6.3.4.3

5

6

DOWELL DIVISION OF DOW CHEMICAL U.S.A.

SERVICE RECOMMENDATION

CEMENTING AND CHEMICAL SEAL RING GROUTING SERVICE RECOMMENDATION

FOR

PARSONS BRINCKERHOFF / PB-KBB

EXPLORATORY SHAFTS:

RICHTON SALT DOME, PERRY COUNTY, MISSISSIPPI
GULF INTERIOR SALT DOMES

DEAF SMITH COUNTY, TEXAS
PERMIAN BASIN

SAN JUAN COUNTY, UTAH
PARADOX BASIN

PREPARED FOR: Sigfried Poppen

SALES MANAGER: Bob Trout

BY: G. A. Correa

PHONE: 713/974-1540

DATE: September 7, 1982

DOWELL DIVISION OF DOW CHEMICAL U.S.A.

September 7, 1982

P.O. BOX 4349
HOUSTON, TEXAS 772104349

Mr. S. Poppen
Parsons Brinckerhoff / PB-KBB
Houston, Texas

SUMMARY: PARSONS BRINCKERHOFF/PB-KBB PLANS TO DRILL ONE OR SEVERAL EXPLORATORY SHAFTS FOR FUTURE REPOSITION OF RADIOACTIVE WASTE.

DEPENDING ON FEASIBILITY, ONE OF THREE LOCATIONS WILL BE CHOSEN AMONG THE FOLLOWING:

PERRY COUNTY, MISSISSIPPI/RICHTON SALT DOME
DEAF SMITH COUNTY, TEXAS/PERMIAN BASIN
SAN JUAN COUNTY, UTAH/PARADOX BASIN

Dowell has prepared a preliminary recommendation to provide cementing and chemical seal ring grouting service for the referenced shafts. The following order of magnitude cost estimate is based on Dowell's current price schedule and assuming a twenty-five percent washout and lost circulation. This estimate should be more than adequate for planning purposes.

Shaft		Estimate Cost
Richton Dome	=	$1,360,000
Permian Basin	=	$1,695,000
Paradox Basin	=	$2,007,000

Dowell is a safety active company. Our service personnel are required to follow established rules and procedures, one of which is an on-location safety meeting prior to starting the job. We invite all other personnel on location to join us in a safe operation.

The costs listed in this recommendation are estimates only. The exact cost will depend on the materials, equipment and time actually required on the job.

Dowell is pleased to submit this estimate for your consideration. We look forward to working with you on this project.

G.A. Correa

G. A. Correa

GAC/sm

CONTENTS

Distribution of Copies

Mr. Poppen - Orig. + 2

Dowell Distribution

G. A. Correa, SRO	- 1
L. D. Boughton, Tulsa	- 1
J. A. Cardwell, SRO	- 1
W. C. Frison, SRO	- 1
C. F. Smith, SRO	- 1
B. Trout, SRO	- 1
SRO Files	- 2

ITEMIZED COST SUMMARY

FOR

RICHTON DOME SHAFT

PERMIAN BASIN SHAFT

PARADOX BASIN SHAFT

RICHTON DOME SHAFT - COST SUMMARY

SYSTEM	VOLUME CU. FT.	NO. OF SKS. OR GALS.	COST (1) PRICE PER SK. OR GAL.	BASE COST (2)	ESTIMATE COST (3)
FRESH WATER FILLER	65,316	37,953 SKS.	8.10	$ 307,419	$ 384,274
NEAT CEMENT	6,658	5,790 SKS.	6.50	37,635	47,043
DOWELL SELF STRESS I	6,390	3,759 SKS.	13.40	50,370	62,962
DOWELL SELF STRESS II	23,168	14,480 SKS.	13.45	194,756	243,445
CHEMICAL SEAL RING	2,896	21,662 GALS.	17.0		368,254 (4)
CHEMICAL SEAL WASH	2,896	21,662 GALS.	7.25		157,049 (4)

TOTAL COST OF MATERIALS ASSUMING NO EXCESS =	1,115,483	
TOTAL COAST OF MATERIALS ASSUMING 25% EXCESS =		1,263,027
PUMPING CHARGES/MANPOWER/TECHNICAL SUPPORT/MOBE AND DEMOBE		100,000
TOTAL ESTIMATE COST		$1,363.027

(1) INCLUDES ALL ADDITIVES AND SERVICE

(2) NO EXCESS ASSUMED

(3) 25% EXCESS DUE TO WASH OUT, LOST CIRCULATION, ETC.

(4) NO EXCESS ASSUMED

Mob + demob

50,000
b. 250/man day

PERMIAN BASIN SHAFT - COST SUMMARY

SYSTEM	VOLUME CU. FT.	NO. OF SKS. OR GALS.	COST (1) PRICE PER SK. OR GAL.	BASE COST (2)	ESTIMATE COST (3)	
FRESH WATER FILLER	88,950	49,416 SKS.	8.10	$ 400,269	$ 500,336	
SALT WATER FILLER	23,600	18,153 SKS.	11.93	216,565	270,706	
NEAT CEMENT	6,600	5,739 SKS.	6.50	37,303	46,628	
DOWELL SELF STRESS II	23,600	13,882 SKS.	13.40	186,018	232,522	
CHEMICAL SEAL RING	2,950	22,067 GAL.	17.00	375,139	375,139	(4)
CHEMICAL SEAL WASH	2,950	22,067 GAL.	7.25	159,623	159,623	(4)

TOTAL COST OF MATERIALS ASSUMING NO EXCESS = 1,374,917

TOTAL COST OF MATERIALS ASSUMING 25% EXCESS = 1,584,954

PUMPING CHARGES/MANPOWER/TECHNICAL SUPPORT/MOBE AND DEMOBE = 110,000

TOTAL ESTIMATE COST $1,695,954

(1) INCLUDES ALL ADDITIVES AND SERVICE

(2) NO EXCESS ASSUMED

(3) 25% EXCESS DUE TO WASH OUT, LOST CIRCULATION, ETC.

(4) NO EXCESS ASSUMED

PARADOX BASIN SHAFT - COST SUMMARY

SYSTEM	VOLUME CU. FT.	NO. OF SKS. OR GALS.	COST (1) PRICE PER SK. OR GAL.	BASE COST (2)	ESTIMATE COST (3)
FRESH WATER FILLER	119,393	66,329 SKS.	8.10	$ 537,268	$ 671,585
DOWELL SELF STRESS I	31,213	19,508 SKS.	13.45	262,384	327,980
DOWELL SELF STRESS II	11,586	6,815 SKS.	13.40	91,325	114,156
CHEMICAL SEAL RING	4,204	31,448 GAL.	17.0	534,616	534,616 (4)
CHEMICAL WASH	4,204	31,448 GAL.	7.25	227,998	227,998 (4)
TOTAL COST OF MATERIALS ASSUMING NO EXCESS =				1,653,591	
TOTAL COST OF MATERIALS ASSUMING 25% EXCESS =					1,876,335
PUMPING CHARGES/MANPOWER/TECHNICAL SUPPORT/MOBE AND DEMOBE					131,000
TOTAL ESTIMATE COST					$2,007,335

(1) INCLUDES ALL ADDITIVES AND SERVICE

(2) NO EXCESS ASSUMED

(3) 25% EXCESS DUE TO WASH OUT, LOST CIRCULATION, ETC.

(4) NO EXCESS ASSUMED

CEMENT AND CHEMICAL SEAL RING SYSTEMS

DISCUSSION

The cement and chemical seal ring systems hereby proposed have been chosen by Dowell with the purpose of providing the best technology available today, therefore assuring a successful operation at a reasonable cost.

To isolate the aquifers Dowell has designed a "Seal System" below and above each aquifer. This "Seal System" consists of 25 feet chemical seal ring plug and at least 100 feet of Dowell's Self Stress cement above and below each chemical gasket. Where salt is present, Self Stress I cement will be used.

Dowell Self Stress I and II are expanding cements which provide improved bonding advantages over other commercially available expanding cements.

Typical densities, yields and mix water figures have been chosen for planning cost estimate and logistics purposes. Actual values might change slightly but not enough to make drastic changes in our cost estimate.

What is the ~~difference between~~ Composition of Self Stress cement?

SLURRY PROPERTIES

SYSTEM	DENSITY LBS. PER GAL.	YIELD CU. FT. SLURRY PER SK.	MIX WATER GALS. PER SK.
NEAT CEMENT	15.8	1.15	4.97
FRESH WATER FILLER	13.5	1.8	9.76
SALT SATURATED FILLER	16.0	1.3	5.0
DOWELL SELF STRESS I (1)	15.2	1.6	7.3
DOWELL SELF STRESS II	14.9	1.7	7.2

(1) SALT SATURATED

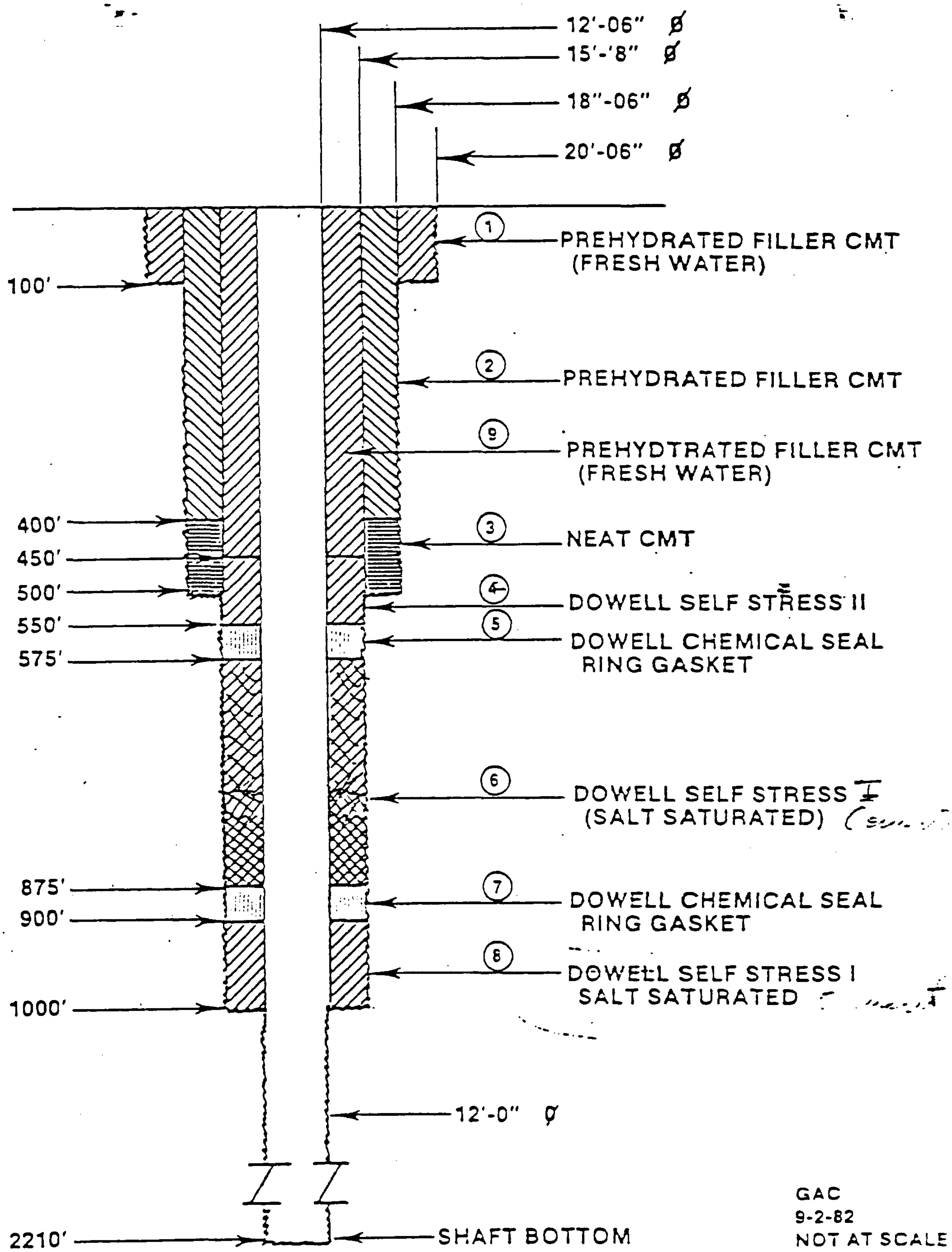
CEMENT SYSTEM AND CHEMICAL SEAL RING
DISTRIBUTION FOR EACH SHAFT
(REFER TO SHAFT DRAWINGS)

SYSTEM NO.	RICHTON DOME SHAFT	PERMIAN BASIN SHAFT	PARADOX BASIN SHAFT
1	B	B	B
2	B	B	B
3	A	A	E
4	E	B	F
5	F	E	E
6	D	F	B
7	F	E	D
8	D	C	F
9	B	E	D
10	-	F	D
11	-	E	F
12	-	-	D

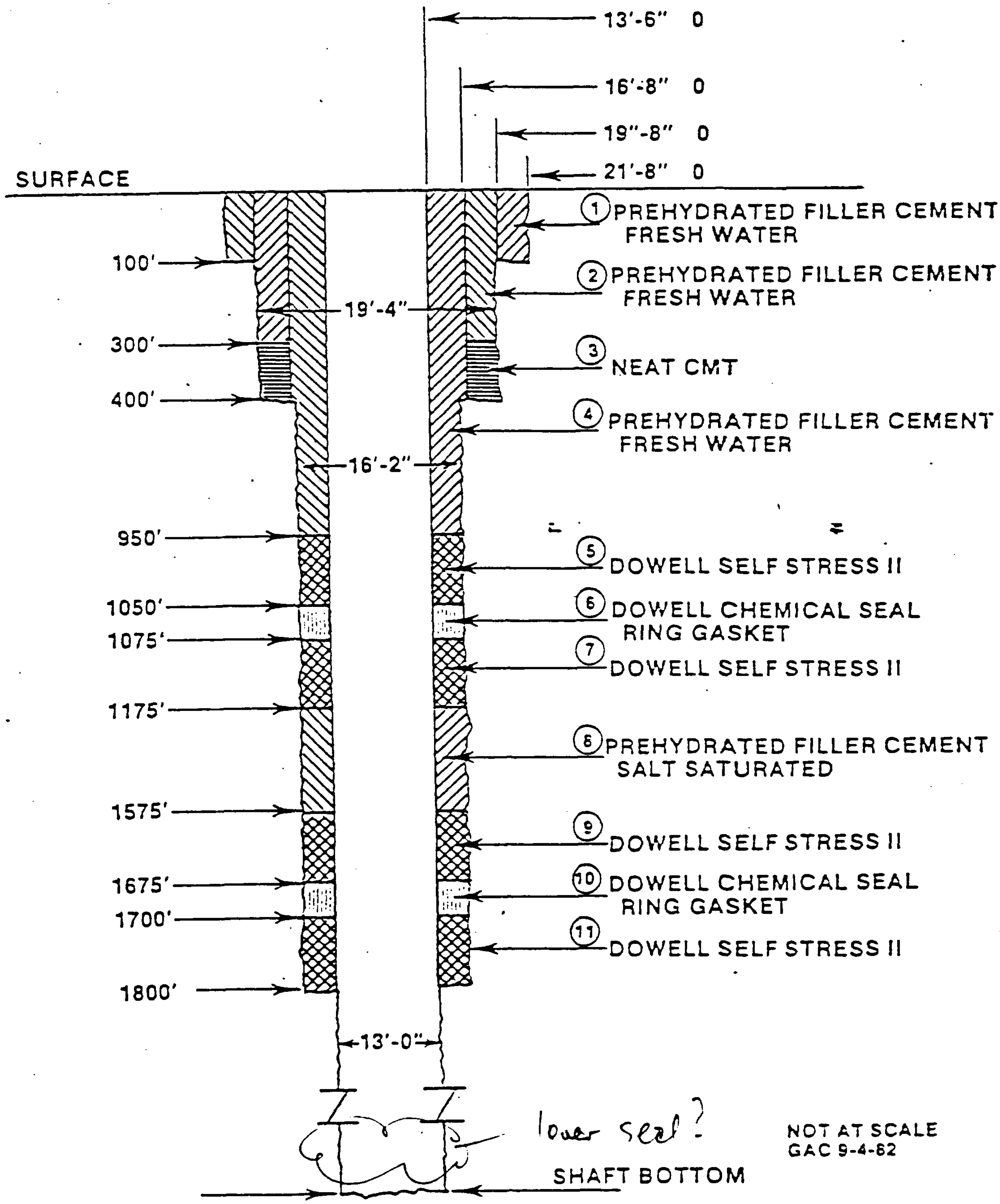
SYSTEM CODE

A: NEAT CEMENT
B: FRESH WATER FILLER
C: SALT SATURATED FILLER
D: SELF STRESS I
E: SELF STRESS II
F: CHEMICAL SEAL RING

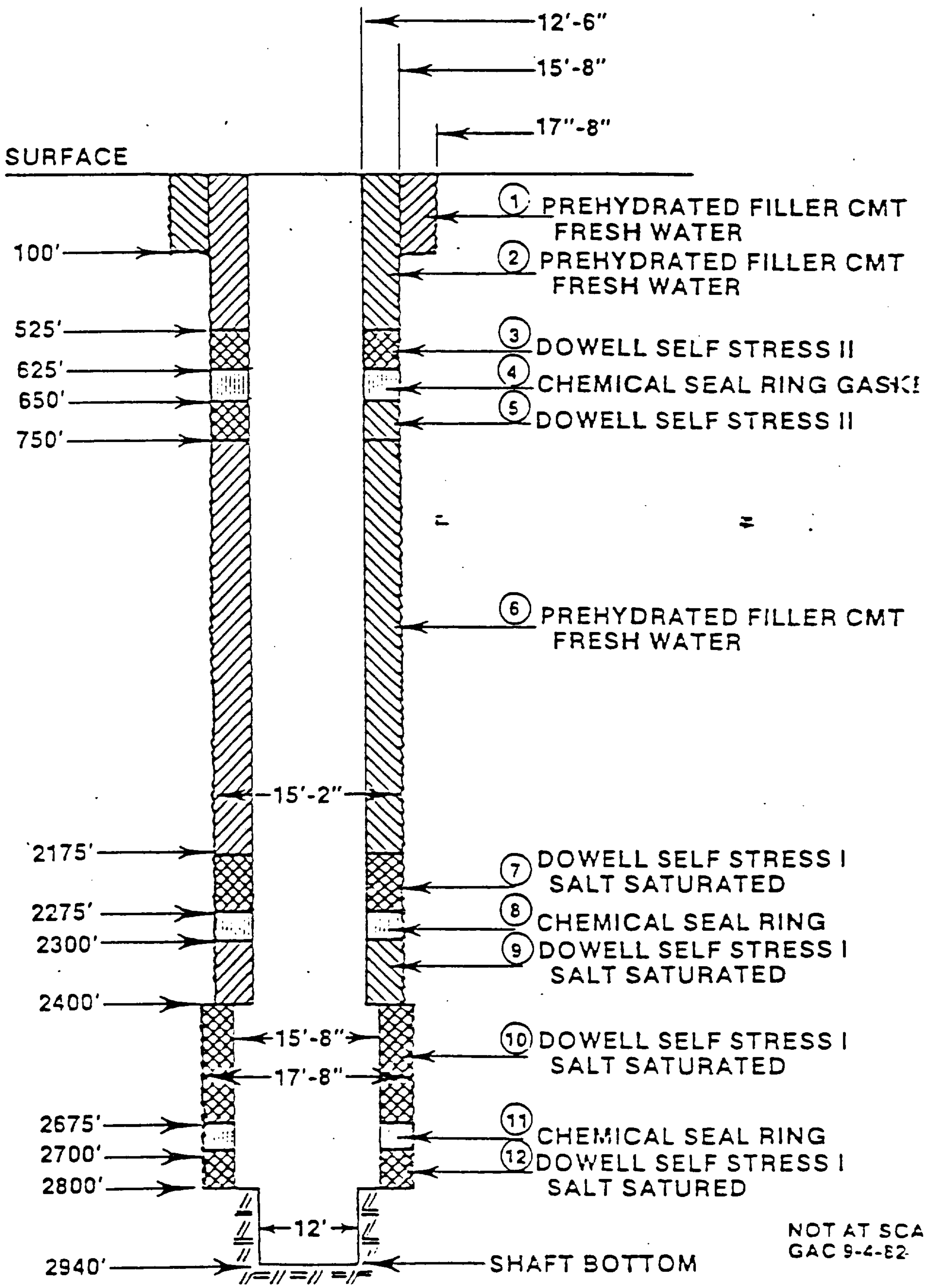
PARSONS BRINCKERHOFF/PB-KBB
RICH DOME SHAFT
PRELIMINARY COMPLETION RECOMMENDATION



PARSONS BRINCKERHOFF/PB-KBB
PERMIAN BASIN SHAFT
PRELIMINARY COMPLETION RECOMMENDATION



PARSONS BRINCKERHOFF/PB-KBB
PARADOX BASIN SHAFT
PRELIMINARY COMPLETION RECOMMENDATION



PROCEDURE - METHODOLOGY

1. The conductor, surface and main shaft casing will be grouted through eight (8) 2-7/8 inch retrievable grout lines placed inside evenly spaced 5-inch slotted casing guides. The casing guides should be welded to the stiffener rings. we talked about slot geometry

2. One double pump cementer will be used to pump through each grouting line at rates around 5 barrels per minute each truck. i.e. 2 ~~trucks~~ pumps per line @ ~~10~~ ≤5 BPM ? 1truck/line

3. The annulus fluid-grout interface should be monitored to insure annulus fills up as designed. Temperature, acoustical sensing devices or mechanical tagging could be used according to availability and driller's preference. Boughton talked about density log run in each of 5" casing guides?

4. To reduce bulk handling and thus cost, all gel will be pre-hydrated and continuously re-circulated during each stage.

5. The area needed for Dowell's equipment and frac tanks is approximately 1/2 acre.

6. Total water needs for each job will be close to 1,000,000 gallons.

CEMENTING COST ESTIMATE FACTORS

1. Dowell's current price schedule was used in preparing this preliminary recommendation. The current schedule at the time service is performed will be the basis for invoicing.

2. Gauge hole and nominal liner size was used to estimate annular volumes and hence volume of cementing materials. This provides a contingency equal to the volumetric displacement of the liner.

3. For cost estimate purposes, a 25% excess was used to account for washout and lost circulation. This figure was chosen as the most probable for this type of mine shaft. Higher or lower washouts or lost circulation will affect this estimate in direct proportion.
Any need for borehole caliper run before cementing? ?

4. The cementing operation hopefully can be performed using one stage per day with stages of 100 to 200 feet fillup. give ~~Once~~ the collapse pressure of the casing is known a definite stage schedule will be designed.

5. The estimate is based on having the following equipment and manpower on location.

    8 Double pump cementers 1 truck & line (2 pumps/truck)
    2 Double pump cementers (standby)
    8 Cement silos - 1,000 sks. capacity each
    4 Compressors
    3 Pick up trucks
    2 Fuel trucks
    2 Ribbon blenders for chemical seal
    2 Frac blenders for prehydrated gel
    4 Automobiles
    1 Project Engineer
    2 Service Supervisors
    20 Operators

6. The cost of frac tank rental is not included in our estimate. For planning purposes frac tank rental varies between $25 to $30 per day if they also supply the water. Water on location is around $1.00 to $1.25 per barrel. Average completion time for any of the shafts is estimated about 30 days and we will use 10 frac tanks at any one time.

DESIGN CONSIDERATIONS

1. The Bottom Hole Static Temperature for each shaft is as follows:

Richton Dome:	96°F
Permian Basin:	96°F
Paradox Basin:	97°F

That is EDBH ?

2. Dowell recommends the drilling of a pilot hole of about 20 inches in diameter with the purpose of controlling any lost circulation zone. If this is done, Dowell will be pleased to design a system which will assure minimum fluid loss during the grouting operation.

3. Ultimate compressive strength for all systems proposed will approach that of neat cement, i.e. 2,000 to 3,000 psi.

4. For similar projects Dowell has developed shear bond strength between salt saturated cement systems and salt rock data. An average figure for the systems proposed in this recommendation would be 60 psi.
What do we need.

why do we need this ?

5. Dowell would be pleased to develop shear bond strength data between casing and cement systems. For this we would need samples of the casing material.

6. Several drilling methods have been used for holes of smaller size. From the cement completion point of view and taking into account the size of these holes, Dowell recommends the conventional fillup from bottom method, as opposed to hanging the pipe from the surface and using mechanical means to support the cement column.
packer

did we discuss this ?

7. Verification of bond shear strength between cement systems, pipe and formation materials will be done during the final stages of completion.

develop this into test plan outline

8. All slurries proposed will actually be tested in the laboratory using the same source of cement, additives and mix water available for each location.

9. Dowell Chemical Seal Ring has been used successfully to prevent the escape of radioactive gases through the tamped column above detonated nuclear devices; to seal water out of gas into a mixed gas-storage cavern; and to isolate high pressure aquifers behind potash mine-shaft linings.

CEMENTING CONSIDERATIONS

plan to characterize hole condition as drilled

1. The hole conditions must be clean of cuttings and debris, and the mud must be solids free, thin and of uniform low viscosity before running the liner.

