GEOTECHNICAL ASPECTS OF SUBSURFACE SEABED DISPOSAL
OF HIGH LEVEL RADIOACTIVE WASTES

by

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Report of the Engineering Workshop on Deep Sea Coring,
November, 1977, Volume 1, A.J. Silva and A.H. Driscoll

1.

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1. INTRODUCTION

This is a report of activities, progress, and status of the geotechnical portion of the Seabed Disposal Program made during the fourth year of our participation in the project. A semi-annual progress report covering the period January through June, 1977 was submitted in August, 1977. In addition a report was presented at the November, 1977, workshop in Las Vegas, Nevada.

Activities during the 1977 calendar year have centered around the following:

a) Geotechnical Properties of Deep Sea Clays: This includes analyses of core samples as part of the sediment characterization studies, stress-strain properties, and compressibility.

b) Experimental Water Migration Studies: These include detailed permeability measurements of core samples and com-

paritive studies of several types of deep sea sediments.

c) Laboratory Hole Closure Experiments: This is a continuation of previous laboratory studies.

d) In-Situ Heat Transfer Experiments (ISHTE): This is a joint effort with personnel at Sandia Laboratories and the University of Washington.

Other activities include preparations for a research cruise in June, 1978 to a new study site on the North Bermuda Rise, and participation in a workshop concerned with development of a long coring facility.

2. PROGRAM OPERATIONS

2.1 Meetings and Trips

The Principal Investigator participated in numerous meetings at several locations throughout the country on various aspects of the research program. Only a few of the more extensive and typical meetings are listed below.

a) In-Situ Heat Transfer Experiment (ISHTE): Meetings were held at the University of Washington (APL), Sandia Laboratories and at University of Rhode Island.

b) Annual meeting of Seabed Program in Las Vegas, Nevada.

c) Long Coring Facility: Two-day engineering workshop at Woods Hole Oceanographic Institution.

d) Other: Several meetings at Woods Hole Oceanographic Institution and Lamont-Doherty Geological Observatory. Meet-

ings at Naval Civil Engineering Laboratory, Port Hueneme, California and New Orleans, Louisiana.

2.2 Presentations

The Principal Investigator made three presentations on various aspects of the research. One was part of a lecture series by the Center for Ocean Management Studies (COMS) at URI. Approximately eighty people attended this illustrated talk on the Seabed Program. A presentation on the geotechnical aspects of the program was made at Naval Civil Engineering Laboratories in Port Hueneme, California.

2.3 Personnel

The following personnel are presently engaged in the seabed disposal project and are involved at the indicated levels. Most of these people contributed to the report on their areas of research.

Armand J. Silva (Ph.D.) - Principal Investigator

D.I. Calnan (BA) Research Associate - Coordinating research effort in laboratory as well as field work.

Professor V.R. Nacci Recently started to assist on direction of laboratory Hole Closure experimentation.

Kenneth Baldwin (MS) University Fellow in Ocean Engineering, (Ph.D.) - Working on Acoustic Properties of Deep Sea Sediments - assisting in instrumentation on all projects as well as adding shear and compressional wave velocity measurements to the suite of sediment properties.

Wilson Lamb (MS) Research Associate for Department of Ocean Engineering - directing instrumentation of Hole Closure Experiment, designing acoustic tripping device for LPC and general electronics needs.

James R. Hetherman (BS) Graduate Research Assistant (MS) - conducting laboratory permeability measurements on deep sea sediments.

Scott R. Bamford (BS) Graduate Research Assistant (MS) - conducting laboratory Hole Closure Studies.

Roger H. Morin (MS) Graduate Research Assistant (Ph.D) - Preliminary ISHTE work.

Stephen A. Akers (BS) Graduate Research Assistant (MS) - Triaxial and Dynamic Shear Strength Studies.

Kathryn Moran (BS) Graduate Research Assistant (MS) - Assisting on Hole Closure and Shear Strength Studies.

2.4 Facilities

a) Laboratory facilities - The physical research facilities are located in three areas with the following groupings of activities: Hole Closure/ISHTE, Stress-Strain/Shear Strength, and Water Migration/Consolidation. The Hole Closure/ISHTE laboratory is located in the Bliss Annex of Civil Engineering at the Kingston Campus with the following facilities: electric winches, a high pressure (4500 psi) vessel; x-ray and gamma ray equipment, sediment preparation and other associated equipment. The shear strength laboratory is situated in the C.E./Geotechnical laboratory. The

water migration/consolidation laboratory and other project-related work (such as core processing) are located at the Narragansett Bay Campus in the recently-completed Ocean Engineering Laboratory. High pressure consolidation/permeability studies are conducted at this laboratory along with all of the basic sediment properties analyses and cruise-related preparations.

b) Gravity coring - A new version of the Large Diameter Gravity Core (LGC) has been successfully field tested and will be used during our upcoming research cruise to the North Bermuda Rise. This thin-walled coring apparatus has been effective in obtaining high quality undisturbed samples of the upper 2-3 meters of the sediment column. Plans are underway to fabricate a special launching system for the LGC.

c) Acoustic measurement of core samples - A system is presently being assembled that will yield a full suite of acoustic properties on "split cores. The system is designed to measure compressional and shear wave velocity and attenuation in two mutually perpendicular directions in the split core, axially along the core and across the core. These core measurements, coupled with normal incidence (3.5 kHz and/or 12 kHz) or Deep Tow (4 kHz) records, geotechnical properties and geological data, will provide more insight for interpretation of acoustic records. This development has been funded as part of another project but the system will be utilized on the June, 1978 cruise.

3. PUBLICATIONS AND REPORTS

The following publications and reports are related to the program. Excerpts from some of these are included in the Appendix.

1. "Physical Properties in Deep Sea Clays" in "High-Level Nuclear Wastes in the Seabed?", Armand J. Silva, Oceanus, Vol 20, No. 1, Winter, 1977.

2. "Consolidation and Permeability Characteristics of Deep Sea Sediments: North Central Pacific Ocean" by Charles R. Nickerson; 1978 Master's thesis.

3. "A Giant Ship for a Giant Corer", Armand J. Silva, Maritimes, Vol. 21, No. 4. November, 1977.

4. "Geotechnical and Normal Incidence Reflection Characteristics of Rockall Trough Sediments" A.J. Silva, K. Baldwin, W. Dow, & C.D. Hollister, EOS, Vol 58, No. 12, December, 1977.

5. "Report of the Engineering Workshop on Deep Sea Coring, by Armand J. Silva and Alan Driscoll," November, 1977. Two volume report. Held at Woods Hole Oceanographic Institution.

4. GEOTECHNICAL PROPERTIES

4.1 Introduction

The relation of the geotechnical research on fine-grained deep-sea sediments to the seabed disposal program has been outlined in previous reports (see Annual Report No.

3). The main thrust of this program has been in the following areas:

a) Permeability/Compressibility Characteristics -

Studies of MPG-1 and MPG-2 are in various stages of progress. An assessment of consolidation and permeability characteristics of MPG-2 has been completed and detailed, special problem studies are under way for samples from MPG-1. (Sec. 4.2, 4.3)

b) Stress-Strain Behavior -

Samples from MPG-1 and the Hole Closure Experiment have been tested to assess stress-strain parameters of deep-ocean sediments subject to both static and dynamic loadings (Sec. 4.5, 4.6)

c) Physical Properties -

Work is continuing on determination of geotechnical properties such as water content, density, grain size distribution, Atterberg limits and acoustic characteristics.

4.2 Geotechnical Properties: MPG-1

Preliminary studies have already demonstrated some degree of lateral coherence in index properties for 2 piston cores taken in MPG-1 (see 3rd Annual Report, March 1977). One core was a standard piston core of about 10 meters taken aboard the R/V Vema in July 1975 (V32-11-PC115) at location $30^{\circ}36.5'N$; $158^{\circ}53.3'W$. One large piston core (LL-44-GPC-3) of 24.38 m length was recovered from the C/S Long Lines in October, 1976, at $30^{\circ}19.9'N$; $157^{\circ}49.4'W$, approximately 65 miles from V32-11-PC115. Figure 4.1 is a summary of lithology, water content, shear strength and acoustic properties of LL44-GPC-3.

CRUISE NO. LL-44; CORE NO. GPC-3; Lat. 30° 19.9' N Long. 157° 49.4' W

Figure 4.1

Five consolidation tests have been completed to date and are summarized in Table 4.1. One sample is from V32-11-PC115 at 7.4 m and the four others range in depth from 12.8 to 19.1 m in GPC 3 of LL44. From the preliminary plots of void ratio, e , versus the logarithm of the effective stress, $\log \bar{\sigma}_v$, the maximum effective preconsolidation stress, $\bar{\sigma}_c$, can be determined (Figures 4.2, 4.3, 4.4, 4.5, 4.6). The samples from MPG-1 all exhibit a normally consolidated condition. That is, the present in-situ overburden stress, as calculated from specific gravity and water content data, is equal, within the limits on accuracy due to sampling, handling and storage, to the maximum preconsolidation stress. This indicates that the area has not undergone any dramatic changes in topography due to removal of overburden and that there is essentially no water migration due to compaction. This information coupled with sedimentation rates established by others yields a picture of a stable stress environment over the past tens of million years. However, it should be noted that only the deeper layers are represented in these analyses and a detailed assessment of the stress history of surficial sediments in MPG-1 is not possible since high quality undisturbed samples are not available for the upper 2 meters. We have a need for undisturbed samples of the surficial materials so that the stress history of the entire sediment column (to the depths sampled) can be reconstructed. Based on previous work in MPG-2 and

Table 4.1

MPG-1 Consolidation Test Results

Sample Designation Core No. & Sample Depth	Initial Void Ratio e_o	Initial Water Content w_o	Lab Comp. Index C_c	Field Corr. Comp. Index C_{cf}	Disturbance Index I_D	Max. Eff Preconsol. Stress $\bar{\sigma}_c$ (g/cm ²)	Over Consolidation Ratio $\bar{\sigma}_c / \bar{\sigma}_o$
<u>V32-5-PC115</u> 738-741 cm	5.14	183	2.02	2.53	.23	420	1.1
<u>LL44-GPC 3</u> 1283-1292 cm	6.24	222	2.67	3.06	.23	630	1.2
1565-1569 cm	6.58	235	3.28	3.51	.22	700	1.3
1838-1843 cm	5.72	200	2.58	2.94	.22	720	1.2
1910 cm	6.45	232	4.20	5.56	.34	970	NA

NA - This sample is horizontally orientated therefore the overconsolidation ratio is not applicable.

CONSOLIDATION RESULTS
 CRUISE NO: VEMA 32 LEG II CORE NO: PC115
 LOCATION: 30° 36.5'N 158° 53.3'W MPG I
 DEPTH IN CORE: 738-742 cm
 URI/MGL

Figure 4.2

CONSOLIDATION RESULTS
 CRUISE: LL 44 CORE NO: GPC-3
 LOCATION 30° 19.9'N 157° 49.4'W MPG1
 DEPTH IN CORE: 1288-1292cm
 URI/MGL

Figure 4.3

CONSOLIDATION RESULTS
 CRUISE: LL 44 CORE NO: GPC-3
 LOCATION 30° 19.9'N 157° 49.4'W MPG1
 DEPTH IN CORE: 1565-1569 cm
 URI/MGL

Figure 4.4

CONSOLIDATION RESULTS
CRUISE: LL44 CORE NO: GPC-3
LOCATION 30° 19.9'N 157° 49.4'W
DEPTH IN CORE: 1838-1843

URI/MGL

Figure 4.5

EFFECTIVE VERTICAL STRESS, KG/CM^2 , $\bar{\sigma}_v$

0.001 0.01 0.1 1.0 10.0

CONSOLIDATION RESULTS

CRUISE NO: LL 44

CORE NO: GPC-3

LOCATION $30^{\circ} 19.9' \text{N}, 157^{\circ} 49.4' \text{W}$ MPG 1

DEPTH IN CORE: 1910cm (Horiz)

/ URI/MGL

Figure 4.6

other ocean sediments we expect that the upper few meters will show an "apparent" overconsolidation situation due to high interparticle bonding of these surficial materials (Silva, et al 1976; Silva and Clukey, 1975).

Plots of the coefficient of permeability, k , versus void ratio, e , are shown in Figures 4.7 through 4.11. The permeabilities shown in Figures 4.7, 4.8 and 4.9 are calculated from time-compression data (Tables 4.2, 4.3, 4.4). Figures 4.10 and 4-11 are revised editions of data previously presented (see 3rd Annual Report) and incorporate both direct measurement and calculated values (Tables 4.5 and 4.6). The linear relationship of e and $\log k$ in all cases is apparent. This linear relationship is especially important in extrapolations to high void ratios which are difficult to test due to the highly sensitive nature of such an open structure. The measured permeability ranges from 3×10^{-7} cm/sec at a void ratio of 5 to a value of 1×10^{-8} for a void ratio of 3. The calculated k 's range from 7×10^{-8} to 6×10^{-9} over the same span of void ratios. This shift to lower values of k from time-compression data seems to be a consistent phenomenon and should be accounted for in any assessment of these sediments. Clukey (1976) and Nickerson (1978) have also noted this discrepancy which points to the need for a more detailed analysis of this problem. Until an empirical relationship to account for this departure from classical consolidation theory is established,

COEFFICIENT OF PERMEABILITY, k VERSUS VOID RATIO e

VEMA 32 LEG 11 PC 115

738 - 742 cm

● COEFFICIENT OF PERMEABILITY BEFORE REBOUND
LOGARITHM TIME METHOD

○ COEFFICIENT OF PERMEABILITY AFTER REBOUND
LOGARITHM TIME METHOD

△ COEFFICIENT OF PERMEABILITY AFTER REBOUND
SQUARE ROOT METHOD

COEFFICIENT OF PERMEABILITY BEFORE REBOUND
SQUARE ROOT METHOD

Figure 4.7

COEFFICIENT OF PERMEABILITY, k VERSUS VOID RATIO, e

LL44 GPC -3 1288 - 1292

● COEFFICIENT OF PERMEABILITY BEFORE REBOUND
LOGARITHM TIME METHOD

○ COEFFICIENT OF PERMEABILITY AFTER REBOUND
LOGARITHM TIME METHOD

△ COEFFICIENT OF PERMEABILITY AFTER REBOUND
SQUARE ROOT METHOD

COEFFICIENT OF PERMEABILITY BEFORE REBOUND
SQUARE ROOT METHOD

Figure 4.8

COEFFICIENT OF PERMEABILITY, k VERSUS VOID RATIO, e

LL44 GPC -3 1565 - 1569 cm

● COEFFICIENT OF PERMEABILITY BEFORE REBOUND
LOGARITHM TIME METHOD

○ COEFFICIENT OF PERMEABILITY AFTER REBOUND
LOGARITHM TIME METHOD

△ COEFFICIENT OF PERMEABILITY AFTER REBOUND
SQUARE ROOT METHOD

■ COEFFICIENT OF PERMEABILITY BEFORE REBOUND
SQUARE ROOT METHOD

Figure 4.9.

