurement and Verification of Prototype Equipment</u>
9.3.1	QA Plans and Activities
9.3.2	Acceptance
9.3.3	Possible Simulation Retest (for major modifications)
9.3.4	Contractor Interface
9.4	<u>Instrumentation and Pilot Test(s) of Prototype System</u>
9.4.1	Conditions for Test and Field Qualification
9.4.2	Test Site Preparation
9.4.3	Test Program
9.4.3.1	Review of test plans for significance and reliability.
9.4.3.2	Acceptance* of test site, instrumentation, equipment.

SECTION 9 TASK SUMMARY
SYSTEM VERIFICATION (Cont.)

Section	Subject Matter
9.4.3.3	In-process monitoring and analysis of sealing process.
9.4.3.4	Summary analysis of test results vs project requirements.
9.4.4	Product Evaluation (if optional program of Section 9.4.2(7) is conducted).
9.4.4.1	Sampling (of borehole and surrounding strata).
9.4.4.2	Reliability Assessment (of product).
9.4.4.3	Acceptance (as field qualification and additional test needs).
9.5	<u>Specifications and Procedures for Field Qualification (or for final product)</u>
	Alternatives:
(1)	Tests accepted: specification and procedures for field operation.
(2)	Failure of some subsystems: test plan and qualification.
(3)	Major changes: field qualification plan.
9.5.1	Procedures (and specifications)
9.5.2	Final Report
9.5.3	Contractor Interface (interface with contractors and operational manuals)

* For both pilot test and field qualification.

SECTION 9

SYSTEM VERIFICATION

This phase is divided into the following tasks (Figure 8-1:

- 9.1 Procure or modify laboratory mockup equipment.
- 9.2 Simulation tests.
- 9.3 Modification of designs (based on Task 9.2) and procurement and verification of prototype equipment.
- 9.4 Instrumentation and pilot testing of prototype system.
- 9.5 Specification and procedures for field qualification.

9.1 Laboratory Mockup Equipment

Subsystems used in the preceding development testing will be modified as required to permit a laboratory scale verification of the operation and effectiveness of the selected integrated subsystems.

9.1.1 Quality Plan

- (1) The proper definition of requirements and their verification for equipment and raw material.
- (2) The specification and test of full instrumentation to monitor and analyze operation of equipment and quality of the product.
- (3) The in-process monitoring of the simulation test.
- (4) Evaluation of test results against requirements and the predicted reliability model.

The primary objective underlying the above R&QA tasks is the assurance that the equipment and instrumentation are of the right design and quality to achieve an adequate simulation of field conditions for the final scaled-up process. As such, power supplies

may be of much less significance than the material feed, the compaction head, the simulated stress or hydrostatic pressure apparatus, and the equipment and test hole instrumentation.

9.1.2 Test Procedures and Laboratory Tests

Planning of test procedures and laboratory tests of samples (plug, surrounding soil cores, ion content of seepage, etc.) is a major engineering and R&QA task, in order to provide for sufficient data payoff from the tests.

9.2 Simulation Tests

9.2.1 Site and Test Support

It is likely that the laboratory simulation test should be carried out in a fully instrumented simulated borehole (mine shaft, existing borehole, column excavation, or similar hole, probably 50 to 500 feet in depth). The simulation test should provide extreme levels of stress to simulate catastrophic failure. Since the interface between plug and hole wall is the critical test surface, methods for infiltrating water or solutions at that location should be provided.

9.2.2 Test Program

The test program starts with a complete analysis of hole conditions and of the surrounding material. Laboratory mockup equipment and instrumentation will then be used to seal the hole, varying material and compaction parameters as necessary. In order to test several plug material profiles with variations in feed or compaction, several holes will be needed.

In this test phase, one or more simulated boreholes will be sealed with inadequate methods, but using materials in accordance with the developed specifications. The intent is the measurement of permeability under poor construction conditions, in order to arrive at a worst-case assessment of the borehole sealing process. Such inadequate construction may, for example, provide a montmorillonite plug under such pressure from inadequate sub- or superstructure as to change the water content of the plug significantly. The permeability measured should compare with predicted values based on laboratory tests. Since an adequately constructed plug/formation system should result in no measurable water flow within practical test time limits (References 2, 4, 5),

the comparison or matrix of "good" and "poor" sealed boreholes provides the basis for the reliability analysis and safety margin of the final product.