There is a possibility that stiffener rings will broach the formation in some spots and cause formation to be dislodged. A sufficiently deep rathole will hold this debris. Direct circulation to condition the hole after the liner has been lowered to desired depth is not easily achieved due to the geometry of the hole and grout lines. Air lifting through drill pipe stabbed into a stab-in shoe might be considered.

2. Two factors cause the liner to expand during cementing and to contract when the liner is evacuated following cementing operations.

One of these is the cement heat of hydration which heats the liner and causes it to expand both radially and longitudinally.

The other is the weight of fluid inside the liner during cementing which creates action similar to inflating and deflating a balloon.

Expansion and subsequent contraction of the liner may create a micro-annulus between the liner and the cement grout. The micro-annulus is a water flow channel.

This adverse action can be counteracted by the use of expanding type cement opposite aquifers, by the use of lower heat of hydration cement systems to support the casing opposite dry formations. Extended cement such definition? as prehydrated gel cements reduce the heat of hydration per unit volume of cement.

? The heat of hydration can be dissipated by circulating water inside the liner once the liner is tacked down and can be filled with water.

Purpose of CSR

Chemical Seal Ring intervals are designed to seal any micro-annulus that is created in the cementing operation.

conditions req'd to achieve good hydraulic bond (shear)

3. The hydraulic bond strength is increased with the surface roughness of the formation and the liner. Rusted, pitted steel is preferred over mill varnish. This will be realized on this project. An excessively rough surface will be more likely to fill with mud or cuttings.

survey of hole conditions

4. A good hydraulic bond to the formation depends upon intimate contact between the cement and the formation. Mud cake buildup is not expected to be a concern in the formations to be drilled during this project.

5. The volume per stage is based on several factors including:

   planning

   a. The collapse rating of the liner
   b. The dissipation of heat of hydration
   c. Material supply logistics
   d. Waiting on cement set time (W.O.C. time)

   Of these, the overriding factor is the logistics. Cement transportation over hundreds of miles is a concern and can be affected by many variables. One stage of reasonable size per day, performed during daylight hours is the maximum that can be expected and realized.

6. Grout lines (furnished by others) must be of sufficient size (2-7/8 inch I.D. minimum) to enable placing cement at a reasonable rate.

7. Grout lines must be handled with a minimum delay. For example, pulling 8 strings, 200 feet each, following a stage of cement requires pulling a total of 1,600 feet.

part of longer term test plan

8. Conditions at the time of cementing may make the use of tailor-made washes and flushes advisable. The full facilities of Tulsa and Regional laboratories are available to optimize all cement systems, washes, flushes, etc.

9. Cement-drilling fluid interface logging service is recommended during cementing operations.

   where is probe run?

10. Annular temperature surveys after each stage are recommended to provide information for planning subsequent stages. where run?

CEMENTING SERVICE SUPPLY RESPONSIBILITY

Dowell will furnish:

- Cement mixing and pumping equipment
- Cement field storage units
- Cementing materials
- Cementing lines and manifold into the grout lines provided by others
- A Project Engineer
- Qualified operating personnel
- Qualified support personnel and services
- Quality Assurance monitoring service

Items to be furnished by others include:

- Mix water tanks
- Fresh mix water - tested by lab
- Crane, welder and electrician service
- Utilities
- Sanitation facilities and drinking water
- Cleared, graded, well-drained site of adequate size and proximity to the drill rig
- One office trailer with utilities and with leisure room for crew of 24.
- Cooling water circulation if used
- Cement-mud interface logging service during cementing operations
- Annular temperature determination following each stage
- Grout line handling equipment and service
- Caliper of hole

DOWELL CEMENTING EXPERIENCE

The Dowell Division of Dow Chemical Company is a service company providing energy related services including acidizing, hydraulic fracturing, cementing, drilling fluids, mining and industrial services. Dowell currently offers services with over 8,000 employees located in more than 130 locations in the lower 48 states and Alaska. Dowell is headquartered in Houston, Texas with Research and Development and manufacturing facilities in Tulsa, Oklahoma and Wichita Falls, Texas.

Dowell entered the cementing business in the mid-1930's in Illinois and Canada. These services were expanded to cover the remainder of the U.S. in the late 1950's. An extremely large percentage of the significant developments in cementing during the past 2-1/2 decades have been introduced by Dowell. Some of these developments are:

1. Dowell developed the first latex cement systems.

2. Dowell developed and patented the first turbulence inducers for cement.

3. Dowell introduced the first effective fluid loss additives for cement.

4. Dowell pioneered low-displacement-rate cementing for better mud removal.

5. Dowell introduced thixatropic cements to solve problems of lost circulation in areas with low fracture gradients. Thixatropic cements were also effective in reducing gas cutting of cement slurries.

6. Dowell developed the first long-term data on cement stability.

7. Dowell developed the first data on the effect of pressure on the setting time and strength of various cement systems. rheology

8. Dowell has developed special systems for cementing in Permafrost areas.

9. Dowell has developed a family of spacers and washes for effective mud removal with both water-base and oil-base muds.

10. Dowell developed Chemical Seal Ring as a sealant to use in conjunction with cement for special sealing problems such as in salt domes.

11. Dowell has pioneered research in rheology of cement systems; and,

12. Dowell has developed a full line of liquid cement additives for use offshore and in remote locations.

Dowell has a fully staffed and equipped research laboratory in Tulsa, Oklahoma and Regional labs throughout the U.S. to aid in the design of cement systems for special applications and to solve unique problems.

Dowell has repeatedly demonstrated its ability to mobilize equipment and qualified and experienced personnel in a timely manner in all types of locations. An example is on Amchitka Island, Alaska, for big-hole cementing for the AEC. Many other examples of mobilization and problem solving are listed under "Big Hole and Related Experience".

DOWELL BIG HOLE CEMENTING

AND RELATED EXPERIENCE

1. Project Dribble at Tatum Salt Dome, Mississippi, for the AEC. Introduced and applied Chemical Seal Ring and Chem-Comp expanding cement which contributed to completing the first "dry test" hole after some five previous "wet" failures.

   Self-Stress ≡

2. Prime cementing contractor at the Nevada Test Site for the AEC. now Halliburton

3. Prime cementing contractor to the AEC at the supplemental test site near Tonopah, Nevada.

4. Prime cementing contractor to the AEC at the supplemental test site on Amchitka Island, Alaska.

5. Cementing subcontractor to the DOE at the Nevada Test Site.

6. Cementing and Sonar Caliper Service to the DOE on the Strategic Petroleum Reserve project at Louisiana and Texas locations. This included use of Chemical Seal Ring in the bulkhead seals installed in the salt mine on Weeks Island which was converted for crude oil storage.

7. Cementing contractor on the LOOP project.

8. Cemented the liner in the largest diameter (196-inch) drilled mine shaft located in New Mexico.

   WIPP experience

9. Cementing Services on numerous mined storage projects.

10. Sealing Service on conventionally sunk potash and salt mines in the U.S., Canada and England.

11. Numerous routine mining and construction projects for private industry.

12. Laboratory studies and field evaluation of various materials, etc. for government agencies included L.R.L., L.A.S.L., W.E.S., Sandia and for prime contractors to government.

Department of Energy
National Waste Terminal
Storage Program Office
505 King Avenue
Columbus, Ohio 43201

RECEIVED
JUL 07 1983
M. H. FARZAN

July 7, 1983

TO: R.C. WUNDERLICH

FROM: RAM LAHOTI R.K. Lahoti

SALT EXPLORATORY SHAFT CONSTRUCTION METHOD

We have reviewed the exploratory shaft preliminary designs based on the "drill and blast" and large diameter "blind hole" drilling methods prepared by the Architect Engineer (A/E) and the recommendation paper prepared by ONWI for the shaft construction method. Also we have reviewed the NUREG/CR-2959, 2854 & 3065 prepared by Golder Associates for the Nuclear Regulatory Commission and published in March 1983 concerning the In Situ Test Facility and Evaluations of Shaft Sinking Techniques. Based on our review of these documents we have concluded that the BPMD's recommendation that "blind hole" drilling method be used for the shaft be accepted.

Following are the key factors contributing to our decision making process:

a. We feel that both methods have proven technology. The "blind hole" drilling method primarily orignated at Nevada Test Site and has been widely used elsewhere. For very large diameters 15' and above the technology for "blind hole" drilling exists but has not been proven.

b. Both methods can cope with most geological conditions. The "drill and blast" method may have a slight disadvantage where large acquifers are present. It is cumbersome, time consuming and very costly to use freezing techniques, where as the "blind hole" drilling method can easily handle large high pressure or artesian acquifers.

c. The "blind hole" drilling method has minimal impact on formation damage and provides excellent control of ground water sealability where as the "drill and blast" method may inflict considerable damage to formations leaving disturbed zones which may be more difficult to grout or seal.

d. The "drill and blast" method provides opportunity for inspection of shaft walls. However, we feel that the data available at the target horizon is the principal reason the shaft is needed. There will be other exploratory holes which will provide other information if needed. Also there is a possibility that the shaft may be partially lined in Gulf Interior Region and Paradox Basin, thus providing an opportunity for the geologists to see or touch the rock if they so desire.

e. In "blind hole" drilling method the advance rate is 2 to 3 times faster as compared with "drill and blast" method. Also with existing technology it is possible to have good control over the verticality. A good example is the two shafts drilled at Crown Point, New Mexico by Conoco. (refer to Hassell Hunter paper).

f. The "drill and blast" method is more hazardous when compared to "blind hole" drilling method since it exposes the worker to hazards in the shaft. We feel that health and safety of the workers should be of prime concern to DOE.

g. In a given formation with no acquifers, the "drill and blast" method may be more economical but in a formation where freezing of ground water is required the cost differential is minimal.

h. The "blind hole" drilling method was used to drill both the 6 and 12 foot diameter shafts at the WIPP Salt Site very succesfully.

By this memo I request that you concur with BPMD recommendation that the "blind hole" drilling method be used for the exploratory shaft in salt.

R. W. Tunderlich 6/22/83
Concurrence

cc: S. Goldsmith, ONWI
H. Farzin, ONWI
J. Neff, NPO

ST# 376-83

Goldsmith 3-14-83

SALT EXPLORATORY SHAFT CONSTRUCTION METHOD RECOMMENDATION PAPER

Purpose of the Exploratory Shaft

The purpose of the exploratory shaft facility (ESF) is to provide access to the designated repository horizon to conduct in situ testing in salt.

Shaft Construction Methods Considered

Shaft construction methods considered in this paper are:

1. Conventional shaft sinking method by drill-and-blast techniques
2. Large hole blind drilling technique.

The project A/E has prepared preliminary designs for both methods and considers both to be feasible construction alternatives.

A third hybrid method of construction consisting of a combination of the above noted methods was considered by the project A/E and was rejected early in the program. Schematics of the two methods considered for the Permian Basin are given in Figure 1. A more detailed description of the design and construction methodology is available as part of the project A/E deliverable(1).

Selection Constraints

Both construction methods satisfy the prime constraint of providing access to the designated repository horizon to permit in situ testing necessitated by NRC ruling of 10 CFR 60. After considering additional selection criteria, including those highlighted and discussed in the Appendix, the decision process was narrowed to determination of which of the two construction methods would best satisfy the following three constraints:

a. Legislated schedule, which requires the in situ testing to support the President's approval on March 31, 1987 of the first repository site
b. Minimum construction hazards
c. Reasonable construction costs.

Evaluation of Construction Methods

A decision may be reached by evaluating each construction method in terms of the selection constraints in order to determine which method best satisfies these constraints.

Effect of Legislated Schedule.--The milestone for the start of shaft construction is April 1984. Based on the preliminary designs, the Exploratory Shaft A/E's conservative estimate of the construction duration for the blind drilled shaft construction method is 19 months. (This construction duration is currently being evaluated by ONWI for reduction potential.) Allowing for a total of 12 months to complete in situ testing (8 months) and analyze and document the data (4 months), the exploratory shaft's initial mission would be completed in time to support the presidential repository site approval milestone of March 31, 1987. The estimated shaft construction duration by means of the conventional method is 29 months. The use of the conventional method for shaft construction, therefore, would miss the legislated milestone by approximately 10 months. The large hole blind drilling method, on the other hand, will meet the legislated schedule. The two option schedules are summarized in Figure 2.

Minimum Construction Hazards.--A properly designed and implemented safety program will help reduce the hazards associated with either construction method. However, the drilled shaft construction method may result in fewer possibilities for hazards during construction. The entire drilling is handled remotely from the surface as opposed to having personnel in the excavated hole during construction, as is the case with the conventional method.

Reasonable Construction Costs.--The A/E's preliminary cost estimates for the blind drilled and conventional shaft construction methods in the Permian Basin, for example, are approximately $62 million and $52 million, respectively. It is anticipated that the estimated cost of the drilled shaft construction method may be reduced if site specific subsurface data becomes available in a timely manner, whereas little potential exists for reduction of the conventional option costs. In light of the fact that only the drilled method can meet the legislated schedule, the probable additional cost of the drilled shaft is reasonable.

RECOMMENDATION

The blind drilled shaft construction method is recommended for the Permian Basin because it supports the legislated first repository site approval schedule. This construction method is also expected to result in fewer possibilities for hazards during construction. The demonstrated superiority of the drilled option in these circumstances is consistent with the industry incentive to develop rotary methods of shaft sinking to improve safety and reduce sinking time[(2)]. The limited additional cost of the blind drilled shaft method is considered acceptable.

REFERENCES

1. "Preliminary Designs - Exploratory Shaft Facility in Paradox Basin and Permian Basin", Parsons Brinckerhoff/PB-KBB, December 1982.
2. "Evaluation of Alternative Shaft Sinking Techniques for High Level Nuclear Waste (HLW) Deep Geologic Repositories", Golder Associates, submitted to NRC, July 1982.

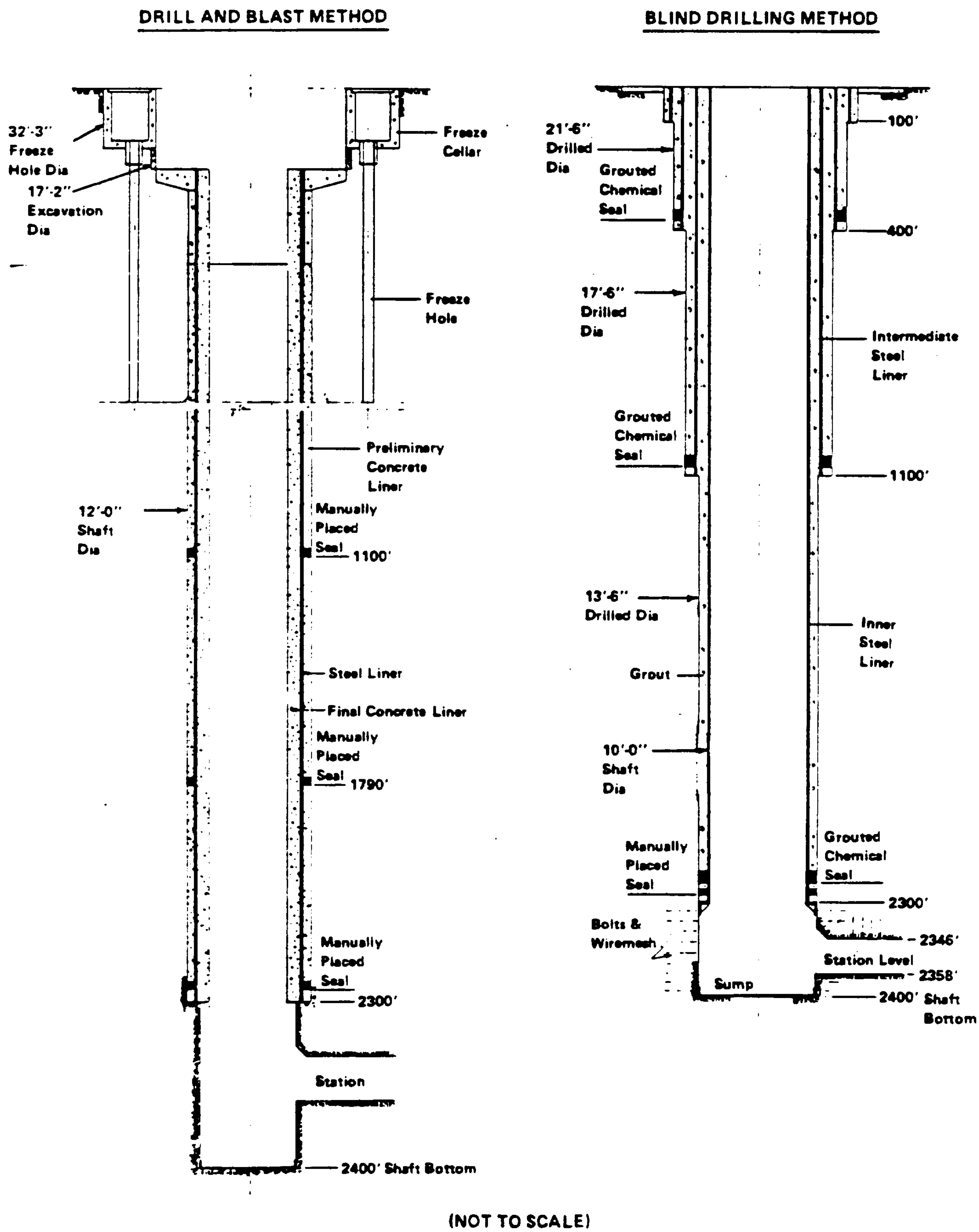


FIGURE 1. SKETCHES OF SHAFT CONSTRUCTION METHODS FROM PERMIAN BASIN PRELIMINARY DESIGNS

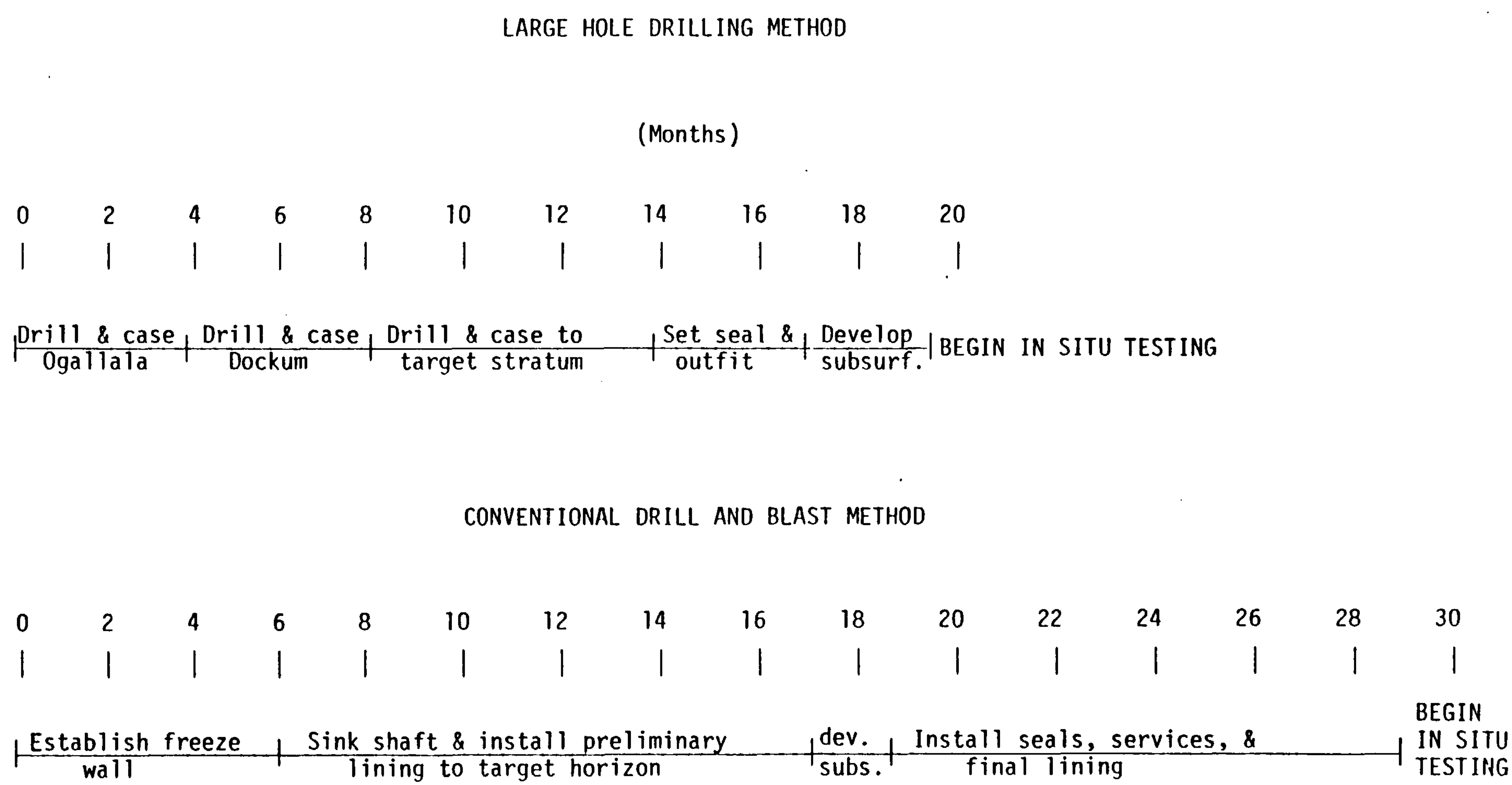


Figure 2. Comparison of Schedules for Alternate Shaft-Sinking Methods

APPENDIX

TO

SALT EXPLORATORY SHAFT CONSTRUCTION METHOD RECOMMENDATION PAPER

TECHNICAL CONSIDERATIONS IN SELECTION OF BLIND SHAFT DRILLING METHOD

FOR THE PERMIAN BASIN

Each of the methods considered for excavation of the Exploratory Shaft possesses particular merits and areas of concern in its execution. The merits of each method of excavation have lead to confidence on the part of ONWI and its retained Architect/Engineer (A/E) that either method will lead to successful construction. The areas of concern in execution of a shaft by conventional drill-and-blast techniques are not pertinent, as the large hole blind boring method has been recommended as the only approach capable of meeting the Program schedule. Therefore, further discussion of areas of concern in shaft execution must center upon those relating to the blind boring method. The ONWI technical staff has identified aspects of shaft drilling which must receive careful attention in design and construction in order to ensure completion of a shaft which accomplishes its Program purpose with high quality. Aspects of shaft drilling evaluated by the ONWI technical staff fall into four basic categories:

1. Information not obtained because of the drilled shaft liner.
2. Assurance that liner seals will protect workers from inundation.
3. Ability to prevent hole collapse while drilling.
4. Ability to prevent hydraulic fracture of the target horizon while drilling.

These issues, and the means by which the drilling program will address each issue, are discussed on the following pages.

1. INFORMATION NOT OBTAINED BECAUSE OF THE DRILLED SHAFT LINER

If the exploratory shaft were constructed by the conventional drill-and-blast technique, all of the shaft wall would be available for mapping, sampling, and direct placement of instrumentation. In shaft sinking by the large hole blind boring method, the shaft will be filled with fluid until after the steel liner is grouted into place. Thus, very little of the stratigraphy above the target salt horizon will ever be exposed, and the shaft will provide extensive data only at the target horizon and approximately 25 feet into the immediately overlying strata. The Permian Basin is notable in the predictibility of its stratigraphy, which is a prime reason for not considering the mapping of shaft excavation walls to be associated with the resolution of site suitability issues. Data availability at the target horizon is the principal purpose of the exploratory shaft, and this purpose is completely fulfilled by the planned blind drilling construction method. Therefore, the decision to employ the drilled shaft method was made with complete awareness that data will not be obtained directly from the exploratory shaft in the categories described below.

1.1 Data Used to Verify Loading Conditions

- Rock quality.
- Quantitiative joint system identification.
- Verification that instruments have been set without damage, in appropriate locations.
- Observation of unexpected conditions.

Uncertainties in the assessment of liner loading conditions will be addressed by two means: the liner design will be conservative, and site data will be obtained from a boring located within a few hundred feet of the shaft. This hole will be completed shortly before the start of shaft sinking, and is intended to verify that the conservatism built into the liner design is adequate. Unanticipated loading conditions revealed by the borehole will be addressed at the site by the addition of extra reinforcement to portions of the steel liner, if necessary.

1.2 Data Used to Verify Adequate Sealing for Safe Working Conditions

- Observation that seals are located in zones of best rock quality.
- Identification of porous zones.
- Quantitative joint system identification.
- Observation that piezometers are placed without damage, in appropriate locations.

The selection of locations for the setting of piezometers and seals will be guided by the borehole to be completed nearby before the start of shaft sinking. Injected seals to be located at the bases of the Ogallala and Dockum formations will fill a sufficient portion of the annular space to ensure adequate performance. These seals will be "backed up" by the complete filling of the annulus above and below the seal with cement grout, and by the installation of a manual seal at the base of the final shaft liner. Each of these three methods of annulus sealing will be independently capable of preventing the inundation of the shaft by waters from the permeable strata.