COEFFICIENT OF PERMEABILITY, k VERSUS VOID RATIO, e
 LL-44 GPC-3 1838-1844 cm

- Δ COEFFICIENT OF PERMEABILITY-MEASURED METHOD
- COEFFICIENT OF PERMEABILITY-SQUARE ROOT TIME METHOD
- + COEFFICIENT OF PERMEABILITY-LOGARITHM TIME METHOD

Figure 4.10

COEFFICIENT OF PERMEABILITY, k VERSUS VOID RATIO, e

LL-44 GPC-3 1910 cm HORIZONTAL

▲ COEFFICIENT OF PERMEABILITY-MEASURED METHOD

○ COEFFICIENT OF PERMEABILITY-SQUARE ROOT TIME METHOD

+ COEFFICIENT OF PERMEABILITY-LOGARITHM TIME METHOD

Figure 4.11

Table 4.2

Time-Compression Data
 VEMA-32-11 PC 115 738-741.5 cm

$\bar{\sigma}_v$ (g/cm ²)	$\bar{\sigma}_{Ave}$ (g/cm ²)	e Final	C_{v1} $\times 10^{-3}$ (cm ² /sec)	K_1 $\times 10^{-7}$ (cm ² /sec)	C_{v2} $\times 10^{-3}$ (cm ² /sec)	K_2 $\times 10^{-7}$ (cm ² /sec)
190	160	4.97	2.55	4.45	2.19	3.83
290	240	4.87	0.86	1.71	1.70	3.38
430	360	4.73	1.64	2.95	2.17	3.90
650	540	4.34	0.69	1.02	1.47	2.18
970	810	3.94	0.27	0.86	0.35	1.10
1500	1235	3.50	0.27	0.67	0.31	0.76
2200	1850	3.13	0.34	0.24	0.61	0.44
3300	2750	2.77	0.23	0.24	0.26	0.28
4900	4100	2.41	0.16	0.13	0.19	0.16

$\bar{\sigma}_v$ - Effective vertical stress

$\bar{\sigma}_{vave}$ - Average effective vertical stress during loading increment

C_{v1} - Coefficient of consolidation as derived from compression versus logarithm of time plot

C_{v2} - Coefficient of consolidation as derived from compression versus square-root of time plot

K_1, K_2 - Coefficient of permeability as determined from C_{v1} and C_{v2} respectively

Table 4.3

Time-Compression Data
LL44-GPC 3: 1288-1292 cm

$\bar{\sigma}_{v2}$ (g/cm ²)	$\bar{\sigma}_{vave}$ (g/cm ²)	e Final	C_{v1} $\times 10^{-3}$ (cm ² /sec)	K_1 $\times 10^{-7}$ (cm/sec)	C_{v2} $\times 10^{-3}$ (cm ² /sec)	K_2 $\times 10^{-7}$ (cm/sec)
190	160	6.11	1.99	2.90	3.54	5.2
290	240	6.00	1.61	1.70	2.86	3.0
430	360	5.87	1.48	2.20	1.69	2.45
650	540	5.67	1.46	2.02	2.07	2.88
970	810	5.38	1.04	1.41	1.45	1.96
1500	1235	4.88	0.98	1.39	0.91	1.30
2200	1850	4.40	0.49	0.74	0.86	1.29
3300	2750	3.90	0.29	0.36	0.49	0.62
4900	4100	3.39	0.53	0.20	0.59	0.22
7400	6150	2.94	0.16	0.09	0.27	0.12

- $\bar{\sigma}_v$ - Effective vertical stress
 $\bar{\sigma}_{vave}$ - Average effective vertical stress during loading increment
 C_{v1} - Coefficient of consolidation as derived from compression versus logarithm of time plot
 C_{v2} - Coefficient of consolidation as derived from compression versus square-root of time plot
 K_1, K_2 - Coefficient of permeability as determined from C_{v1} and C_{v2} respectively

Table 4.4

Time-Compression Data

LL44-GPC 3: 1565-1569 cm

$\bar{\sigma}_v$ (g/cm ²)	$\bar{\sigma}_{vave}$ (g/cm ²)	e Final	C_v $\times 10^{-3}$ (cm ² /sec)	K_1 $\times 10^{-7}$ (cm/sec)	C_{v2} $\times 10^{-3}$ (cm ² /sec)	K_2 $\times 10^{-7}$ (cm/sec)
190	160	6.47	1.34	1.54	12.9	14.8
290	240	6.38	1.38	1.73	6.03	7.56
430	360	6.26	1.60	2.00	9.40	12.9
650	540	6.08	1.94	2.43	3.04	3.80
970	810	5.80	1.55	1.79	1.93	2.23
1500	1235	5.26	5.06	6.14	1.46	1.74
2200	1850	4.69	0.64	0.98	0.73	1.11
3300	2750	4.08	0.45	0.60	0.42	0.57
4900	4100	3.54	0.73	0.29	1.15	0.45
7400	6150	2.99	0.23	0.13	0.30	0.17

- $\bar{\sigma}_v$ - Effective vertical stress
 $\bar{\sigma}_{vave}$ - Average effective vertical stress during loading increment
 C_{v1} - Coefficient of consolidation as derived from compression versus logarithm of time plot
 C_{v2} - Coefficient of consolidation as derived from compression versus square-root of time plot
 K_1, K_2 - Coefficient of permeability as determined from C_{v1} and C_{v2} respectively

Table 4.5

Time-Compression Data
 LL44-GPC 3: 1838-1844 cm

$\bar{\sigma}_v$ (g/cm ²)	$\bar{\sigma}_{vave}$ (g/cm ²)	e Final	C_{v1} $\times 10^{-3}$ (cm ² /sec)	K_1 $\times 10^{-7}$ (cm / sec)	C_{v2} $\times 10^{-3}$ (cm ² /sec)	K_2 $\times 10^{-7}$ (cm / sec)	K direct meas. $\times 10^{-7}$ (cm / sec)
259	216	5.47	-	-	15.98	19.60	5.2
389	324	5.42	-	-	11.46	57.13	4.8
584	487	5.37	-	-	35.96	8.67	-
875	730	5.12	-	-	6.78	9.82	2.7
1261	1068	4.83	-	0.22	6.86	3.57	-
1981	1621	4.18	1.64	0.15	2.64	1.63	0.98
2953	2467	3.80	1.11	0.15	1.24	1.00	0.36
4323	3638	3.28	0.12	0.28	0.77	0.39	0.16
6094	5209	2.93	0.25	0.06	0.34	0.28	0.07

$\bar{\sigma}_v$ - Effective vertical stress

$\bar{\sigma}_{vave}$ - Average effective vertical stress during loading increment

C_{v1} - Coefficient of consolidation as derived from compression versus logarithm of time plot

C_{v2} - Coefficient of consolidation as derived from compression versus square-root of time plot

K_1, K_2 - Coefficient of permeability as determined from C_{v1} and C_{v2} respectively

K direct measure - Coefficient of permeability as determined from direct measurements

Table 4.6

Time-Compression Data
 LL44-GPC 3: 1910 cm (Horizontal)

σ_v (g/cm ²)	$\bar{\sigma}_{vave}$ (g/cm ²)	e Final	C_{v1-3} $\times 10^{-3}$ (cm ² /sec)	K_1 $\times 10^{-7}$ (cm/sec)	C_{v2-3} $\times 10^{-3}$ (cm ² /sec)	K_2 $\times 10^{-7}$ (cm/sec)	K direct meas. $\times 10^{-7}$ (cm/sec)
390	325	6.02	-	-	-	-	2.21
584	487	5.86	-	-	4.49	5.36	-
875	730	5.54	-	-	4.03	4.54	1.35
2101	1488	3.88	-	-	-	-	0.347
2942	2522	2.87	-	-	0.59	0.82	0.178
4413	3678	2.19	-	-	0.51	0.58	0.089
6303	5358	1.95	0.052	0.050	0.13	0.12	0.044

$\bar{\sigma}_v$ - Effective vertical stress

$\bar{\sigma}_{vave}$ - Average effective vertical stress during loading increment

C_{v1} - Coefficient of consolidation as derived from compression versus logarithm of time plot

C_{v2} - Coefficient of consolidation as derived from compression versus square-root of time plot.

K_1, K_2 - Coefficient of permeability as determined from C_{v1} and C_{v2} respectively

K direct measure - Coefficient of permeability as determined from direct measurements

direct measurement of k appears to be necessary.

4.3 Geotechnical Properties: MPG-2

The consolidation/permeability characteristics of MPG-2 surficial sediments is the subject of a Master of Science thesis by C.R. Nickerson, 1978. The samples were taken from Kasten Core 67 on Leg 3 of YALOC-74 aboard the R/V Yaquina. The sediment studied is classified as a normally consolidated soft light brown inorganic clay of high plasticity and normal activity. The average specific gravity (corrected for salts) is 2.75.

As can be seen in Table 4.7, a high degree of apparent overconsolidation is evident in the upper part of the core (15-18 cm). This is attributed to the strength of interparticle bonds and aging effects. At 3 meter depth the sediment approaches a normally consolidated condition. Void ratios are in line with previous findings and agree closely with estimations of void ratio based on specific gravity and water content data. The disturbance indices (I_D) of 0.20 to 0.29 indicate some small disturbance but the samples appear representative of in-situ conditions.

Permeability tests were performed on six of the ten consolidation samples from YALOC-74-K-67. The values of permeability were calculated from direct measurements as well as time compression data (Fig. 4.13 to 4.18). A comparison of calculated versus measured coefficient of permeability, k , was made and a difference in trends observed.

Table 4.7

Consolidation Test Results, MPG-2

YALOC-74 Leg 3 Kasten Core 67

Depth in Core	Back Pressure	Initial Void Ratio,	Initial Water Content	Initial Degree Saturation	Lab. Comp. Index	Field Corr. Comp. Index,	Reloading Comp. Index	Distur- bance Index	Max. Eff. Preconsol. Stress	Over- Consol. Ratio,
		e_o	w_o	S_i	C_c	C_{cf}	C_e	I_D	$\bar{\sigma}_c$ Kg/cm ²	$\bar{\sigma}_c/\bar{\sigma}_o$
(cm)	(psi)									
15-18	0	2.861	101	98.2	0.74	0.81	0.05	0.27	0.152	17.7
15-18	100	2.861	96	94.7	0.54	0.57	0.05	0.22	0.090	10.5
15-18	350	2.861	96	99.2	0.39	0.51	0.05	0.20	0.069	8.0
300-304	0	2.685	94	100.0	0.81	0.85	0.13	0.20	0.280	1.8
300-304	50	2.685	98	100.0	0.72	0.75	0.08	0.20	0.230	1.5
300-304	100	2.685	96	100.0	0.69	0.75	0.09	0.22	0.235	1.5
300-304	200	2.685	93	99.4	0.68	0.74	0.08	0.29	0.188	1.2
Artificially Sedimented Samples										
AS-1*	100	3.839	133	97.8	1.06	1.14	0.05	0.17	0.080	----
AS-2*	200	6.062	276	100.0	----	----	----	----	0.015	----
AS-3*	400	5.094	204	100.0	2.24	2.22	0.09	0.19	0.027	----

*AS = Artificially Sedimented.

COEFFICIENT OF PERMEABILITY, K_h , VERSUS VOID RATIO, e
(VISCOSITY CORRECTED FOR TEMPERATURE AND PRESSURE)

YALOC-74 LEG 3 KASTEN CORE 67

300-304 cms/ BACK PRESSURE = 50 psi

○ COEFFICIENT OF PERMEABILITY LOGARITHM TIME METHOD
● COEFFICIENT OF PERMEABILITY SQUARE ROOT TIME METHOD
△ COEFFICIENT OF PERMEABILITY DIRECT MEASUREMENT

Figure 4.13

COEFFICIENT OF PERMEABILITY, K_h , VERSUS VOID RATIO, e
(VISCOSITY CORRECTED FOR TEMPERATURE AND PRESSURE)

YALOC-74 LEG 3 KASTEN CORE 67

300-304 cms BACK PRESSURE = 100 psi

- COEFFICIENT OF PERMEABILITY LOGARITHM TIME METHOD
- COEFFICIENT OF PERMEABILITY SQUARE ROOT TIME METHOD
- △ COEFFICIENT OF PERMEABILITY DIRECT MEASUREMENT

Figure 4.14

COEFFICIENT OF PERMEABILITY, K_h , VERSUS VOID RATIO, e
 (VISCOSITY CORRECTED FOR TEMPERATURE AND PRESSURE)

YALOC-74 LEG 3 KASTEN CORE 67

300-304 cms BACK PRESSURE = 200 psi

○ COEFFICIENT OF PERMEABILITY LOGARITHM TIME METHOD
 ● COEFFICIENT OF PERMEABILITY SQUARE ROOT TIME METHOD
 △ COEFFICIENT OF PERMEABILITY DIRECT MEASUREMENT

Figure 4.15

Figure 4.16

COEFFICIENT OF PERMEABILITY, K_h , VERSUS VOID RATIO, e
(VISCOSITY CORRECTED FOR TEMPERATURE AND PRESSURE)

YALOC -74 LEG-3 KASTEN CORE 67

ARTIFICIALLY SEDIMENTED -2 BACK PRESSURE -200PSI (1379kPa)
 ○ COEFFICIENT OF PERMEABILITY LOGARITHM TIME METHOD
 ● COEFFICIENT OF PERMEABILITY SQUARE ROOT TIME METHOD
 ▲ COEFFICIENT OF PERMEABILITY DIRECT MEASUREMENT

Figure 4.17

COEFFICIENT OF PERMEABILITY, K_h , VERSUS VOID RATIO, e
 (VISCOSITY CORRECTED FOR TEMPERATURE AND PRESSURE)

YALOC-74 LEG 3 KASTEN CORE 67

ARTIFICIALLY SEDIMENTED-3 BACK PRESSURE=400psi

○ COEFFICIENT OF PERMEABILITY LOGARITHM TIME METHOD
 ● COEFFICIENT OF PERMEABILITY SQUARE ROOT TIME METHOD
 △ COEFFICIENT OF PERMEABILITY DIRECT MEASUREMENT

Figure 4.18

The field samples, at 300-304 cm, show fairly consistent correlation between direct measurement and values calculated from the square root of time method. Values for k derived from logarithm of time data are much lower than either of the other two sets. For the artificially sedimented samples, the two values calculated from time data were close but much lower than the direct measurement values. These direct measurement results indicate a fairly linear behavior for permeability with respect to void ratio.

