EPA Contract No. 68-01-6288
January 1984

SMC Martin
900 West Valley Forge Road
P.O. Box 859
Valley Forge, Pennsylvania 19482

INJECTION WELL PROCEDURES MANUAL: A CASE STUDY OF THE RAFT RIVER GEOTHERMAL PROJECT, IDAHO

Office of Drinking Water
Ground Water Protection Branch
U.S. Environmental Protection Agency
Washington, DC 20460

December 1983

INJECTION WELL PROCEDURES MANUAL: A CASE STUDY OF THE RAFT RIVER GEOTHERMAL PROJECT, IDAHO

by

David L. Kraus
Gregory J. Burgdorf
William Zamor

SMC Martin Inc.
900 West Valley Forge Road
P. O. Box 859
Valley Forge, PA 19482

EPA Contract #68-01-6288
Task #8

Project Officer

Mario Salazar

Task Officers

Joseph F. Keely
Harold M. Scott

TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
Background	1
Purpose and Scope	1
Use of Manual	2
II. PROJECT HISTORY	4
III. PHYSICAL SETTING	11
Geography	11
Review Comments	13
Geology	15
General	15
Stratigraphy	15
Hydrogeology	18
Geological Structure	20
Review Comments	24
IV. WELL CONSTRUCTION AND COMPLETION TECHNIQUES	31
Drilling and Construction Summary of Well RRGI-6	31
Drilling and Construction Summary of Well RRGI-7	34
Review Comments	38
V. WELL LOGGING AND TESTING	42
Borehole Geophysical Analysis	42
Introduction	42
The Logging Program	42
Induction Log	43
SP Curve	44
Acoustic, Density, Neutron Logs	45
Other Borehole Tools/Miscellaneous Indicators for Fracture Detection	47
Injection Zone Testing	47
Pump and Injection Tests	47
Review Comments	54
First Case	54
Well RRGI-7	56
VI. AREA OF REVIEW CALCULATIONS	58
Potential Injection Formulation	58
Review Comments	62
VII. GEOTHERMAL FLUID CHARACTERISTICS AND COMPATIBILITY TESTS	65
Water Chemistry	65

TABLE OF CONTENTS
(Continued)

	Page
Water Compatibility Test	67
Filter Studies	71
Review Comments	73
VIII. MONITORING WELL PROGRAM	77
General Ground-Water Trends and Test Responses	77
Individual Monitoring Well Responses	79
Review Comments	82
IX. SUMMARY	85
REFERENCES	
APPENDIX A: Conversion Factors	
APPENDIX B: Permit Application Checklists	

LIST OF FIGURES

Figure		Page
1	Raft River Well Field Location (from Dolenc et al, 1981).	5
2	Location and Construction Features of Raft River Well System (from Dolenc et al, 1981).	9
3	Raft River Valley and Major Structural Features Adjoining the Valley (from Dolenc et al, 1981).	16
4	Water Level Contours in the Raft River Valley (from Walker et al, 1970).	19
5a	An Early Interpretation of the Bridge Fault Zone (from Dolenc et al, 1981).	22
5b	A Later Interpretation of the Bridge Fault Zone (from Dolenc et al, 1981).	22
6	Site Suitability for Deep Well Injection (from Reeder et al, 1977).	25
7	Seismic Risk Areas of the United States (from Algermisen, 1969).	29
8	Well Construction of RRGI-6 (from Miller and Prestwich, 1979a).	33
9	Well Construction of RRGI-7 (from Miller and Prestwich, 1979b).	37
10	Bulk Density-Porosity Plot from Schlumberger Modified to Show Raft River Rock Types (from Dolenc, et al 1981).	46
11	Pressure Buildup During Injection Test of Well RRGI-6 (from Dolenc et al, 1981).	50
12	Pressure Buildup During Injection Test of Well RRGI-7 (from Dolenc et al, 1981).	51
13	Plot of Pressure Buildup Data from an Injection Test of the Mt. Simon Formation in Ohio (from Everett, 1980).	55

LIST OF TABLES

Table		Page
1	Logs Run on RRGI-6 (from Dolenc et al, 1981).	32
2	Logs Run on RRGI-7 (from Dolenc et al, 1981).	35
3	Summary of Well RRGI-6 Parameters (from Dolenc et al, 1981).	52
4	Summary of Well RRGI-7 Parameters (from Dolenc et al, 1981).	53
5	Predicted Pressure Response (kPa) at the end of 1 Year (t_1) and 3 Years (t_3) of Operation, at 85% Usage, in Each Well (from Dolenc et al, 1981).	59
6	Selected Physical and Chemical Data from the Raft River Project Wells (from Dolenc et al, 1981).	66
7	Water Compatibility for Geothermal Wells RRGE-1, RRGE-2, RRGE-3, RRGP-5 and RRGI-6 (from Dolenc et al, 1981).	69
8	Monitoring Well Summary (from Dolenc et al, 1981).	78

I. INTRODUCTION

Background

The Safe Drinking Water Act (SDWA) was adopted in 1974 in an effort to correct deficiencies of the Clean Water Act of 1972. The SDWA incorporated several provisions relating specifically to ground-water protection.

Among these provisions is the requirement that the U.S. Environmental Protection Agency (EPA) develop minimum requirements for state programs regarding the protection of underground sources of drinking water (USDWs) from pollution by subsurface fluid injection. The SDWA also requires that EPA adopt and administer an Underground Injection Control (UIC) program in states failing to meet those requirements or in those states that decline primacy with regards to a UIC program. In administering the UIC program, the responsibilities of each EPA regional office will include reviewing permit applications for injection facilities.

Purpose and Scope

Under EPA Contract #68-01-6288, Task #8, SMC Martin was requested to prepare an injection well procedures manual which would provide EPA Region X with assistance in the evaluation of injection well permit applications. The manual discusses a real world example of an injection well located in a complex hydrogeologic setting and is written for an audience familiar with injection well technology,

hydrogeology and the Underground Injection Control Program (UIC). The case study was to be used as an aid to the Regional staff to review, condition and approve or disapprove a permit application.

The selected case study describes operations at the Raft River Geothermal Field, Idaho. The case study includes detailed discussion and analysis on the site geology and hydrogeology, disposal well siting, construction and completion techniques, geophysical and mechanical integrity testing, area of review calculations, wastewater characteristics and compatibility tests, and design of the monitoring well network. These topics were chosen on their importance in the siting and permitting of an injection facility under the UIC program, and the availability of information to develop suitable evaluations of the injection well system.

Use of Manual

The case study presented in this manual is the Raft River Geothermal Project, Idaho operated by U.S. Department of Energy. The technical investigations were prepared and reported by EG&G, Idaho. In the preparation of this case study, information was extracted from several published EG&G reports. This case study was not intended to represent a precise summary of all facets of the Raft River operation, but only to present selected data relevant to a permit reviewer.

The case study is written in an instructional format. Although the case study wells are Class V geothermal injection wells, the requirements of the UIC program for all five classes of injection wells and additional geologic and engineering factors are discussed. At the conclusion of a section or chapter, critical topics which should be considered in the approval or disapproval of a permit application are noted. A discussion is then presented for each topic considering basic geologic rationale and the UIC program requirements. In addition, the reader is given technical questions to answer or evaluate in several chapters.

Figures in this manual were taken directly from several publications and contain metric and/or English units. Unit conversion procedures were not attempted on the manual's figures. The permit writer must be knowledgeable of both unit systems since permit applications may contain either unit system. Conversion factors are given in Appendix A to aid the permit writer.

II. PROJECT HISTORY

The Raft River Geothermal 5MW(e) Pilot Plant, located in the Raft River Valley of south-central Idaho, utilizes a supply and injection system which is an integrated network of production and injection wells designed to supply the power plant with moderate temperature geothermal fluid. This network consists of three designated production wells: one backup production well; two injection wells; several monitoring wells, and one deep-well whose production was too low for pipeline connection (Figure 1).