1.3 Data Used to Test Adequate Sealing Against Radionuclide Migration

- Observation to select best rock quality locations to be used at the closure of the repository for permanent sealing.
- Identification of porous zones to be avoided in permanent sealing.
- Quantitative joint system identification.
- Observation that piezometers are placed without damage, in appropriate locations.
- Confirmation that site stratigraphy isolates aquifers.
- Direct observation of excavation damage to rock.
- Confirmation that short-distance variations in lithology do not lead to aquifer interconnection.
- Excavation of large samples to be transported to laboratory and tested by the existing sealing program.
- Visual verification that rock surfaces are clean prior to grout and seal placement.

Assurance of complete sealing against radionuclide migration through repository shafts is a prime consideration at the time of repository closure. The Exploratory Shaft will be designed and constructed with licensability provisions to be used during the repository operation, but selection of horizons for final repository closure seals was not considered to carry sufficient weight to justify missing of the legislatively-mandated shaft completion milestone. Every effort will be made to gather data which will aid in selection of the suitable horizons for eventual sealing of the shaft, but the exclusion of some such data collection at this stage of the program is considered to be acceptable.

2. ASSURANCE THAT LINER SEALS WILL PROTECT WORKERS FROM INUNDATION

The potential for large inflows of water while there are workers in a shaft or subsurface facility is a primary concern regardless of the method of construction. The ONWI staff consider it extremely important to verify that adequate confidence can be given in the ability to place, test, and repair the critical seals which protect workers in the subsurface.

Such seals are to be located in three places: below the Ogallala aquifer (a depth of about 400 feet), below the Dockum aquifer (a depth of about 1100 feet), and at the base of the shaft liner (a depth of about 2300 feet). The upper two seals will be injected into the annulus between the rock wall and the shaft liner, and will not be visually verifiable. The seal at the base of the shaft liner will be placed manually, and will be visually inspected. Repairs can be effected to <u>any</u> seal or grouted portion of the annulus.

2.1 Reason for Confidence in Sealing Design

The Ogallala and Dockum formations are considered the only sources of sudden, large-quantity water inflows which threaten subsurface personnel. Other permeable zones could lead to inflows which would be undesirable, but which could be managed by the facility's dewatering system. Between the base of the Dockum formation and the bottom of the shaft, the annulus is filled by three independant, redundant lines of protection against large-quantity flows. These are: 1) the injected chemical seal at the base of the Dockum, 2) the cement grout which fills the annulus between that seal and the base of the liner, and 3) the manually-placed chemical seal at the base of the liner.

The injected seal and the cement grout derive from long-proven standard oil-field practice. The manually-placed, chemical seal derives from mining industry practice. The Project A/E has indicated that this type of seal has been proven both in practice and in testing for 20 years.

2.2 Possibility of Seal Testing

The confidence based upon the sealing design and past performance of similar seals is such that special testing is not considered requisite. Proof of performance will be immediately provided when the base of the shaft liner is drilled out, and the shaft does not fill with water. However, should additional demonstration of seal adequacy be required, proven methods of seal testing are available from the gas storage industry. In order to demonstrate that a facility is capable of retaining natural gas without leakage, drilled shafts are sealed at the top of the liner, and the liner and storage cavern are filled with gas under high pressure. If the pressure can be maintained without significant drop for a specified period of time, the sealing system is determined to be adequate.

Such testing of any of the seals placed in the Exploratory Shaft is entirely possible, although it is not considered necessary. Each test would carry with it a penalty in cost and scheduling. A pressure system capable of resisting about 200 psi would be required to test the seal at the base of the Ogallala formation, 500 psi would be required to test the seal below the Dockum, and 1000 psi would be needed to demonstrate the adequacy of the seal at the base of the liner.

2.3 Techniques for the Repair of Faulty Seals

With the multiple lines of defense provided by the sealing system, a sudden, major inundation of the shaft by flow through the annulus is not a credible event. However, if small seeps should occur at any point into the shaft opening, remedial action may be considered appropriate. The approximate approach to reducing such seeps would be as follows:

a. Employ data from planned sidewall piezometers to predict the approximate source of the inflowing water.

b. Drill through the shaft liner at the highest location consistent with the flow source, to attack the problem under the lowest possible pressure.

c. Inject chemical grout capable of set-up in flowing water through holes drilled in the liner, to seal off the water-producing zone.

d. Verify the effectiveness of the remedial action by observation of the side-wall piezometers, and by observation that the inflow has ceased.

e. If necessary, remove and reconstruct the basal seal.

3. ABILITY TO PREVENT BOREHOLE COLLAPSE WHILE DRILLING

During the drilling of geologic boreholes in the Permian Basin, difficult drilling conditions have been encountered in the Ogallala, Dockum, and upper Alibates formations. These difficulties have generally been attributed to the collapse of the borehole walls, despite the presence of drilling fluid (commonly termed "mud") in the holes. The common expression for the worst such borehole collapse condition is "flowing sand", a term which implies the inward movement of loose sand under water pressure. The issue is that "flowing sand" conditions may arise during the drilling of the Exploratory Shaft, and might lead to progressive upward collapse of the hole to the point where the drilling head would be buried, or the entire shaft might collapse.

Protection of the drilled shaft against such conditions has long been a topic of import to the A/E retained by ONWI to design the Exploratory Shaft Facility. In response to its own concerns, and assuming a worse case condition in the Ogallala formation of deep loose saturated sands, the A/E has provided two standard oil-field approaches to the control of hole collapse: multiple casings (liners), and a carefully formulated and controlled mud program.

3.1 Multiple Casings

The drilling technology staff of the A/E analyzed the detailed drilling records from the earlier geologic boreholes which had experienced caving difficulties. Adding this program experience to their own extensive drilling experience in the Permian Basin, the A/E staff built two protective casings into the drilled shaft design. The first of these casings is to be set at the base of the Ogallala formation, and will thereafter protect the hole from caving in that formation. The second protective casing is to be set in a competent anhydrite bed in the Alibates, which immediately underlies the Dockum formation. The rocks below this point are more competent than those above, and are not expected by any authority to present difficult conditions. (The first of these two multiple casings may not be used if the Ogallala is determined to be in a better condition when the nearby borehole is completed.)

3.2 Controlled Mud Program

The advance formulation and field control of the fluid used to maintain an open borehole is a science and an art developed through years of oil-field experience. The principle parameters which can be varied by the mud engineer are the weight, viscosity, and chemistry of the fluid. The A/E has formulated a fairly simple two-phase mud program for the drilling of the Exploratory Shaft, but has emphasized the critical importance of field monitoring and control of the fluid characteristics as the hole is advanced. The basic mud program will be approximately as follows:

a. from 0 to 1100 feet, drill with a bentonite and fresh water mud with a weight of 8.6 to 9.0 pounds per gallon, a viscosity of 28 to 32 seconds per quart, and a pH maintained between 9.5 to 10.5 by the use of lime

b. at 1100 feet, flush out the mud completely, clean the system and ponds

c. from 1100 to 2400 feet, drill with a salt gel and saturated brine, with a weight of 10.0 to 10.4 pounds per gallon, a viscosity of 28 to 32 seconds per quart, and a pH maintained between 10.5 and 11.5 by the use of lime.

4. ABILITY TO PREVENT HYDROFRACTURE OF THE TARGET HORIZON

Hydrofracture refers to a condition of rock failure surrounding a borehole, caused by the fluid pressure within the borehole exceeding the minor principle stress in the rock mass. In the simplest view of the matter, hydrofracture should not occur unless the mud weighs more than the rock, or the mud is pressurized. However, hydrofracture has been known to occur at fluid pressures less than total overburden pressure. This leads to a potential concern that hydrofracture might occur near to the target stratum, compromising the integrity of the host salt. Hydrofracture of strata well above the target stratum is not considered to be detrimental.

In the drilling of the Exploratory Shaft, this matter will be the concern of the mud engineer only, as the drllling fluid will not be pressurized at any time. To resolve the hydrofracture issue, it is necessary to demonstrate that the fluid pressure in the hole as drilling approaches the target stratum is less than the expected minor principal stress.

By returning to the previous mud data, we observe that the maximum mud weight is expected to be 10.4 pounds per gallon, or 78 pounds per cubic foot. The unit weight of the lightest rocks expected to be encountered (salt) is about 135 pounds per cubic foot. The heaviest rocks anticipated to be encountered (dolomites) may weigh as much as 165 pounds per cubic foot.

Assuming that the minor principal stress (assumed to be horizontal) is approximately 95% of the major principal stress (assumed to be vertical), and that the vertical stress is due to an average rock density of 150 pounds per cubic foot, then the minor principal stress will increase with depth by about 142 pounds per foot. The mud pressure increases with depth at the rate of only 78 pounds per foot, thus the mud pressure should remain at only about 55% of the minor principal stress throughout the hole.

It becomes evident that the prevention of hydrofracture is not so much a technical concern as it is concern over quality assurance. ONWI and the construction manager will place heavy emphasis upon the quality control, monitoring, and documentation associated with the mud program during drilling.

or Review and Approval

	Name	Initials	Date
Originator	GE Raines	GER	10/28/83
Concurrence	JF Kircher	GER for	10/28/83
Approved	WM Hewitt	[illegible]	10/28/83

BMI/ONWI- XXX

No.

Internal Distribution

NE Carter
S Goldsmith
WA Carbiener
WM Hewitt
JF Kircher
RS Kingsley
GE Heim
SC Matthews
MA Glora
JR McDowell
OE Swanson
SJ Basham
DE Clark
TM Solack
G Jansen
EG McNulty
AB Gureghian
SK Gupta
GE Raines
ONWI Files
LB
DP Moak
MA Balderm
SS Nelson
MJ Conroy

October 31, 1983

J. O. Neff, Program Manager, NPO

NPO MILESTONE #133H337 - LETTER REPORT ON SEAL PERFORMANCE REQUIREMENTS TO NPO

The enclosed report, "A Preliminary Study of Performance Characteristics of a Generic Seal System at the Richton Salt Dome" was prepared to address this milestone as potential input to the establishment of seal system requirements. The analysis was performed using a generic conceptual shaft seal system design, a resistance network flow model, and estimates for site parameters. As such, the results are considered to be preliminary and will be updated as more information concerning site parameters and seal system design are available. The report concludes that seal performance is primarily dependent upon the permeability of the "affected zone" and less so on the width of the affected zone and the permeability and length (thickness) of seal components. Travel times from the base of the shaft to the top of the caprock are well in excess of 1,000 years unless the permeability of the affected zone is increased over its baseline value by about a factor of 1,000 or more. In addition, thermal buoyancy was evaluated and found not to impact performance.

We plan to incorporate any comments DOE provides and the results of peer review prior to issuance of this report as an ONWI report. Following completion of these reviews, we will evaluate the implications of this report's results on shaft system design requirements and construction specifications. You may contact Dr. G. E. Raines for discussion of this report or to provide comments.

Original signed by
Wayne A. Carbiener 10/31/83

Stanley Goldsmith
Director

SG:GER/rb

In triplicate

Enclosure

WBS 1.3.3

PRELIMINARY STUDY OF PERFORMANCE CHARACTERISTICS OF A GENERIC CONCEPTUAL SEAL SYSTEM AT THE RICHTON SALT DOME

NPO MILESTONE 133H337

By

A. B. GUREGHIAN AND G. E. RAINES

ABSTRACT

The performance assessment of a typical (or conceptual) shaft seal system of a high-level waste repository at the site of the Richton Dome in south-eastern Mississippi is presented. An analysis of the movement of water in the shaft seal system was performed. Flow resulted from an arbitrarily imposed hypothetical potentiometric head applied at the level of the repository horizon. A zone extending radially from the shaft into the adjacent rock was assumed to be damaged by construction and was defined as the "affected" zone. These assumptions enabled the evaluation of the impact of the material and hydraulic properties of the prospective seals and the affected zone on relative ground-water flow movement through the pathway of interest. Furthermore the probability of occurrence of thermally induced fluid convection resulting from the heat load generated by the waste form at the repository level was also investigated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Salt domes within the USA are being considered as potential nuclear repository sites for solid HLW. The Richton Dome located in southeastern Mississippi or considered in this report.

The shaft seal system is an important component of the engineered barriers of an HLW repository whose objective is to prevent or delay ground-water contact with the waste form or, in the context of this analysis, to limit the prospective rate of releases of radionuclides to peripheral bodies of water. A generic conceptual seal system, i.e., containing typical seal components, was used for this study.

Seal designs must address three potential pathways for fluid flow (see Fig. 1): the plug (or seal material), the interface between the seal material and the host rock; and an affected zone (or damaged zone) in the host rock. In the context of this analysis, the affected zone has been treated as a part of the host rock with a permeability exceeding its in situ value by several orders of magnitude.

This report provides a mathematical analysis designed to predict shaft seal performance in a salt dome. For this preliminary analysis, the geometrical configuration of the system was assumed to be unchanged by creep or dissolution of salt, consolidation of crushed salt, precipitation of anhydrite, etc. The analysis is restricted to the upward movement of the fluid through the portion of the shaft seal system stretching between the repository horizon and the base of the Hattiesburg Formation located some 410 m above it, where fluid motion is initiated as a result of an arbitrary hypothetical piezometric head imposed at the repository level. Since we are not currently aware of any credible breach scenarios, this head is assumed to result from a non-mechanistic event. Ground-water flow and travel time are calculated for the imposed hydraulic gradient and for various thicknesses and hydraulic conductivities of the seal components and affected zones.

Results from the analyses indicate that the flow rate is strongly affected by the hydraulic conductivity of the affected zone and to a lesser extent by the width of the affected zone. An increase of the hydraulic conductivity of the affected zone by one order of magnitude has more impact in promoting the flow rate than a sixfold increase of the width of the affected

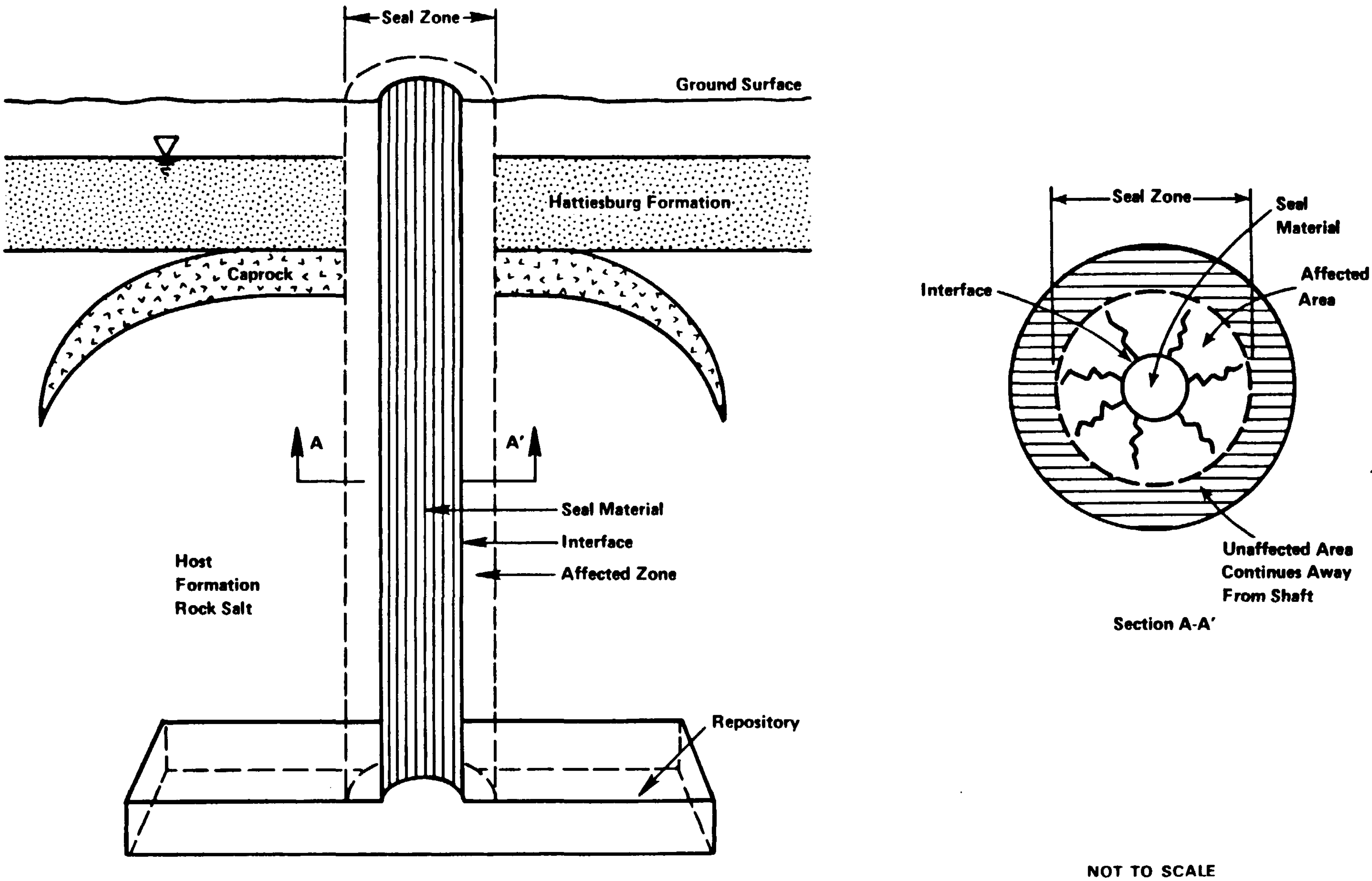


FIGURE 1. CONCEPTUAL ILLUSTRATION OF COMPONENTS OF POTENTIAL FLOW PATHS OF PERMEANT

zone. Because of the strong correlation between ground-water travel times and flow rates, the impact of a hydraulic conductivity increase is usually reflected in appreciable decreases in travel times, however the latter seem to be less sensitive to increases of the affected zone width.

The analyses of potential thermal convection (i.e., buoyancy) effects which could stimulate upward flow and hence induce a circulation of water in the shaft seal system indicate that under a hypothetical and very conservative high constant temperature of 200 C prevailing permanently at the base of the shaft, such a physical phenomenon is unlikely to be significant.

HYDROGEOLOGY OF RICHTON DOME

The Richton Dome site lies within the southeastern part of Mississippi Salt Basin, a deep asymmetrical depression which extends northwest-southeast from northern Louisiana to southwestern Alabama (see Figs. 2 and 3.)

The Richton Dome site is situated in the Piney Woods physiographic subprovince of the Gulf Coastal Plain. Surface elevations over the dome range between 150 and 300 m above mean sea level (MSL). These elevations are typical of the nondissected areas and around the dome. Elevations at the representative site are about 250 ft above MSL.

SUPRADOME AREA

Three stratigraphic units are found over the supradome area:

- the Hattiesburg Formation
- the Citronelle Formation
- Alluvium.

The Hattiesburg Formation overlies about 50 percent of the northern and west central portion of the supradomal area and is the surficial unit at the reference site. This formation consists of silty clay with lenses of silty sand and varying minor amounts of sand.

The Citronelle Formation covers about 30 percent of the northern portion of the supradomal area as well as most of its southern and eastern portions. This formation consists of coarse to fine sands with lenses and interbeds of silt, silty clay, and clay. Gravelly sand occurs near the base of the Citronelle, and ponds and lenses of gravel are found throughout the unit.

Alluvial deposits are encountered on the western side of the dome.

CAPROCK

A detailed description of the caprock core description is given in ONWI-277 (Drumhuller et al, 1982). In borehole MRIG-9 (Figs. 4a-4b), the top 23 feet of the caprock consisted of vuggy, banded calcite. This section is very fragmented and jointed. Core recovery in the calcite zone was reported to be less than 50 percent. The central portion of the caprock, some 190 ft thick,