The instrumentation needed has been described in previous sections, and the test may include a large proportion of the total instrumentation spectrum investigated. This ensures a higher probability of success in the selection and design of the final field instrumentation for field qualification, for in-process monitoring of "production" borehole sealing, and for monitoring of the product over its life.

9.2.3 Data System

A key R&QA activity is the design and operation of an effective data gathering and recording system, as discussed in Section 3. The importance of adequate documentation of test variable changes and test results cannot be stressed too much in a simulation test or development phase, since many changes are inherent in such programs and traceability can be easily lost.

9.2.4 Analysis of Test Results

The final task of simulation testing is the analysis of data and presentation of conclusions relevant to the whole system, but particularly to the next decision point. This addresses itself to any necessary modifications in specifications, equipment, instrumentation, and process required for the pilot test. The analysis includes necessarily:

- (1) Effectiveness of equipment.
- (2) Effectiveness of instrumentation.
- (3) Effectiveness of product (sealed plug/formation system), including plug/hole interface.
- (4) Diagnosis of failures or bottlenecks in the integrated system.
- (5) Reliability of subsystems and overall system.
- (6) Reliability of product under extreme or accelerated conditions.

The result of this phase is the pinpointing of the necessary modifications for a scaled-up pilot test.

9.3 Modification of Designs (Based on Section 9.2) and Procurement and Verification of Prototype Equipment

9.3.1 Quality-Assurance Plans and Activities

The R&QA task consists of quality-assurance inputs to the design review, the verification of drawings and engineering change orders, the modification of specifications and procedures to accommodate the changes, the development of quality plans to monitor changes in-process and provide for acceptance testing.

9.3.2 Acceptance

For modified equipment and instrumentation, acceptance will include the verification of process capability, if changes are of such a nature as to affect functional characteristics.

Laboratory tests, analysis of prior simulation data and the reliability analysis should provide a sufficient baseline to ensure a high probability for the success of process changes. It is anticipated that these will be minor, e.g., change the number of blows of a compacting head or the weight of a lift.

9.3.3 Possible Simulation Retest

Changes that are major will presumably require a retest on the laboratory simulation site, e.g., the need to provide for water or solutions containing Na ions to prepare the interface between plug and borehole or between successive plug layers. If the laboratory simulation test program has been carefully planned, then the need for such additional tests should not arise.

9.3.4 Contractor Interface

R&QA will review feasibility of such modifications with the contractors concerned. Compatibility of such changes with the integrated total system will be verified.

The R&QA activity will provide for the transmittal of necessary documentation to contractors and ensure that the quality assurance at their facilities is adequate. On delivery, or at the contractor's facility, they will then provide for acceptance of the modified hardware or software.

9.4 Instrumentation and Pilot Test(s) of Prototype System

As outlined in the simulation test program (Section 9.2.2), the final product (plug/formation system) constructed with adequate methods (i.e., to the requirements and specifications of the project), cannot in all probability be tested for permeability within any reasonable time span. The water flow under the most stringent conditions of hydrostatic head would not be measurable with instrumentation available at this point or with any new instrumentation design which can be conceived to date.

Therefore, at least one pilot borehole, or several, need to be constructed with less than adequate methods, as determined in Section 9.2, to allow permeability measurements on a full prototype system. Again, this permeability will be compared to predicted values based on laboratory tests and to the results of the simulation test (Section 9.2).

An adequately constructed borehole(s) will be used to demonstrate the lack of permeation, as well as to qualify process and equipment. Reliability analysis of data and predictions will then demonstrate the insignificantly low probability of permeation in the adequately constructed and controlled plug/formation system. The reliability of the latter can then be equated to that of the surrounding geologic formations, stable to, say, 5,000,000 years.