In late 1974 and early 1975, after an extensive feasibility study for a geothermally based electric generating station was completed, a cooperative venture was initiated by the U.S. Department of Energy's Idaho Operations Office (DOE-ID), the Raft River Rural Electrical Cooperative, and the Idaho Department of Water Resources (IDWR), to drill a geothermal exploration well in the southern Raft River Valley of Idaho. The U.S. Geological Survey (USGS) conducted an intensive exploration program to define an optimum location for a production well in 1973-1974; the site ultimately selected was located between two shallow boiling water wells along the southwest alluvial fan of the Jim Sage Mountains. A major consideration in selecting this location was the anticipated interception, at depth, of the Bridge Fault.

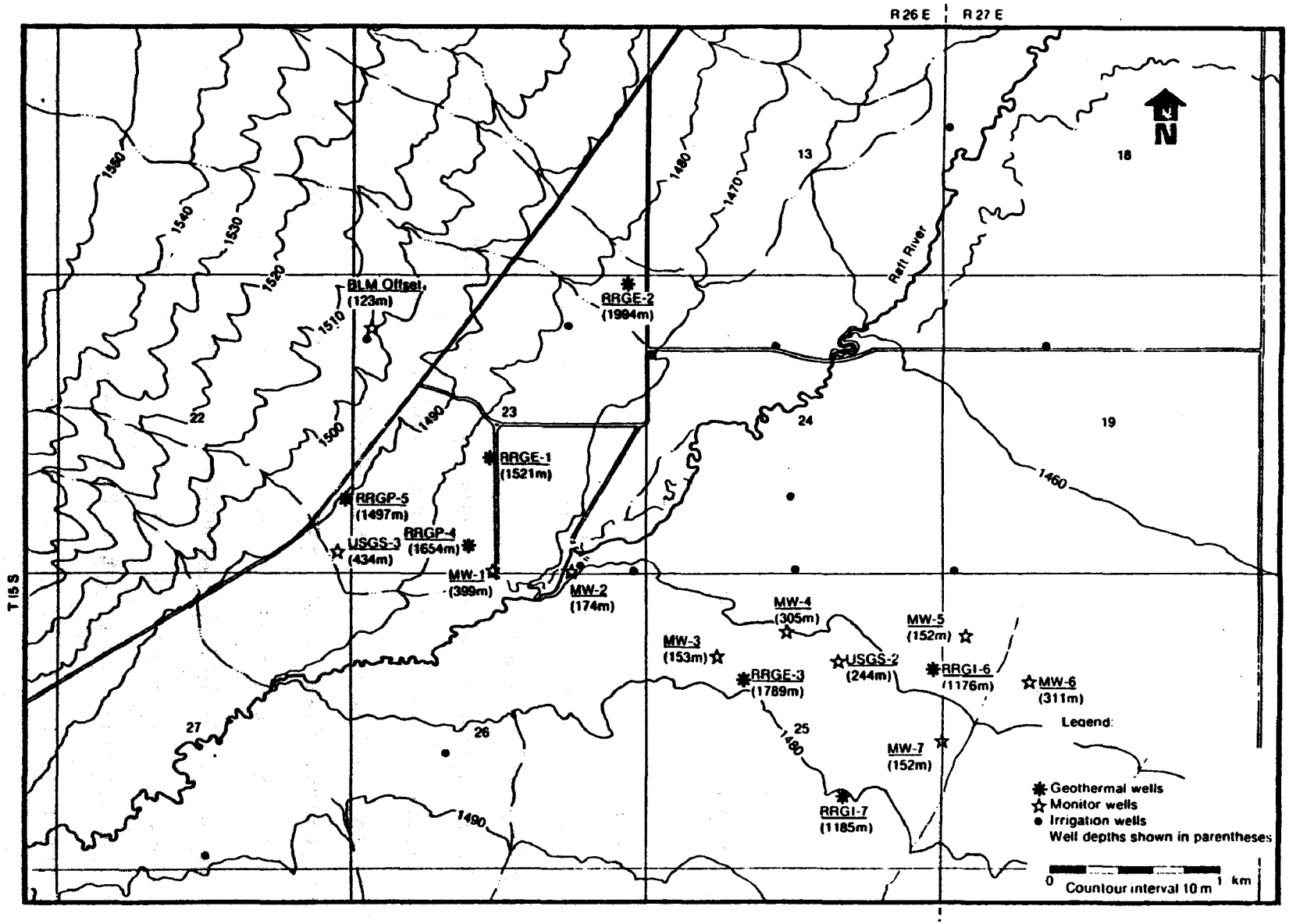


Figure 1. Raft River Well Field Location (from Dolenc et al, 1981).

The Raft River Geothermal Exploration Well No. 1 (RRGE-1), drilled to a total depth of 4,990 feet (1,521m), approximately 500 feet (152m) into basement rock, encountered 295°F (146°C) bottomhole temperatures with an artesian flow. This well verified the existence of a low-salinity hydrothermal resource approaching 300°F (150°C). The major production zone in RRGE-1 was found from 3,700 feet (1,128m) to 4,500 feet (1,372m).

A second exploration well, RRGE-2, spudded in approximately one month later, was also designed to intercept the Bridge Fault at depth. The well was drilled to a total depth of 4,987 feet (1,825m), over 980 feet (300m) into the Precambrian basement rock. The major production zone encountered at this well location was from 4,249 feet (1,295m) to 4,800 feet (1463m). Fracturing of the zone from 5,000 feet (1524m) to 5,200 feet (1,585m) contributed little to the artesian flow of this well.

After a period of flow testing, wells RRGE-1 and RRGE-2 were injection tested for about five months. In 1976, RRGE-2 was deepened to a total depth of 6,540 feet (1,994m). As no fractured sections were encountered, this deepening of the well did not result in any significant increase in flow.

In 1976, RRGE-3 was spudded 900 feet (274m) southeast of RRGE-2. This well was drilled to determine if the geothermal resource extended beyond the fault zone in the center of the

valley. This well was originally planned to have three directional legs in an attempt to increase production and minimize well drilling costs. The deepest leg, drilled to a total depth of 5,920 feet (1,804m), produced the highest flow rate of all the legs. The maximum fluid temperature encountered was 302°F (150°C), but the flow from the three legs was less than that from RRGE-1 and RRGE-2.

Based upon the drilling experience with the RRGE-1 and RRGE-2 wells, namely, the encountering of a permeable zone between 1,600 feet (448m) and 3,000 feet (915m) the fourth geothermal well, RRGI-4, was drilled with the intent of its use for return injection purposes. This well, spudded in 1977, was drilled to a total depth of 2,840 feet (866m) and uncased from 1,900 feet (580m) to its total depth.

Injection testing of RRGI-4 in 1978 revealed significant pressure responses in nearby monitoring wells MW-1, USGS-3, and BLM offset. An increased water level in the monitoring wells during injection testing indicated that a hydraulic connection existed between the injection zone and the shallow aquifer system, and that the use of RRGI-4 as an injection well could result in contamination of the shallow aquifer system.

As a result of these injection tests, the decision was made that injection operations would be more appropriate in a deeper zone near the RRGE-3 well. Consequently, RRGI-6 was spudded in 1978, and drilled to a total depth of 3,845 feet

(1,172m). The well was uncased (open hole) from 1,700 ft (518m) to the total depth, leaving a large zone for injection. Indications are that the zone can accept up to 850 gpm (536L/s).

As it had become evident that the geothermal reservoir was fracture controlled, another attempt was made to intercept the Horse Well and/or Bridge Fault systems at depth with RRGP-5. An additional injection well, RRGI-7, was drilled 2,300 feet (700m) southwest of the RRGI-6 well and was nearly identical in construction with RRGI-6. It was cased to 2,040 feet (622m) and uncased (open hole) to its total depth of 3,845 feet (1,172m).