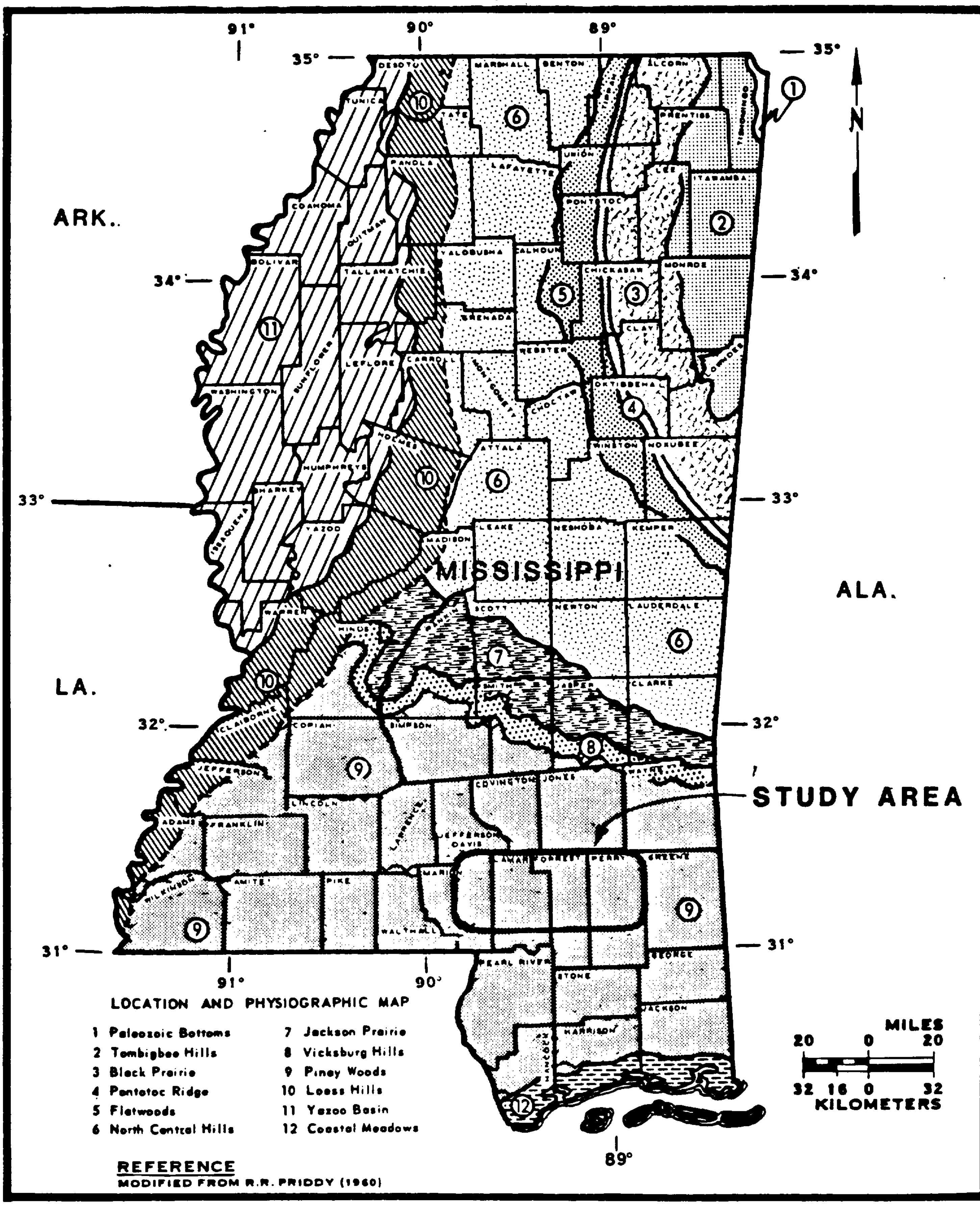


FIGURE 2. PHYSIOGRAPHIC MAP

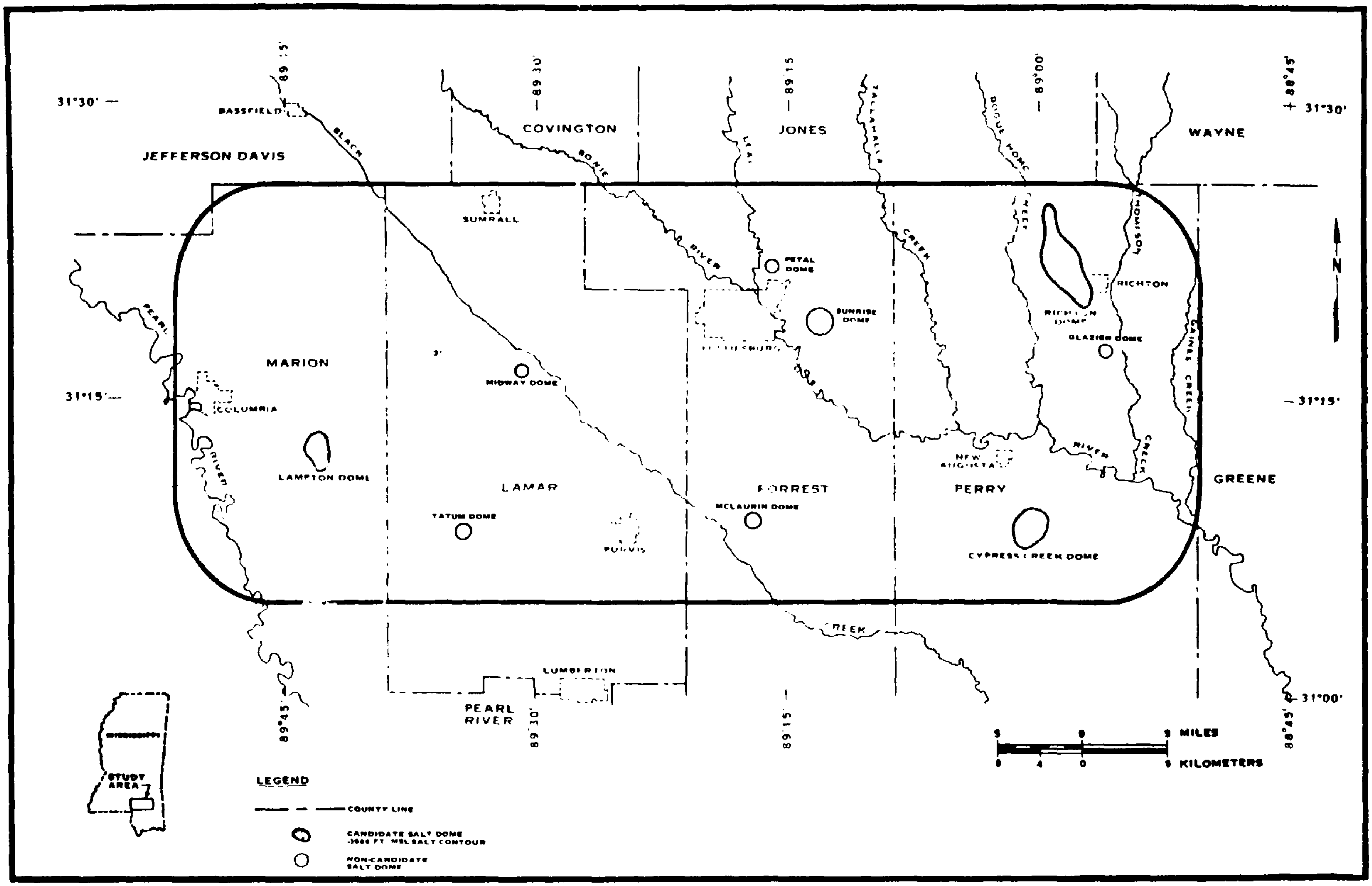


FIGURE 3. LOCATION MAP

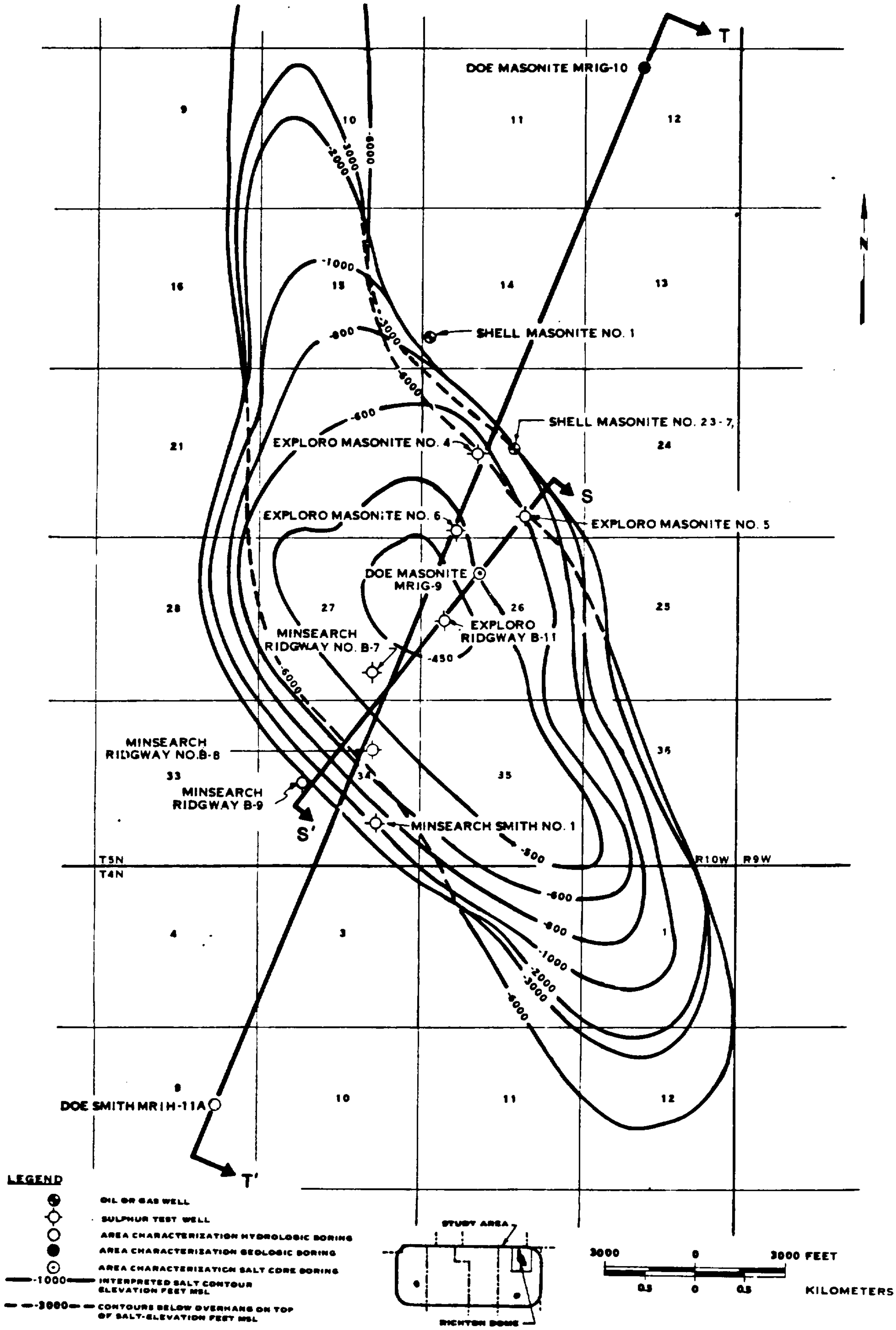


FIGURE 4a. BOREHOLE LOCATIONS OVER DOME AREA

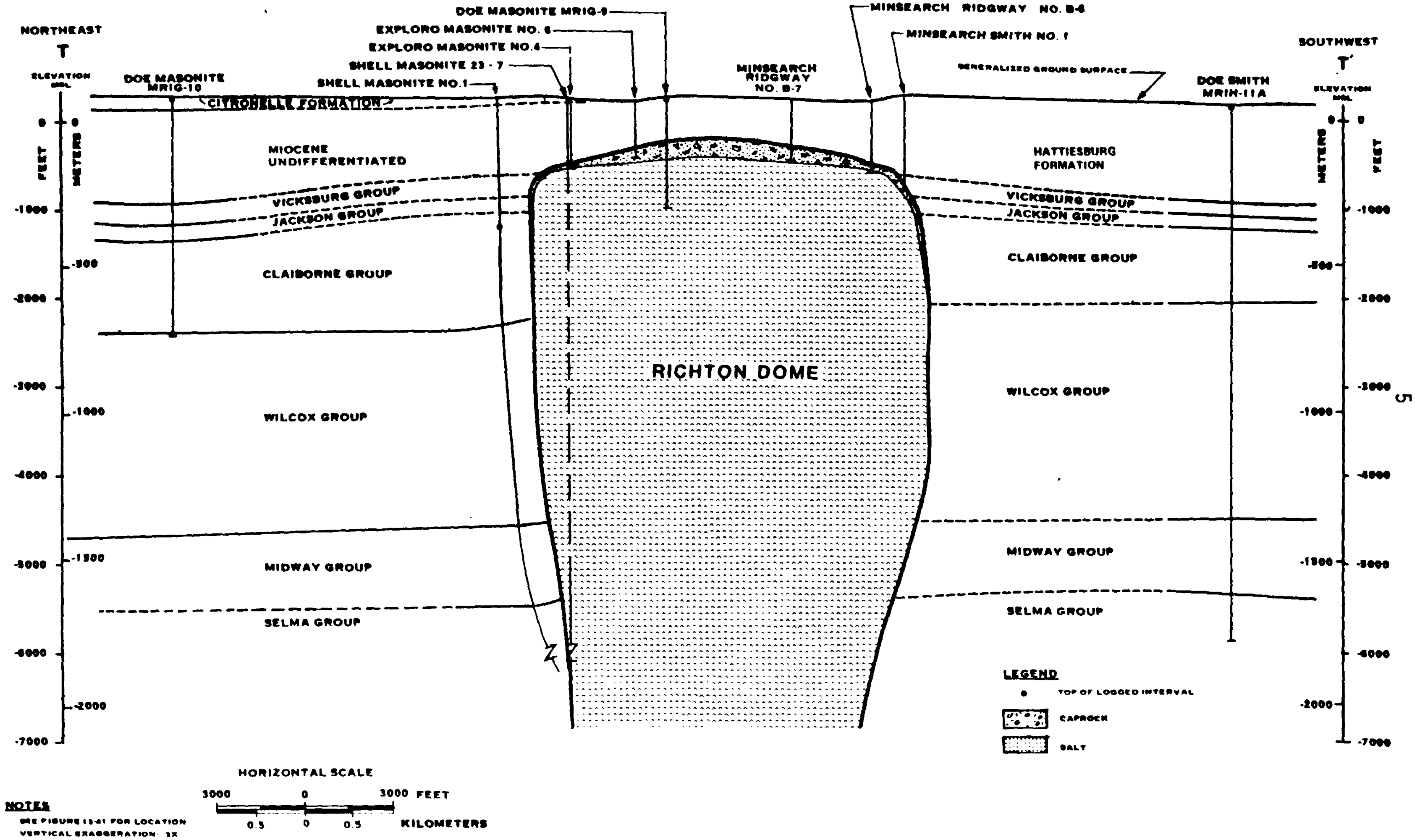


FIGURE 4b. BOREHOLE LOCATIONS ON CROSS SECTION OF DOME AREA

is composed of anhydrite with gypsum with minor (less than 2 percent) native sulphur and calcite. The lower portion of the caprock stretching down to the salt (5 ft) is composed of anhydrite sand thus making a transition between the two geological units.

SALT

The salt encountered in borehole MRIG-9 consisted of fine to coarse equidimensional prolate halite with an anhydrite zone in the upper 6 ft. Anhydrite was found to comprise, on the average, less than 10 percent of the salt core samples, occurring as bands, disseminated grains, or distinct inclusions, as reported in ONWI-277 (Drumheller et al, 1982).

The advantage of using salt as a prospective medium for the burial of high-level waste is not only confined to its quasi-impermeable nature but also to a physical property inherent to such a plastic material, i.e., its plastically healing property under the influence of confining pressure and temperature (Shor et al, 1982). However, it is important to minimize the contact of water with the salt. Consequently, an important seal location occurs at the interface of the caprock and the overlying water-bearing formation. This seal is required to prevent communication of water from the upper portion of the caprock to the salt caprock interface, as well as to provide a second major barrier against nuclide migration.

FLUID MOVEMENT THROUGH THE SHAFT SEAL SYSTEM

The primary function of the shaft seal design at a typical site will be to prevent water inflow into the repository. Assessment of the natural processes and events operating at Richton have yielded no credible breach scenarios. However, for the purposes of this analysis, a non-mechanistic event is assumed where water has intruded and brought the entire shaft seal system to a state of complete saturation. Physical processes may perturb the system and hence initiate the flow of fluid from the repository to the biosphere via the shaft seal system. In this case, the function of the shaft seal system would be one of minimizing the amount of radionuclide releases to the biosphere. In addition some thermally induced convection of fluid may be anticipated during the first few hundred years after decommissioning.

The analysis of steady flow of fluid through the seals requires a prior knowledge of a set of input parameters which include the following:

(1) the hydraulic conductivity, porosity, thermal conductivity, and specific heat capacity of the various sealing materials

(2) the thickness of the various seals

(3) the extent and the range of permeability variation of the affected zone

(4) the depth of the repository from the base of the Hattiesburg Formation

(5) the hydraulic and temperature gradients prevailing between the base of the shaft and the overlying aquifer.

In order to perform this analysis some assumptions were made;

- An arbitrary hypothetical driving force was imposed at the level of the repository horizon expressed in terms of a hydraulic gradient to permit sensitivity analyses.
- The steady flow of fluid from the repository level to the base of the Hattiesburg Formation is confined within a pair of streamlines or stream tube where the cross-sectional area normal to the direction of flow is assumed constant.
- The portion of the shaft at the interface of the caprock and the Hattiesburg formation was assumed to be at the same hydrostatic pressure as the aquifer itself.
- The interface was assumed to form an integral part of the affected zone.
- The porosity variations owing to changes of the permeability of the various sealing materials were assumed to vary according to the Kozeny-Carman equation (Kozeny, 1927; Carman, 1937). Bulk Density variations were inherent to the latter.
- The average permeability of the whole system was assumed to obey the relations obtained from standard analysis of flow in stratified solids in series or in parallel. Morever the permeability was assumed to be isotropic at any point.

- The average porosity of the whole system was assumed to comply with some statistical averaging procedures, namely weighted arithmetic mean, weighted geometric mean, and weighted harmonic mean.
- The geometrical configuration of the system was assumed to be unchanged by creep or dissolution of salt, consolidation of crushed salt, precipitation of anhydrite, etc.

THEORY

The laminar flow of liquid in a porous media is governed by Darcy's law (Darcy, 1856) written as

$$Q = - AK\nabla\Phi \tag{1}$$

where the vertical component of the specific discharge is defined as

$$v = - \frac{k}{\mu}\left[\frac{\partial p}{\partial z} + \rho_f g\right] \tag{2}$$

Under nonisothermal flow conditions an additional equation is required,

$$\rho_f = \rho_{f_o} \left[1 - \beta \left(T - T_o\right)\right] \tag{3}$$

which is the equation of state. In these equations the symbols are defined as

ρ_f is fluid density
ρ_{f_o} is fluid density at reference temperature
Φ is total head ($p + \rho_{fo} gz$)
K is hydraulic conductivity ($k\rho_f g/\mu$)
k is intrinsic permeability
T is absolute temperature
T_o is absolute reference temperature
p is fluid pressure
μ is fluid viscosity
β is volumetric thermal expansion coefficient of fluid

g is acceleration of gravity

A is cross-sectional area normal to the direction of flow

Q is volume rate of flow

v is Darcy velocity

z is vertical ordinate

∇ is gradient operator.

Subscripts f and s denote the fluid and solid media (within the framework of a representative volume of a saturated porous media) respectively.

Note that in Eq. 3 the influence of pressure and concentration on the fluid density have been omitted on conservative grounds.

Consider a vertical tube filled with porous material resting on a horizontal surface and saturated by a homogeneous liquid (see Fig. 5). The vertical side is thermally insulated (e.g., adiabatic) and the lower (z = 0) and upper (x = L) boundaries are isothermal. Temperature T_1 at the bottom is greater than T_0 at the top and lateral boundaries are impermeable to fluid.

Initially the system shown in Fig. 5 is assumed to be in static equilibrium, so that the pressure is hydrostatic thus we have

$$v_o = 0 \; ; \; T_o = T_1 + \frac{(T_o - T_1)z}{L}. \tag{4}$$

Under these conditions the system is said to be "statically stable". If one is to determine whether the system is "dynamically stable" (i.e., whether any disturbance caused by a temperature gradient will generate discernible convective currents) the complete solution of this problem becomes beyond the scope of this work; however, we shall restrict our investigation to the minimum temperature gradient and average permeability required to initiate a convective current. Introducing the following nondimensional parameters

$$v^* = \frac{vD}{\alpha} \; ; \; T^* = \frac{T-T_o}{T_1-T_o} \; ;$$

$$\Phi^* = \frac{\Phi k_o}{\mu\alpha} ; \; \mu^* = \frac{\mu}{\mu_o} \; ; \; k^* = \frac{k}{k_o} \tag{5}$$

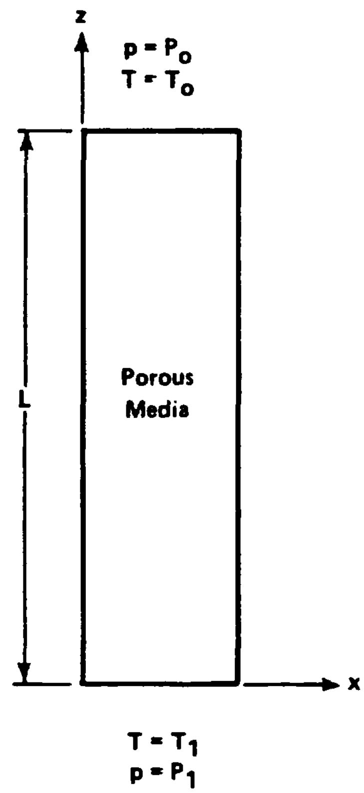


FIGURE 5. CROSS SECTION OF A VERTICAL TUBE FILLED WITH POROUS MATERIAL

where α is average thermal diffusivity, $\Gamma_m/(c\rho)_m$

Γ_m is average thermal conductivity, and

$(c\rho)_m$ is average volumetric heat capacity.

Γ_m and $(c\rho)_m$ are defined as (see Green, 1963)

$$\Gamma_m = \Gamma_f\phi + \Gamma_s(1-\phi) \tag{6}$$

$$(c\rho)_m = \rho_f c_f \phi + \rho_s c_s\ (1-\phi) \tag{7}$$

where Γ, c, and ϕ denote the thermal conductivity, specific heat capacity, and porosity respectively and subscripts f and s refer to solid and fluid media.

Dropping the superscripts, Eq. 4 may now take the following form

$$v = -\frac{k}{\mu}\frac{\partial\Phi}{\partial z} + \frac{k}{\mu}\,RaT$$

where Ra is the Rayleigh number, a dimensionless quantity (see Wooding, 1958) written as

$$Ra = \frac{k_o \rho_o \beta g \Delta T L}{\mu\alpha} \tag{9a}$$

In Eq. 8 it may be noticed that in addition to the potential gradient term which under isothermal conditions is the main fluid driving force, the second member on the right hand side of this equation resulting from buoyancy forces may contribute to the overall movement of the fluid, provided R_a is above its critical value Ra_c.

For a tall cylindrical tube with low aspect ratio (i.e., diameter of tube/length of tube) Bau and Torrance (1982) redefined a Rayleigh number in the form

$$\bar{Ra} = \frac{k_o \rho_o \beta g \quad (-\partial T/\partial z) D^2}{\mu \alpha} \tag{9b}$$

where D is the diameter of the tube.

The value of Ra_c mathematically derived by Horton and Roger (1945) and Beck (1972) corresponds to $4\pi^2$ (i.e., for Eq. 9a) whereas the one pertinent to Eq. 9b was found experimentally to correspond to 13.56. At first sight the latter value seems to be the more conservative of the two, yet the ratio of these two equations, i.e., $[\Delta TL/(\partial T/\partial z)D^2]$ shows that Eq. 9a yields a larger number for our system. Therefore Eq. 9a with its associated critical Rayleigh number should be considered as the criterion for the evaluation of the thermal convection effects.

Permeability - Porosity Relationship

Permeability and porosity for a given medium are closely related to each other. Indeed a reduction of the porosity due to an increase in the confining pressure is reflected in a drop in permeability.

A well-known relationship given by Carman (1937) and Kozeny (1927), i.e. the Kozeny-Carman equation, has been used in this work to correlate permeability and effective porosity. This equation is written as

$$k = A \frac{\phi^3}{(1-\phi)^2} \tag{10}$$

where A is a coefficient depending upon the shape of the porous cross-sectional area, the tortuosity factor of the sample, and the specific surface area of the porous matrix. For all practical purposes A may be assumed a characteristic constant of a soil or rock specimen.

Permeability of Crushed Salt

Laboratory test results relating permeability of salt crystal aggregate to porosity and crystal size are reported by Shor et al (1981). The latter have shown that the permeability is function of the particle size and the void ratio (i.e. $\phi/(1-\phi)$) which in turn is assumed to depend on temperature and stress. Since the last two physical factors have been overlooked in this work, the porosity-permeability relationship used here was based on one derived by D'Appolonia (Kelsall et al, 1982, ONWI-405) through a regression analysis correlating these two parameters based on experimental data from Shor et al (1981) and others:

$$k = D\ 0.0178 \exp(21 + 6 \ln \phi) \tag{11}$$

where k is the permeability expressed in (darcies)* and D is the average particle diameter (0.34 cm). Because the pore velocity depends on the porosity, i.e.

$$V = \frac{v}{\phi} \tag{12}$$

which in turn enables one to predict the travel time of a particle moving along a streamline, therefore strong emphasis was given to the evaluation of porosity in a heterogeneous system like the one considered herein.

Evaluation of Porosity

In the course of our investigations the permeabilities of the various sealing materials were hypothetically increased. Consequently for each material other than salt, the corresponding porosity was calculated using

*(1 darcy = 9.87×10^{-9} cm^2)

Eq. 10 with the assumption that the variations of the constant A were small enough so that one could write

$$\frac{k_1}{k_o} = \frac{\phi_1{}^3}{(1-\phi_1)^2} \bigg/ \frac{\phi_o^3}{(1-\phi_o)^2} \tag{13}$$

where subscripts zero and one refer to the baseline and inflated values respectively. Eq. 13 is a cubic in ϕ and the root of interest is found by Newton's method. Note that when the value of k is particularly low, (i.e., less than 1 md or 10^{-6} cm/sec), ϕ is very much less than one. Then Eq. 13 may be reduced to

$$\frac{k_1}{k_o} = \left(\frac{\phi_1}{\phi_o}\right)^3 \tag{14}$$

Laboratory data for crystalline rock samples reported by Norton and Knapp (1977) seem to fit this kind of approximation. As far as salt was concerned the related porosity was calculated based on Eq. 11. Thus having outlined the methodology used for the porosity evaluation of a typical material when its permeability is subjected to variations, there remains the task of evaluating the average porosity of a composite or nonhomogeneous porous medium.

Because of the large variations in the porosity values, the estimation of this parameter necessitates a set of empirical models which bear some relevance to the well-established physical averaging procedures for estimating the mean permeability (see below) of a nonhomogeneous flow system, in order to obtain a credible upper and lower bound of the travel time.

a) weighted arithmetic mean

$$\bar{\phi}_a = \sum_{i=1}^{n} \phi_i \frac{A_i}{A} \tag{15a}$$

where A_i/A is the fractional area of a typical cell with porosity ϕ_i and n is the total number of cells within the area of interest A. Note that the mass of fluid with density ρ_f equal to unity present within a representative elementary area A_o of a saturated porous material may be written as ϕA_o.

b) weighted geometric mean

$$\phi_g = \phi_1^{\frac{A_1}{A}} \quad \phi_2^{\frac{A_2}{A}} \quad \ldots\ldots\ldots \phi_n^{\frac{A_n}{B}} \tag{15b}$$

c) weighted harmonic mean

$$\bar{\phi}_h = \frac{A}{\sum_{i=1}^{n} \frac{A_i}{\phi_i}} \tag{15c}$$

Evaluation of Permeability

Effective stress in a porous medium produces deformation which affects the void ratio and consequently alters its permeability (see Terzaghi and Peck, 1967). Usually for a given material the permeability decreases with depth. Anisotropy is another important factor which deserves some attention particularly in the caprock and affected zone where the horizontal permeability in the preferential direction of the fractures (i.e., horizontal direction) will exceed the vertical permeability. However the method of analysis adopted in this work, which is essentially one-dimensional, overlooks this particular type of permeability variation.

The derivation of one continuous value of permeability may be determined by two averaging procedures pertinent to the case. In Case A, the flow system is comprised of layers of porous materials separated from one another by infinitely thin, impermeable (i.e., parallel combination of beds) barriers. In this case the average permeability may be written as

$$\bar{k} = \frac{\sum_{i=1}^{n} k_i d_i}{\sum_{i=1}^{n} d_i} \qquad (16a)$$

where d_i is the thickness of a particular bed. In Case B, the flow system is comprised of layers of porous materials in series, and the average permeability may be written as

$$\bar{k} = \frac{L}{\sum_{i=1}^{n} \frac{L_i}{k_i}} \qquad (16b)$$

It may be noted that permeability of a porous medium, as an intrinsic property of the medium, is a function of the effective grain diameter and is not influenced by the properties of the permeant except in the case of a plastic material like rock salt which will deform under the influence of temperature. Hydraulic conductivity (kg/γ) takes into account the kinematic viscosity (i.e., $\gamma=\mu/\rho$) of the fluid (water or brine) along with the intrinsic properties of the medium that defines its permeability. Hydraulic conductivity is a more appropriate index than intrinsic permeability in the context of the resistance network analysis as used here, since the parameters which constitute it are lumped into it. Consequently, the range of variations used for K in our parametric study of the shaft seals performance is supposed to embody the ones related to each one of its components.

Properties of Host Media

The portion of the host media relevant to our analysis (i.e., the one stretching between the base of the Hattiesburg Formation and the prospective repository horizon, see Fig. 5) consists essentially of the salt dome and a caprock overlying the latter. The main parameters of interest which will be influencing the flow rate and the travel time through the shaft seal system are the porosity, the permeability, and the thermal conductivity. A short review of the data extracted from the literature for these parameters is presented below.