It would not be feasible to include all of the results contained in Nickerson's thesis in this report and the interested reader is encouraged to consult the original manuscript for additional details. Some excerpts from the thesis are included in the Appendix of this report.

4.4 Comparative Sediment Studies

The installation of the walk-in refrigerator will allow continuation of comparative sediment studies using artificially sedimented samples. Tests on undisturbed illites and smectites will be compared with artificially prepared illites, smectites, radiolarian oozes, and calcareous oozes. Undisturbed samples of radiolarian and calcareous oozes will be obtained on the cruise of the R/V Knorr in April 1978. These will allow for a comparison of artificial and undisturbed samples and provide more meaningful comparative studies.

Permeability results of the first series of comparative studies are shown in Figure 4.19. The results for illite

PRELIMINARY RESULTS
VOID RATIO, e VERSUS COEFFICIENT OF PERMEABILITY, k

Figure 4.19

and smectite are for undisturbed samples from GPC-3/LL44 whereas the tests on the oozes are for artificially sedimented samples. Therefore it is not possible to draw definite conclusions from these results. However, tentatively it is noted that the oozes are much more permeable for most ranges of void ratio than either the illite or smectite. In addition it seems clear that illite is more permeable than smectite. However it should be emphasized that the natural (in-situ) void ratio of the smectite in MPG-1 is considerably higher than for the illite and therefore comparisons at the same void ratio are not meaningful for application to the natural sediment column. For example the average void ratio of the upper five meters (illite) is approximately 3 and Figure 4.19 shows a permeability coefficient, k , of about 1.5×10^{-7} cm/sec for this region. The void ratio at 15 meters (smectite) is approximately 6 with a k of about 2.4×10^{-7} cm/sec. (Table 4.6) Therefore the in-situ permeabilities of the illites and smectites are approximately the same.

4.5 Stress-Strain Properties

The triaxial testing facilities were essentially completed in 1977 with the construction of three pressure systems and the purchase of a Wykeham-Farrance triaxial loading press. Computer and plotter routines have also been completed to process and analyze the test data. The testing program was divided into two phases, the first involving test-

ing of samples taken from the Hole Closure Consolidation tanks, and the second phase consisting of tests on six undisturbed samples obtained during the VEMA-32 cruise of July 1975 (MPG-1 site). The test data from these samples have been analyzed for the conventional shear strength properties. The included tables present values for each sample and values of friction angle and cohesion intercept for each set of samples. (Tables 4.8, 4.9, 4.10)

The angle of internal friction, $\bar{\phi}$, for V-32, PC115: 206 to 242 (Fig. 4.20-4.23) samples is low in comparison to other marine samples. ($\bar{\phi} = 22.9^\circ$) The good quality of the stress-strain curves and stress path plots would indicate that disturbance was not a factor in the low friction angle. The A factor (pore pressure parameter) for these samples of approximately 1.0 indicate that the sample was consolidated to an effective stress greater than the past overburden stress which puts the stress paths in the normally consolidated range. The samples V-32, PC115, 483-533 cm have an internal friction angle of 28.3° which is a more reasonable value for marine clays. The curvature of the stress path and the A factor of 0.14 for the sample 483-493 would indicate that the sample is overconsolidated. (Figure 4.24-4.27)

The Hole Closure samples also exhibit low angles of internal friction. Further testing of the clay material in the Hole Closure experiments is required to define the properties of the sediment. (Fig. 4.28-4.35)

Table 4.8
 TRIAXIAL TEST
 SUMMARY SHEET

URI/MGL

Sample I.D.	α	$\bar{a}$ kg/cm ²	$\bar{\phi}$	$\bar{c}$ kg/cm ²
VEMA - 32				
PC - 115				
Series 1*				
206 - 216				
219 - 229	21.3°	0.038	22.9°	0.041
232 - 242				
Series 2**				
483 - 493				
499 - 509	25.3°	0.045	28.3°	0.051
523 - 533				
Hole Closure - I				
Unit 1*				
U1N5				
U1N4	23.0°	0.094	25.1°	0.104
U1N6				
Unit 3*				
U3N3				
U3N1	19.2°	0.153	20.4°	0.163
U3N1A				

*Least squares fit through failure points.

**Failure envelope for samples 499-503 and 523-533 only. Sample 483-493 assumed to be in the overconsolidated region of the curve.

Table 4.9

TRIAXIAL TEST SUMMARY SHEET

URI/MC

Sample I.D.	Consolidation Pressure kg/cm ²	Strain at Failure %	Deviator Stress kg/cm ²	q_f kg/cm ²	$\bar{p}_f$ kg/cm ²	A_f	Secant* Modulus kg/cm ²
VEMA-32 PC-115							
206-216	0.563	10.2 **	0.386	0.193	0.409	0.90	27.8
219-229	1.126	10.2 **	0.692	0.346	0.773	1.01	47.2
232-242	1.688	10.4 **	0.996	0.498	1.192	1.00	65.4
VEMA-32 PC-115							
483-493	0.141	9.6	0.334	0.167	0.261	0.14	15.8
499-509	0.844	10.9 **	0.716	0.358	0.661	0.76	43.0
523-533	1.689	11.5	1.272	0.636	1.248	0.85	69.8

*Secant Modulus determined at 1% strain

** Stress-strain curves exhibited no peaks, indicated value is approximate failure strain.

Table 4.10

TRIAXIAL TEST SUMMARY SHEET

URI/MG

Sample I.D.	Consolidation Pressure kg/cm ²	Strain at Failure %	Deviator Stress kg/cm ²	q_f kg/cm ²	$\bar{p}_f$ kg/cm ²	A_f	Secant* Modulus kg/cm ²
HC-I Unit 1							
U1N5	1.055	7.4	0.754	0.377	0.725	0.71	54.6
U1N4	1.759	9.4	1.354	0.677	1.272	1.16	98.4
U1N6	2.802	8.7	1.806	0.903	1.954	1.75	134.4
HC-I Unit 3							
U3N3	0.863	6.7	0.796	0.398	0.743	0.65	56.8
U3N1	1.691	9.6	1.210	0.605	1.230	0.88	95.2
U3N1A	2.789	8.8	1.700	0.850	2.025	0.95	122.6

*Secant Modulus determined at 1% strain

V-32 PC-115

V-32 PC-115

206-216 CM

CONSOLIDATION PRESSURE = 0.563 KG/CM**2

DEV. STRESS KG/CM**2

SAMPLE NO. 1

U. KG/CM**2

A FACTOR

STRAIN %

URI/MGL

Figure 4.21

V-32 PC115

219-229 CM

CONSOLIDATION PRESSURE = 1.126 KG/CM**2

Figure 4.22

V-32 PC115

232-242 CM

CONSOLIDATION PRESSURE = 1.689 KG/CM**2

Figure 4.23

V-32 PC-115

V-32 PC-115

483-493 CM

CONSOLIDATION PRESSURE = 0.141 KG/CM**2

Figure 4.25.

V-32 PC-115

499-509 CM

CONSOLIDATION PRESSURE = 0.844 KG/CM**2

Figure 4.26

STRAIN %

URI/MGL

V-32 PC-115

523-533 CM

CONSOLIDATION PRESSURE = 1.689 KG/CM**2

SAMPLE NO. 3

Figure 4.27

HC-I UNIT 1

U1N5

10.16 CM

CONSOLIDATION PRESSURE = 1.056 KG/CM**2

DEV. STRESS KG/CM**2

SAMPLE NO. 2

U. KG/CM**2

A FACTOR

STRAIN %

URI/MGL

Figure 4.29

0171

20.48 CM

CONSOLIDATION PRESSURE = 1.759 KG/CM⁺⁺²DEV. STRESS KG/CM⁺⁺²

SAMPLE NO. 1

U. KG/CM⁺⁺²

A FACTOR

STRAIN %

URI/MGL

Figure 4.30

U1N6

10.16 CM

CONSOLIDATION PRESSURE = 2.802 KG/CM**2

SAMPLE NO. 3

DEV. STRESS KG/CM**2

U. KG/CM**2

A FACTOR

STRAIN %

URI/MGL

Figure 4.31

HC-I UNIT 3

U3N3

40.64 CM

CONSOLIDATION PRESSURE = 0.863 KG/CM**2

DEV. STRESS KG/CM**2

SAMPLE NO. 3

U. KG/CM**2

A FACTOR

Figure 4.33

STRAIN %

URI/MGL

U3N1

50.88 CM

CONSOLIDATION PRESSURE = 1.691 KG/CM**2

Figure 4.34

U3N1A

40.64 CM

CONSOLIDATION PRESSURE = 2.789 KG/CM²DEV. STRESS KG/CM²

SAMPLE NO. 2

U. KG/CM²

A FACTOR

Figure 4.35

STRAIN %

URI/MGL

Additionally, a preliminary assessment of the dynamic properties of sediments has been initiated. Two undisturbed samples; VEMA-32, PC-115 382-392 cm and 637-647 cm were sent to Goldberg, Zoino, Dunnicliff Associates Inc. where resonant column tests were performed. Values of shear modulus G , versus confining pressure $\bar{p}$, for the two samples are presented in Table 4.11 and Figure 4.36. The values of shear modulus were analyzed at a shear strain of 0.10%. As a comparison, values of shear modulus were determined for a kaolinite clay using the data and equations developed by Humphries and Wahls (1968). From the data, values of void ratio were extrapolated to the confining pressures used to test the two VEMA samples. Using equation 1, the shear moduli were calculated and have been plotted versus confining pressure.

$$\text{Eqn. 1} \quad G = 235.839 \bar{p} - 2.3267 \bar{p}^2 + 0.01091 \bar{p}^3 - 11938.4 e + 17655.6$$

where G = Shear modulus in psi

$\bar{p}$ = Effective confining pressure, psi

e = Void ratio

The kaolinite clay exhibits larger values of shear modulus at each confining pressure. This can be attributed to the higher void ratios of the VEMA samples.

The following is a preliminary investigation into the determination of bulk modulus of sediment samples. The two methods presented have been considered and the latter chosen

Table 4.11

SHEAR MODULUS

Sample	Confining Pressure	Shear Modulus *
	$\bar{p}$	G
	kN/m ²	kN/m ²
V-32 PC115	6.9	308.0
382-392	13.8	437.2
	27.6	675.6
	55.2	1242.0
V-32 PC115	6.9	248.4
637-647	13.8	308.0
	27.6	536.5
	55.2	943.9
Kaolinite	6.9	3332.0
**	13.8	7465.8
	27.6	13085.2
	55.2	21411.4

* at 0.1% Shear Strain

** Humphries & Wahls (1968)

SHEAR MODULUS

V-32 PC-115 382-392 cm. ▲

V-32 PC-115 637-647 cm. ●

Kaolinite (Humphries & Wahls, 1968) ■

Figure 4.36

as the testing procedure to be used due to our capability for incorporating this procedure into the testing program. With some alterations to existing equipment, measurements of bulk modulus could be made prior to testing, during consolidation, and during shearing of a triaxial compression sample.

A.W. Bishop (1973) derived an expression for the pore pressure ratio $\Delta u/\Delta \sigma$.

$$\Delta u/\Delta \sigma = \frac{1}{1 + n (C_w - C_s)/(C - C_s)} \quad \text{Eqn. 1}$$

n = porosity

C = compressibility of soil skeleton

C_w = compressibility of water

C_s = compressibility of mineral solids

The compressibility of the water, C_w , can be determined from tables. The compressibility of the mineral solids can be determined using the Voigt-Reuss-Hill averaging method (Hamilton, 1971). Values of n , Δu , and $\Delta \sigma$ can be measured or calculated. Solving Eqn. 1 for C , the compressibility of the soil skeleton, the inverse of this value is the bulk modulus of the soil skeleton, K . The system (total) undrained bulk modulus may be determined by the expression:

$$K_u = K_s \frac{K + Q}{K_s + Q}$$

$$Q = \frac{K_w (K_s - K)}{n (K_s - K_w)}$$

from Gaussmann
(1951)

K_s = bulk modulus of mineral phases = $1/C_s$

K = bulk modulus of soil skeleton = $1/C$

K_w = bulk modulus of water = $1/C_w$

K_u = undrained bulk modulus

Thus if Δu and $\Delta \sigma$ can be measured and the bulk modulus of the water, skeleton and mineral phases calculated, the undrained bulk modulus may be determined.

The second method of determining the bulk modulus of a sediment sample requires that shear-wave velocity and compressional wave velocity be measured. Knowing these two values and the mass density of the sediment, the bulk modulus can be calculated assuming the sediment to be an isotropic homogeneous elastic medium (see Hamilton, 1971). The following formulas are used to calculate the bulk modulus.

$$C_1 = \frac{\lambda + 2\mu}{\rho}^{1/2}$$

$$C_t = \frac{\mu}{\rho}^{1/2}$$

$$K = \lambda + 2/3\mu$$

or

$$K = \rho (C_1^2 - 4/3 C_t^2)$$

C_1 = compressional wave velocity

C_t = shear wave velocity

ρ = mass density of sediment

μ = shear modulus

λ = Lamé's constant

K = bulk modulus

5. HOLE CLOSURE

The laboratory hole closure apparatus has been redesigned to measure stresses and displacements within the sediments during dynamic and quasi-static penetration of a projectile. Preparation of three different sediments from the Pacific and Atlantic oceans will include consolidation to stress levels simulating in-situ water content conditions. The quasi-static emplacement experiments will include constant strain (1.5 cm/sec) penetration with continuous recording of the penetration resistance with an internal load cell monitoring system. The dynamic penetration experiments will involve recording of the projectile's acceleration history (and consequently the penetration resistance) with an accelerometer, hardwired to external signal conditioning and recording equipment. Initial velocities will range from 20 to 30 m./sec. Pore pressure response of the sediment will be monitored around the penetration path with transducers emplaced in the sediment. The stress field will be monitored with an array of acoustic hydrophones previously set at varying radial distances from the expected penetration path. Sediment displacement will be monitored acoustically with a transducer pulse-echo system mounted in the tank wall. The results of hole closure experiments will be used as an experimental check on computer model simulations conducted at Sandia Laboratories.