Drilling at the project site was completed in 1978 with the deepening and conversion of RRGI-4 (determined unsuitable for injection because of hydraulic connection with shallow aquifer system) into a production well (RRGP-4). Originally planned as triple-legged well, only two legs were drilled because of low flows encountered and funding constraints. The legs were drilled to a total depth of 5,420 feet (1,652m) and 5,510 feet (1,558m), but maximum artesian flow realized was only about 51 gpm (3.2L/s). In order to attempt to stimulate the flow in one leg of RRGP-4, hydraulic fracturing was performed. Well construction details and well locations are shown on Figure 2.

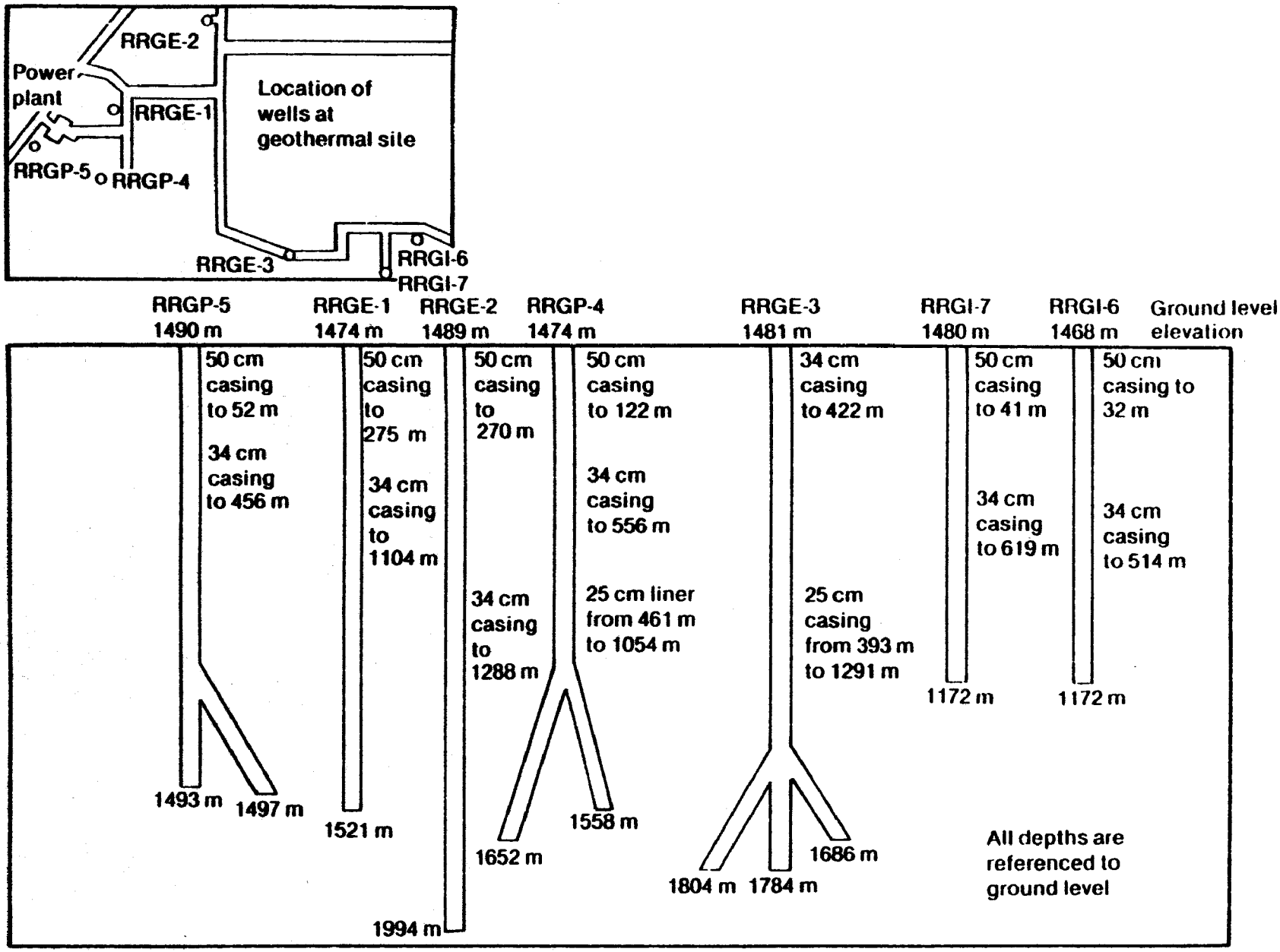


Figure 2. Locations and Construction Features of Raft River Well System (from Dolenc et al, 1981).

Deep well injection disposal of produced brine water was chosen for several reasons:

1. A high volume discharge stream does not exist in the Raft River Valley. The Raft River is a perennial/intermittent stream with a low discharge rate and sensitive ecosystem;

2. Recycling or a usable conversion of the hot brine waste fluid is impractical and uneconomical at this time; and

3. No acceptable alternative methods of brine disposal exist in the nonpopulous area of the Raft River Valley.

III. PHYSICAL SETTING

Geography

The Raft River Valley in south-central Idaho is a 250 square mile basin bound on the east by the Black Pine Mountains and the Sublett Range, on the west by the Jim Sage and Cotterel Mountains, and on the south by the Raft River Range. The valley opens onto the Snake River Plain to the north. The Raft River enters the basin at the south end of the Jim Sage Mountains and flows northward (Figure 1). The Known Geothermal Resource Area (KGRA) is located at the south end of the valley near the Idaho-Utah border. The wells are depicted in Figure 2. The present topography near the KGRA is characterized by coalescing alluvial fans and pediments fringing the flood plain of the Raft River.

The habitat of the Raft River Valley is a delicate cold-desert ecosystem which is very susceptible to degradation. Once destroyed, it is difficult to re-establish this ecosystem and a long period of regeneration is required. The vegetation communities are dominated by low-growing shrubs and forbs which support a diverse wildlife population.

The Raft River is the only significant stream in the area and plays an important part of the valley's ecosystem. The many cultivated fields within and surrounding the project site depend entirely on ground water for irrigation. Ground-water withdrawal has increased substantially since 1948, and

in 1963, the State of Idaho declared the basin a critical ground water area closed to further ground-water development. Cultivated fields with irrigation wells are located directly north and west of the two project injection wells.

Several small communities exist in the Raft River Valley; however, no communities or housing occur within the geothermal project site.

REVIEW COMMENTS

Note: 1) Size and shape of basin

2) Sensitive ecosystem

3) Importance of Raft River

4) Heavy dependence on ground water

5) Cultivated fields and irrigation wells to the north and west of injection wells

6) Sparsely populated area

1) The Raft River Valley comprises a relatively small basin, only about 250 square miles. The amount of injection capacity is directly related to the size of the basin. The basin is bounded by mountain ranges with the only discharge outlet to the north.

2,3) The permitting authority should recognize the serious physical effects of any ground-water contamination in this area. The Raft River is an effluent stream gaining its base flow from ground water during low precipitation periods and supports a delicate ecosystem. Any ground-water contamination poses a significant threat to the river.

Questions: Are the injection well locations sited to help prevent any possible contamination of the river?

What is the direction of ground-water flow and its discharge points? Remember ground-water flow lines are perpendicular to the equipotential/piezometric surface contour lines in homogenous, isotropic aquifers. Typically, heterogenous and anisotropic conditions exist and must be adequately characterized for an aquifer before accurate determinations of flow rate and directions can be made.

4,5) The potential impact of ground-water contamination on the area's agriculture should be noted. The permit applicant must know the depth of local irrigation wells and USDW zones. The number and location of these wells must be determined for the area of review calculations as discussed in Section VI.

6) One positive aspect of the injection well sites is that they are in a sparsely populated area containing few domestic wells. The permit applicant must notify any surrounding landowner or tenant of the land within one-quarter mile of the injection site. If an area permit is obtained, only one notification is necessary for the entire project.