Porosity

The porosity of intact rock salt is normally less than one percent; however it is expected that at the salt caprock interface porosity may be higher due to natural causes or resulting from drilling dissolution.

Porosity values from rock salt from various areas of the Midwest and Southeast of the U.S. are given in Table 1.

Table 1. Porosity of Rock Salt (ONWI-355)

ϕ%	Location	Reference
1.71	Grand Saline Dome, Texas	Ode' 1969
0.59	Hutchinson Dome Texas	Ode' 1969
0.1-0.8	Southeastern, New Mexico	Sandia Lab, 1978
8.59*	Tatum Dome Mississippi	U.S. Corps of Engineers, 1963

(*) caused by high degree of fracturing

Caprock porosity has not yet been determined as such, since a detailed examination of the porosity is complicated due to the non-homogeneity of its structure (Karably et al, 1983). It is, however, believed that the porosity is relatively high in the upper portion of the caprock owing to the highly brecciated nature of this geologic unit. Porosity data obtained for Oakwood Dome as reported by Kreitler and Dutton (1981) seem to indicate that this ranges between 1.3 and 13.0 percent in the upper calcite zone and drops within a range of 0.8 to 3.3 percent in the anhydrite section.

Permeability

Permeability of domal salt in its undisturbed state is so low that its measurement may present difficulties (Acres American, 1977). A characteristic feature of salt is its self-healing property, i.e., the permeability of a disturbed sample may recover its in situ value when subjected to a confining pressure on the order of its original in situ stress.

Permeability values for rock salt are given in Table 2. Note that the data reported for Tatum Dome were deemed to be too high compared to data from petrographic studies; this discrepancy might have been caused by the testing and handling procedures.

Table 2. Permeability of Rock Salt (ONWI-355)

k millidarcy (md)*	Location	Reference
5×10^{-5}	Southeastern, New Mexico	Sandia, Lab, 1978
6.01	Tatum Dome Mississippi	U.S. Corps of Engineers, 1963
7.3×10^{-3}	Gulf Coast	Battelle Northwest Lab, 1980

* 1 md = 10^{-6} cm/sec

By contrast to the rock salt the permeability of the caprock is relatively high owing to the presence of fractures. Laboratory measurements of samples collected at Oakwood Dome (Krietler and Dutton, 1981) indicate that the permeability ranges between <0.01 and 43 md. Generally speaking the permeability decreases with depth and at the transition zone the reported vertical and horizontal permeability ranges between 0.29 md and <0.01 md.

Those areas where permeabilities are the highest, the uppermost portion of the caprock where faulting, brecciation and dissolution features are dominant, and the caprock-salt interface where anhydrite sand and solution features enhance fluid flow, are the most likely locations of aquifer zones in caprock. Pump-test data reported from well MRIG-9 at the Richton Dome (see Karably et al, 1983, ONWI-355) gave hydraulic conductivity values of 2.8×10^{-4} cm/sec (280 md) and 1.74×10^{-6} cm/sec (1.74 md) for the caprock and salt-caprock interface zone respectively.

The disproportion between laboratory and field data suggests that the latter seem to have yielded ultra conservative values and cannot be representative of the entire caprock property as such, where most of the material present there (85% of the total volume) is anhydrite, which is known to have a rather low hydraulic conductivity of 10^{-8} cm/sec (0.01 md) if unfractured. Given those facts and for the purpose of our study, the baseline value of the hydraulic conductivity for the entire caprock was assumed to correspond to 10^{-6} cm/sec (1 md).

Thermal Conductivity

Table 3 gives a tabulated list of thermal conductivities on for salt, caprock, and other candidate materials for the shaft seals.

Geologic Consideration

Fig. 6 shows a very simplified stratigraphy of the Richton Dome at the shaft location. The typical shaft will be sunk through 169 m (554 feet) of sediment of the Hattiesburg Formation, 65 m (213 feet) of caprock, and 345 m (1132 feet) of salt (Stearns-Roger, 1983).

The Hattiesburg Formation consists of interbedded sand and clay with minor amounts of mudstone, siltstone, and lignite. The water table is about 32 m below the ground surface.

The caprock (Fig. 7) is composed of vuggy banded calcite in the upper portion 7 m (23 ft) and anhydrite below. The anhydrite contains numerous gypsum veins and zones. Limited zones of the caprock are fractured or brecciated. A 1.5 m (5 ft) zone of anhydrite sand is present at the salt-caprock contact.

Information about the character of the salt within the dome is limited because only one core hole has penetrated the dome to a distance of 150 m (500 ft). The salt encountered was predominately crystalline halite (90 percent) with disseminated bands of clasts and anhydrite.

Table 3. Thermal Conductivities of Selected Materials

Type of Material	Thermal Conductivity $W{-}m^{-1}{-}^{o}K^{-1}$	Reference
Salt*	7.11	Guyod , 1946
Rock Salt*	3.35 - 6.28	Clark , 1966
Oklahoma	5.33	Clark , 1966
Carlsbad, N.M.	5.33	"
Michigan	5.55	"
Caprock		
Louisiana	5.73	"
Carlsbad, N.M.	5.4	"
Anhydrite	2.72	"
Concrete	0.63	Guyod , 1946
Gypsum	1.26	Gudsow , 1970
Soil		
Clay	0.24	"
Silty Loam	0.37	"
Sandy Loam	0.33	"
River Sand	0.27	"

*Thermal Conductivity of Salt decreases moderately with a temperature increase.

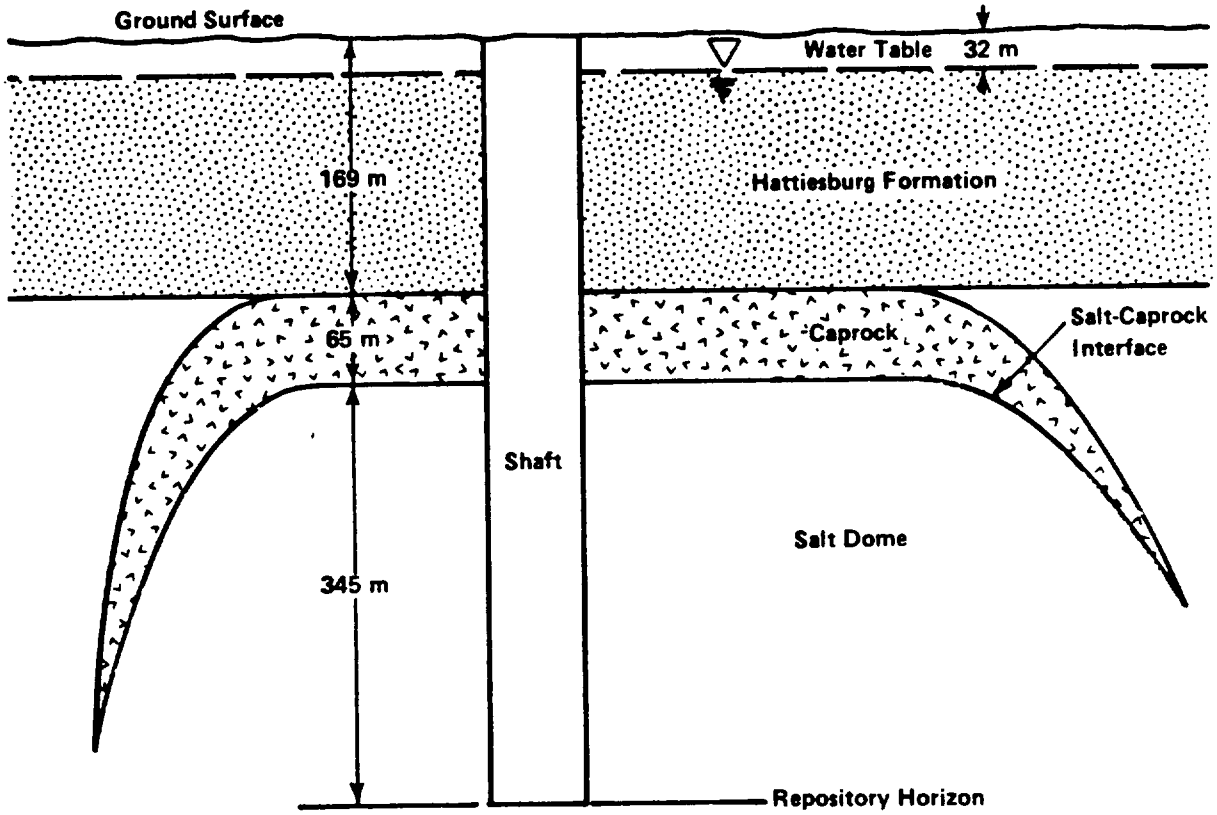


FIGURE 6. RICHTON DOME STRATIGRAPHY (Not to Scale)

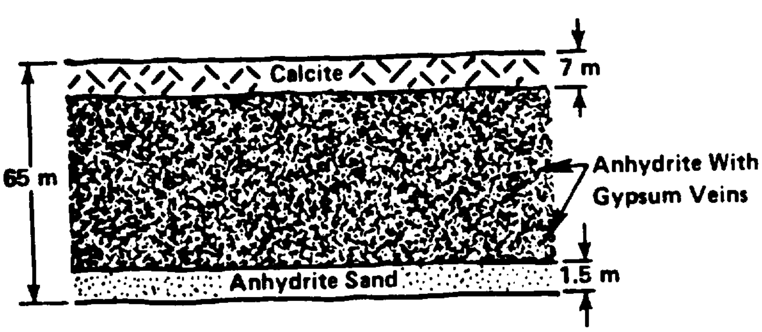


FIGURE 7. CAPROCK STRATIGRAPHY (Not to Scale)

Affected Zone

The affected (or damaged) zone (see Fig. 1) which is encountered in the shaft well is induced by the drilling operation and stress relaxation effects and is considered as a potential flow path around the plug (D'Appolonia, 1980, ONWI-55). The testing techniques used to evaluate damage zone characteristics due to drilling are based on visual inspection of the zone and the evaluation of the rock strength within the damaged zone. Experimental work carried out at the University of Arizona (Daemen, et al, 1982; Mathis and Daemen, 1982) on granite samples has shown that the damage caused around a hole by drilling was independent of the hole diameter; furthermore, the damaged zone flow can be incorporated with flow along the plug-rock interface and considered as one flow path.

The other major cause to the creation of an affected zone around a circular opening may be attributed to the loosening of crystal fabric in response to stress relief. Kelsall et al (1982) report in ONWI-411 that laboratory data related to the effects of crystal loosening suggested that the increase in permeability is unlikely to exceed one order of magnitude.

A review of field studies conducted in salt mines indicates that blast damage is generally confined to within 1 to 1.5 m of a tunnel face (Golder, 1977; Acres, 1977).

RESULTS AND DISCUSSION

In order to assess the performance of a typical shaft seal system, a scenario is formulated wherein hypothetical potential and temperature gradients are assumed to prevail permanently between the upper and lower boundaries of the system, i.e., the base of the shaft and the interface between the caprock and the overlying aquifer. Note, however, that each of these factors, which are known to promote fluid flow out of the repository, were investigated independently of each other. These factors, potential and thermal gradients, are related to hydrcdynamic forces and buoyancy effects respectively.

As mentioned earlier in this report, the key parameters governing the potential flow of fluid through the shaft seal system which conforms to the above scenario include the magnitude of the potential and temperature gradient, the hydraulic conductivity, porosity, thicknesses of the various sealing materials, and the width of the affected zone. Considering those facts a parametric study was performed in order to assess the sensitivity of the system to each one of these parameters. However, the reader must be warned that the quantitative results reported in this section must be interpreted with caution as the dynamic analysis which involves the flow rates and travel times result from the arbitrarily imposed potential gradient.

INPUT PARAMETERS

The shaft seal system chosen for this analysis and shown schematically in Fig. 8 includes the following components:

- Two bulkheads; the first located at the interface of the Hattiesburg Formation and the caprock, and the second at the interface of the caprock base and the salt dome. These are known to be very sensitive locations for potential water intrusion from the overlying aquifer. The bulkheads are cylindrical concrete structures composed of low permeability materials keyed into the walls of the shaft specially intended to prevent water inflow through the affected zone as well as the seal host interface. In the baseline case the bulkheads are assumed to give an effective areal cutoff of 50 percent relative to the width of the affected zone.

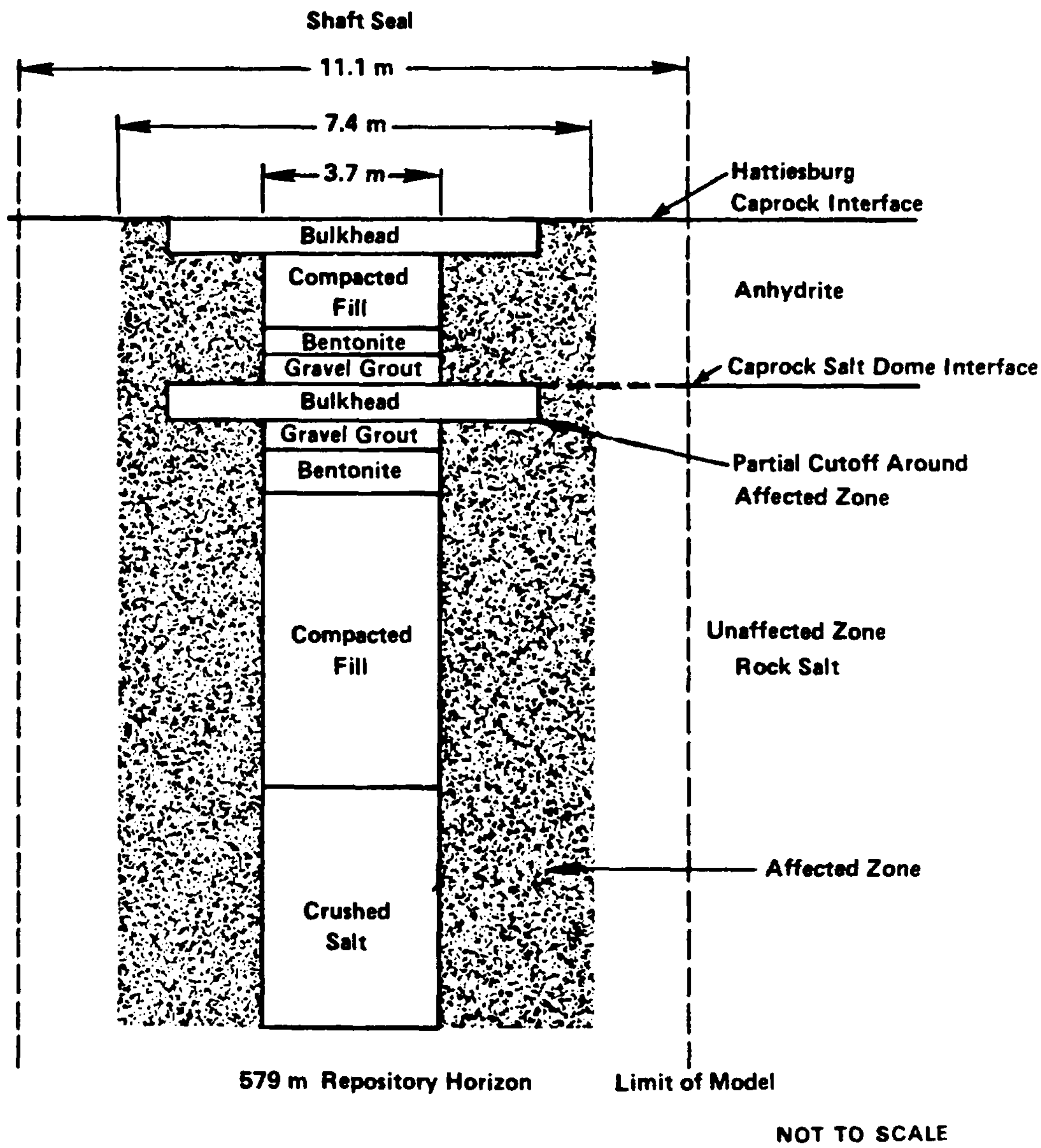


FIGURE 8. MODEL FOR SHAFT SEAL PERFORMANCE ASSESSMENT

- Gravel grout and bentonite are placed in the shaft above and below each of the bulkheads. These backfill components are high-density, low-permeability materials and are meant to provide a low interface permeability while tending to deflect the bearing stresses away from bulkheads.
- Compacted fill is an earth backfill composed of sand and gravel mix with a large clay component and possibly a small amount of cement. It is particularly designed to assure longevity and in terms of its sorptive properties to provide an adequate buffer zone to potential radiouclide migration.
- Crushed salt fills the lower portion of the shaft.

The summary of values for input parameters used in this analysis is reported in Tables 4 and 5. Base case values chosen are not necessarily typical but could probably be achieved with careful attention to techniques and quality control. The characteristics of the model geometry as indicated in Figures 6 and 8 are given in Table 6.

All analyses were performed for three cases; i.e., where the hydraulic conductivity of the affected zone (Kd) was allowed to vary by one, two, and three orders of magnitude greater than that of undisturbed salt (Ku) in the host rock and the anhydrite in the caprock.

METHOD OF ANALYSIS

A rigorous solution of this problem requires the steady-state solution of Laplace's equation which is usually obtained through the use of some well-known numerical method (e.g., finite-element or finite-difference). In this work a simplified electrical resistance network analysis was performed under the assumption that the flow through the pathway of interest is unidirectional, i.e., vertically upwards.

Table 4. Summary of Input Parameters Used in Performance Assessment

	(cm/sec) Base Case Values	Range of Values
<u>Hydraulic Conductivity</u>		
Rock Salt	10^{-9}	10^{-9}
Crushed Salt	10^{-8}	$10^{-8} - 10^{-6}$
Caprock (Anhydrite-Calcite)	10^{-7}	$10^{-7} - 10^{-4}$
Bentonite	10^{-11}	$10^{-11} - 10^{-8}$
Concrete	10^{-11}	$10^{-9} - 10^{-6}$
Compacted Fill	10^{-7}	$10^{-7} - 10^{-5}$
Gravel Grout	10^{-9}	$10^{-9} - 10^{-6}$
Affected Zone	10^{-9}	$10^{-9} - 10^{-5}$
<u>Porosity</u>	%	
Rock Salt	0.62	
Crushed Salt	1.3	
Caprock (Anhydrite-Calcite)	0.3	
Bentonite	40.0	
Concrete	25.0	
Compacted Fill	27.0	
Gravel Grout	5.0	
Affected Zone	0.6	
Thickness of Affected Zone (m)	1.85	0.46 - 1.9
Percentage areal cutoff	50%	0 - 100
Diameter of Shaft (m)	3.7	
Diameter of model (m)	11.0	
Thermal Conductivity	$W\text{-}m^{-1}\text{-}°K^{-1}$	
Rock Salt	5.0	
Crushed Salt	5.0*	
Caprock	2.72	
Concrete	0.63	
Bentonite	0.3	
Compacted Fill	0.3	
Gravel Grout	0.2	

*Crushed salt thermal conductivity will actually be lower than that of rock salt prior to reconsolidation which will take place in the high temperature regions. This conductivity was assumed to avoid overcomplicating this simplified analyses.

Table 5. Physical Properties of Water (at 40°C)

Symbol	Definition	Value
ρ_f	density of water	9.92×10^{2} kg.m^{-3}
c_f	specific heat of water	4.18×10^{3} J kg^{-1} °K^{-1}
c_s	average specific heat of shaft seal system	8.8×10^{2} J kg^{-1} °K^{-1}
β	volumetric thermal expansion of water	3.85×10^{-4} °K^{-1}
μ	viscosity of water	6.53×10^{-4} kg.m.$^{-1}$sec^{-1}
Γ_f	thermal conductivity of water	6.23×10^{-1}W.m.$^{-1}$ °K^{-1}
ΔT	temperature difference	200°C

Table 6. Model Geometry and Baseline Values of Sealing Materials

Total length	410 m
Length in salt dome (zone 1)	345 m
Length in caprock (zone 2)	65 m

Baseline length of seals expressed in terms of percentage length of their respective zones:

Material Type	Symbol	% Zone 1	% Zone 2
Concrete	CC	2	2
Gravel Grout	GG	20	20
Compacted Fill	CF	71	75
Bentonite	BN	3	3
Crushed Salt	CS	4	0

The resistance network model used is shown in Fig. 9 where R_1, R_2, and R_3, denote the hydraulic resistances of a typical section of the permeant flow path, namely the sealing material, the affected zone, and the unaffected host formation respectively. The latter pair correspond either to rock salt or anhydrite depending upon the location of interest. The hydraulic resistance characteristic for each section is obtained from Eq. 16a and subsequently the total resistance of the system is then obtained by summing these in series using Eq. 16b. The imposed potential head at the base of the repository was assumed to be 41 m H_2O yielding a hydraulic gradient of 0.1.

A two-dimensional conceptualization of the prospective near-field steady-state flow pattern resulting from the prevailing potentiometric head at the repository level is shown in Fig. 10. It may be seen that the flow region of interest (i.e., through the shaft and affected zone) may be may be assumed to be bound by a pair of streamlines; see hatched region, where zone 1 refers to the portion of the shaft seal imbedded in the salt dome and zone 2 refers to

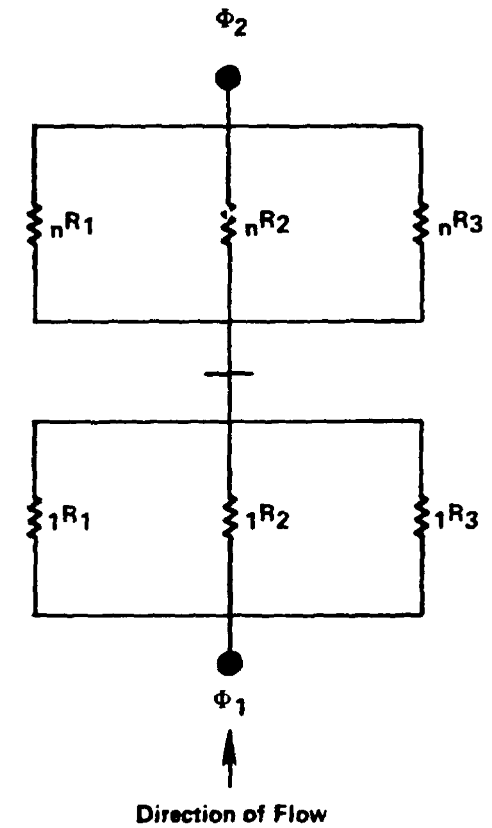


FIGURE 9. RESISTANCE MODEL USED FOR SHAFT AND PERFORMANCE ASSESSMENT

Note: Subscript 1 Refers to Sealing Material; 2 Refers to Affected Zone; and 3 to Unaffected Host Rock

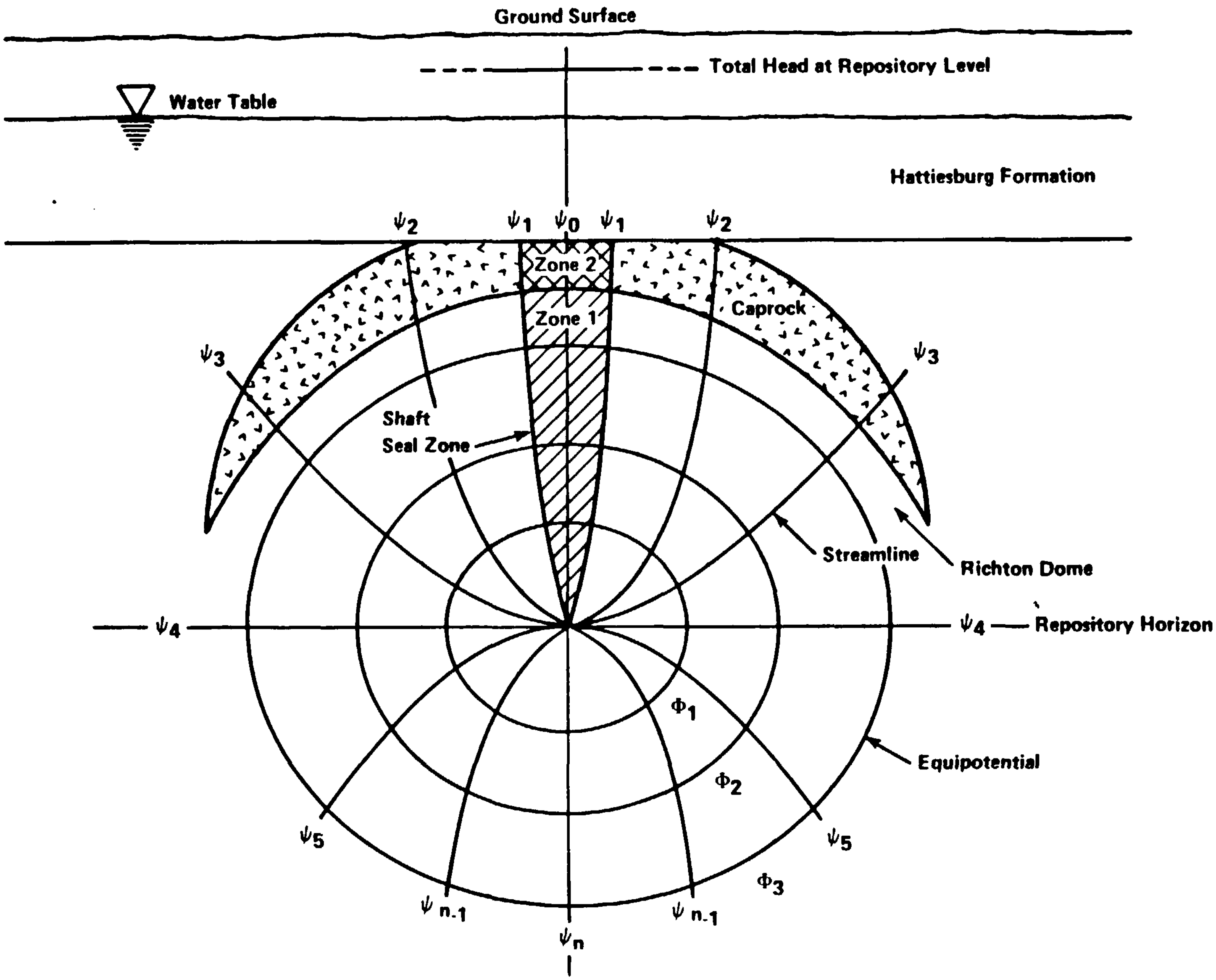


FIGURE 10. CONCEPTUAL PATTERN OF EQUIPOTENTIALS AND STREAMLINES FROM REPOSITORY

the portion lying within the caprock which dimensions may seem to vary from bottom to top. In this analysis the cross-section area of the streamtube was assumed to be constant throughout its length and its diameter was assumed to correspond to three times that of the shaft.