9.4.1 Conditions for Test and Field Qualification

This phase provides for the field test of the complete scaled-up system on a fully instrumented test site containing one or more boreholes. It is possible to use this test as the field qualification, if the following conditions can be satisfied.

- (1) Operating equipment and instrumentation are essentially the same as will be used in production and are manufactured by the same methods.

Note: It is not intended that minor changes (i.e., those which do not affect function and can be checked out on acceptance testing) should require additional field qualification subsequent to Section 9.4.

- (2) The instrumentation does not contain modifications which affect sensing, amplification, transmission or, recording to such a degree that performance may be affected.

Note: In order to avoid unnecessary requalification of the whole system, efforts will be made to conduct instrumentation subsystem requalification only if major modifications are made. This, however, will take place under pilot test or field conditions.

- (3) The process of downhole feed, material mix, type of adjacent plug layers, strata configuration of the borehole, interface adhesion promoters, etc., does not require changes from the pilot test process to the extent that process parameters are beyond the test domain explored. In the effect, it is proposed to conduct the pilot test and to decide on the basis of results whether this constitutes field qualification.

9.4.2 Test Site Preparation

The pilot test will be conducted on an actual borehole site in a formation identical, or very similar, to that of the actual storage site. Tasks are summarized as follows:

- (1) Summary of geological and solid mechanical data of the formation and validation of its identity or similarity to the "production" site.
- (2) Complete logging data (methods discussed in Section 4.2) of borehole(s) to be tested and validation of similarity to "production" boreholes.
- (3) Instrumentation to provide and/or record data on:
 - (a) Feed efficiency.
 - (b) Compaction process.
 - (c) Permeability (even if prediction is for significant values on adequately constructed systems, it is needed for inadequately constructed systems). Permeability instrumentation is a requirement for inadequately constructed plug/formation systems.

- (4) It is realized that the sensing and recording of all of the above may be difficult, costly and in some instances unnecessary because of the high reliability of laboratory or simulation test data. The type of data required is a project management decision, based on R&QA and engineering analysis inputs.
- (5) Amplification, transmission, recording of data. It is probable that data enhancement or filtration methods need to be used, for example, autocorrelation or background elimination. The type of method is similar to computerized image intensification in optical or display information.
- (6) Setup of equipment for power, feed, and compaction requires capability of variation through anticipated operational conditions, including the instrumentation to record performance. The type of string and compaction head must permit frequent stoppage of operation for hardware examination, core sampling, or other test functions.
- (7) Testing of inadequately sealed borehole for permeability and possibly external effects such as seepage, hydrostatic head changes, interfaces, stressing, or infiltration. This is aimed at an enhanced reliability forecast of the product life (time to failure).
- (8) Test history recording to provide full traceability of equipment and site configuration and of test conditions. The latter is of particular significance, since the pilot test of necessity includes variations, extending to worst-case conditions.

9.4.3 Test Program

The test plan is based on the requirements of the work statement and the results of previous laboratory and simulation tests, as well as on the decisions of consecutive design reviews. It is desirable that this plan evolve from a design review or test planning review intended specifically to design this test for maximum benefit in significant information.

R&QA tasks implementing the test plan are as follows.

9.4.3.1 Review of test plan to ensure significance and reliability of data.

9.4.3.2 Review of test site, instrumentation, equipment, etc. to provide formal acceptance of the test, both as a pilot test and as possible field qualification.

9.4.3.3 In-process monitoring and continuing analysis of sealing process, including:

- (1) Subsystem performance.
- (2) Integrated system performance (interactions, bottlenecks, etc.).
- (3) Borehole conditions above, at, and below plug or fill.
- (4) Effect on formation strata, e.g., pore pressure.

9.4.3.4 Summary

The final R&QA task is the summarization and analysis of test information and the measurement of performance against project requirements including reliability analysis.

9.4.4 Product Evaluation

Analysis of data and reliability assessment will be performed as in Section 9.4.3. As discussed previously, it would be necessary to test an inadequately sealed borehole(s) after completion of the process.