Geology

General

The Raft River KGRA lies in a north-south trending, structurally-downwarped Cenozoic basin. The bounding mountain ranges differ stratigraphically, being composed of a) primarily Paleozoic limestones (Black Pine Range), b) Precambrian gneiss mantled by allochthonous Paleozoic metamorphosed and nonmetamorphosed rock (Raft River Range), c) Tertiary rhyolites and tuffaceous sediments (Jim Sage Mountains) (Figure 3).

The basin fill consists of poorly consolidated sediments derived from the surrounding mountain ranges. The upper sediments are lenticular deposits of alluvial, fluvial, and loessal origin known as the Quaternary alluvium and colluvium, and the Pleistocene Raft River Formation. The lower sediments are marine deposits of sand, silt, minor conglomerate, and tuff of the Tertiary Salt Lake Formation. These rocks directly overlie a series of Precambrian metasediments capping an intruded quartz monzonite basement. All of the exploratory and production wells, RRGE-1 through 4 and RRGP-5, penetrate the total thickness of the basin sediments and are terminated in the quartz monzonite basement. The injection wells, RRGI-6 and 7, are terminated in, and open to, fractured and porous Salt Lake Formation rock.

Stratigraphy

The surface sediments are Quaternary alluvium and colluvium. Underlying these deposits is the Pleistocene

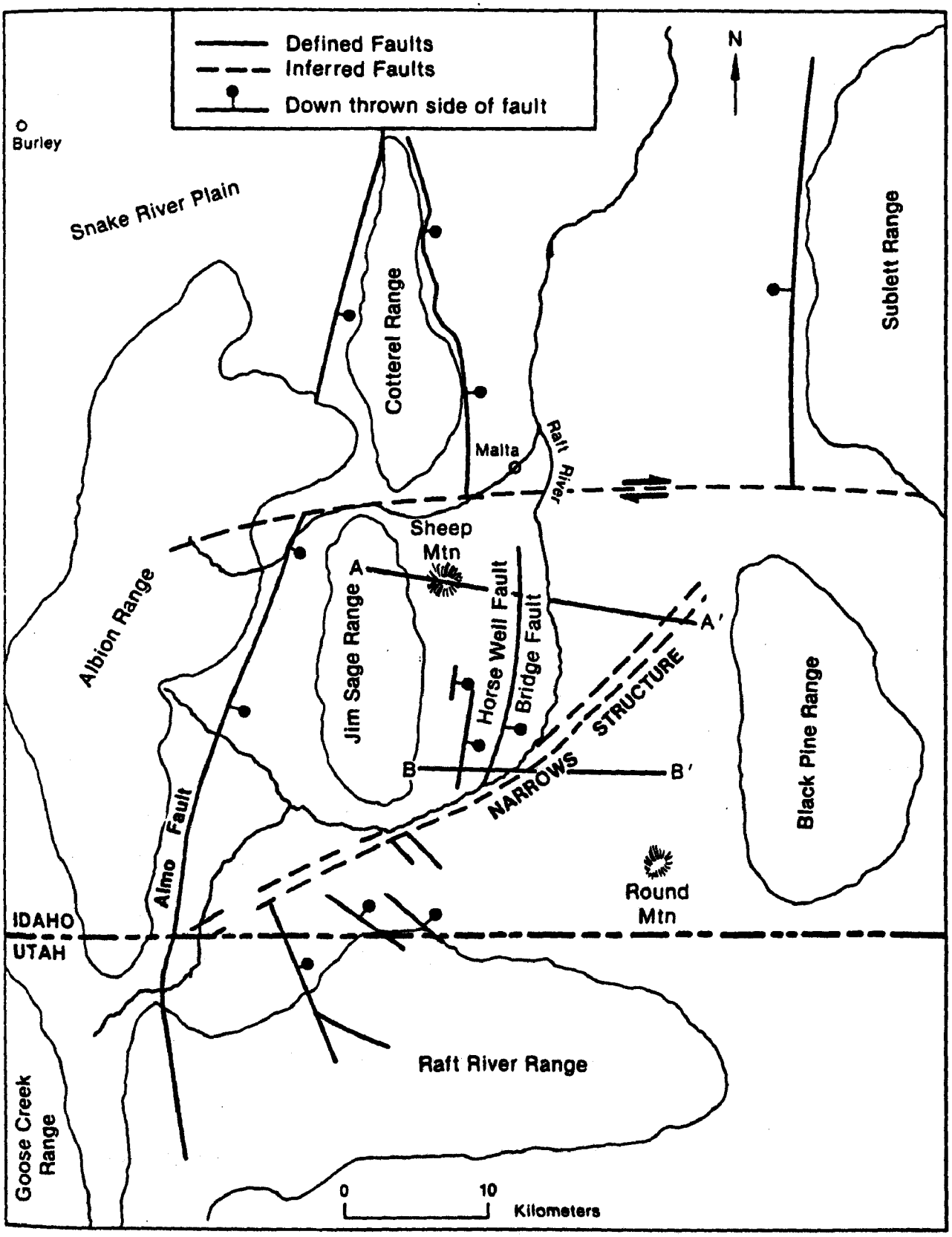


Figure 3. Raft River Valley and Major Structural Features Adjoining the Valley (from Dolenc et al, 1981).

Raft River Formation which consists of unconsolidated quartzose sand and silt, tuff, and minor rhyolitic gravels. The sediments are poorly sorted, angular, and reach up to 1,000 feet in thickness. Cuttings from shallow monitor wells at the KGRA indicate a fluvial and alluvial depositional environment much like the present. The lenticular nature of deposition makes well-to-well correlation of sediments impossible.

The Tertiary Salt Lake Formation underlying the Raft River Formation is a lacustrine deposit up to 2,500 feet in thickness. No definitive break occurs between the relative abundance of volcanic material which increases downward into the lacustrine deposits. The Salt Lake Formation consists of light green, thin-bedded to massive, tuffaceous siltstone and sandstone with minor amounts of shale and conglomerate. Quartz and feldspar are the most abundant minerals present.

Hydrothermal alteration in both the Salt Lake Formation and the Raft River Formation has resulted in: replacement of the primary calcite by silica; fracture filling by secondary calcite; clay mineral alteration; and the emplacement of secondary minerals, i.e., biotite and muscovite, and pyrite and other sulfides. Calcite fills the fractures, and the silica forms a "caprock" above the geothermal reservoir.