6. ISHTE PROGRAM

In conjunction with personnel from the University of Washington/APL and Sandia Laboratories, work is proceeding on two phases of the In-Situ Heat Transfer Experiment: (a) preparation for high-pressure laboratory experiments to be conducted at URI and Battelle/Columbus and (b) geotechnical aspects of design for the in-situ experiment.

Tentative Test Program for ISHTE Lab Simulation (Figure 6.1)

- 1) Implant heat source and monitoring instruments in tank with homogenized, remolded sediment.
- 2) Transfer sediment tank to pressure vessel.
- 3) Fill with water and pressurize to maximum rated pressure (approx. 3500 psi).
- 4) Calibrate and adjust instruments to initial conditions.
- 5) Activate heat source and recirculation pump. Pump will discourage temperature stratification of surrounding water.
- 6) Proceed with monitoring and recording of test parameters.

After completion of testing within the vessel, the sediment sample will undergo a full range of geotechnical measurements.

This analysis will include:

- water content/density
- shear strength

EXISTING PRESSURE VESSEL
WITH TANK
(SECTIONAL VIEW)

MORIN 11-7-77
URI/MGL

SCHEMATIC DIAGRAM
OF TEST APPARATUS

MORIN 11-9-77
URI/MGL

Figure 6.1

- Conductivity
- Permeability/Consolidation

Instrumentation:

- Primary - Thermocouples or thermistors (Approx. 12) to monitor temperature field.
- Secondary - Pressure transducers (Approx. 6) to measure sediment pore pressures.
- Tertiary - (Tentative) - Velocimeters (Approx. 3) to measure consolidation rate.

7. OTHER

Extensive effort has gone into preparations for an upcoming research cruise in the North Bermuda Rise Area (MPG-3) in June, 1978. Large-diameter gravity and piston cores are a major part of this cruise and a considerable modification to the R/V Endeavor's equipment has been required. The deep-sea winch has been converted to carry 5/8" wire and a jacking system added to assist on pullout. A core handling and extrusion system has also been developed.

8. SUMMARY

Consolidation tests indicate that the sediment column in MPG-1 and MPG-2 regions is normally consolidated within the depths sampled. There are no hiatus' that can be discerned in the stress-history data, the over-consolidation ratio appears to be approximately unity except for surficial sediment in MPG-2. The phenomenon of apparent overconsolidation in the upper few meters has been observed in a wide variety of deep sea sediments and is attributed to high interparticle bonding stresses which overshadow the overburden stresses. The water content/density profile shows a dramatic increase in porosity (decrease in density) beginning at about six meters in MPG-1 (from an average water content of 110% for the upper six meters to a value of 230% at 11 meters). This is due to a minerology change from illite in surficial sediments to smectite, which is finer grained and much more active with respect to cation exchange capacity, in deeper layers. Permeability of smectites at in-situ porosities are estimated to be of the order of 3×10^{-7} cm/sec. Illites are estimated from MPG-2 data to have a higher permeability, 1 to 3×10^{-6} cm/sec. Stress-strain tests show an effective angle of internal friction to range from 23° - 28° for the upper five meters with an effective cohesion intercept of 41 - 51 g/cm². A triaxial test program is underway to determine shear strength in the smectites and consolidation properties in the upper layers of MPG-1 are underway. The hole closure apparatus has

been redesigned to measure stresses and displacements within the sediment during penetration. Preparation of various sediment types will include consolidation to in-situ conditions. The results of these experiments will be used as an experimental check on computer modeling efforts.

Initial work is commencing on an In-Situ Heat Transfer Experiment (ISHTE). The purpose of ISHTE is to assess the time effects on the sediment of a hot buried container.

APPENDIX A

Oceanus

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HIGH-LEVEL NUCLEAR WASTES IN THE SEABED?

\$2.75

Physical Processes in Deep-Sea Clays

by Armand J. Silva

The fine-grained sediments that blanket portions of the ocean basins possess several characteristics that are favorable for the disposal of high-level radioactive wastes: 1) the sorption properties of the clays tend to inhibit the movement of dissolved radionuclides (see page 28); 2) the rate of water migration through the sediments is very slow compared to other geologic formations; 3) the strength of clays is generally very low — facilitating the emplacement of canisters; and 4) since the sediments are in a plastic state, they do not fracture if disturbed and tend to "heal" if disrupted. The primary force for water migration comes from the heat generated by the waste container. Therefore, it is important to understand the physical interactions between the canister and surrounding sediment so that the long-term dispersal of waste materials can be predicted.

Assumptions — Problems

Our studies to date have been based on certain assumptions regarding the form of the waste (see page 26), and the state of technology of delivery systems. These include:

The Waste Form

Radioactive material will be converted into a solid glass of relatively low leachability.

The Canister

Present plans call for use of a corrosion-resistant metal. Initial studies presume a cylindrical shape approximately 30 centimeters in diameter (1 foot) by 3 meters long (10 feet). It is assumed that the canister will develop cracks or leaks after a few hundred years.

The Radioactivity

The level of radioactivity and rate of decay of the full suite of elements is such that the waste elements must not be allowed to escape from the seabed for a million years.

The Heat

The heat generated by a freshly filled 3 meter canister is approximately 1 to 10 kilowatts, or roughly equivalent to that produced by 10 to 100 reading lights. However, the canisters can be stored temporarily, allowing them to cool before emplacement.

The Emplacement Technology

It is assumed that if a suitable barrier exists, present technology can be adapted for efficient delivery of waste canisters to depths of tens of meters into the sediments or, if necessary, into underlying rock formations.

There are several challenging problems associated with the use of deep-sea clays as a repository for high-level waste or as an added barrier if the canisters are placed in underlying rock formations.

The Radioactivity Problem

The sediment cover must: 1) provide enough mass between the canister and the water column to ensure that living organisms will not be contaminated by radioactivity, and, 2) ensure that the migration through the medium will be low enough to allow dissipation of radioactivity before reaching the sea floor.

The Heat Problem

The heat generated by waste a year after removal from a reactor is high (approximately 8 kilowatts per ton of heavy metal processed) but decays to approximately 0.5 kilowatts per ton after 30 years. However, even if the waste is allowed to cool for a number of years, the temperature buildup, if the canisters are in a poorly conducting material (such as deep-sea clay), will be considerable. The basic questions are: 1) will cooling take place by

conduction, or will convection (circulation) play an important role (convection could take place either by movement of only the pore water of the sediments or by fluidization of the entire sediment/pore water system); and 2) will the change in temperature alter the chemical characteristics of the sediment, cause significant pressure gradients to be set up, or otherwise modify the disposal environment?

The Water Migration Problem

Clay sediments in the deep sea are saturated with seawater and typically have high porosities (usually, more than 50 percent of the total volume is water). However, the resistance to water flowing through the clays is very high (or, alternatively, the permeability is very low). The rate of water migration is controlled primarily by two factors: 1) the permeability of the sediment, which is essentially a constant for a given clay, and; 2) the pressure gradient (the velocity of water is directly proportional to the gradient). This pressure gradient can arise from physical (stresses), thermal, and chemical factors. Existing natural gradients due to overburden stresses (compaction), cyclical water pressures, etc., must be taken into account but are very small. Of greater concern are gradients produced by a concentrated heat source, such as a waste canister. Such thermal gradients may well produce an upward flow of pore water away from the waste canister that tends to carry radionuclides toward the sea floor.

The Penetration Problem

If the canister is to be pushed into the sediment, the driving energy must be sufficient to overcome the strength of the clays. Any emplacement plan entails disruption of the sediment, which will affect its physical properties. In addition, any cavities created by emplacement procedures must be adequately sealed to prevent rapid migration of wastes back up into the ocean.

Geotechnical Properties of Sediments

Information on the physical properties of sediments provides part of the data base necessary for long-term prediction of the behavior of potential repository sites. A combination of spot sampling by coring or drilling and sub-bottom acoustic profiling techniques are used in these studies. So far, we have looked at deep-sea clays generically without becoming very specific about site investigations.

Two areas in the Pacific, about 600 miles and 800 miles north of Hawaii, were selected for initial studies, but the methodology used is equally applicable to any potential disposal site. Typical

profiles of water contents at the two Pacific sites are illustrated in Figures 1 and 2. Both of these profiles show an upper zone (5 meters thick in Figure 1 and 2 meters thick in Figure 2) of constant water content (and constant density) and gradual increases to very high water contents of approximately 240 percent near the bottom of each core. These unusual increases — a decrease in water content and increase in density with depth due to overburden stresses is more common — are due to a change of mineralogy from illite-rich clay in the surficial layers to smectite-rich clay at greater depths.* The constancy of water content within the upper illitic clays is attributed to high interparticle bonding forces within

Figure 1. Water content profile in a core taken 600 miles north of Hawaii at 31°-05.0'N, 158°-31.0'W (study site MPG-1). Note almost constant water content (and density) in upper five meters of illitic clay and steady increase of water content caused by a transition to smectite-rich material. The smectite is much more fine grained than the illite.

*Illite is a common clay mineral with a platy (flaky) structure similar to that of mica, having moderate potential for adsorbing ions. Smectite clays are characterized as being platy shaped, extremely fine grained, very plastic, with high potential for sorbing ions. Bentonite or "drilling mud" is a smectite.

the sediment fabric that tend to inhibit the natural compaction process. A typical scanning electron micrograph of an undisturbed illitic clay is shown in Figure 3. The fineness of the deeper clays can be visualized by realizing that the particles in six grams of smectite (a penny weighs three grams) have a combined surface area equal to that of a football field.

Until recently the longest core taken in the Pacific study areas was about 10 meters. In order to extend our knowledge to greater sediment depths, a research cruise was undertaken on the *C/S Long Lines*, a cable-laying ship, in October, 1976. During this expedition, a large diameter, 7.5 ton corer

Figure 2. Water content profile in a core taken 800 miles northeast of Hawaii at 33°-8.7'N, 151°-15.8'W. The water content is nearly constant in the upper 1.6 meters and increases dramatically to over 240 percent in the lower zones where the clay changes from illite-rich to smectite-rich.

(Giant Piston Corer) was used to obtain a 24.4 meter core in the Pacific study area (Figure 4). This core is undergoing extensive analysis and therefore only preliminary data are available at this time. A plot of strength versus depth (Figure 5) shows that the shear strength is over 300 grams per square centimeter at a

Figure 3. Typical scanning electron micrograph of the internal "fabric" of an illitic clay showing open "card house" structure of flat particles with large voids that are filled with sea water in the natural condition. The electro-chemical surface characteristics of the particles produce a net attraction to water molecules thus decreasing the mobility of the pore fluid and resulting in a matrix of low permeability.

24 meter depth. Although this is not an extremely high strength, it does indicate that penetrations greater than 25 meters in this area would require larger driving forces or other means of overcoming the sediment strength, such as drilling, jetting, or vibratory coring. Except for occasional thin (1 to 5 centimeter) layers of altered volcanic ash and one layer impregnated with ferromanganese hydroxides at a 10 meter depth, the sediment at this core site appears to consist of an upper 4 meter zone of brown illitic clay followed by a transition to dark reddish-brown smectite-rich clay that is quite uniform to the bottom of the core.

Figure 4. Giant Piston Corer (15,000 pounds) being launched from the C/S Long Lines. Note rotating weight stand platform in vertical orientation and handling system (rails, brackets, etc.) installed on ship especially for this coring operation. Only a few large ships can launch and retrieve the large diameter (11.4 centimeters) corer in deep water.

We have begun laboratory experiments to determine the permeability characteristics of these deep-sea clays. Typical results for a sample of illitic clay are shown in Figure 6. This graph shows that the permeability decreases with decreasing void space (void ratio is the volume of voids divided by volume of solids). Most of the test results indicate that for a hydraulic gradient of unity (hydraulic

gradient is a measure of rate of pressure loss when flow occurs) water will migrate through the sediment at 10^{-6} to 10^{-7} centimeters per second or approximately 3 to 30 centimeters a year. The actual hydraulic gradient due to thermal effects will be much smaller than unity and, therefore, the rate of water migration will be much slower. It should be remembered that the effectiveness of the sediment as a barrier is also dependent on other properties, such as ion sorption (see page 28), kinematic dispersion, and molecular diffusion.

Thermal Effects

Understanding the response of sediments to the heat generated by a waste container is perhaps the most complex problem we face and one that is being studied from several points of view. Existing theory is being used by W. P. Schimmel of Sandia Laboratories, a government research complex in New Mexico, to mathematically model and thereby predict the temperature and flow fields around a heat source within the sediment. In addition, we have begun laboratory and field experiments to test the theoretical predictions and gather more data. The question of whether the canisters will be cooled by convection or conduction is far from trivial because the very low permeability of the saturated clays and the low interstitial water velocities involved require highly sophisticated measurements.

Studies to date indicate that the temperatures around a canister will be approximately those predicted for a heat source in a conducting medium. Since the thermal conductivity of the clays is quite low (bricks made of clay are good insulators), fairly high temperatures will build up near the canisters (over 200 degrees Centigrade). Thus, substantial thermal gradients will exist around each container (Figure 7). These temperature gradients will give rise to hydraulic gradients that in turn will cause water to migrate outward from the heat source (Figure 7). Because the temperature decreases and the flow field expands, however, the hydraulic gradient diminishes rapidly with distance from the canister.

Fortunately, the radioactive elements that produce most of the heat have short half-lives, so that the waste will lose essentially all its thermal energy after a few hundred years. Thus, containment of the radioactive elements by the glass waste and by the canister, combined with the fact that the permeability of the clays is very low, should minimize any dispersion of radioactive elements due to thermal effects during the first one to two centuries after burial.