9.4.4.1 Sampling

Such a test plan includes core samples of the borehole and surrounding strata and may include intentional flooding or local infiltration of the sealed borehole. Under the latter test conditions, core sampling and pore pressure measurements in plug and surrounding locations may be necessary for additional confirmation of reliability analysis.

9.4.4.2 Reliability Assessment

Analysis of such data provides a reliability forecast of the sealed borehole over anticipated life and becomes part of the summary presented for project decision.

9.4.4.3 Acceptance

The final R&QA task of Section 9.4.4 is the recommendation of acceptance of the test as field qualification, necessary subsystem tests to verify questionable results or provide for modifications, corrective action for deficiencies or failures, and the consequences of accepting the system as is, or of modifications.

9.5 Specifications and Procedures for Field Qualification (or for Final Product)

The following alternatives are possible:

- (1) If the project decision is acceptance of the pilot test as field qualification, specifications and procedures will be prepared by the R&QA activity for field equipment and operation.
- (2) If certain subsystems only need retest under field conditions, a test plan for their qualification will be prepared and qualification performed by R&QA.
- (3) If the pilot tests indicate major changes, these specifications and procedures will be prepared for a field qualification. The tasks are essentially the same as in the pilot test (Sections 9.1 - 9.4), except that less instrumentation and variation of test conditions may be necessary. The field qualification may take the form of instrumenting a few essential parameters and sealing one or several boreholes. Data analysis reliability forecast, and recommendations are of the same type as in Section 9.4.

9.5.1 Procedures

In any of the above eventualities, the preparation of the procedures and specifications consists of the revision in the documentation package for pilot testing and includes changes resulting from the pilot test and the project decisions based on pilot results.

9.5.2 Final Report

A second task is the completion of the final report summarizing the results of the project and providing traceability for all decision bases. It is inherent in the project requirements that interim reports will have been prepared at the completion of each project phase, as well as at the intervals specified by project management (and/or the work statement).

9.5.3 Contractor Interface

The third R&QA task is the discussion and negotiation of specifications and procedures with the respective contractors, providing continuing feedback to project management, to ensure the adherence of equipment, instrumentation, and operations to project requirements. If field operation is the next phase of the road map, alternative (1), operational manuals will be prepared by, or under the administration of, the R&QA function.

SECTION 10

FIELD QUALIFICATION

The tasks considered for this section are considered to be similar to Section 9.4 Instrumentation and Pilot Testing and Section 9.5 Procedures for Full Qualification, but on a reduced instrumentation and analysis scale.

10.1 Field Qualification

As discussed in Section 9, it is anticipated that the pilot test program will result in field qualification. Separate requalification of subsystems under field conditions has been described in Sections 9.4 and 9.5, and the program in the event of a full system field qualification, has been similarly delineated.

Briefly, such a field qualification program essentially retraces the steps of the pilot tests under reduced instrumentation and with less variation of test condition. Analysis, project decision, and preparation of operational documentation takes the shape of that in Section 9.

SECTION 11

FIELD OPERATION

The tasks to be considered for this phase are:

- 11.1 Natural Material Control
- 11.2 Borehole Conditions
- 11.3 Instrumentation and Data Analysis
- 11.4 Equipment Monitoring, Failure Analysis, Corrective Action
- 11.5 Feed and Compaction Monitoring
- 11.6 Sealed Borehole Acceptance
- 11.7 Work-in-progress and Final Reports

Field operation is defined as the complete system of sealing a borehole.

The R&QA tasks for field operation are delineated below, realizing that at the project stage represented by the subject report, these tasks are at best hypotheses and will be revised or amplified by the results of different project stages.

11.1 Natural Material Control

- (1) Audit of material source and procurement method (e.g., from existing formation).
- (2) Analysis of material.
- (3) Procedure and audit of mixing, classifying, grinding, etc.
- (4) Storage conditions.
- (5) Transport to site or feed input.
- (6) Audit (analysis) of storage and transportation on size, moisture content, other critical variables.