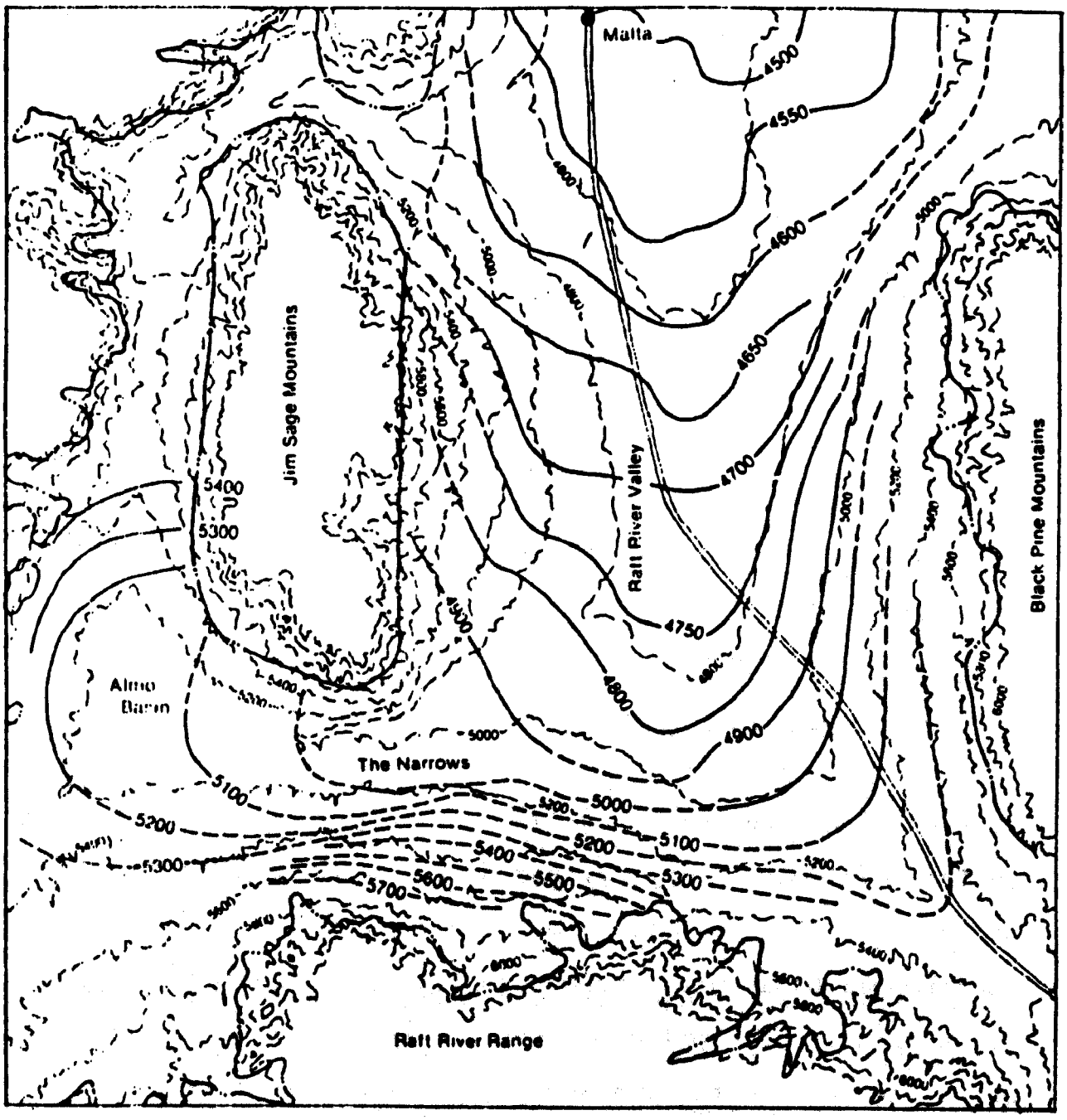
The Salt Lake Formation unconformably overlies part of the Precambrian rock assemblage. The metasediments and adamallite basement rocks in the basin appear flat lying

with no major identifiable structures based on reflection seismic surveys. Low-angle faults have probably thinned or erased the units, with movement related to that seen in the Raft River Range. The upper part of the stratigraphic section seen in the Raft River Range, Cambrian through Mississippian units, are absent in this part of the valley.

Hydrogeology

Ground water in the basin occurs in both unconfined and confined conditions in the poorly consolidated sediments of the Salt Lake Formation, the sands and gravels of the Raft River Formation, and Recent alluvial deposits. Recharge to these aquifers results directly from local precipitation and from infiltration of surface water and irrigation runoff. Depth to the water table in the basin varies from the surface to 100 feet (Figure 4).

The shallow aquifers are considered phreatic, although some wells reveal locally confined conditions. Nearly all water encountered below 990 feet (300m) is confined. Piezometric levels in these deeper aquifers in the geothermal area range from 100 feet (30m) to more than 330 feet (100m) above land surface. Because of the increase in head with depth, each aquifer is probably recharged in part by upward leakage from underlying aquifers through fractures. This is especially evident in the geothermal area, where wells as shallow as 390 feet (120m) tap hot water. Nearly all irriga-



—4700— Water-level contour
Dashed where position uncertain
Contour intervals 50 and 100 feet

- - -5000- - - Ground level contours

Figure 4. Water Level Contours in the Raft River Valley (from Walker et al, 1970).

tion wells in the area show some thermal and chemical evidence of upward leakage from the geothermal resources.

Water levels in the shallow aquifer near the Raft River have declined over the past 30 years due to extensive irrigation pumping. Analysis of five years of water level data from USGS-2 (a 787 feet [240m] deep core hole) verified this trend. Two years of ground-water records from the monitor wells are inconclusive for long-term trends.

Seasonal water-level changes are apparent in several monitor wells. A water-level high occurs in early spring, reflecting shallow recharge. Water levels decline between mid-spring and the end of the irrigation season. A steady water-level rise then occurs as a result of the termination of irrigation pumping.

Geological Structure

The geologic structure of the Raft River Basin near the KGRA has been studied extensively using geophysical techniques, surface geological mapping, and aerial photography. The gross structure, as defined by gravity techniques, is a downdropped basin with steep normal faults inferred at the range fronts. The principal faults exposed at the surface which lie in a north-trending zone on the west side of the valley are called the Bridge Fault Zone and Horse Well Fault Zone. South of Sheep Mountain the fault zone widens to the west and distributes vertical displacement between a series

of normal faults trending slightly east of north. Surface dip of the faults is 60 to 70°. An early interpretation of the Bridge Fault Zone shows continued steep dips to depth, displacing the metasediments and quartz monzonite basement (Figure 5a). A later interpretation infers a shallowing of dip with depth, flattening to parallel the bottom of the Tertiary sediments, with no displacement of the basement (Figure 5b). Covington (1976) postulates that movement on the concave upward faults produced many near vertical open fractures near the base of the Tertiary sediments.

The Bridge and Horse Well Fault Zones are terminated north of the Raft River by a poorly understood geologic structure called the Narrows Zone. This structure trends to the northeast across the basin and is thought to be a basement shear associated with a large regional feature called the Humboldt Zone. The Narrows Zone is inferred by a compilation of anomalous data from geophysical surveys that suggest major changes occurring in a northeast trend.

The geothermal system in the Raft River Basin occurs at the intersecion of the Narrows Zone and the Bridge Fault Zone. Hydrothermal water is believed to circulate to depth along basement fractures, possible along the southwest extension of the Narrows Zone, then rises at the intersection of the two major structures where it spreads laterally into the Tertiary sediments. Upward leakage through fractures in

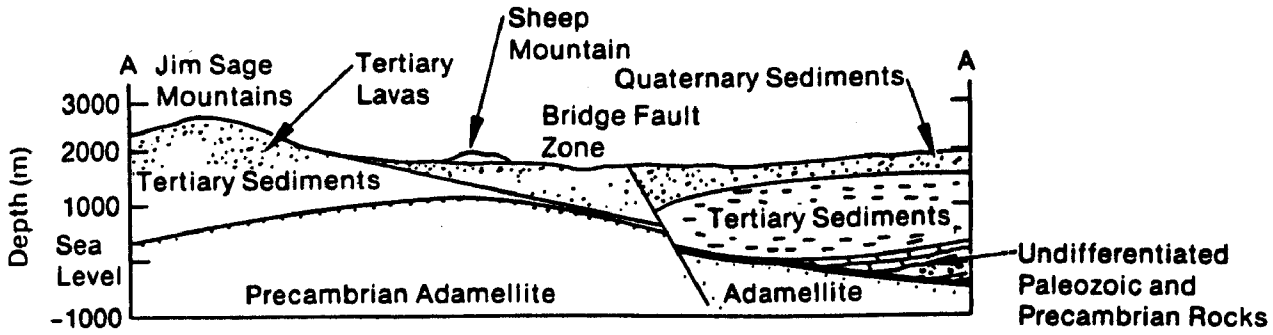


Figure 5a. An Early Interpretation of the Bridge Fault Zone (from Dolenc et al, 1981).