Figure 5. Shear strength profile in a core taken with the large diameter piston corer (Giant Piston Corer) 600 miles north of Hawaii. Shear strengths were measured on board ship soon after recovery of core. The measurements show an upper 4-meter zone with essentially constant strength and then a gradual increase in shear strength with depth, but at a diminishing rate of increase. This information could be used to predict the depth of penetration of emplacement devices.

Figure 6. Results of laboratory permeability tests conducted on an illitic clay. Void ratio is the volume of voids divided by volume of solid particles in a given sediment space. Coefficient of permeability is the velocity of water migration produced by a unit hydraulic gradient (change in pressure head divided by length of drainage path).

Figure 7. Temperature variation and flow field caused by a heat source in a relatively impervious but saturated porous media such as clay. The bell shaped curve on the right side shows the rapid decrease in temperature on a horizontal plane beginning at the canister wall. The lines on the left radiating out from the source illustrate the flow of water generated by the heat field in the sediment surrounding the canister. (Adapted from W. P. Schimmel and C. Hickox)

Emplacement Techniques

Possible methods of placing canisters at the proper depth in a sediment or rock layer range from controlled drilling by a surface ship or bottom-crawling apparatus to a streamlined projectile falling through the water column. The untethered, free-falling penetrometer approach appeals because it is simple, but the full spectrum of possible techniques will have to be studied before a total delivery system can be designed. In a sense, it is premature to enter into a detailed analysis and design of emplacement techniques before we know whether the seabed disposal concept is feasible. On the other hand, procedures should at least be considered in a preliminary fashion in order to assess their effects on the sedimentary barrier. In this assessment, however, we are considering only technology that is currently available (with some modifications and refinements).

The first three concepts that follow are shown in Figure 8. Cost comparisons also are included, but not discussed, although this probably would not be the deciding factor in selecting an emplacement technique.

Projectile Emplacement

The streamlined waste container would be dropped from a ship through the water column. A terminal velocity of more than 30 meters per second

Figure 8. Engineering concepts for emplacement of radioactive waste canisters in the seabed.

(approximately 70 miles per hour) would be reached before the canister began to penetrate the soft sediments. Depending on the sediment strength characteristics, we expect that penetration could exceed 30 meters. The penetrating projectile would rupture the sedimentary material. However, laboratory studies indicate that closure would occur immediately behind the falling canister.

Winch-Controlled Emplacement

In this option, the waste canister would be attached to the bottom of a device designed to penetrate into the sediment, using either its momentum (similar to a piston corer), or some other driving mechanism, such as vibration or jetting. The waste container would be released before withdrawal of the emplacement device but only after it had been determined that the proper depth of penetration had been attained. One advantage of this method is that the canister could be recovered in the event of a malfunction. If necessary, it would be possible to provide a sealant (perhaps of the same clay) that could be left to fill the cavity above the canister as the device is pulled out.

Drilled Hole

The technology for deep-sea drilling from a surface ship has been developed by the Deep-Sea

Drilling Project, a joint effort by several marine research centers. This emplacement technique has the advantage that many canisters could be placed in a single drilled hole, probably with a sealant between canisters. Such drilling probably will be necessary if burial depths greater than about 50 meters are needed to provide an adequate barrier.

Other Concepts

Additional procedures that are intriguing but require more study involve the use of remotely controlled or manned bottom-crawling equipment to bury waste packages. If the required sediment cover does not exceed a few meters, it might even be possible to place the waste in a continuously excavated trench (that could then be backfilled) much in the same fashion as modern pipelaying operations on land.

Hole Closure Problem

As previously mentioned, any emplacement procedure will necessarily disrupt the sedimentary layer. In order to prevent "short-circuiting" of the barrier, it is essential that the cavity created by the emplacing device be filled — either with the same type of sediment or with a suitable sealant. Thus, it is important to know the behavior of the sediment during and subsequent to penetration.

Figure 9. Test frame for laboratory experiments to study hole closure behavior of sediments when subjected to dynamic and static (slow) modes of canister emplacement. Before penetration, the homogenized sediment in the tank (51 centimeter diameter) is consolidated to a predetermined stress level to simulate natural overburden conditions.

As a first step in studying the complex problem of "hole closure," we have carried out a series of laboratory simulation experiments. Results of these preliminary studies are being used to design additional laboratory and in-situ experiments as well as to give direction to theoretical analyses. The experiments have included penetration by high-velocity projectiles fired from a compressed air gun and by a penetrometer pushed in at a relatively slow rate (approximately 10 centimeters per second).

For each experiment, a completely homogenized and saturated sediment was consolidated in a tank (51 centimeters in diameter by 107 centimeters high) to a stress corresponding to in-situ overburden conditions at the depth to be studied. The tank was then transferred to a test frame (Figure 9), the consolidating stress reapplied and the penetration tests (two dynamic and two static) carried out. The configurations of cavities left in the wake of the projectile were preserved by pouring in a quick setting epoxy resin 1 hour and 24 hours after the emplacements.

Two distinct closure patterns have been observed in the 12 penetration tests completed to date (three different overburden stress conditions were simulated — 10 meters, 19 meters, and 28 meters). Except for a small cavity near the surface due to cratering, all the dynamic tests were followed

by immediate and total closure of the hole (Figure 10). In contrast, the static (slow) penetration tests were not followed by immediate closure. Instead, the walls of the cavity (Figure 11) flowed gradually inward with the softer (upper) sediments closing at a faster rate than the stiffer materials at greater depth. It may be possible, however, to modify the static penetration/withdrawal device so as to force closure from deeper to shallower depths (perhaps by taking advantage of natural suction pressures).

Figure 10. Typical appearance of sediment after dynamic penetration of a projectile. The hole has closed immediately and completely. Distortion of the sediment in the wake of the projectile is shown by the highlighted layers that were originally horizontal.

These initial experiments suggest that closure of a completely penetrating projectile would be immediate and total, but closure of a hole left open by an emplacement rod would be gradual.

Emplacement in Rock

Disposal in the deeper lithified sediments (greater than 500 meters, where material is no longer plastic) is also being considered. Owing to higher shear strength and reduced plastic properties, these sediments are susceptible to fracturing that could lead to fast migration of fluids along cracks. The transition downward from soft to lithified deposits may be gradual or abrupt, and sometimes alternating layers of unlithified and lithified sediments are found. Our knowledge of the variation of lithification at depths of more than 30 meters below the sea floor comes mainly from Deep-Sea Drilling Project holes.

Disposal within the igneous oceanic basement beneath the sediments also has been considered but has not been pursued to the same extent as the sediment studies. To date only a few holes have been drilled 500 meters or more into basement by the Deep-Sea Drilling Project. The emerging picture is that the basement has great lateral inhomogeneity, comprising: 1) a layer of basaltic pillow lavas (resulting from underwater eruption and rapid chilling of molten lava), fractured blocks and breccia, sediment-filled cavities, and inter-layered sediments overlying and invaded by quantities of basalt, grading down to 2) basaltic dykes — more massive than pillow lava but with numerous vertical contact boundaries of variable properties — overlying at depths of several kilometers, and 3) more massive horizontally layered gabbros and related rocks.

The whole basement complex is cut by fractures and fissures to depths of 100 meters or more. Ocean water circulated through these cracks while the rock was cooling during crustal formation and circulation may continue to this day. This has resulted in extensive alteration of the basalts and the development of secondary mineralization. Because the nature of the igneous basement is poorly known and unpredictable, neither it nor the overlying lithified sediments appear to warrant serious consideration as disposal sites at the present time.

Additional Problems

Several interesting problems concerning the

Figure 11. Sketch of hole profiles in a homogeneous sediment after slow rate of penetration (10 centimeters per second) of a projectile. The profile on the left was taken 1 hour after test, and the one on the right 24 hours. Note the continuing closure with time that indicates gradual creep or flow of the walls due to overburden stress.

sediment are still outstanding. Some of the more intriguing:

Mass Fluidization

There is a possibility that the material immediately adjacent to the canister may be transformed into a viscous fluid due to convection. This situation could result in the canister sinking through the sediment column (assuming it is denser than the surrounding fluidized material). The conditions under which this process might take place cannot be predicted from present knowledge.

High-Temperature Alterations

Very little is known about how the physical and chemical properties of the sediments are modified by a thermal gradient under pressure — the pressure due to depth of water exceeds 500 atmospheres (10,000 psi) over most of the deep-sea floor.

Aquifers

Continuous layers of highly permeable sediments within the clay formations could provide pathways for quick lateral migration of pore water, with eventual release at outcroppings that could be far from an actual containment site. Detailed core sampling and seismic studies of potential disposal sites can assure that such layers are absent.

* * *

At this stage of the program, we do not know whether the unlithified sediments of the deep seabed form an effective barrier to contain high-level wastes. However, we have not been able to uncover data that disqualify soft, fine-grained deep-sea clay as a potential disposal medium for radioactive wastes. If future studies support this conclusion, we will then conduct exhaustive field studies at specific potential disposal sites to assure that the local geologic conditions are adequate to contain the wastes until they have decayed to harmless by-products.

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Suggested Readings

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APPENDIX B

University of
Rhode Island

DEPARTMENT OF OCEAN ENGINEERING

CONSOLIDATION AND PERMEABILITY CHARACTERISTICS
OF DEEP SEA SEDIMENTS:
NORTH CENTRAL PACIFIC OCEAN

by

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A Thesis

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Consolidation and Permeability Characteristics
of Deep Sea Sediments: North Central Pacific Ocean

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ABSTRACT

Ten one-dimensional consolidation tests have been conducted on both "undisturbed" and artificially sedimented samples from the central North Pacific Ocean (latitude $33^{\circ} 11.75'N$ longitude $150^{\circ} 59.86'W$) in modified Anteus back-pressure consolidometers. Permeability characteristics were determined on six of the samples using a constant head permeability procedure, with hydraulic gradients of 5 to 25, and were also calculated according to consolidation theory. Modifications to the Anteus consolidometers allowed for tests to be conducted at back-pressures of up to 400 psi (2758 kPa) with greater sensitivity than commercially available units. A comparison between back-pressured and non-back pressured tests showed a significant decrease in the compression index, however, the effect of back-pressure on consolidation character- at pressures beyond saturated conditions has tentatively been shown to be negligible. Direct permeability measurements for "undisturbed" samples ranged from 2.22×10^{-7} cm/sec to

6.98 x 10⁻⁷ cm/sec and generally agree with values predicted by the Kozeny-Carman equation. Direct permeability measurements for artificially sedimented samples were lower than values predicted by the Kozeny-Carman equation and ranged from 0.81 x 10⁻⁷ cm/sec to 5.24 x 10⁻⁷ cm/sec. A poor correlation between coefficients of permeability calculated from consolidation theory and direct measurement was shown for all samples. It is suggested that the values of permeability calculated from time-comparison data are unreliable due to the variation of gradient and/or the formation of a filter cake at the sediment-porous stone interface during consolidation loading. Additional constant head permeability tests run at different gradients and the same void ratios showed that no threshold gradient existed and that flow was governed by Darcy's law.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Ten one-dimensional consolidation tests were conducted on both "undisturbed" and artificially sedimented samples of deep-sea sediment from the central North Pacific Ocean in modified Anteus back-pressure consolidometers. Permeability characteristics were determined on six of the ten samples using a constant head permeability procedure. Extra permeability tests were conducted to determine if the sediment exhibited non-Darcian flow. Supplementary data was generated in the form of water content, grain size, specific gravity, Atterberg limits, mineralogy, and scanning electron microscopy to evaluate the sediment behavior.

Considering the results of the work conducted, the following conclusions have been made.

1. The modified Anteus back-pressure consolidometers performed well during the testing program. Improvements were made in the design of confining rings and the increase in pressure range for the regulatory and loading systems.
2. The artificial sedimentation procedure proved functional but results were not as good as desired.

There was no provision for applying consolidating stresses in the sedimentation columns and therefore there was no direct control of void ratio. Further improvements in this area are suggested.

3. Based on physical property data the deep-sea sediment studied can be classified as a normally consolidated soft light brown inorganic clay of high plasticity and normal activity. Apparent over-consolidation shown in the upper 1.5 meters of the core is probably caused by a strong flocculated structure and ion-bonding coupled with aging effects. Mineralogy data indicates that the primary clay mineral present is illite with lesser amounts of chlorite, smectite, and kaolinite.
4. Scanning electron micrographs show the sediment fabric to be fairly open and composed of interweaving bunches (aggregations) of flocculated clay clusters with silt particles distributed throughout the sediment matrix. Micrographs of samples processed by the acetone substitution drying technique were of higher quality than samples prepared by slow air drying.

5. For the field samples the compression index for the back-pressured tests was less than for non-back-pressured tests. However, the effect of back-pressure on consolidation characteristics at pressures beyond saturated conditions has tentatively been shown to have negligible influence on consolidation processes within the range of back-pressures used (0 psi to 400 psi or 0 kPa to 2758 kPa). Further research at back-pressures of at least one magnitude higher than used in this study is suggested.
6. Direct permeability measurements for "undisturbed" samples generally agree with values predicted by the Kozeny-Carman equation. Scatter of direct measurement data did not allow for comparison of differences in permeability due to back-pressure. Values of permeability for field samples ranged from 2.22×10^{-7} cm/sec to 6.98×10^{-7} cm/sec.
7. The direct permeability data for the artificially sediment samples were lower than values predicted by the Kozeny-Carman equation with measured coefficients of permeability varying from 0.81×10^{-7} cm/sec to 5.24×10^{-7} cm/sec.

8. A poor correlation was shown between coefficients of permeability calculated from time-compression data and direct measurement for both "undisturbed" and artificially sedimented samples. It is suggested that the discrepancies are due to the variation of gradient and/or the formation of a filter cake at the sedimented-porous stone interface during consolidation loading.
9. Additional constant head permeability tests run at different gradients and the same void ratio to study the relation between rate of water migration and gradient showed that no threshold gradient existed and that Darcy's law was obeyed exactly. It is proposed that the cases where artificially sedimented samples suggest a threshold gradient are attributable to migrating loose sediment particles that may have obstructed or blocked flow channels.