11.2 Borehole Conditions

- (1) Logging data or additional sampling.
- (2) Verification of wall condition (e.g., drilling need).
- (3) Control and audit of any required wall preparation (e.g., removal of zone infiltrated with drilling mud).
- (4) Continuing spot check of conditions in surrounding formation (core samples, pore pressure, etc.).
- (5) Stress or shift spot check (inclinometer, strain gages, etc.) as required.
- (6) Spot check on some AQL basis of adhesion of compacted material to borehole wall.

11.3 Instrumentation and Data Analysis

- (1) Calibration and maintenance (both of equipment monitors such as accelerometers on compacting head and of downhole or AQL test hole sensors).
- (2) Continuing recording and analysis of data, with feedback to project and to operational site.
- (3) Verification of operation versus predicted results and project requirements.

11.4 Equipment Monitoring, Failure Analysis, Corrective Action

- (1) Monitoring of operation of subsystems such as power, feed, compaction.
- (2) Failure analysis and corrective action.
- (3) Reliability of changes dictated by local or in-process conditions.

11.5 Feed and Compaction Monitoring

- (1) Monitoring of feed efficiency.
- (2) Monitoring of sample testing of layer quality of plug or fill.
- (3) Stress or hydrostatic effects on formation and plug.

11.6 Sealed Borehole Acceptance

- (1) Review of operational and test records, monitoring of surrounding formation (AQL core sampling and hydrostatic measurement).
- (2) Comparison of above data with an instrumented borehole (either the pilot test hole(s) or boreholes provided for area monitoring).

11.7 Work-in-Progress and Final Reports

- (1) Feedback of operational quality to project management and operational sites.
- (2) Final data summary and report as an area is completed, including assessment of reliability and future recommendations.

SECTION 12

PRODUCT LIFE MONITORING

12.1 Monitoring Requirements

Based on the test data and reliability analyses of the program phases previously conducted, the reliability of the final product, i.e., an adequately constructed and controlled plug/formation system, is equivalent to that of the surrounding geologic formations. As such, it is to be of the order of 5,000,000 years of stability.

Therefore, post-seal product life monitoring is not deemed necessary, except for special project purposes on one or more selected boreholes.

12.2 Contingency Plans

Although the probability of an external event disrupting the borehole or the storage area is extremely small, it may be advisable to provide contingency plans for such an occurrence.

APPENDIX A

BOREHOLE LOGGING

In order to develop a suitable plug, it is essential that the characteristics of the borehole be determined in detail. The oil industry has developed various techniques for determining the stratigraphy of formation fields and lithology and it is proposed that these electrical, nuclear, and acoustic techniques be evaluated for application to detailed formation analyses. It is further proposed that an effort be expended to adapt an existing gravity gradiometer for borehole usage. (See Appendix B.)

A.1 Preliminary Investigation

If mud has been used in the drilling operation, it has generally been conditioned so that the hydrostatic pressure of the mud column is greater than the pressure of the formations. The differential pressure forces mud filtrate into the permeable formations and the solid particles of mud are deposited on the borehole wall where they form a mud cake. Mud cake usually has very low permeability and considerably reduces the rate of infiltration. Very close to the hole, all the formation water is flushed away by the filtrate. Further out from the borehole, the displacement of formation fluids is less and less complete resulting in a transition zone culminating in an uninvaded zone. It is possible that an invaded zone possesses appreciable vertical permeability in which case a gravity migration may occur.

It is proposed that the borehole be investigated as to presence of drilling mud and to determine, if possible, the history of the drilling operation and the analysis, if any, of core material.

A.2 Borehole Analysis - Existing Techniques

The following techniques will be evaluated to determine which method(s) would be relevant.

A.2.1 Spontaneous Potential (SP) Curve

The SP curve is a recording versus depth of the difference between the potential of a movable electrode in the borehole and the fixed potential of a surface electrode.

The SP is useful to:

- (1) Detect the permeable beds.
- (2) Locate their boundaries and to permit correlation of such beds.
- (3) Determine values of formation-water resistivity.
- (4) Provide a qualitative indication of bed shaliness.