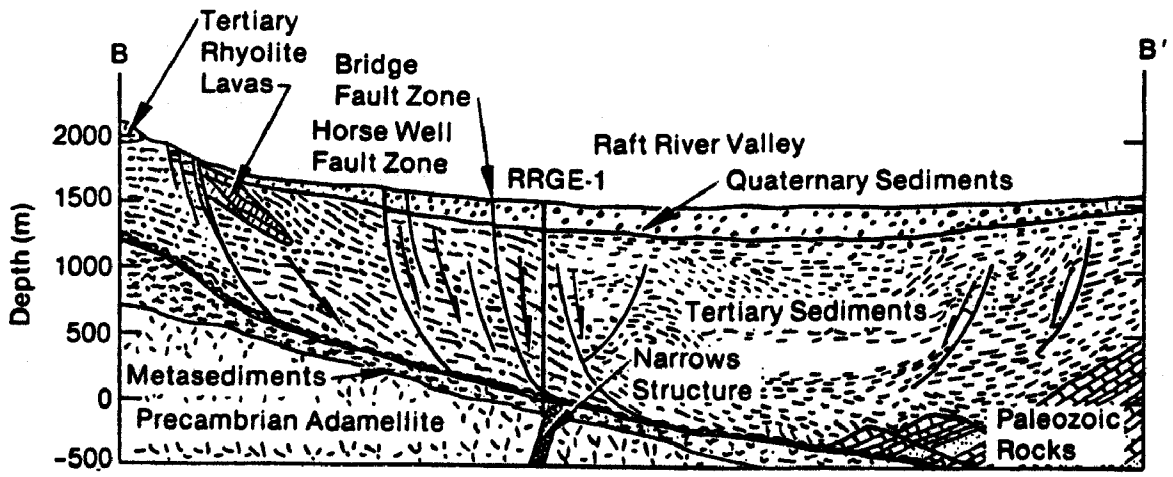


Figure 5b. A Later Interpretation of the Bridge Fault Zone (from Dolenc et al, 1981).

the Salt Lake Formation provides hot water to the shallow hot wells in the valley (Crook and BLM wells). No evidence of a local heat source is apparent.

REVIEW COMMENTS

Note: 1) Structural and stratigraphic basin

2) Unconsolidated surface alluvium and Pleistocene Raft River Formation

3) Consolidated Tertiary Salt Lake Formation

4) Basement and metasediment rocks

5) Faulting and fracturing in Tertiary and basement rock

6) Seismic risk in Raft River Valley

7) Structural analysis

1) The Raft River Valley is a structural and stratigraphic basin with a significant thickness of sedimentary rock. Although major synclinal basins are geologically more favorable sites for deep well injection, the Raft River Valley appears to have an acceptable thickness of sedimentary rock over an areal extent suitable for the geothermal project. Because this geological-complex basin and range area is surrounded by impermeable igneous and metamorphic rock, the reserve capacity to receive volumes and injected wastes is considered small and must be calculated (Figure 6).

2) The shallow ground-water aquifers in the Raft River Valley consists of the surface alluvium and the Raft River Formation. These unconsolidated sand and gravel units are classified underground sources of drinking water (USDW) and must be protected from any contamination under the

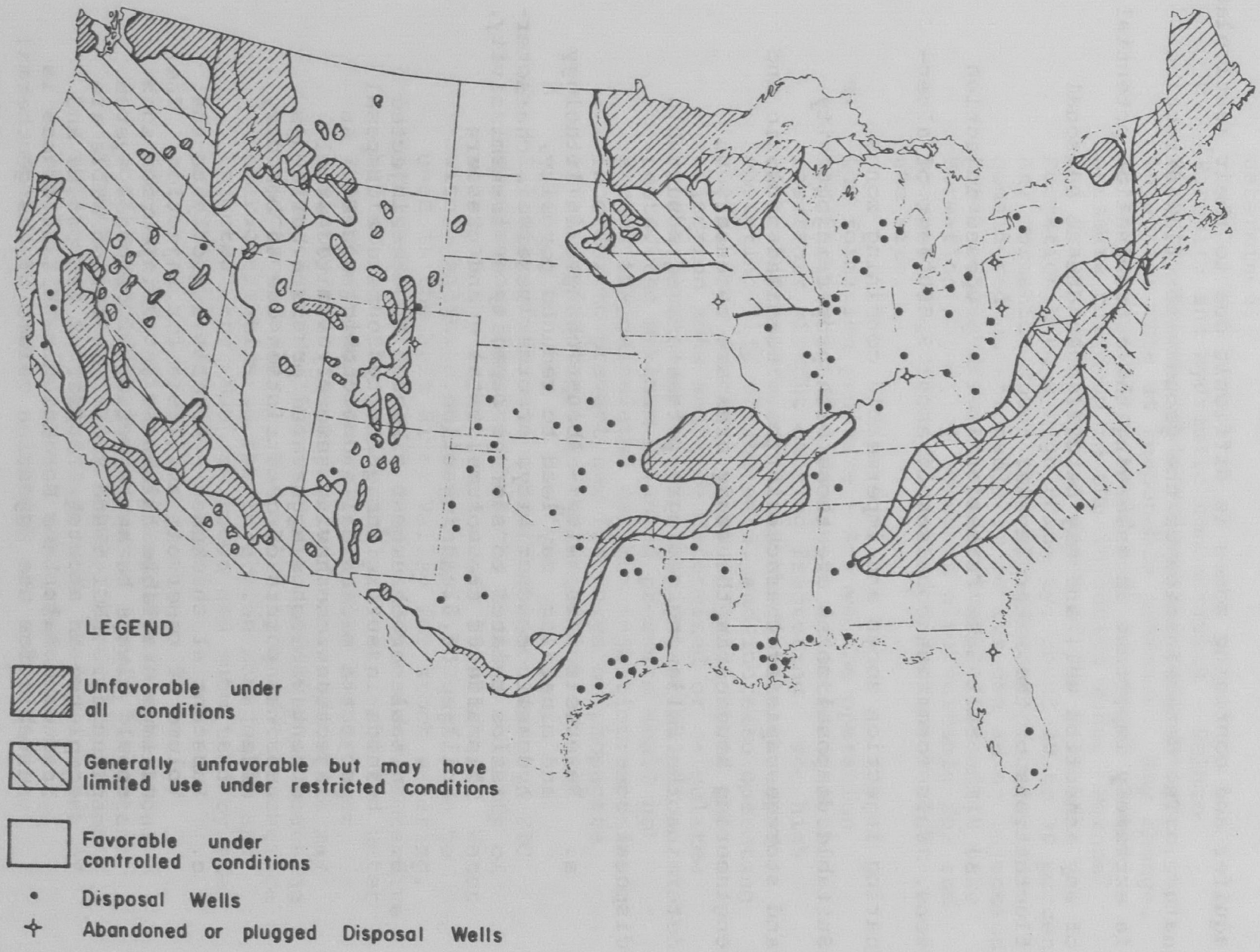


Figure 6. Site Suitability for Deep Well Injection (from Reeder et al, 1977).

provisions of the UIC program. Mapping of the various aquifer and confining zones is difficult due to their lenticular nature. The determination of the groundwater flow direction is extremely important in assessing the contamination potential of any injection well and may be difficult due to seasonal fluctuations of the water levels.