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b

APPENDIX C

maritimes

A Giant Ship for a Giant Corer

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Our assignment was to obtain a long core sample of clay sediments about 600 miles north of Hawaii where the water is three and one-half miles deep (5700 meters). This in itself was not an unusual task, but the special requirements and the type of ship available for the work posed some interesting problems and led to unique core-handling procedures.

The project is government supported, part of a research program using the talents of several institutions and academic disciplines and the team

included URI ocean engineers and oceanographers. The purpose of the program is to determine whether it is feasible to bury high-level radioactive wastes in the seafloor of remote areas which are geologically stable. (See article by G.R. Heath in November 1976 *Maritimes*.)

Our studies to date suggest that fine-grained deep sea sediments possess several characteristics which make them suitable for containing wastes for a million years or more, the period of radioactivity of some nuclear waste materials. Among these characteristics are a very low rate of water migration through the sediments and high sorption properties. Our studies are now focused on the properties of these clays.

Cores already taken in the study area were either very short (1 to 3 meters) or highly distorted with a maximum length of 8 meters. Since waste canisters may need to be buried at depths of over ten meters and because certain studies require samples with a minimal disturbance to the layers of sediment, we had an urgent need to obtain longer and less disturbed core samples. As a result, we decided to make use of a giant piston coring (GPC) system which had been developed by the author and a group from Woods Hole Oceanographic Institution headed by C.D. Hollister.

We soon discovered that no oceanographic research vessel capable of handling the heavy weight (15,000 lbs or 6800 kg) and length (up to 140 ft or 33 meters) of the GPC would be available in the area for the next few years. The only ship which could do the job was the American Telephone and Telegraph trans-oceanic cable-laying ship *C/S Long Lines*. Plans were therefore made to install the necessary equipment while that ship was taking on telephone cable in Portsmouth, New Hampshire, and the scientific staff met her later in Hawaii.

The *C/S Long Lines* is a modern cable-laying ship, 520 feet long, with a displacement of 17,120 tons, and a lifting capability in deep water of 60,000 pounds. The ship is not equipped to do oceanographic research, and it was therefore necessary to modify it extensively. For example,

we had to build a complete shipboard laboratory, in which to sample and test the recovered cores. Launching and recovery of the giant corer posed more difficult problems. We had to design and install a custom-built system to assemble it along the side rail of the ship and to support it. The key element of the support system was a large rotating steel cradle in which the heavy upper weight stand of the corer rests (see photo). After the corer was lowered from a horizontal into a vertical position, it was lifted out of the cradle with a crane. The next operation involved a complicated transfer of the entire corer from the side of the ship to the bow, a distance of approximately 120 feet. The corer was then lowered to the sea floor with a two-inch diameter steel and hemp cable called grapnel rope.

This brings us to the major problem we encountered. Calculations indicated that the stretch of the grapnel rope due to the weight of the corer would exceed 50 meters (170 feet). Therefore, when the corer reached the sea bottom, the grapnel rope would snap back like an elastic band. This could raise havoc with the coring operation during its penetration into the soft sediments. It was thus necessary to devise some method of minimizing or eliminating the cable rebound. Several different schemes were investigated including an encapsulated water mass to increase dynamic inertial effects, a steel drag plate attached to the cable to slow down the rate of rebound, and an inverted parachute above the corer (concave upward) to provide drag resistance. Then someone at Sandia Laboratories in New Mexico came up with the bright idea of turning the parachute right side up in such a way that the weight of the corer would be supported entirely by the parachute. The technique which was adopted is illustrated in the diagram, and the parachute can be seen in the photograph directly above the corer weight stand.

During the final stages of the corer's descent, the cable was payed out at a speed slightly greater than the terminal velocity of the corer/parachute combination (4.8 knots) for a

The giant piston corer being launched from the side of the ship. Parachute is visible at top.

time long enough to transfer the corer weight from the cable to the parachute (see diagram). By the time the corer reaches the bottom, the parachute is completely deployed, the cable tension at the bottom is essentially zero, and hence there is no rebound of the cable during penetration of the corer into the sediments. The technique has the beauty of simplicity, and with it we were able to recover an excellent core sample 24.4 meters (80 ft.) long - three times the length of previous cores recovered in the same area.

Biologists, geologists, chemists, engineers, and physicists are analyzing the core to evaluate the effectiveness of the sediment strata as a containment medium for nuclear waste canisters.

The diameter of the core sample is 11.4 cm. (4.5 in.). The lack of distortion near the outer edges of the sample and the preservation of features in the sample are evidence that it was not disturbed to any appreciable extent by the coring process.

In addition to the author and G. Ross Heath, professor of oceanography from URI, nine students from the Graduate School of Oceanography and the Department of Ocean Engineering participated in the cruise. The students had valuable hands-on experience directly related to their educational and research interests. Funds for the Seabed Disposal Program are provided by the U.S. Energy Research and Development Administration.

Parachute action as corer is launched. From left: 1) Corer before final descent. 2) Corer lowered at terminal velocity (4.8 knots). Weight of corer is gradually transferred from ship cable to parachute. 3) Trigger weight reaches bottom and corer begins free fall. 4) Corer completes free fall and sediment penetration.

APPENDIX D

GEOTECHNICAL AND NORMAL INCIDENCE REFLECTION
CHARACTERISTICS OF ROCKALL TROUGH SEDIMENTS

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Analysis of geotechnical and acoustic data, core measurements of compressional wave velocity and 3.5 kHz and 12 kHz near bottom normal incidence records, indicate some interesting relationships between geotechnical properties and normal incidence reflection. The two large diameter (11.4 cm) Giant Piston Cores retrieved in the Rockall Trough (both within 1 km of 56° - 17° N, 12° - 31° W) reveal many thin (< 2 cm) lithologic laminations.

The acoustic reflectors are separated into three groups (strong, moderate, weak) with respect to changes in geotechnical and acoustic properties and normal incidence amplitude. Strong reflectors are characterized by at least a 6% increase in compressional wave speed (C), 25% increase in bulk density (ρ), an increase of 7.5×10^5 rayls in specific acoustic impedance (Z) and the normal incidence reflection coefficient (β) ranges from .1346 to .1661. Water content (w) and porosity (n) decrease by at least 60% and 35% respectively and grain size analyses indicate the sediment is primarily sand sized and the material between is predominantly lutite. Weak reflectors display negligible changes in C, ρ , w and n whereas important parameters appear to be Z, which increases by 10^5 rayls, shear strength increasing by 100% and grain size distribution which reveals a large percentage of silt and essentially no sand. The moderate reflectors have characteristics from both strong and weak groups. Grouping reflectors in this fashion correlates well with the normal incidence records.

1. 025348SILVA
2. 1977 Fall Meeting
3. Oceanography
4. Sediment Dynamics
5. No
6. No
7. 30% 1976 Spring Meeting

APPENDIX E

REPORT OF THE ENGINEERING WORKSHOP ON DEEP SEA CORING

NOVEMBER, 1977

VOLUME I

PREPARED BY

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ENGINEERING WORKSHOP ON DEEP SEA CORING
NOVEMBER, 1977

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INTRODUCTION

The Engineering Workshop on Deep Sea Coring, held at the Woods Hole Oceanographic Institution on 29-30 November, 1977, was convened to assess existing technologies for the recovery of long, undisturbed sediment cores from oceanic depths.

Prior to this workshop G.R. Heath polled a group of potential users from the scientific community and various funding agencies to see if there would be interest in a workshop on the future of coring technology. The results of the survey confirmed a definite need for obtaining good quality cores from the upper 50 to 200 meters of sediment as well as a need to assess existing technologies to determine the most efficient means of recovering long cores. However, it was suggested that a meeting to consider engineering aspects should precede the larger meeting of scientists. Because of time constraints, funding limitations, and the nature of the assignment it was decided that the engineering meeting should be restricted to a relatively small but representative group of 10 to 12 who could devote the necessary effort to produce a report prior to the scientific meeting. A few of the intended participants were not able to attend so that the final list of attendees included nine in the working group and five observers. It is recognized that some important institutional groups were not represented at the workshop, there was no intention of excluding anyone, and it is hoped that the workshop group was effective in presenting a broad view during the preliminary meeting.

The task of the Engineering Workshop was to review currently available coring technologies, to determine the most effective means of sample recovery, and to recommend a course of action to be followed in the future.

The following report summarizes the thinking of the working group at the conclusion of the workshop.

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WORKSHOP OBJECTIVES

For purposes of discussion in this report, sediment sampling depths have been classified in the following way.

Surficial sampling - upper 2 meters

Shallow penetration - 2-15 meters

Moderate penetration - 15-50 meters

Deep penetration - 50-200 meters

During the first session of the workshop, the objectives were presented, discussed, and modified slightly to reflect thoughts of the group. These statements were then used as guides to focus attention of discussions.

Objectives

1. Moderate Penetration: Formulate recommendations to improve existing coring techniques for the upper 50 meters. The eventual goal is to develop a detailed proposal in early 1978 for final design, fabrication, and implementation.
2. Deep Penetration: Develop a conceptual system for obtaining continuous sediment samples to depths of up to 200 meters. The goal is to initiate a feasibility study from which a planning/design proposal can be developed.

HISTORY

Piston coring as a technique for the recovery of undisturbed sediment cores was initially developed by B. Kullenberg in the late 1940's as a means of obtaining core samples longer and of superior quality to those obtainable with the open barrel gravity core. Since these beginnings the principle and theory of operation of the piston core have remained essentially unchanged while physical sizes and core lengths have been varied to meet special needs. Engineering aspects of the piston core have been sporadically investigated by various individuals, (Horslev, 1949, and Patten, 1969, etc.) but comprehensive studies of dynamics, barrel diameter versus length, etc. have not been carried out.

Various attempts have been made to recover undisturbed sediment samples using alternate means of achieving a suitable driving force. These have ranged from the use of vacuum chambers, (Rollenberg 1948), which utilized a vacuum to raise the piston during penetration, to a rocket powered coring device developed by the Japanese. None of the various alternatives has succeeded in replacing the basic piston core device as a practical and economical means of obtaining long, sediment samples.

The primary limitations experienced with piston coring devices revolve around ship configurations, winch limitations, wire strength, and the physical limitations of the corer itself. The simplicity of the piston core concept has established it as the primary sediment sampling tool of the oceanographic community.

With increased need for longer and larger diameter core samples, development of systems such as the WHOI Giant Piston Corer, the SIO "Big Bertha", and the LDGO large diameter pis-

ton core have extended the sampling range while still retaining the concept of a piston core. The longest piston core to date is 30 meters of undisturbed sample recovery and 50 meters seems feasible.

Sampling to deeper lengths has been accomplished by the Deep Sea Drilling Project using a specialized drilling ship. However, during the drilling process the upper 20 meters of unconsolidated sediments are usually lost or badly disturbed by the rotating drill bit and due to ship motions. The gap which currently exists between the maximum sample depth obtainable with the piston core and the beginning of drill core recovery represents an area which will require substantial study and development before sampling can become a routine process.

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ASSUMPTIONS, PROBLEMS, CONCEPTS

The best methods of achieving the stated objectives will depend on many factors such as the characteristics of the oceanic province to be cored, acceptable degree of disturbance, class of ships, etc., and it was agreed that several concepts should be thoroughly studied and compared in order to optimize the system which is selected for development. Many of the problems which must be considered in design/development work have been identified by past experience and it is therefore imperative that these be catalogued and addressed in future analyses. The engineering workshop group has begun the study process and this section presents most of the ideas which were discussed during the sessions. Undoubtably there will be many other thoughts which can and should be incorporated in future analyses, and it is hoped that those presented in this report will serve as catalysts. The engineering group feels that the attainment of the second objective (deep penetration) will require different technology and more extensive developmental work, and therefore a decision was made to deal with the two objectives separately. In addition, it seems probable that, even if a 200 meter capability is developed in the near future, there will be much more demand for the 50 meter coring system and therefore a relatively less expensive system should be maintained for moderate penetrations.

A. ASSUMPTIONS

In order to design the systems for attaining the stated objectives it is necessary to set forth some specifications and requirements. Perhaps it would have been more logical to have the scientific workshop meeting first since most of the needs come from the scientific community. However, a few of the workshop participants represented a fairly broad spectrum of oceanographic interests and it was possible to generate a tentative set of assumptions which were then used as a guide for the engineering workshop. The following table summarizes the assumptions and specifications which were discussed.

Item Objective Specification	Moderate Penetration (50 meters)	Deep Penetration (200 meters)
Sediment type	Unlithified, mostly fine grained	Unlithified
Water depth	6000 m.	6000 m.
Ships	Existing oceanographic fleet. Possible Agor class.	Large oceanographic: SEAPROBE, CHALLENGER etc. or new ship
Operational Timing	Preferably in 1979 or early 1980.	1982
Deployment/Handling System	Winch and cable	Large cable or pipe
Station time requirements	Routine coring, (a few hours per core)	Moderate station time, perhaps one or two days per station
Positioning	Normal oceanographic	Dynamic with transponders
Portability	Yes. Entire system to be used on many selected vessels.	No. Restrict use to few vessels.
Development cost	Should be "reasonable" and affordable with existing budget by combination of a few agencies	Could require considerable initial costs
Operational cost	Affordable by oceanographic community. Similar to Deep Tow system or less	Not exorbitant. Affordable as <u>part</u> of large scale projects
Sample quality	Suitable for detailed stress-strain studies, magnetics, etc.	Suitable for "routine" geotechnical properties, magnetics, etc.

B. Problems

The following is a partial list and summary of topics and problems which have been identified for consideration in these and future studies. Most of these ideas follow directly from the stated objectives and general assumptions which have been outlined together with previous experiences in deep sea sediment sampling.

1. Moderate Penetration (50 meters)

- a) Ships - Deck space and rail space requirements may be critical on present oceanographic vessels. Assembly of a 50 meter core in a horizontal position will limit types of ships which can be utilized. Therefore, KNORR and MELVILLE plus some NOAA ships can be used for maximum lengths but smaller vessels could be adapted for lesser needs (30 meters).

Ship dynamics play an important role in determining performance and limitations. Cable oscillations and load surges must be determined and accounted for or eliminated.

Vertical assembly may be possible but this would further limit number of ships, require considerable development costs and consume valuable ship time during launch and recovery of the core. This should be considered in long range development but may not be feasible for immediate (1980) future.