The time required for the flow to travel an increment of distance Δz is given by the expression

$$\Delta t = \frac{\Delta z}{V} \tag{17}$$

where V, the pore velocity, is given by Eq. 12. The total time required by the fluid particle to transfer from the base of the shaft to the top of the caprock will be the summation of the individual increments, Δt, over the given distance which in our case was approximated as follows:

$$t = \sum_{i=1}^{2} \frac{\bar{\Phi}_i Z_i}{v} \tag{18}$$

Z and $\bar{\Phi}$ are the length and average porosity of a typical zone respectively where i refers to the two zones of interest.

Base Case Analysis

In the base case analysis the properties of the sealing materials were kept constant and the only variations were those related to the permeability of the affected zone. The selection of an appropriate model for porosity (see Eq. 15) was based on the results yielded by the travel times associated to each one of these models see Fig. 11a, 11b, and 11c. In this instance the weighted geometric mean model (i.e., Eq. 15b) was retained owing to the nature of the predicted results which seemed to be fairly representative of an overall average of the results displayed by the three models.

In the absence of an affected zone, the performance of our conceptual design of the shaft seal system expressed in terms of flow rate indicate that

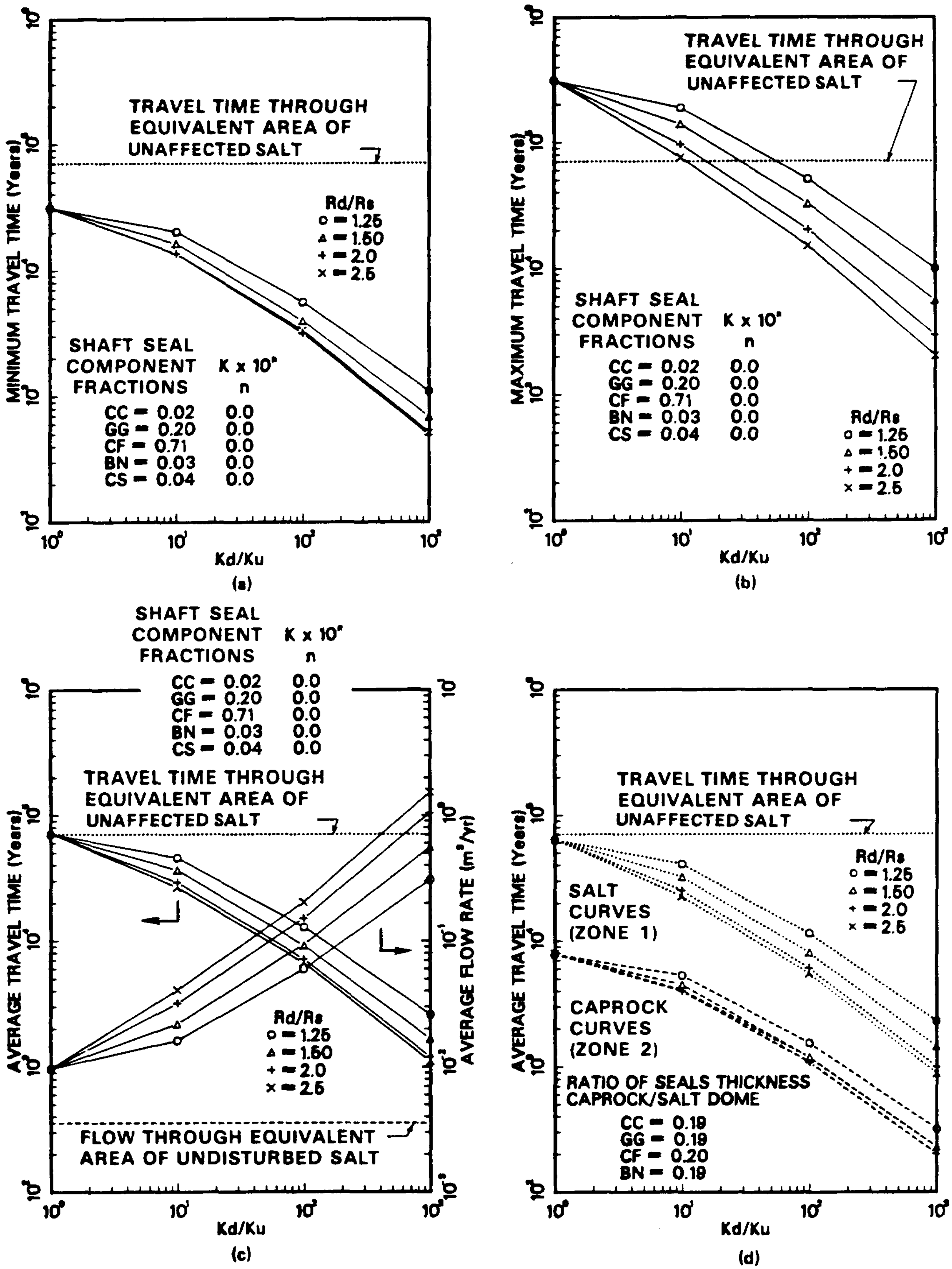


FIGURE 11. INFLUENCE OF AFFECTED ZONE

approximately three times as much flow as would occur in the host media without a seal system (see Figure 11c). Note however that in this instance the travel times are approximately equal.

Influence of the Affected Zone

Figure 11c shows the average flow rates and travel times computed for a selected range of hydraulic conductivity ratios of affected to unaffected zone respectively. In this simulation the properties of the seals were fixed at their baseline values (see Table 5) and the computation was performed for a range of thickness ratios Rd/Rs, where Rd is the radius to the edge of the affected zone and Rs is the radius of the shaft. Note that the two bulkheads (see Fig. 8) are assumed to provide only a 50 percent areal cutoff of the affected zone. Results indicate that the flow rate is strongly affected by the hydraulic conductivity of the affected zone and to a lesser extent by the width of the affected zone. Indeed, a one order of magnitude increase of the ratio of Kd/Ku has more impact in promoting the flow than a sixfold increase of the width of the affected zone. This is somewhat surprising since the flow area increases approximately with the square of the increase in width of the affected zone. Figures (12a-c) show that the variations of flow rates owing to changes of the width of the affected zone are linear, whereas this relationship is parabolic with respect to the ratio of Kd/Ku. Travel times are significantly altered by variation of the conductivity of the affected zone; a reduction of almost two orders of magnitude are witnessed over a three orders of magnitude increase of the ratio of Kd/Ku.

Note that the rate of variations of flow rates and travel times within the range of Kd/Ku values lying between one and ten are fairly slow, particularly for low ratios of Rd/Rs; however a fairly rapid increase is witnessed beyond that mark. This clearly indicates that the effectiveness of the seals in retarding the flow becomes less significant as the width of the affected zone increases or the ratio of Kd/Ku becomes large.

Figure 11d shows the variations of travel time in the two zones of the stream tube (see Fig. 10) lying in the salt dome and caprock respectively. In the absence of affected zone, the fluid residence time in caprock (Zone 2) represents approximately 10.2 percent of the total travel time. This

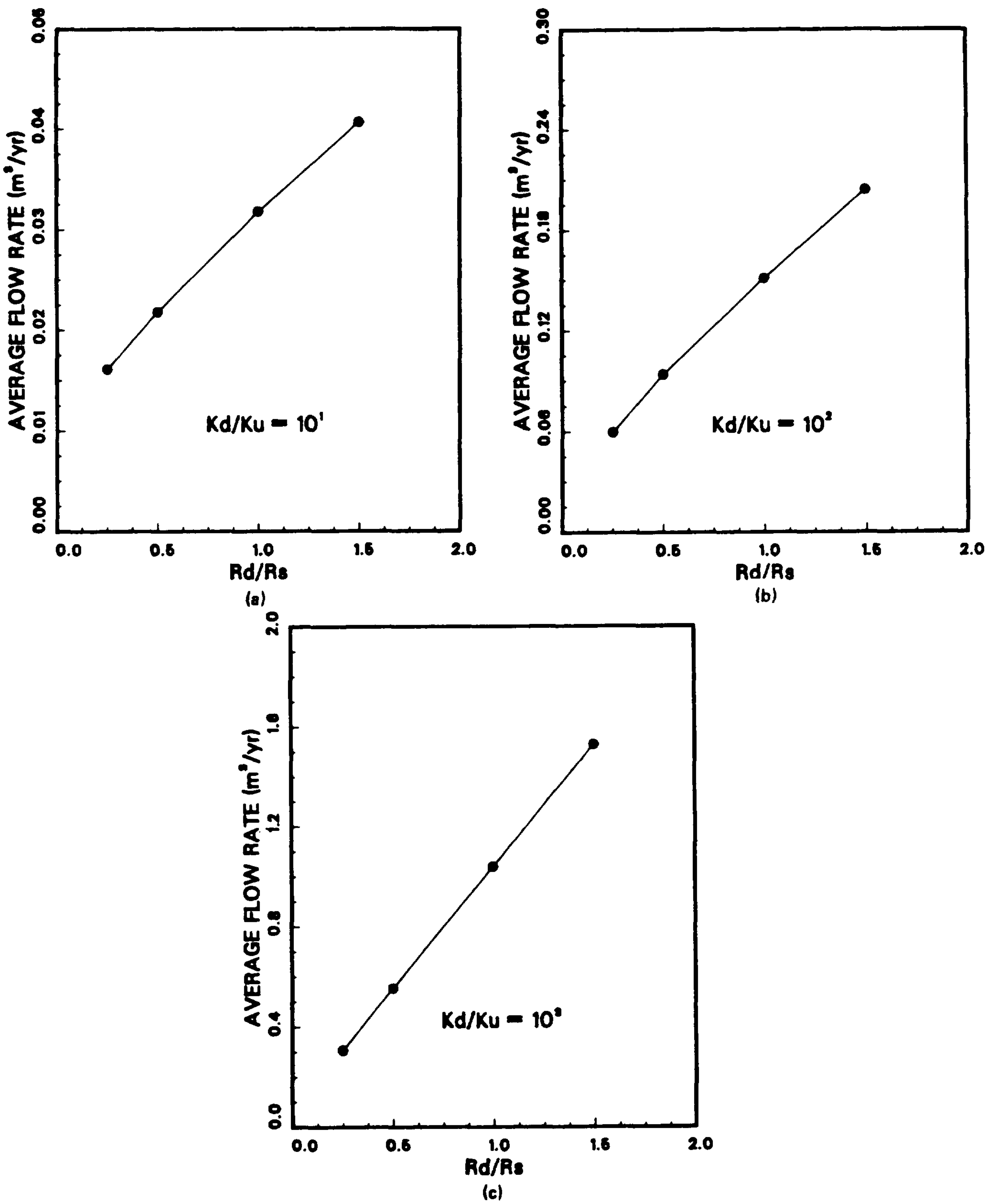


FIGURE 12. VARIATIONS OF FLOW RATES

percentage seems to increase with increasing values of Kd/Ku to reach 19 percent when the latter is subjected to a three orders of magnitude increase above its baseline value. These results indicate that the overall porosity of the zone lying in the caprock increases more rapidly than its counterpart in the salt dome, and this is inherent to the presence of anhydrite whose porosity (lower than rock salt) is less significantly affected due to changes in its hydraulic conductivity.

Figure 13 shows the variation of the Rayleigh number as a function of Kd/Ku. Although this dimensionless parameter is strongly influenced by changes in the hydraulic conductivity of the affected zone yet the maximum calculated value, i.e., $Ra = 3 \times 10^{-2}$, is far below its critical value of 40. Therefore buoyancy effects may safely be discarded in this case. Note that the influence of the magnitude of the affected zone on the Rayleigh number seems to be more significant relative to the impact due to increases of Kd/Ku values than in the case related to flow rates where the reversed situation seemed to prevail.

Parametric Study

In order to evaluate the relative sensitivity of the parameters for the engineered system by contrast to the one considered earlier, a series of tests was conducted involving a variation of the following parameters:

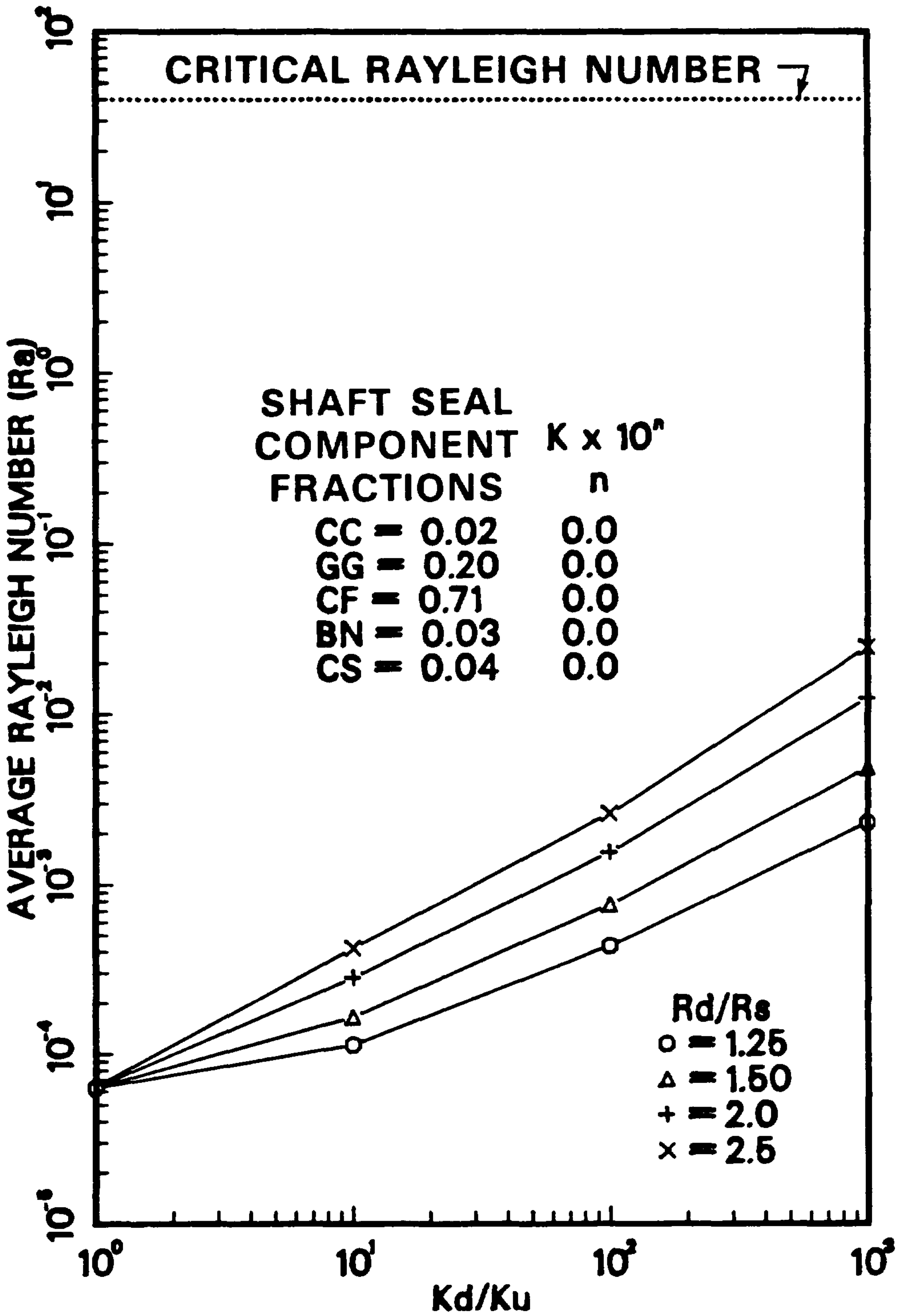
- hydraulic conductivity
- thickness of various seals
- extent of bulkhead areal cutoff.

Figures 14a, 15a, 16a, and 17a show the effects of variations of the hydraulic conductivity of bentonite, crushed salt, concrete, and gravel grout, respectively which were subjected to increases of 1, 2, and 3 orders of magnitude.

(a) Bentonite

Varying the hydraulic conductivity of bentonite (Fig. 14a), which in the baseline case represents 3 percent of the total seal, has a minor effect on the flow rate and travel time. Slight increases of the flow rates due to an increase of the ratio of Kd/Ku seem to occur when the latter is less than 10 and close to 1. However, as the latter ratio exceeds 10 the

INFLUENCE OF TEMPERATURE



INFLUENCE OF HYDRAULIC CONDUCTIVITY OF BENTONITE

INFLUENCE OF BENTONITE THICKNESS

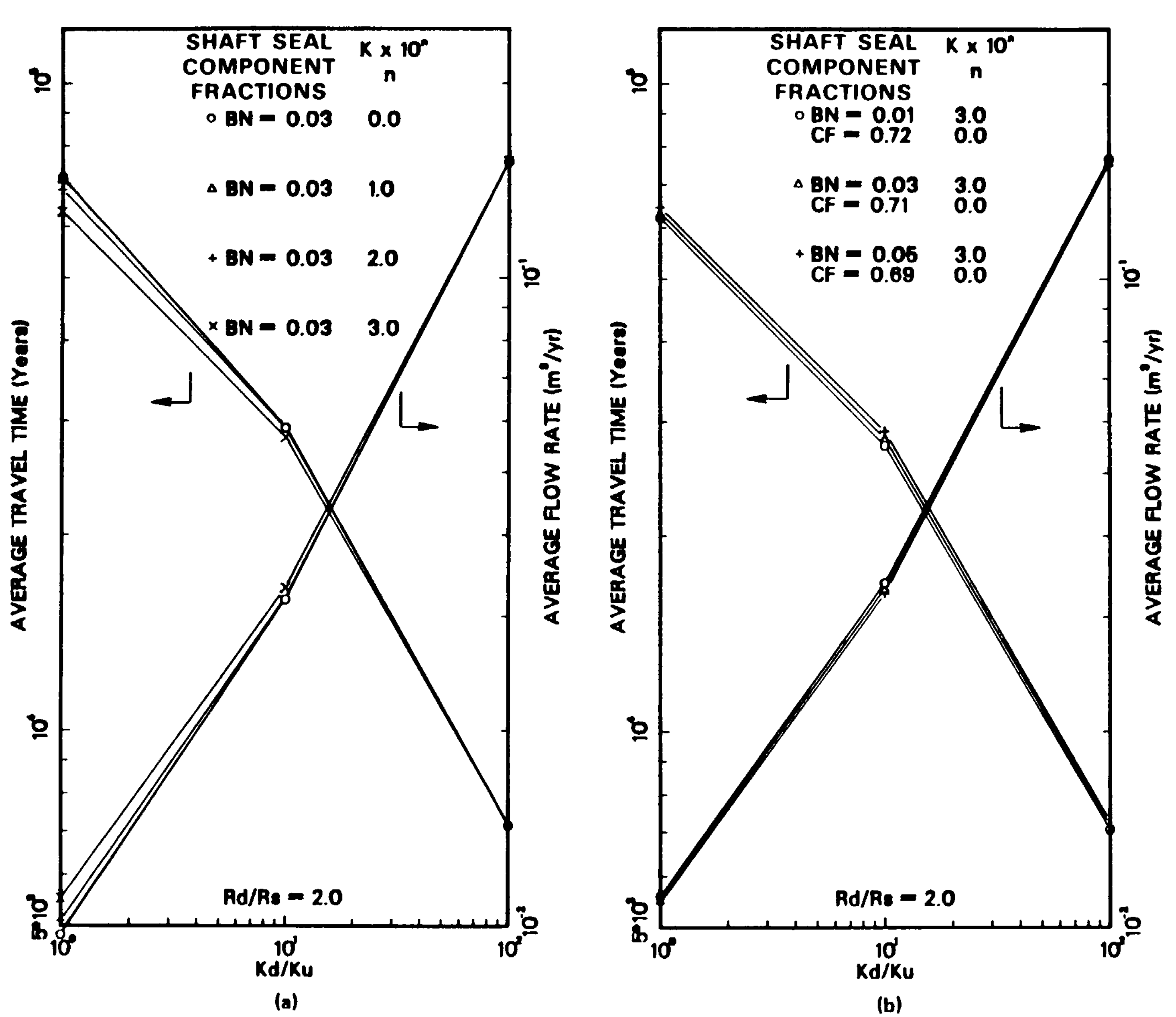


FIGURE 14. BENTONITE PARAMETERS

influence of this on flow rate and travel time seems to die out.

(b) Crushed Salt

Varying the hydraulic conductivity of crushed salt (Fig. 15a), which in the baseline case represents 4 percent of the total seal, has a minor effect on the flow rate and travel time; however, these are slightly more significant than in the case of bentonite. The minor increases in flow rate and travel time registered in this case seem to be unaffected by the increases in the ratio of Kd/Ku. These changes where relatively significant when the hydraulic conductivity of this particularly seal component was increased by one order of magnitude, further increases had little impact.

(c) Concrete

Varying the hydraulic conductivity of concrete (Fig. 16a), which in the baseline case represents 2 percent of the total seal, has a minor effect on the flow rate and travel time; however, this effect is slightly more significant in the case of crushed salt than with concrete. By contrast to crushed salt, increases in flow rate and travel time registered at low values of Kd/Ku seem to damp out as Kd/Ku increases. The reported changes were relatively significant when the hydraulic conductivity of this particular seal component was increased by one and two orders of magnitude; any further increase shows negligible effects.

(d) Gravel Grout

Varying the hydraulic conductivity of gravel grout (Fig.17a), which in the baseline case represents 20 percent of the total seal, has a marked effect on the flow rate and travel time. Increases in flow rate and travel time registered at low values of Kd/Ku seem to damp out in a manner related to an increasing conductivity value for this seal. The large percentage of this component in the seal system tends to amplify even further the impact of the affected zone on the overall performance of the system.