3) The Salt Lake Formation is the proposed injection zone. This formation consists of about 2,500 feet of alternating injection zones and impermeable confining zones. Suitable disposal zones are those with proper injectivity and storage capacity characteristics. Detailed geologic and engineering studies in the study area are necessary to determine the following geologic parameters of a suitable disposal zone:

a. Reservoir uniformity - Abrupt changes in lithology and mineralogy may lead to reduced porosity, hydraulic conductivity, or other reservoir characteristics related to storage capacity or transmissivity. This affects the volume, rates , and pressure build-up of fluid injection.

b. Suitable areal extent - Needed to take injected fluids in sufficient quantity to make a disposal project a mechanical and economic success. An injection zone having severely limited areal extent will show aggravated pressure build-ups near the points of constriction due to boundary effects.

c. Substantial thickness - Relates directly to the volume of reservoir available for injection. The maximum available thickness in an injection zone should always be an objective of disposal system planning. RRGI-6 and RRGI-7 injection wells are completed in about 1,800 feet of the porous and fractured Salt Lake Formation. This thickness is suitable for the injection volume of the geothermal

project. Areal changes in thickness must be determined.

d. Porosity and hydraulic conductivity - Relate directly to available volume and indirectly to the injection rate at reasonable pressure. Any changes in these parameters would have an impact on the pressure build-up in the injection zone. Porous and fractured injection zones of the Salt Lake Formation have a high porosity, about 20 to 30 percent. Any formation lower than ten percent porosity is considered questionable as to its use as an injection zone. The hydraulic conductivity of the Salt Lake Formation injection zones is also suitable for the proposed injection volume and injection rate at the site.

e. Low formation pressure - Allows the operation margin at which fluids can be injected into the reservoir without causing fracturing. Too high initial pressure may limit the intake rate and operating life of the well, and increase operating costs. The fracture pressure gradient of the injection zone shall be determined or calculated by the permit applicant. Besides stimulation tests, the maximum wellhead pressure shall not exceed the calculated maximum injection pressure in order to prevent new fractures or propagate existing fractures in the injection zone.

f. Salinity of formation and injection water - UIC regulations require that the minimum salinity of water in the injection zone is 10,000 mg/l. Water with a salinity of less than 10,000 mg/l can be used in the Raft River Valley for stock watering, irrigation of certain crops and use as a protective buffer. In the geothermal project, injected water from the production well actually has a lower salinity than the injection zone water which may cause clay swelling, reducing porosity and causing injection failure. The salinity and other chemical characteristics of the injection zone water and injected water must be known and submitted by the permit applicant.

g. Adequate overlying confining layers - Vertical confinement of injected waste is very important for the protection of USDWs. Several tuff and tuffaceous siltstone layers in the upper part of the Salt Lake Formation may act as overlying confining zones. Although not automatically

required under UIC regulations, a desirable permit condition for many operations may be the prior field determination of porosity and hydraulic conductivity of each confining stratum. This data would assist in the evaluation of a confining layer's adequacy.

4) Confining pressure in the basement geothermal production zone is greater than the injection zone pressure causing an upward leakage of fluid. In most cases, the salinity of water and the hydrostatic head increases with depth. Occasionally, a fresh water zone may be beneath a possible injection zone. An underlying confining layer is of major importance in such a case.

5) The faulting and fracturing in the Tertiary and basement rock should be of major concern. Although fracturing in the basement rock provides a flow path for geothermal water, it also acts as a contamination pathway from the Salt Lake Formation injection zone into the water-bearing Raft River Formation. An increased water level in observation wells during injection into RRGI-4 determine that the hydraulic connection exists between the shallow aquifer system and the injection zone in the west-central part of the project site. A proposed injection well (RRGI-4) was deepened and converted into a production well (RRGP-4) because of the extensive fracture system encountered in the well. Injection testing and the development of an extensive monitoring system must be performed to confirm any hydraulic relationship between the injection zone and USDW(s).

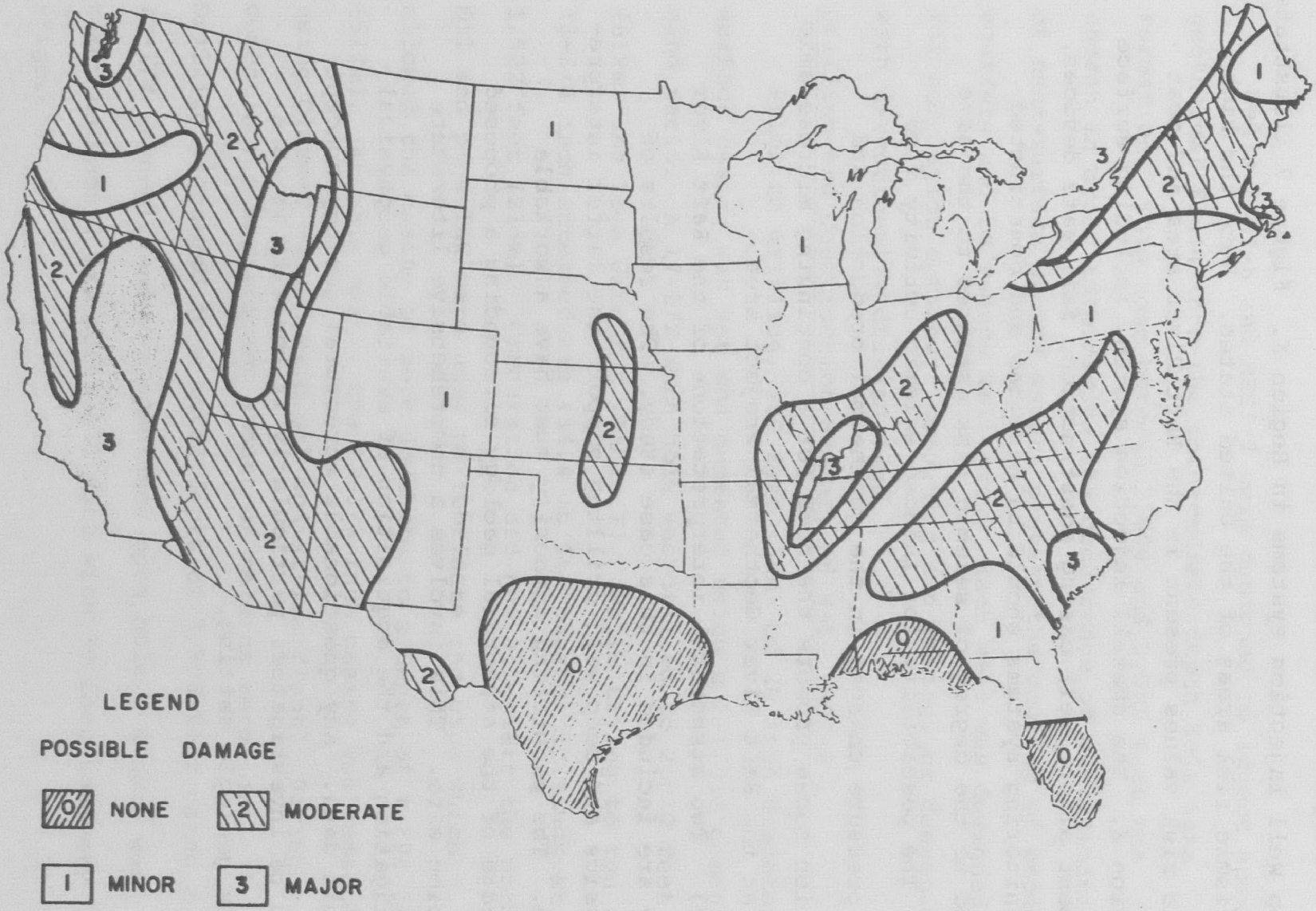


Figure 7. Seismic Risk Areas of the United States (from Algermisen, 1969).

6) Seismic risk should be considered in the planning of deep well injection systems in Region X. Figure 7 illustrates the seismic risk areas of the United States. Note the high seismic risk values present in the Raft River area and most of Region X. The overall injection system, including surface treatment plant, well casing construction, fail safe devices, and monitoring systems should be designed and constructed related to the degree of seismic risk assigned to the site area. The possibility for induced seismic activity from local pressure changes in the geothermal production and injection zones prompts the need for a continuing microseismic study at the Raft River Geothermal Project area.

7) Two structural interpretations of the Raft River Valley are included in this case study. The results of geophysics and deep well drilling support the latter interpretation. The permitting authority must have a workable knowledge of the structural geology surrounding a proposed injection site. This involves a comprehensive literature investigation and the acquisition of available geophysical and well data. Any questionable structural geology concept should be investigated, particularly if the site is in a complex geologic setting.

IV. WELL CONSTRUCTION AND COMPLETION TECHNIQUES

Wells RRGI-6 and RRGI-7 were designed to inject spent geothermal fluid into the intermediate depth Salt Lake Formation. This zone between 2,000 and 3,500 feet was chosen in order to minimize the occurrence of contamination of near-surface ground water, prevent the cooling of production aquifers and to reduce well cost. Each well was designed for completion options: deepening and casing, or deepening with directionally drilled legs.