- b) Winches and cables - In order to achieve the goal of 50 meters sample recovery is expected that heavy weights will be involved and breakout forces will be large (in excess of 20,000 kg) unless some means of reducing traction stresses is provided. Therefore, a very definite need exists for substantiably in-

creasing the winch/cable capabilities. It seems obvious that a traction winch is the best means available. If provision is made to substantially reduce breakout forces (50% reduction) the net lifting capacity required at the bottom may exceed 20,000 kg (9,000 kg Corer plus 11,000 kg traction/breakout). However, in the event that no traction reduction system is available, the breakout forces may be much higher. Both steel and non-metallic cables should be considered.

Another major problem which must be solved is that of cable dynamics and more specifically the cable rebound which occurs during free fall and penetration. A parachute support system has been used successfully with the GPC (see Vol. II) but other methods should also be explored.

Other problems and aspects related to the winch/cable system are listed below.

- Cable terminations

- Cable attachments (wire clamps)

- Electro-mechanical cable

- Tapered cable

- Accumulators and/or constant tension system

- Tensiometer/recorder system

These topics were discussed to varying degrees and some tentative decisions and opinions were noted and will be discussed elsewhere in the report.

c) Handling system: The handling system must be capable of quick assembly, launch, retrieval, disassembly and temporary storage of the core in reasonable sea state and weather conditions using a small staff (3 or 4 people). Total turn-around time less than 12 hrs. should be attainable for a 50 meter recovery. The system should provide for safe handling of recovered samples and minimize the need for attachments such as launch and retrieval lines, brackets, etc.

d) Core configuration: Several aspects which must be studied and evaluated are listed below:

Weight stand configuration: i.e. size, weight and shape

Core pipe, couplings: The volume displacement and traction surfaces should be minimized while maintaining adequate strength and buckling stability.

Core cutter/nose cone/core catcher assembly: Should be streamlined and designed in accordance with established recommendations for sampling devices.

Piston: One piece piston with washers appears to work well but should consider break-away feature.

Liners: Question of advantages and disadvantages of liners. Should investigate possibility of very thin-wall liner to minimize sediment displacement.

Tripping: Should eliminate mechanical tripping method. Core mounted automatic acoustic release probably is best.

Orifice Effect: Constriction at top of core barrel
Provides some damping of energy. (.

Safety Release: This could be automatic (hydrostatic pressure release) or actuated from ship.

- e) Plugging problem: There appears to be a stage during penetration when internal wall friction stresses prevent further sampling even though the corer continues to penetrate.
- f) Breakout problem: For penetrations exceeding 30 meters, the breakout forces will increase drastically due to high shear strength in deeper strata.
- g) Corer Instrumentation: Several types of instruments can be mounted on the corer (ex: accelerometer, core orientation, subbottom profiler, thermisters, velocimeter)
- h) Sample Processing: This includes extrusion, labelling, shipboard testing, sampling, description, photography, storage, etc.
- i) Quality Control: All components should be adequately inspected and tested (nondestructive testing)
- j) Maintenance: Proper consideration must be given to maintenance both on shore and during cruises.
- k) Management and Staffing: The system should be properly managed and have a small group of specially trained personnel available.

2. Deep Penetration (200 meters)

- a) Ships - The type and size of ship required depends to a large extent on the method used to advance the core.

If a bottom supported structure is employed, the handling and positioning problems will be different than if a pipe string is used with manipulations controlled at the surface. However, it appears probable that a ship possessing a center well with derrick will be required.

- b) Lifting system - A pipe string has obvious advantages in terms of lifting capacity but the make-up time is high. A winch/cable system may be more practical. If a large diameter pipe is used, it may be possible to use one string with multiple coring operations occurring through the pipe.
- c) Decoupling - Unless a bottom supported structure is used it will be necessary to isolate ship motions from the coring operations.
- d) Penetration scheme - Drilling seems to disturb sediments excessively. Continuous jacking will probably result in "plugging" when internal traction stresses become large. Intermittent jacking/sampling may be feasible. Also, a combination of drilling and jacking (ahead of the drilling) may be attractive. Bottom mounted turbo-drilling should be considered.
- e) Other - Several of the problems discussed for moderate penetration also apply here (plugging, breakout, instrumentation, processing, etc.)

C. Basic Concepts

After extensive discussion of alternative courses of development, the workshop participants agreed that three parallel activities should be pursued. Two of these would be oriented toward attainment of objective No. 1 (50 meter samples).

The immediate goal is to improve on the most successful and proven piston coring system, thereby having available a coring capability in the shortest possible time frame. However it was the opinion of the group that other methods requiring more developmental effort may prove to be more efficient than the usual free-fall piston coring technique and therefore studies should be continued to develop the optimal combination for recovery of continuous 50 meter samples of unlithified fine-grained sediments. The third activity would be a more ambitious program to design a total system for obtaining samples of the entire sediment column to depths of up to 200 meters. It seems likely that attainment of objective No. 2 (200 meter samples) will require different technology and much larger expenditures than for objective No. 1. The three concepts are summarized below and discussed in greater detail in the next section (Analysis and Discussion).

1. Upgrading of Giant Piston Coring System (50 meters) -
The idea is to modify and improve the piston coring system to make it more reliable and extend recovery capabilities such that sample lengths up to 50 meters can be obtained. This seems like an attainable goal for some of the softer sediment accumulations since a GPC length of 40 meters has already been successfully launched and recovered (with "undisturbed" length of 30.5 meters). Many of the problems that have been identified can be solved with minor new technological developments.
2. Piston Corer with Penetration Assist System (50 meters) -
The basic concept is to use the proven free-fall piston coring technique for initial penetration and to add an assist system which would provide additional

energy to complete penetration to 50 meters. Several assist systems have received preliminary analysis (see Appendices A and B) and others should be considered. Based on workshop discussions it appears that the impact method holds the most immediate promise for deep sea applications but others that are being developed (such as the Bootstrap, Seafloor Jacking and Hydraulic Ram) should receive adequate attention.

3. Deep Coring (200 meters) - Two different methodologies were discussed.

- a) Ship supported device: This would entail a pipe string or large diameter cable supporting the core barrels and ancillary equipment required to advance the barrels (such as jacking, drilling, jetting vibration, etc. devices). It is probable that re-entry capability would be required. One of the crucial problems to be solved would involve decoupling of ship motions from the penetration operations.
- b) Bottom supported structure: In this method a large self-contained apparatus would be lowered to the seafloor with all coring or drilling operations being remotely controlled. The coring operations would therefore be completely isolated from ship motions.

Of the two options, the first one (ship supported device) seemed to be the most feasible at the time of workshop discussions.

ANALYSIS AND DISCUSSION

Much of this section is based on workshop proceedings generated at the sessions. Drafts of material submitted at the workshop and later revised are included as Appendix B and no effort is made to identify contributors here. The reader is urged to read the original drafts since they contain more detail than is presented in the following discussion. In this section the three concepts mentioned in the previous section are discussed in greater detail with some preliminary analyses based on input from the workshop participants.

A. Upgraded Giant Piston Corer (GPC) System:

It is the unanimous opinion of the participants that the GPC represents the most advanced state of the art system with promise for approaching the first objective (50 meters) in the shortest time frame. It is of course very apparent that the GPC has been plagued with a variety of problems but almost all of these can be overcome with application of current technology and the remainder can be solved with modifications and modest development. The intent here is not to provide design solutions but rather to draw attention to some critical aspects and propose options for upgrading the GPC system. A tentative schedule for developing the proposed system is shown in Figure 1.

1. Modeling: It is imperative that the entire system including ship motions, cable dynamics, free fall, and penetration behavior be mathematically modeled in as much detail as possible using computer analyses. Studies should be broad enough to encompass a wide variety of environmental and seafloor conditions.

Figure 1. Tentative schedule for development of the upgraded Giant Piston Corer system for 50 meter recovery.

In addition it would be highly desirable to perform some scale model tests in the laboratory to ascertain and/or verify pertinent parameters and behavior. The prototype system should be instrumented to provide proper monitoring during initial field trials. In addition, consideration should be given to instrumenting other current coring systems used by various groups to provide as much real data as possible for designing the new coring system.

2. Winch/Cable System

The winch and cable capabilities available on oceanographic research vessels place limitations on deep sea coring. Many past problems with the GPC can be attributed directly to the winch/cable system and others are indirectly caused by some inherent limitation of the winch and/or cable. The most obvious need is to increase the net lifting capacity at the seafloor to enable safe handling of the heavy coring gear under dynamic sea state conditions and to provide adequate force to pull a 50 meter corer out of the sediment.

The maximum pullout force requirements can not be ascertained with any degree of accuracy at this time since it depends on many factors such as corer weight, core barrel diameter, sediment strength, and possible provision for reducing the traction stresses. However, even if a traction reduction scheme is incorporated in the coring system it would seem prudent to provide an overload capacity (by reducing the safety factor under emergency conditions) such that the corer can be retrieved in the event of a malfunction. (An

alternative would be to incorporate a "weak-link" feature above the corer so that the cable can be saved if the friction-reduction system does not function properly) Based on experiences with the GPC, the breakout traction stresses are approximately 50% of the static (vane) shear strength. For a barrel diameter of 18 cm and average static shear strength of 300 gm/cm^2 the breakout force is 42,000 kg (92,400 lb) and the net required seafloor lifting capacity (including corer) will be in the vicinity of 50,000 kg. (110,000 lb). This of course assumes that 50 meter penetration can be achieved in fairly stiff sediments. The modeling work may indicate that, with piston coring techniques, 50 meters penetration may only be attainable in softer sediment deposits and the breakout force will be decreased proportionately. However, it seems obvious that a much greater cable strength than is currently used will be necessary. Because of the required high load capacity and length of cable (6000 meters) it is recommended that the cable be stored with essentially no tension and therefore it will be desirable to use a traction winch with separate storage drum.

Some discussion has centered around the desirability of having an electrical conductor cable to permit direct communication with corer instrumentation and facilitate data acquisition. This should be explored further but present consensus of the workshop group seems to be that this would add disproportionately to the cost and that present conductor cables may not be durable enough for this type of repetitive, heavy load use.

4. Handling System: The most recent GPC handling system (see Vol. II) seems to be quite efficient and with minor refinements and modifications can be adapted to a variety of ships. The key features are: a) out-board rotating weight stand platform b) a davit-rail-trolley system for assembly and disassembly of the corer c) in-board pipe rack and d) extrusion bench with hydraulic winch. The permanent retrieval lines (which penetrate with the core barrel) should be eliminated. An extrusion van should be available to permit processing of recovered cores during inclement weather conditions.
5. Corer Configuration and Components: Based on the modifications discussed during the course of the workshop it appears that more than one (possibly two) types of core weight will be required if special needs and maximum efficiency of the system are to be achieved. One would be of a less complicated design housing a variety of instrumentation and used in sediment of low shear strength. The other will incorporate an energy assist system similar to the weight plus impact concept.

The most recent GPC core weight was hydrodynamically designed with a complicated streamlined shape so that terminal velocities could be approached if significant free-fall distance was used (80 meters).

However, it now seems more likely that free-fall distances much less than this (perhaps less than 30 meters) will be utilized and therefore a less complicated shape will probably be adequate. The core weight should retain most of the GPC features (i.e. internal free-fall loop compartment, variable weight option, compartments for instruments, etc.).

The step-tapered core barrel design with constant inside diameter is advantageous from the point of view of providing added buckling stability in the topmost sections. Structural stability calculations would be incorporated in the numerical modeling and studies should be made to optimize the diameter to wall thickness ratio with proper consideration for penetration requirements. The couplings must be carefully designed to provide proper stability and maintain a seal.

The question of whether or not to have a removable thin-walled liner is discussed elsewhere. It would be possible to make this an option if a different type of coupling is provided such that internal traction forces are transferred to the core barrel through a shoulder at the couplings. The problem of increased wall diameter (causing more sediment disturbance) could be alleviated considerably by having the bottom barrel section unlined but of the same inside diameter as the remainder of the corer (with liner).

6. Triggering: The mechanical (trigger core) method of releasing the corer above the seafloor should not be used in the future, except perhaps as an emergency back-up system. The most feasible method appears to be a self-contained automatic acoustic release system mounted on the corer. As of the writing of this report, work has already begun on this system with the goal of deep sea field trials in early summer, 1978. Some details of the system are included in Appendix B.
7. Penetration: Past experience with the GPC have shown that certain combinations of factors can lead to a condition whereby the corer no longer continues to obtain sample but rather penetrates the sediment strata as a closed end tube - in other words the corer becomes plugged due to excessive inside traction forces. Therefore in order to obtain continuous sediment samples of 50 meter length in some of the stiffer materials, it will be necessary to overcome these effects so that the corer energy can be fully utilized in actual coring.

The parameters that control penetration are the frontal area, the inside and outside surface areas of the barrel, the corer nose shape and bearing capacity factor in the sediment, the inside and outside frontal area clearance ratios, the sediment adhesion to the inside and outside surface of the barrel, the kinetic energy at impact, the corer weight and its turbulent flow drag characteristics, and the motion of and frictional forces coming from the piston. The resulting combined ef-

fect on the penetration behavior of the corer can be predicted in a comprehensive dimensional analysis. In such an analysis, results will depend upon the variables that are controlled at constant levels or adjusted according to assumptions or stipulations; hence controls and adjustments should be selected with care. Presently, it appears realistic to perform an analysis to determine the requirements for barrel wall thickness, piston restraining force, and expected core length as functions of barrel diameter and sediment strength. It should thus be possible to select the best combination of corer configuration. It is anticipated that a larger diameter core barrel will be necessary to achieve the desired results.

One change which appears to hold promise is to incorporate an active lubrication scheme such that the inside of the core barrel receives a thin layer of lubricant during penetration. This might be applied in a controlled fashion from within the piston or at other locations (such as at the nose cone) along the core barrel.

8. Breakout: In normal piston coring, the maximum line tension occurs during pull-out of the corer, after penetration. The break-out force consists principally of outside adhesion along the core barrel plus a suction force at the nose. As indicated earlier (winch/cable system) the total break-out load for a 50 meter core can be expected to be very high (over 50,000 kg) and therefore the use of breakout reduction aids is necessary. The suction force can be relieved by providing small diameter relief tubing on the outside of the barrel such that a passage-

way from ambient seawater pressure exists to the nose. A good low-friction coating could go a long way toward reducing side traction stresses. Other schemes such as electro-osmosis and expendable sleeves should also be investigated.