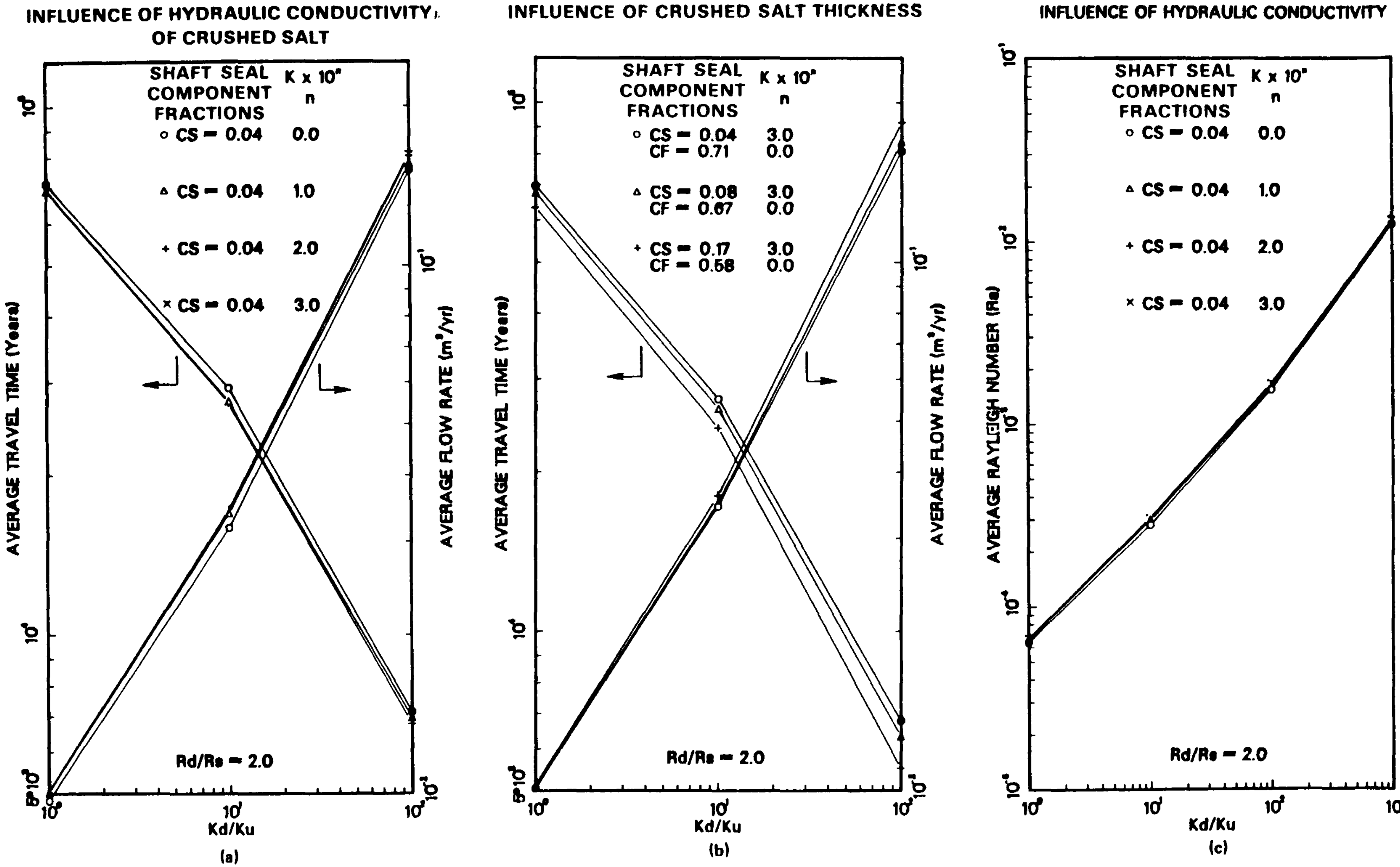


FIGURE 15. CRUSHED SALT PARAMETERS

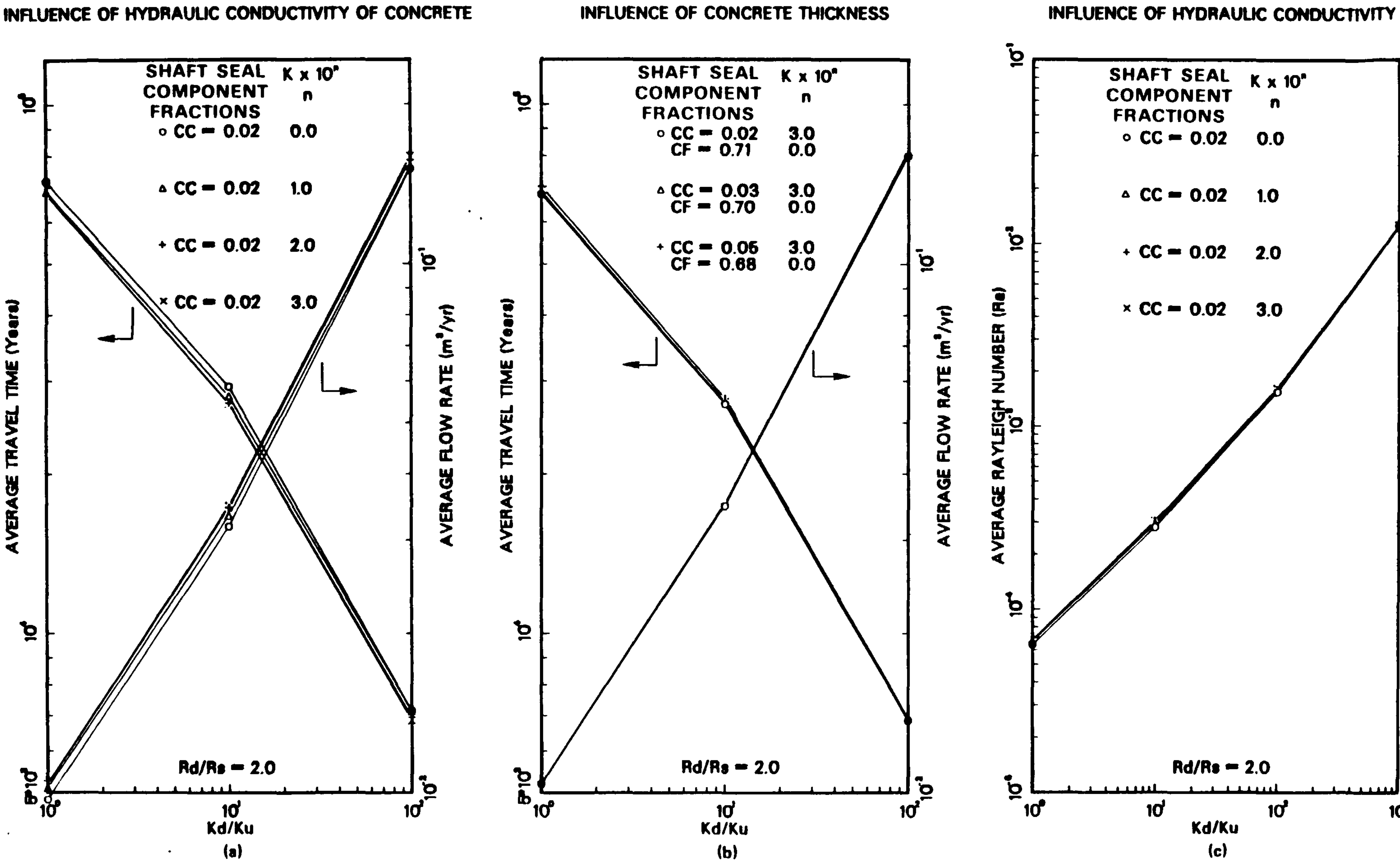


FIGURE 16. CONCRETE PARAMETERS

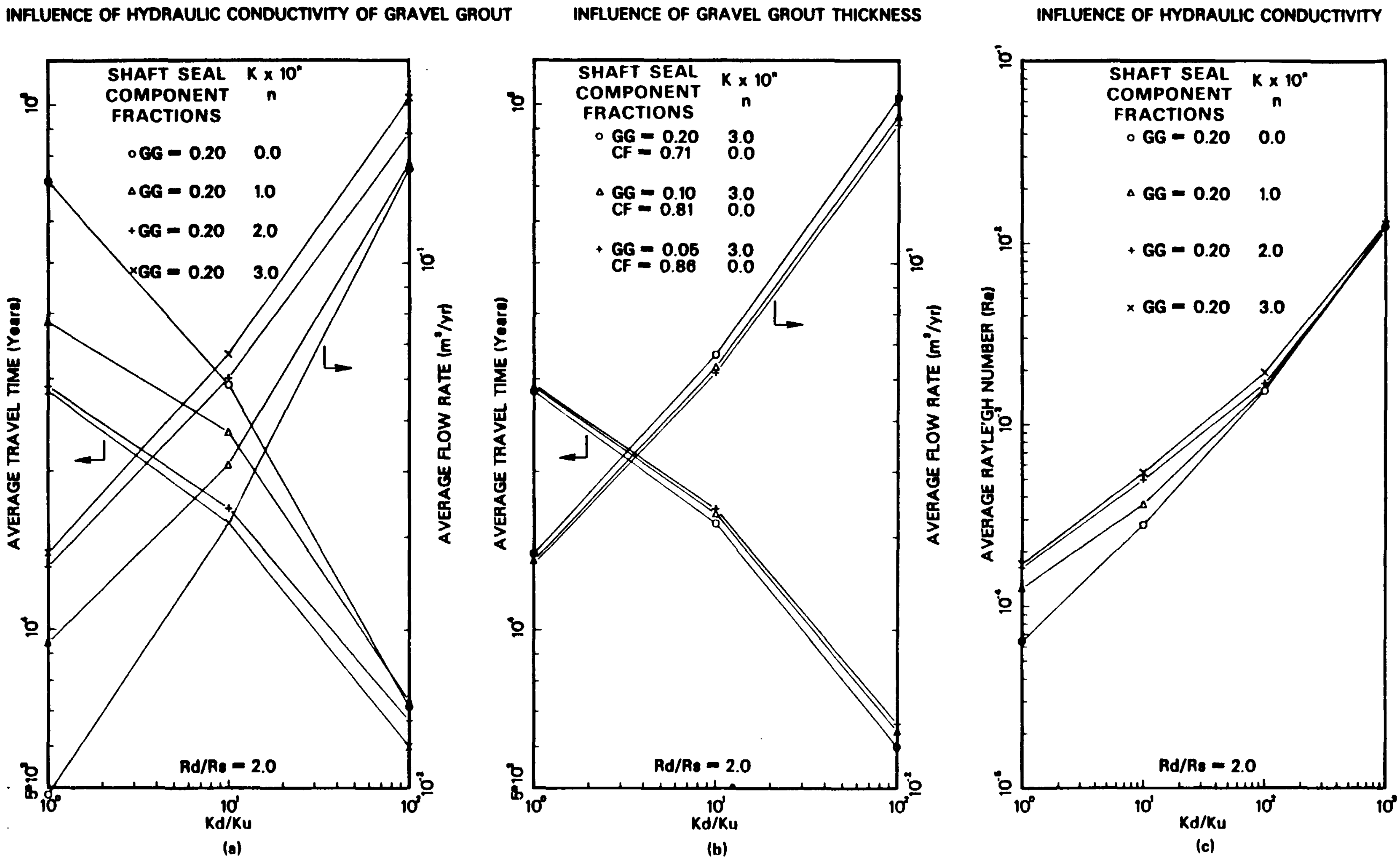


FIGURE 17. GRAVEL GROUT PARAMETERS

(e) Compacted Fill

Varying the hydraulic conductivity of compacted fill (Fig. 18a), which in the baseline case represents 71 percent of the total seal, has the most important effect on the flow rate and travel time compared to the remaining seals. As before, increases in flow rate and travel time registered at low values of Kd/Ku seem to damp out in a manner related to an increasing conductivity value for this seal. The large percentage of this component in the seal system tends to amplify even further the impact of the affected zone on the overall performance of the system.

Figures 14c, 15c, 16c, 17c and 18c show the influence of varying the hydraulic conductivity of the various seals on the Rayleigh number. In all cases the influence is negligible. Therefore changes in hydraulic conductivity of the various seal components have negligible impact on the buoyancy forces which seem to be influenced mainly by the hydraulic conductivity of the affected zone.

Influence of Thickness of Various Seals

In the course of our investigation regarding the influence of thickness of the various seals on the overall shaft seal system performance, the hydraulic conductivity of the material under investigation was increased by three orders of magnitude above its baseline value. Moreover the thickness of the particular seal was subjected to variations above and below its baseline values in the two zones of interest. In most cases this was achieved at the expense of a proportional change in the thickness of compacted fill with properties confined to its baseline values. However when dealing with compacted fill thickness, the total length was adjusted by the compacted fill variation. Note also that Rd/Rs is equal to the base case, i.e., 2. Results reported in Figures 14b, 15b, 16b, 17b, and 18b show that the most sensitive components classified by order of importance are: compacted fill, gravel grout, crushed salt, bentonite, and concrete.

In the case of crushed salt (see Fig. 15b) minor changes are observed when Kd/Ku is less than 10; however an amplification in the variations of the

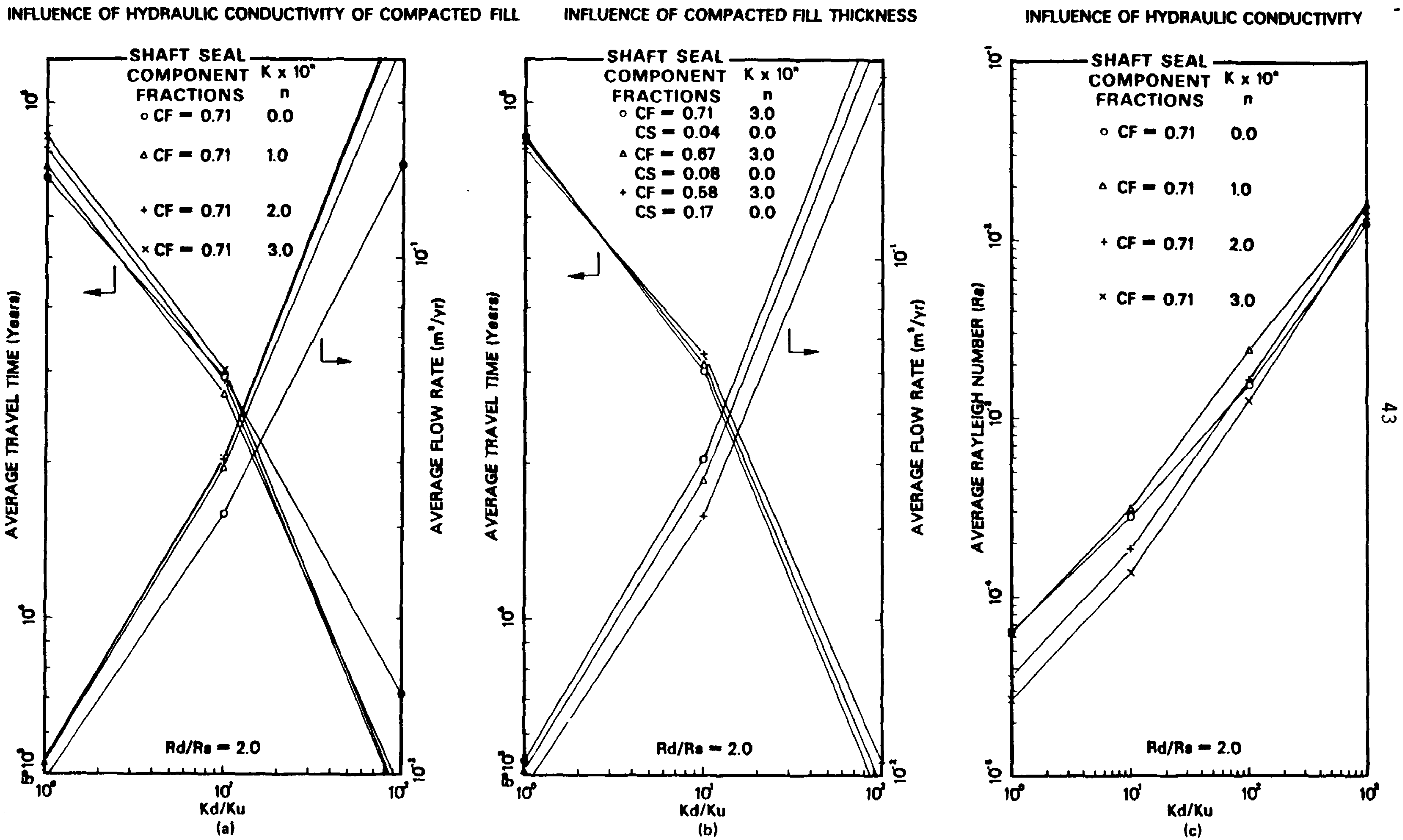


FIGURE 18. COMPACTED FILL PARAMETERS

flow rates are witnessed when the hydraulic conductivity of the host media increases further, where it is observed that variations in flow rates and travel times are more sensitive to an increase in thickness of this particular material. This state of affairs results from the fact that the crushed salt has a conductivity lower than the material it substitutes for when its thickness is subjected to an increase. A similar reasoning applies in the converse case.

In the case of gravel grout (see Fig. 17b) the changes reported as a result of the variation of its thickness are less significant than the variations resulting from changes of its hydraulic conductivity. Reducing the original thickness of this seal by 50 and 75 percent show that the impact on flow rate and travel time follow a linear relationship. The rate of change of flow rates and travel times owing to these changes remain fairly constant.

In the case of compacted fill (see Fig. 18b) reductions of 4 and 13 percent resulted in a small decrease in flow rates and travel times yet the observed changes do not seem to minimize the effects of an increasing conductivity of the affected zone.

The neglegible changes demonstrated for variations in bentonite and concrete thicknesses do not warrant a discussion.

Figure 19 shows the influence of areal cutoff provided by the bulkhead on the flow rates and travel times. It may be seen that a reduction of the cutoff from its baseline value of 50 percent to zero has a negligible impact on the predicted results. However, when the bulkhead extends to the edge of the affected zone then the impact of a 100 percent cutoff becomes very significant particularly as the ratio of Kd/Ku increases. An increase of almost one order of magnitude in flow rate is registered when the hydraulic conductivity of the affected zone is increased by three orders of magnitude.

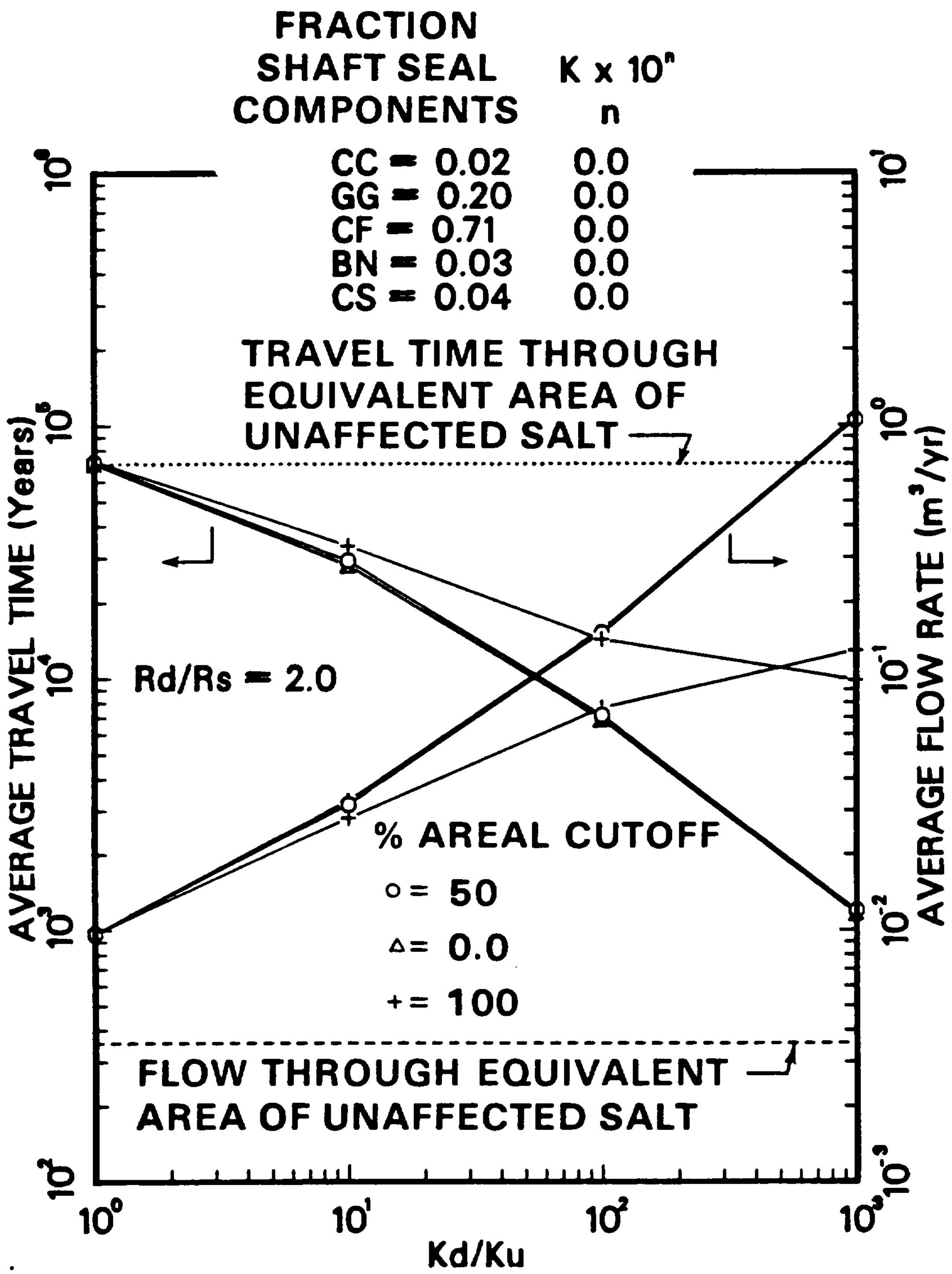


FIGURE 19. INFLUENCE OF PERCENT OF AREAL CUTOFF

CONCLUSIONS

The performance of a shaft seal system is influenced significantly by the hydraulic conductivity of the affected zone and to a lesser degree by the width of the latter. In the event where the hydraulic conductivity of the affected zone exceeds its baseline value by one order of magnitude or above the adverse impact of this on the overall performance of the shaft seal seems to be preponderant, and in this connection only a bulkhead with an areal cut-off exceeding 50 percent of the width of the affected zone could mitigate appreciably these undesirable effects.

Varying the hydraulic conductivity of the various seals has no major effects on the system flow rate. Varying the thickness of the various seals within a range of 25 to 50 percent above or below its baseline values has no significant effect on the overall performance. Buoyancy effects which seem to be sensitive to variations of the hydraulic conductivity and width of the affected zone yet are so unsignificant that the potential of buoyancy driven flow which may cause a circulation of water in the system when the latter is under hydrostatic conditions may be completely discarded.

REFERENCES

Acres American Inc., 1977. Weeks Island Mine, Geotechnical Study, proposal for Gulf Interstate Engineering Company, 2 Volumes, Houston, TX.

Battelle Northwest Laboratories, 1980. "Perspectives on the Geological and Hydrological Aspects of Long Term Scenario Analyses", PNL-2928.

Bau, H. H., and K. E. Torrance (1982). "Low Rayleigh Number Thermal Convection in a Vertical Cylinder Filled with Porous Materials and Heated from Below, Trans of the ASME vol. 104, pp. 166-173.

Beck, J. L., 1972. "Convection in a Box of Porous Material Saturated with Fluid", Phys. of Fluids, Vol. 15, Number 8, pp. 1377-1383.

Carman, P. C., 1937. "Fluid Flow Through Granular Beds", Trans. Instn. Chem. Engs., 15, pp. 150-166.

Clark, S. P., 1966. "Handbook of Physical Contracts", Geol. Soc. Am. Memoir 97.

D'Appolonia Consulting Engineers, Inc., 1980. Repository Sealing Design Approach - 1979, ONWI-55, prepared for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Daemen, J.J.K., and others, 1982. "Rock Mass Sealing", Annual Report, University of Arizona, Contract N-NRC-04-78-271.

Darcy, H. (1856). Les fontaines publiques de la Ville de Dijon, Paris, Victor Dalmont.

Drumheller, J. C., and S. I. Fuerst, B. P. Cavan, and J. A. Saunders, 1982. Petrographic and Geochemical Characteristics of the Richton Salt Core, ONWI-277, prepared by Law Engineering Testing Company for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Elder, J. W., 1967. "Steady Free Convection in a Porous Medium Heated from Below", Journal of Fluid Mechanics, Vol. 27, pp. 29-48.

ERTEC, Inc., 1983. Preliminary Overburden Characterization at Richton Dome, ONWI-481, prepared for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio.

Golder, 1977. Geotechnical Study of Cote Blanche Island Salt Mine, Golder Associates, Kirtland, WA.

Green, D. W., 1963. "Heat Transfer with a Flowing Fluid Through Porous Media", Ph.D. Dissertation, University of Oklahoma.

Gussow, W. C., 1970. "Heat: The Factor in Salt Rheology", Geology-Technology Gulf Coast Salt, Louisiana State Unviersity, p. 125-148.

Guyod, H., 1946. "Temperature Well Logging", Well Instrument Developing Co., Houston, Texas, p. 47.

Horton, C. W. and F. T. Rogers, Jr., 1945. "Convection Currents in a Porous Medium", Journal of Applied Physics, Vol. 16, pp. 367-370.

Karably, L. S., Jr., B. L. Jernigan, I. C. Petre, and J. M. Sullivan, 1983. Salt, Caprock, and Sheath Study, ONWI-355, prepared by Law Engineering Testing Company for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Kelsall, P. C., J. B. Case, and C. R. Chabannes, 1982. A Preliminary Evaluation of the Rock Mass Disturbance Resulting from Shaft, Tunnel, or Borehole Excavation, ONWI-411, prepared by D'Appolonia Consulting Engineers, Inc., for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Kelsall, P. C., J. B. Case, D. Meyer, and W. E. Coons, 1982. Schematic Designs for Penetration Seals for a Reference Repository in Bedded Salt, ONWI-405, prepared by D'Appolonia Consulting Engineers, Inc., for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Kozeny, J., 1927. Uber Kapillare Leitung des Wassers in Boden, Ber. Wien Akad., 136A. pp. 271-306.

Kreitler, C. W., and S. P. Dutton, 1981. Preliminary Report on Oakwood Dome Caprock: Preliminary Report prepared by DOE under Contract N-DE-AC97-80ET46617.

Mathis, S. P., and J.J.K. Daeman, 1982. "Rock Damage Induced by Drilling: An Experimental Assessment of Potential Leakage Around Borehole Seals", Proc. Waste Management '82, Tucson, Arizona, March 8-11.

Norton, D., and R. Knapp, 1977. "Transport in Hydrothermal Systems: The Nature of Porosity", American Journal of Science 227, pp. 913-936.