The SP cannot be recorded in holes filled with nonconductive muds because such muds do not provide electrical continuity between SP electrode and formation. The deflections in the SP curve result from electric currents flowing in the mud in the borehole. These SP currents are caused by electromotive forces in the formations, which are of electrochemical and electrokinetic origins.

The movement of ions which causes the SP phenomenon is possible only in formations having a certain minimum permeability (a small fraction of a milli Darcy is sufficient). There is no direct relationship between the value of permeability and the magnitude of the SP deflection, nor does the SP deflection have any direct relation to the porosity.

A.2.2 Resistivity Logs

In resistivity logs, currents are passed through the formation via certain electrodes and voltages are measured between certain others. These measured voltages provide the resistivity determinations. So that there will be a current path between electrodes and formation, the equipment must be run in holes containing electrically conductive mud or water.

A modification of the above uses of a focusing electrode to reduce the effect of borehole and adjacent formations.

A.2.3 Induction Logging

If the walls are not coated with a nonconductive mud such as oil-base muds or an empty hole, then an induction logging device can be utilized. This method can be used even if the borehole contains

conductive mud, provided the mud is not too salty and the formation not too resistive. In this method high-frequency ac of constant intensity is sent through the transmitter coil which induces secondary currents in the formation. These currents flow in circular ground-loop paths coaxial with the transmitter coil and the magnetic fields produce induced signals in the receiver coil and are essentially proportioned to the conductivity of the formation.

A.2.4 Microsensitivity Devices

These devices are used to measure the resistivity of the flushed zone and to delineate permeable beds by detecting the presence of mud cake. A sidewall pad tool is utilized and the pad carrying short spacing electrode devices is pressed against the mud cake. As drilling mud filters into permeable formations, mud solids accumulate on the hole wall, forming a mud cake. The resistivity of the mud cake is about equal to, or slightly greater than, the resistivity of the invaded zone near the borehole. This method is generally used to measure permeability of specific formations and is used with other methods described herein.

A.2.5 The Sonic Log

The sonic log is a recording versus depth of the time required for a compressional sound wave to traverse 1 foot of formation. This is the interval transit time and is the reciprocal of the velocity of the compressional sound wave. The interval transit time for a given formation depends upon its lithology and porosity.

This method is generally used in conjunction with other porosity logs to determine porosity, lithology, and overpressured formations.

A.2.6 Formation Density Log (Gamma Ray)

In this technique, a radioactive source applied to the borehole wall emits medium-energy gamma rays into the formation. From the Compton scattering (loss of energy due to collision with electrons in the formation) the scattered gamma rays are counted at the detector and give an indication of formation density. Electron density depends on the density of the rock matrix material, formation porosity, and density of fluid filling the pores.

Correction factors are needed when the contact between the equipment and the formation is not perfect (due to mud cake or roughness of the borehole walls).

A.2.7 Neutron Logs

This technique is used for delineation of porous formations and determination of porosity. They respond to the amount of hydrogen present in the formation. High-energy neutrons are emitted from a radioactive source. The greatest loss of energy occurs when a neutron strikes a nucleus of practically equal mass, i.e., a hydrogen nucleus. The counting equipment generally monitors neutrons or gamma rays emitted when nuclei such as chlorine capture neutrons. This method is useful in conjunction with other methods for porosity determination, lithology, and for shaling sand interpretation.

A.2.8 Gamma-Ray Log

This technique monitors the natural radioactivity of the formations and a detector, generally a scintillation counter, measures the gamma radiation. It is used for the definition of the shale beds.

A.2.9 Thermal Decay Time Log

This technique monitors the rate of decay of thermal neutrons in the formations. It is necessary for full interpretation that the porosity and water salinity be known.

APPENDIX B

BOREHOLE GRAVITY GRADIOMETER

It is proposed to adapt an existing gravity gradiometer for use in borehole logging. A design study is proposed, to develop an instrument that will house a tilt, directional meter, temperature, pressure indicators, and a formation density (gamma ray) device. This instrument will measure the full gravity component and will not be subject to large correction errors to which the methods outlined in Appendix A are susceptible.