9. Instrumentation: There are many in-situ measurements that could be made with the corer if a proper data acquisition system were provided. Some of the measurements would be: acceleration history of corer, piston motion and forces, sediment acoustic velocity measurements during penetration, core orientation and inclination, and high resolution profiling at the core site. Therefore, it is recommended that an integrated, self contained, data acquisition system be designed which can be mounted in the core weight. Additional details of a proposed system are included in Appendix B.
10. Sample Processing: A debate continues on the desirability of having a removable liner so that the core can be stored and then processed at a shore facility. The present consensus appears to be that the cores should be extruded and processed as soon as possible after recovery and therefore there is no need for a liner. However, even if a liner is used in the new design, it seems certain that it will be necessary to process at least some of the cores while at sea. Therefore a good, versatile sample processing facility should be planned so that the desired data and samples can be obtained. Considerable effort has been devoted to developing a ship-board sampling/testing system for the GPC and proper attention should be given to this

aspect in the future. Due to space limitations it is usually necessary to do the initial extrusion and sampling on the open deck and it is recommended that a closed van be made part of the system (this van can also be used for storage of materials during shipment). Split cores should be photographed using good, consistent, photographic techniques so that a continuous true-color photograph can be assembled. Subsequent sampling and testing procedures should be carefully designed to minimize disturbance and retain the maximum amount of sediment in the core for future analyses. Storage of cores should be in a refrigerated van.

B. Assisted Giant Piston Corer

It is the opinion of the engineering workshop group that a parallel effort should be initiated to design and build a better, more efficient system than is possible with the basic GPC. Several concepts were presented and analyzed, including most of the schemes which have been or are being studied by various groups. The range of discussions is indicated in the Edited Minutes included as Appendix A of this report and summarized below.

1. Giant Piston Corer (or similar large weight free-fall device)
2. Vibracorer
3. Hydrostatic (or hydraulic ram) corer
4. Bootstrap corer (or a similar jacking scheme)
5. Water mass corer (i.e. encapsulated water mass to provide momentum)
6. Impact (i.e. similar to pile driver)
7. Other - some possible methods which were mentioned

but not thoroughly discussed are; jetting, osmosis, and rocket assist.

After considerable discussion it seemed that the most logical and efficient way to go would be to use the free-fall weight mode to achieve initial penetration followed by another source of energy to complete penetration to the desired 50 meter depth. In this way, it should be possible to reduce the weight of the coring unit and lead to a more efficient and reliable system. Some of the limitations and problems with each of the methods are mentioned in the Edited Minutes and are discussed in greater detail in Appendix B. The vibration technique would probably cause excessive disturbance and the water mass principle is only a variation of the usual free-fall weight. The three combinations which seem to hold some promise and should be considered more fully are:

- Weight plus hydrostatic ram

- Weight plus jacking or bootstrap

- Weight plus impact

The hydrostatic method is being developed by LDGO and therefore it should be possible to coordinate activities. The jacking method is presently water-depth limited but could be applied to deep water work whereas the bootstrap method may be penetration limited. In summary the consensus was that the "weight plus impact" combination may prove to be the simplest and best choice for near future development (before 1982) and it is therefore recommended that this scheme be given first priority in the feasibility study.

A preliminary analysis of the weight plus impact scheme is included in Appendix B and excerpted below. It should be noted that all the problems and developments associated with the upgraded GPC system (previous action) also apply here and therefore only additional important aspects are mentioned.

Assumptions (Piston Corer plus Impact Combination)

- a. Should be operational in 1 to 3 years
- b. To be used in conjunction with cable, winch and ship requirements developed for the GPC
- c. System portable for use on different ships.
- d. Modified after GPC developments
 1. Acoustic release of core device for initial embedment
 2. Parachute drag to reduce cable rebound
 3. Instrument package to contain accelerometer, shear wave measuring device, sampler orientation device, etc.
 4. Possibly expendable outer sleeve to reduce breakout

Double Impact System (see attached sketch - Fig. 2)

- a. Total weight approximately 5 tons: Two separate masses, 2 1/2 tons each; 10 m freefall of second mass; second mass held in place by shear pins or mechanical latch; mechanical or acoustic release for second mass.
- b. Cycle time

Equipment could be made up in horizontal position while underway or made up in 1 to 2 hours in a vertical position using rotary table, power tongs and standard drilling techniques. Sampler could be dropped and retrieved in 2 hours disassembled in vertical position in 2 hours using 2 m lengths (only one crane required) or rotated to horizontal position in one hour.

Double Impact:

Figure 2
Piston Corer Plus Double Impact

Multi-impact System (see attached sketch - Fig. 3)

a. Total weight 5 tons

Sliding weight, attached to retrieval cable

Piston taken up on spring powered wheel or drum

Piston position needs to be known to determine if driving is helping or if sampler is plugged

Winch can raise and automatic mechanical trip will allow weight to fall (over run in vertical direction necessary to take out boat motion)

Parachute drag can still be used

Falling weight should be at least 1 ton and travel 3 to 5 m

C. 200 Meter Coring Capability

The Deep Sea Drilling Project group has been interested in developing a capability for recovering "undisturbed" samples of deep sea unlithified sediments to depths in excess of 100 meters. A preliminary analysis of three different options (by S. Serocki) is included in Appendix B and excerpted below. It is recommended that a comprehensive feasibility study be initiated along the lines of the preliminary work included here so that a decision can be made in the near future on the best system to develop.

SYSTEM CONCEPTS - 200 METER CORE

Three concepts are described based on: (1) Drill ship capabilities; (2) Recovery vessel capability and; (3) Oceanographic/recovery vessel capability.

1. Drill Ship Capability - Hydraulic Ram Concept

Soft sediments are badly disturbed during GLOMAR CHALLENGER coring operations. The disturbance is caused primarily by motion at the end of the drill string and the unfavorable end area ratio. The following section out-

Multit-impact

Figure 3

Piston Corer Plus Multi Impact

lines a concept that utilizes drillship capability to recover "undisturbed" core.

a. Concept Description

Circulation pumps are used to eject a core barrel section through the end of the drill pipe into the sediment. The core barrel is effectively decoupled from the drill string by the high rate of penetration of the core barrel.

b. Design Parameters

Length - 30 feet,

Core Diameter - 2-7/8 inches,

Rate of Penetration - Approximately 10 feet/second,

Force Available - 10 to 20,000 lbs (hydraulic).

c. Operation

Drop core barrel through drill pipe to landing seat just above bit.

Apply pump pressure to release and eject core barrel.

Core barrel reaches end of travel with upper end of barrel stopped at bit.

Pull up on drill string to extract core barrel from sediment.

Retrieve core barrel through drill pipe.

Wash or rotate drill string to next coring point.

Continue with hydraulic ram core or drop "conventional" barrel. (Round trip of drill pipe not required to continue coring indurated section).

d. Comments

This concept has been selected for an initial feasibility study and preliminary design by the Deep Sea Drilling Project Development Engineering group. Problems which will require study include venting of water

above the core, internal core traction, incorporation of a piston in the design, and the probable disturbance of the upper core section due to the stroked-out movement at the lower end of the previous hydraulic ram core.

2. Recovery Vessel

a. Discussion

The hydraulic ram concept discussed above may be considered for vessels such as the Alcoa Seaprobe. The essential elements required are:

Drill string capability

Wireline core barrel compatibility

Pump system capable of delivering on the order of 300 gallons per minute at pressures of 1000-5000 psi (to 300 HP approximately)

A study is recommended to determine if the operating depth of the Seaprobe could be increased to the 18,000 foot depth range by the use of aluminum drill pipe.

Aluminum pipe allows greatly expanded depth capability at no increase in total weight of the drill string.

Major renovations in the racking system and the wireline system would likely be required.

b. Recommendation

Prepare feasibility study to determine maximum feasible drill string length based on aluminum pipe.

Determine equipment requirements and modification costs for wireline core retrieval operations, include circulation and rotating capability for unlithified sediments. Circulation pressures in the 1000-1500 psi range and rotating capability in the 7000 ft-lb torque range would likely suffice for limited sediment penetrations. The study should also consider drill string dynamics.

3. Oceanographic/Recovery Vessel Capability

In the absence of a drill string capability, a bottom supported jacking system offers an alternate method of recovering "undisturbed" core in the depth range significantly beyond gravity/piston core devices. Its deployment will likely require a large oceanographic vessel on the order of 250 feet in length with a center well arrangement and a derrick. The Alcoa Seaprobe might also be considered for deployment of the device. The following sections discuss a concept for a sea-floor supported deep penetration coring system.

a. Concept Description

A jacking unit is lowered to the seafloor by a dual traction winch wire rope system. A length of steel core tube is lowered by a third traction winch, using the dual lowering ropes as guides. The pipe is lowered and guided into the jacking unit. The jacking unit grips the pipe and applies thrust to take the sample in approximate 5 to 7 foot strokes. The core tube is then jacked out and brought to the vessel by the wireline. Additional core tube is made up and the process repeated in increments until the unlithified sediments are cored.

The system is described schematically in Figures 4 to 6 and in the Data Package (Vol. II). It may be noted that the jacking unit is operational. The principal modification is the use of a wire rope capability to "feed" drill pipe or core tube to the unit and the design for self contained power at great water depths.

b. Design Parameters

Water Depth - 18,000 to 22,000 ft range,
Core Diameter - Nominal 3-6 inches,

DYNAMICALLY POSITIONED VESSEL

NOTE:

FIGURES 4, 5 & 6 ADAPTED FROM
McCLELLAND ENGINEER'S BROCHURE
"STINGRAY" CONE PENETROMETER SYSTEM
FOR MARINE GEOTECHNICAL INVESTIGATIONS

Figure 4
JACKING UNIT INSTALLATION

Figure 5
INITIAL 50 M CORING CYCLE

Rate of Penetration - 15 ft/min,

Weight - 50,000 pounds,

Maximum Thrust - 40,000 pounds,

Stroke - 5 feet,

Hydraulic System - Maximum 156 gallons/minute at 200 psi
Cylinder Area: 2 @ 100 square inch each

Power - Self contained battery system rated at 4800
ampere hours (24 volts) (three hours operation
with factor of safety of two)

Control - Double armored 7-conductor cable attached
to jacking unit lowering line.

Dimension - Approx. 13' x 13' x 15' high

One feature of the system would be a tapered core tube design. The deeper cores would be at reduced diameters allowing wall clearance and reduced or negligible pull out at the previously cored intervals.

A dynamically positioned vessel some 250 feet long with a center well and derrick would be required. Costs of major items not including the dynamically positioned vessel are listed in Appendix B.

Traction winch systems would use one-inch 3 x 19 steel construction wire rope with 100,600 lb breaking strength and be self-powered.

Design problems to be evaluated would include:

- Incorporation of piston

- Dynamics of system during deployment

- Cable drag load, vortex shedding

- Cable entanglements

- Internal core traction

With regard to cable entanglement, industry has used a 4-guideline system in establishing exploratory wells in water depths to 3600 feet in "severe" current areas. A two-guideline system would thus appear feasible con-

sidering that only two guidelines would be employed in the proposed concept and currents would be much reduced in deeper water.

The use of a hard wire control cable would also allow monitoring of sediment frictional forces and other soil parameters of experiments.

A limited logging and instrumentation capability could also be considered as the guideline system allows a means of hole re-entry.

System development time is estimated at three years.

c. Recommendation

Prepare study to establish feasibility and application of a bottom supported unit for deep penetration coring; the study should include:

- a. Preliminary design, cost, capability and limitations.
- b. Schedule for development.
- c. General vessel requirements for deployment of system.
- d. Compatibility with available large oceanographic vessels including the Alcoa Seaprobe.

SUMMARY AND RECOMMENDATIONS

The engineering workshop group is very enthusiastic and optimistic about development of reliable, efficient coring capabilities to obtain good quality, long, continuous samples of deep sea sediments. Based on our assessment of current technology, needs, and resources we feel that it would be prudent to organize a phase development program with the first objective being to obtain a 50 meter coring capability by upgrading existing piston coring systems. This 50 meter system could then be modified and added to as some of the other promising systems are developed and refined. It is our opinion that the technology necessary to extend coring penetrations significantly beyond 50 meters will be quite different than for the upper 50 meters and the time and expense necessary to develop such a capability will be considerably greater. However, it is reasonable to consider development of a 200 meter capability and feasibility studies of such systems should proceed in parallel with the 50 meter system. The following is a summary of the workshop group recommendations. Additional operational and procedural suggestions are contained elsewhere in this report.

1. Work should begin immediately to upgrade the most recent Giant Piston Coring system to enable "routine" recovery of up to 50 meter cores of deep sea unlithified sediments from a selected number of oceanographic research vessels. The entire system, including the winch/cable, handling, corer, and sample processing equipment should be portable and compatible with as many ships as possible without requiring major structural changes to the vessels used. The work should be programmed so that the system is fully operational and available by late 1979 or early 1980.

2. A parallel activity should begin as soon as possible to modify and add to the free-fall piston coring technique at least one other penetration assist method with the goal of making the 50 meter capability more efficient and reliable. Several options should be seriously considered including a) weight plus hydrostatic ram b) weight plus jacking and c) weight plus impact. Based on preliminary discussions and analyses it appears that the "weight plus impact" combination may prove to be the best choice for the near future.
3. For development of a 200 meter capability, three different concepts should be studied:
- a) Drill ship with operation of a drop core barrel through the drill string.
 - b) Recovery vessel with derrick, drill string, and wireline core barrel capability.
 - c) Oceanographic vessel with seafloor jacking unit

It is recommended that an engineering feasibility study be initiated as soon as possible so that a decision can be made as to which system to develop. The study should result in a proposal for engineering work to design the selected system. These efforts should be closely coordinated with those of the Deep Sea Drilling Project.

- Note -

APPENDICES A and B

The appendices have not been included in copies of the workshop report for general circulation. A few complete copies of the engineering workshop report will be available at the March, 1978 workshop at the University of Rhode Island. In addition, a limited number of complete copies are available and interested people should request these through the authors.