Ode', H., 1978. "Review of Mechanical Properties of Salt Relating to Salt-Dome Genesis in Diaparism and Diapirs", American Assoc. Pet. Geol. Memoir 8, pp. 53-78.

Sandia Laboratories, 1978. Draft Characterization Report for the Waste Isolation Pilot Plant (WIPP) Southeastern New Mexico, prepared for DOE under Contract AT (29-1)-789.

Shor, A. J., C. F., Baes, and C. M. Canonico, 1981 "Consolidation and Permeability of Salt in Brine", ORNL-5774, Oak Ridge National Laboratory, Oak Ridge, TN.

Stearns-Roger, 1983. Engineering Factors and Costs for NWTS Repository Site Selection, Richton, Mississippi, June.

U.S. Army Corps of Engineers, 1963. "Petrographic Examination and Physical Tests of Cores Tatum Salt Dome, Mississippi", Technical Report G-614.

Terzaghi, K., and R. B. Peck, 1967. Soil Mechanics in Engineering Practice, p. 729.

Wooding, R. A., 1958. "An Experiment on Free Thermal Convection of Water in Saturated Permeable Material", Journal of Fluid Mechanics, pp. 582-600.

Cement-plug leakage and drilling damage evaluated

Floyd L. Burns
S-Cubed, La Jolla, Calif.

Richard Lingle
Terra Tek, Salt Lake City

Anthony Andrews
Battelle Memorial Institute,
Columbus, Ohio

Open-hole cement plugs have been set, and subsequently recovered and examined. This article gives observations on the quality of plugs and the nature of drilling damage.

This work has provided some valuable insight on the performance of borehole plugs. Flow through plugged boreholes in anhydrite was shown to occur primarily at the plug/wellbore interface where the observed flow path coincided with a "gypsumized" interface zone—a possible result of hydration during drilling or from contact with the grout. When the mean permeability value for drilled and undrilled plug samples were compared, no drilling damage was evident. The only evidence of drilling induced damage (microfracturing) was on the scale of 0.1 in. as determined by microscopic examination.

Based on the success of this preliminary work, our program is now conducting similar tests in basalt, welded tuff, and rock salt, using cement grouts specially formulated for each rock type. The phenomenon of drilling induced microfracture damage is not yet fully understood. With obvious importance to borehole plug performance, it will continue to be investigated. The feasibility of simulating full-scale drilling experiments in the laboratory, with a level of precision greater than comparable field tests, has been successfully demonstrated. The obvious advantages are far reduced costs, and the ability of retrieving the drilled samples and plugs for analyses.

Fig. 1

Bell Canyon test plug

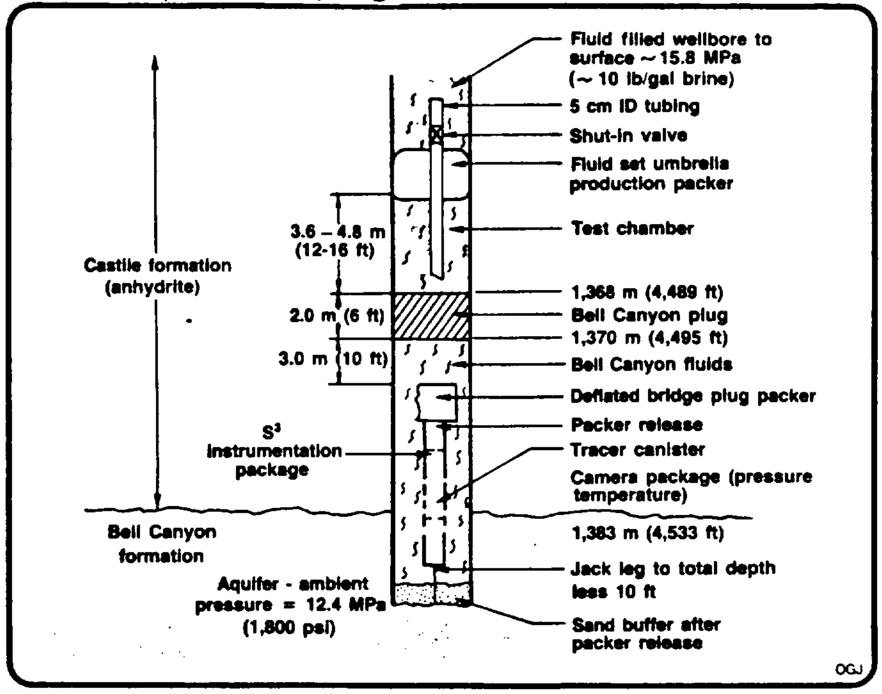


Table 1

Drilling test parameters

Bit type	Drilling fluid	Bit weight, lb	rpm	Bore pressure, psi	Confining pressure, psi	Overburden pressure, psi
Reed	Air	20,000	60	50	500	1,500
Type FP 53	Water based mud	20,000	60	2,000	3,000	5,000
Roller cone	Mud & water flush	20,000	60	2,000	3,000	5,000
7⅞ in.	Mud & water flush	20,000	60	2,000	3,000	5,000
Christensen	Water	20,000	60	2,000	3,000	5,000
Type MD 262	Water based mud	20,000	60	2,000	3,000	5,000
diamond	Mud & water flush	20,000	60	2,000	3,000	5,000
7⅞ in.						

Borehole sealing. The disposal of radioactive waste is one of the key elements of the nuclear fuel cycle. Deep disposal in geologic media can potentialy isolate the waste for long periods of time. To provide the necessary containment using this method of disposal, borehole penetrations within and adjacent to the disposal site must be appropriately sealed.

The National Waste Terminal Storage Program (NWTS), under the development and management of The U.S. Department of Energy, was initiated in 1976 to provide permanent disposal of nuclear wastes. In support of the NWTS program, the Battelle Project Management Division-Office of Nuclear Waste Isolation (ONWI) has the specific objectives of identifying and characterizing geologic sites for use as nuclear waste repositories, and managing the development and application of specific supporting data and base technologies. Site investigations of subsurface repositories for nuclear waste are currently being conducted in domal and bedded rock salt, basalt, and tuff formations.

As a part of ONWI's objective, the performance of borehole plugs and the effects of drilling-induced damage on plug performance were investigated by the Sandia National Laboratory, Terra Tek Inc. (TTI), and TTI's drilling research laboratory. Anhydrite was chosen for the first series of plug tests because it frequently occurs as a cap rock. Due to its relative insolubility and low permeability, the anhydrite cap rock may serve as a primary zone for sealing.

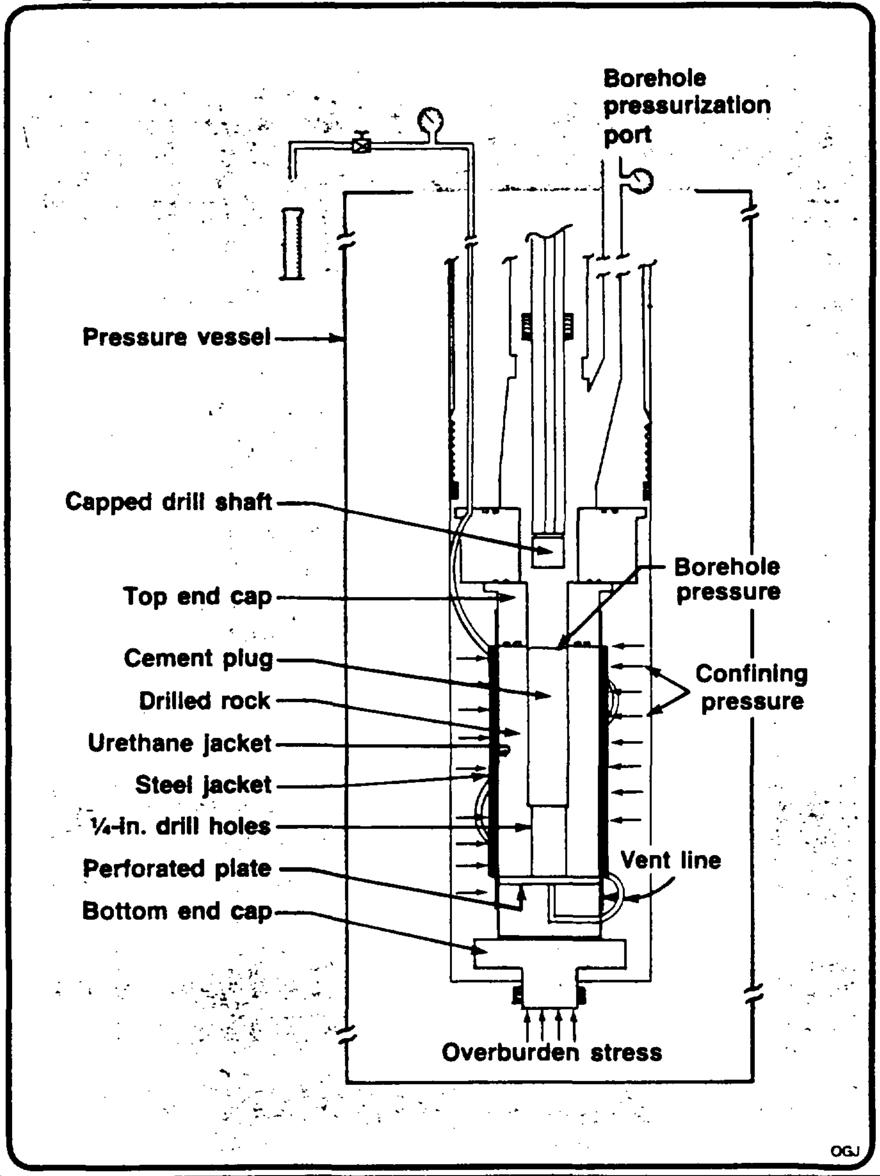
Other related studies sponsored by ONWI include the development of borehole sealing materials, such as cements, and the development of borehole instrumentation to test for very low ranges of permeability.

Substantial penetration sealing technology exists in the civil engineering, mining, and petroleum industries that is unrelated to the disposal of radioactive wastes. However, the quantitative measurement of plug performance is rarely performed.

The primary functions of repository

Fig. 2

Plug flow test setup



seals are to control radionuclide release through penetrations to the repository, though seal performance is considered in terms of water flow rate and travel time rather than in terms of radionuclide release. The seal design criteria require the functional use of long life seal materials, seal zones (including adjacent distrubed rock) that exhibit extremely low permeabilities, and the ability of the seal to retard potential radionuclide migration.

Drilling damage. To design effective borehole seals, the damage induced by drilling must be measured. One way to do this is to measure the permeability in the annular zone surrounding a wellbore and compare it with the permeability of the undrilled rock.

The intrinsic permeability is an indirect measure of the communication in porous material between pores, or as in the case of anhydrite, the communication through crystal grain boundaries and microfractures.

Two modes of formation damage may occur to the wellbore annular zone as the result of drilling: mud filtrate invasion due to circulation of high pressure drilling fluids; and micro-fracturing due to a combination of impact from the drill bit and stress relief in opening the hole.

In oil production, mud filtrate invasion of permeable formations is a concern because it decreases the annular zone permeability and inhibits oil production. In sealing boreholes, any micro-fracturing that would occur in the impermeable formations is of concern because it would increase the annular zone permeability and thereby reduce the ability to seal it.

Mud filtrate is also a concern because it will inhibit bonding between the seal material and the wellbore, and in effect, create a preferential flow path around the plug. This article compares the results of field and laboratory experiments to evaluate the performance of borehole plugs.

Table 2

Flow test parameters

Confining pressure - 2,960 psi
Ram induced overburden pressure - 5,300 psi
Borehole pressure - 2,000 psi
Bit weight - 20,000 lb
Bit revolution - 60 rpm
Mud flow rate - 300 gpm
Penetration rate - 0.118 ft/min

Table 3

Plug composition

Ingredients	Wt %
Class H cement	52.2
Expansive additive	7.0
Fly ash	17.6
Salt (NaCl)	—
Dispersant	0.2
Defoamer	0.02
Water	21.4

Table 4

Plug flow test

Fluid collected, cc	Elapsed time, sec	Flow 10^{-2}cc/sec
49.5	600	8.25
50.9	600	8.48
50.8	600	8.47
50.4	600	8.40

The first of these experiments, the Bell Canyon test, was conducted by Sandia National Laboratory and Systems, Science and Software Inc. (S-Cubed). Terra Tek later conducted a similar experiment under simulated wellbore conditions in its Drilling Research Laboratory.

Both experiments measured flow rates, comparable within an order of magnitude, in similarly plugged boreholes. Probably of even more significance, the post-test examination of Terra Tek's plugged borehole sample revealed the actual flow path occurring at the plug/wellbore interface.

Bell Canyon test. the Bell Canyon test was conducted in an abandoned hole (AEC-7) at the site of the waste isolation pilot plant in southeastern New Mexico.[1] The test involved placement of a 6-ft long, 7⅞-in. diameter, grout plug in the lower anhydrite member of the Castile formation (4,495 ft), above the Ramsey sands high-pressure aquifer of the Bell Canyon formation (4,534 ft).

A bridge plug and an instrument package, including an automatic tracer gas release mechanism, were placed in the borehole below the plug. The Bell Canyon test setup is shown in Fig. 1.

The plug performance was assessed using two techniques: shut in tests (i.e., pressure build-up tests), and tracer transit-time tests.

The shut-in test measured volumetric flow into the test region between the plug and an overlying packer. Fluid was removed from the packed off zone above the plug until the pressure at the top of the plug approached atmospheric. The test region was shut-in until pressure build-up approached the Bell Canyon aquifer pressure.

Volumetric flow rates were then interpreted from the resulting pressure history data. Transport time measurements of flow through the plug/formation was provided by the tracer test.

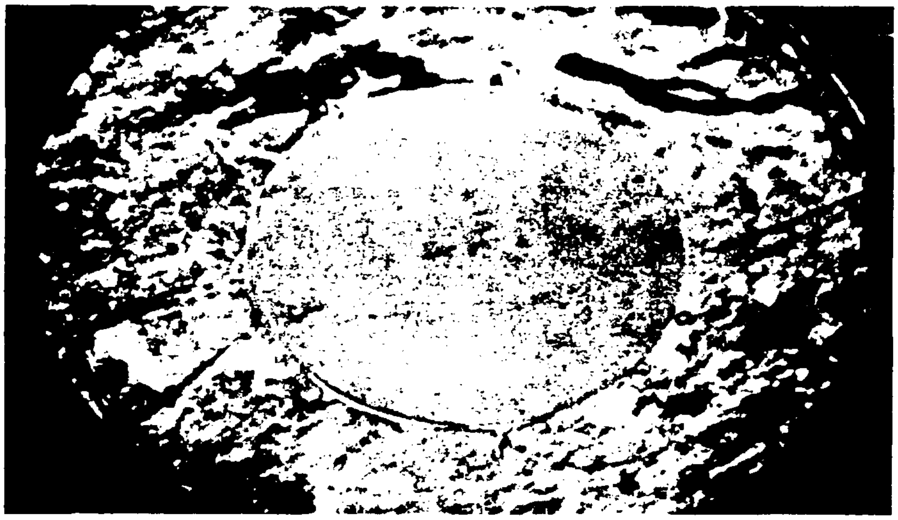
Discrete releases of tracer gas were programed to occur below the plug during the test period. Detection of the tracer above the plug was taken as positive confirmation of flow through the plug/formation system. Measurements were made of the time between tracer release and detection above the plug. The ratio of plug length to tracer flow time was then used to provide a representative estimate of fluid flow velocity through the system.

The test data suggest that predominant flow into the test region occurred through the cement plug/borehole interface region with a small contribution to total flow occurring through the wellbore damage zone, the plug core, and the surrounding undisturbed anhydrite bed.

Terra Tek laboratory test. Using specialized laboratory equipment to simulate downhole wellbore conditions, Terra Tek's drilling research laboratory (DRL) conducted a full-scale drilling program, to duplicate the downhole conditions of the Bell Canyon test.[1] Using the DRL wellbore simulator, the performance of borehole plugs was evaluated under conditions that were encountered earlier.

Seven anhydrite test samples, 36 in. long by 15½-in. diameter, were cored from anhydrite blocks. The sample cores were then placed in the DRL wellbore simulator and drilled according to the parameters shown in Table 1. Downhole conditions were held constant during drilling.

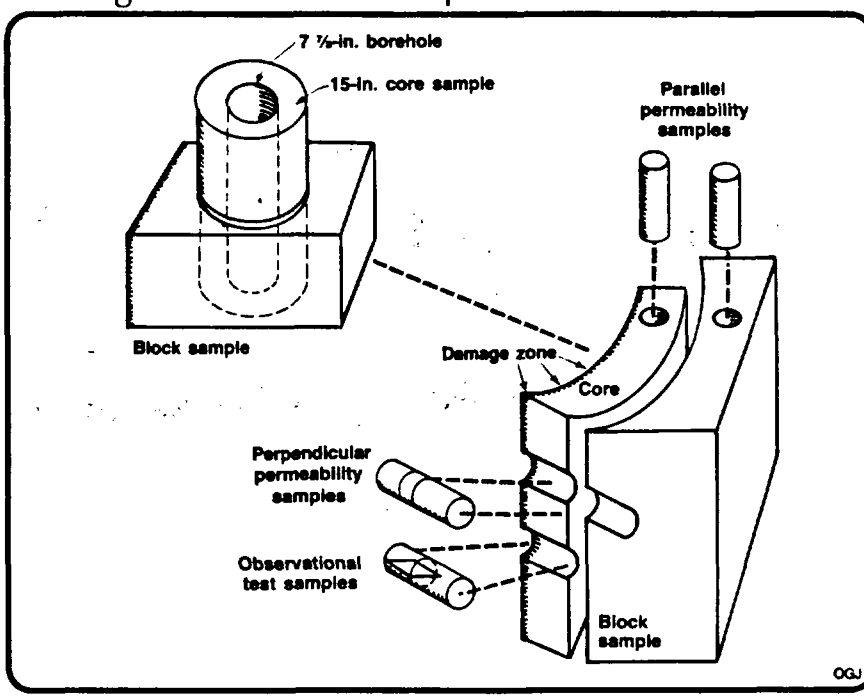
Flow tests assess damage. In order to establish the extent of the damage to the drilled anhydrite test samples, flow tests were conducted on a drilled sample without removing it from the pressure vessel.



Cross section of a plugged borehole shows plug and drilled formation integrity with minor leakage, highlighted by red dye, around 70% of the cement-to-formation bond (Fig. 3).

Fig. 4

Damage assessment samples



Two techniques were used: 1) constant pressure, where permeability is determined from the measurement of flow volume for a known time interval; and 2) transient pressure pulse (for non-measurable flow), where permeability is calculated from the pressure time history of an applied pressure pulse. Attempted flow rate measurements were unsuccessful because no flow was detected. The transient pressure pulse technique with water was also unsuccessful because pressure equilibration could not be achieved in the time scheduled. A transient pulse test using compressed nitrogen was then conducted on an air drilled sample for which the results indicated a permeability on the order of 10^{-7} darcies.

A tracer dye, added during circulation of the drilling fluid, showed no penetration of the fluid into the anhydrite sample. The only discernable damage, revealed by microscopic examination, extended less than a few grain diameters (less than a 0.1 in.). The flow tests further substantiated that no excessive damage was induced by the drilling and/or stress applied to the samples. These results established a baseline for flow through plugged samples.

Laboratory plug flow tests. To duplicate the Bell Canyon test, a plug test was conducted on bored-out an-

Bell Canyon and Terra Tek plug tests

	Bell Canyon	Terra Tek
Test material	Anhydrite	Anhydrite
Plug composition	Cement	Cement
Plug diameter, in.	7⅞	7⅞
Plug length, ft	6.56	1.25
Pressure differential, psi	1,800	2,000
Vertical stress, psi	4,500	5,300
Horizontal stress, psi	?	2,960
Measured flow, cu ft/day	21.36	254.26
Relative equivalent conductivity	1.0	2.0
Measured arrival time, hr	36-38	—
Formation permeability, microdarcies	0.1-1.0	0.1-1.0
Maximum flow velocity, ft/day	3.94	—

hydrite samples (Fig. 2). An anhydrite sample was drilled in the wellbore simulator while subjected to the parameters shown in Table 2. Drilling stopped at 24 in. leaving 12 in. of intact rock at the bottom. The borehole was then flushed with water to remove any mud cake. The bored-out sample was then plugged with a freshwater cement grout mixture identical to that used in the Bell Canyon test. It has a relatively low ratio (0.27) of water to cementitious solids. The cement mixture (Self-Stress II cement) used to prepare the grout was obtained from Dowell. It is based on Class H portland cement containing a proprietary expansive additive. Grout ingredients are listed in Table 3.

The cement grout plug was allowed to cure under 2,000 psi hydrostatic head for 14 days. The plugged sample was removed and set up for the plug flow test, as shown in Fig. 4.

Flow testing, using water containing a red fluorescent dye, was conducted in the wellbore simulator under a confining pressure of 2,960 psi, overburden pressure of 5,300 psi, and borehole pressure of 2,000 psi. To ensure that all air was expelled from the sample and system, a 60-hour period was allowed for flow to reach equilibrium. At the end of the equilibrium period, the fluid was collected for four, 600-sec intervals (Table 4).

At the conclusion of the flow test, the sample was removed from the vessel and cut perpendicular to the direction of drilling, thereby exposing a cross-sectional view of the grout/anhydrite interface.

Plug flow zones identified. The results of the laboratory flow test are very encouraging.

Due to the presence of the dye, the flow zone was easily identified with the unaided eye on a cross section of the flow test sample.

Flow was revealed to occur through an annular zone comprising about 70% of the grout/anhydrite bonded interface. At the interface zone, alteration of anhydrite to gypsum was observed, as shown in Fig. 4. A comparison of the two tests is shown in Table 5. Flow data are in relatively good agreement (within a factor of two).

Considering the differences in experimental technique, there is a significant correlation in results. Factors such as rock type, the pressure cycle history, unloading of the laboratory sample after grout curing, and drilling parameters could all, individually or combined, have easily accounted for the discrepancy.

Permeability measurements. Damage to the borehole sidewall was studied with dye-penetrant techniques, microscopic examinations, and permeability measurements of sidewall samples (Fig. 5).

Permeability-test plugs for analysis were obtained by first removing 4-in. cores from both the anhydrite block sample and its drill-test sample. Smaller 1-in. test plugs were then prepared from the 4-in. cores both parallel and perpendicular to the drill-test sample axis.

The plug was placed in a test chamber with two reservoir volumes, and joined by communication through the plug. A pressure pulse is generated and decays with time due to fluid flow in the test plug. The permeability is calculated from the plot of the pressure decay curve versus time.

The anhydrite test samples exhibited large variations in permeability, ranging from 10^{-7} to 10^{-2} darcies, in both the drilled and undrilled samples. When the mean permeability values for the drilled and undrilled plugs are compared, no drilling damage is evident. Damage as measured by permeability tests is insignificant compared to the variation in range of permeability in the undrilled anhydrite.

Acknowledgements

This article is based on reseach sponsored by the U.S. Department of Energy, National Waste Terminal storage Program, under contract DE-ACO6-76RLO1830. The authors thank Charles Ballinger of Battelle Columbus Laboratories for his assistance in preparing this paper.


Burns


Lingle

Floyd Burns is a senior project manager for S-Cubed. From 1978 to 1982, he was a senior project manager for the Battelle project management division, Office of Nuclear Waste Isolation. He managed the repository sealing program for research and development of materials and methods to plug boreholes and shafts for nuclear waste repositories in deep geologic formations. Prior to joining Battelle, he was employed by the Alyeska Pipeline Service Co. as a project engineer.

He has also managed drilling programs in oil exploration and designed special drilling tools and instrumentation for monitoring drilling. Burns has a BS in geology from the University of Southern California, and graduate work in petroleum and geologic engineering.

Richard Lingle is staff engineer for the research and development division of Terra Tek Inc. He joined Terra Tek in 1973, and since 1979 has been the principal investigator for experimentally determining wellbore damage as it relates to plugging boreholes.

Prior to joining Terra Tek, he was employed at Sandia National Laboratories in the operation of its high pressure shock wave physics and ultrasonic laboratories. Lingle studied electrical engineering at San Jose State College, California.


Andrews

Anthony Andrews is a project manager in the Repository Sealing Program at the Battelle project management division, Office of Nuclear Waste Isolation. He joined Battelle in 1978, and until 1980 was the quality assurance specialist for exploratory drilling and geologic exploration of nuclear waste repositories sites. Prior to joining Battelle, he was employed by the Cleveland Electric Illuminating Co. as a quality assurance engineer for nuclear power plant construction. Andrews has a BA in geology from Cleveland State University and graduate work in engineering/geology at Ohio State University.

References

1. Christensen, C.L., Sandia National Laboratories, and Peterson, E.W., Systems, Science and Software, April 1981, The Bell Canyon Test Summary Report; Sandia National Laboratories, SAND80-1375
2. Lingle, R., Stanford, K.L., Peterson, P.E., and Woodhead, S.F., Terra Tek; August 1981; Technical Report on Wellbore Damage Zone Experimental Determination, prepared for the Office of Nuclear Waste Isolation, Battelle Project Management Division; ONWI 349