B.1 Gravity Gradiometer Feasibility Study

A gravity gradiometer will be investigated to operate in holes up to 19,000 feet deep and temperature up to 375°F with a maximum outside diameter of 3-1/2 inches. The density logging instrument would be a scaled-down version of an existing gravity gradiometer. The sonde will house a tilt, directional meter, temperature and pressure indicators, and a gamma ray density logging device. Major problems are the torquing and sensing capabilities, methods of shock mounting instruments, and thermal control of absolute temperature to 10 millionths °F over the range 60 to 375°F.

B.2 Task 1. Feasibility Study

Subtask 1. Electronics Feasibility Study

Packaging, circuit constraints and requirements, and a definition of suitable components. Thermal effects and probability of satisfying electrical constraints.

Subtask 2. Scaled-Down Gravity Gradiometer

Study and analysis of torquing, sensing, and erection dynamics of a scaled-down gravity gradiometer.

Subtask 3. Materials

Investigate materials suitable for use. Dimensional stability of potential materials for shell and float. Investigate micro yield strength and microcreep stability.

Subtask 4. Thermal Analysis

Generate a computer model determining the number of shields and controls. Determine effects on performance. Consider mechanism for cooling electronics and instruments.

Subtask 5. Fluid Analysis

Select a flotation fluid for high-temperature application.

Subtask 6. Final Report

Design specifications and capability limits outlined

B.3 Task 2. Gravity Gradiometer Prototype Build and Evaluation

This task entails building a model from the design specification established in Subtask 4 and running evaluation tests to determine conformance to the specifications. This task will only be performed if the feasibility study of Subtask 4 warrants such action.

PART 2

LIST OF REFERENCES

1. Juran, J. M., Quality Control Handbook, McGraw-Hill, New York, 1962 (Section 13 Statistical Methods in the Quality Function, Section 11, Process Capability).
2. Martin, R. T., Feasibility of Sealing Boreholes with Compacted Natural Earthen Material (Volume I), MIT Research Report 75-28, Cambridge, Massachusetts, June 1975.
3. Mitchell, J. K. and J. S. Younger, Abnormalities in Hydraulic Flow through Fine Grained Soils, ASTM-STP-417, 1967, p. 106-141.
4. (Volume II), (same as Reference 2).
5. (Volume III), June 1976 (same as Reference 2).

PART 2

BIBLIOGRAPHY

"General Principles for Reliability Analysis of Nuclear Power Generating Station Protection Systems", IEEE Trial Use Guide, IEEE, ANSI N41.4, 1972.

Chelson, P. O., Reliability Computation Using Fault Tree Analysis, NASA Technical Report 32-1542, Jet Propulsion Laboratory, 1971.

Fortney, R. A., J. T. Snedeker, S. E. Howard, and W. W. Larson, Safety Function and Protection Sequence Analysis, American Nuclear Society Winter Meeting, November 11-16, 1973.

Lambe, T. W. and R. V. Whitman, Soil Mechanics, John Wiley, New York, 1969.

Schlumberger, Log Interpretation, Volume I - Principles, Schlumberger Limited, New York, 1972.

Schlumberger, Log Interpretation, Volume II - Applications, Schlumberger Limited, New York, 1974.

A Study of Borehole Plugging in Bedded Salt Domes by Earth Melting Technology, Final Report, Westinghouse Astronuclear Laboratory, Wanl-TME-2870, June 1975.

Schlumberger, Log Interpretation Charts, Schlumberger Limited, New York, 1972.

Scott, R. F., Principles of Soil Mechanics, Addison-Wesley, Reading, Massachusetts, 1963.

Esmond, F. G., Reliability Analysis Based on Operational Success Criteria, NASA Tech. Brief 72-10214 (ARC-10490), September 22, 1971.

Barlow, R. E. and P. Chattersee, Introduction to Fault Tree Analysis, University of California, Berkeley, ORC 73-70, December 1973.

MIL-STD-105 Sampling Procedures and Tables for Inspection by Attributes.