Drilling and Construction Summary of Well RRGI-6

Prior to drilling, 100 feet (34m) of 20 inch diameter surface casing was set and cemented using a 2-1/2:1 cement-sand ratio. A 17-1/2 inch hole was drilled to 2,030 feet (619m) and logs were run (Table 1). While trying to run the 13-3/8 inch intermediate (54.4 lb/ft) casing, it stuck at 1,522 feet (215m). Circulation did not alleviate the problem. Oil and pipe lax were used to lubricate the pipe which allowed the casing to move downhole to a depth of 1,698 feet (517m). At this point, the 13-3/8 inch casing was cemented using Class-G cement with gel and silica flour. During cementing, a significant amount of returns were lost. Drilling proceeded to a total depth of 3,858 feet using a 12-1/4 inch bit and was completed open hole. A core was taken between 2,290 and 3,035 feet with 30 feet recovery (Figure 8).

Table 1. Logs Run on RRGI-6 (from Dolenc et al, 1981).

DATE	TYPE	DEPTH (FT)
4/16:4/17/78	Compensated Neutron	100-2017
	Dual Induction (focused)	90-2020
	Acoustilog	100-2011
	Temperature	4-2016
	Caliper	38-2018
	Epilog	120-2020
4/30/78	Differential Temperature	1660-3782
	Acoustilog	1700-3773
	Dual Induction (focused)	1700-3784
	Densilog-Neutron	1700-3789
5/8/78	Epilog	2000-3790

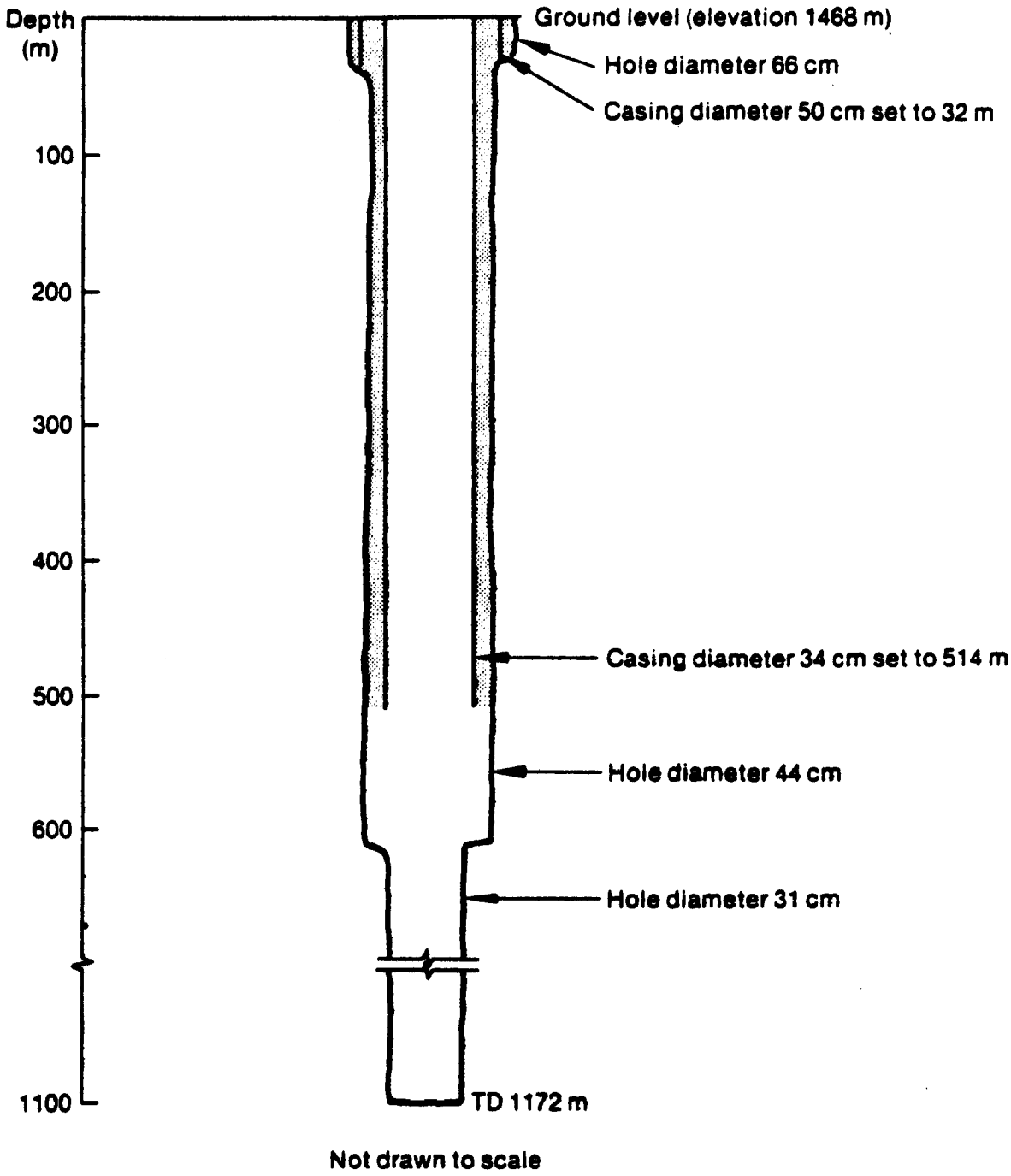


Figure 8. Well Construction of RRGI-6 (from Miller and Prestwich, 1979a).

An eight-hour injection test was run on the well immediately after total depth was reached. Following the testing, the well was airlifted to clean and develop the well, and to remove injected fluid in order to collect formation-water quality samples. After the well recovered, a small artesian flow was maintained.

Mud logging services were conducted during the entire drilling of the well to monitor drilling fluid, cuttings return and fluid temperature. From the mud logging service, the formations were encountered at the following drilled depths:

Alluvium	Surface
Raft River	580 feet (177m)
Salt Lake	1,280 feet (390m)

Drilling and Construction Summary of Well RRGI-7

The drilling and construction of RRGI-7 is similar to RRGI-6. A 20-inch surface casing was set at 150 feet (46m) and cemented with plant-mix concrete. Drilling began with a 17-1/2 inch bit using a low-solids mud. Bit plugging problems developed upon entering gravel sections. Drilling proceeded to 2,054 feet (610m) and the hole was logged (Table 2). After logging, 13-3/8 inch casing was run to a depth of 2,044 feet (623m) and cemented with Class-G cement, gel and silica flour. The blowout prevention equipment (BOPE) was attached to the well and pressure tested before drilling out

Table 2. Logs Run on RRGI-7 (from Dolenc et al, 1981).

DATE	TYPE	DEPTH (FT)
7/31:8/3/78	Epilog	150-3800
7/23:7/25/78	Acoustilog	160-2055
	Differential Temperature	100-2054
	Caliper	10-2016
	Compensated Neutron	160-2050
	Dual Induction (focused)	150-2052
	Densilog	2049-3798
	Acoustilog	2050-3800
	Compensated Neutron	2050-3789
	Differential Temperature	2050-3800
11/14/78	High Resolution Temperature	34-3801
8/1/78	Dual Induction	2050-3789

the casing shoe. The hole was then reentered with a 12-1/2-inch bit and drilled to a total depth of 3,888 feet (1,172m) with open hole. At 3,828 feet, a 30-foot core was cut with a 19-foot recovery (Figure 9). The hole was cleaned and logs were run from total depth to the casing shoe. Several short-term airlift flow tests and injection tests were conducted to stimulate the reservoir, and remove all injected water and cuttings.

Mud logging service was performed during the entire drilling of the well. From the mud logging service, the formations were encountered at the following drilled depths:

Alluvium	Surface
Raft River	510 feet (155m)
Salt Lake	1,180 feet (360m)

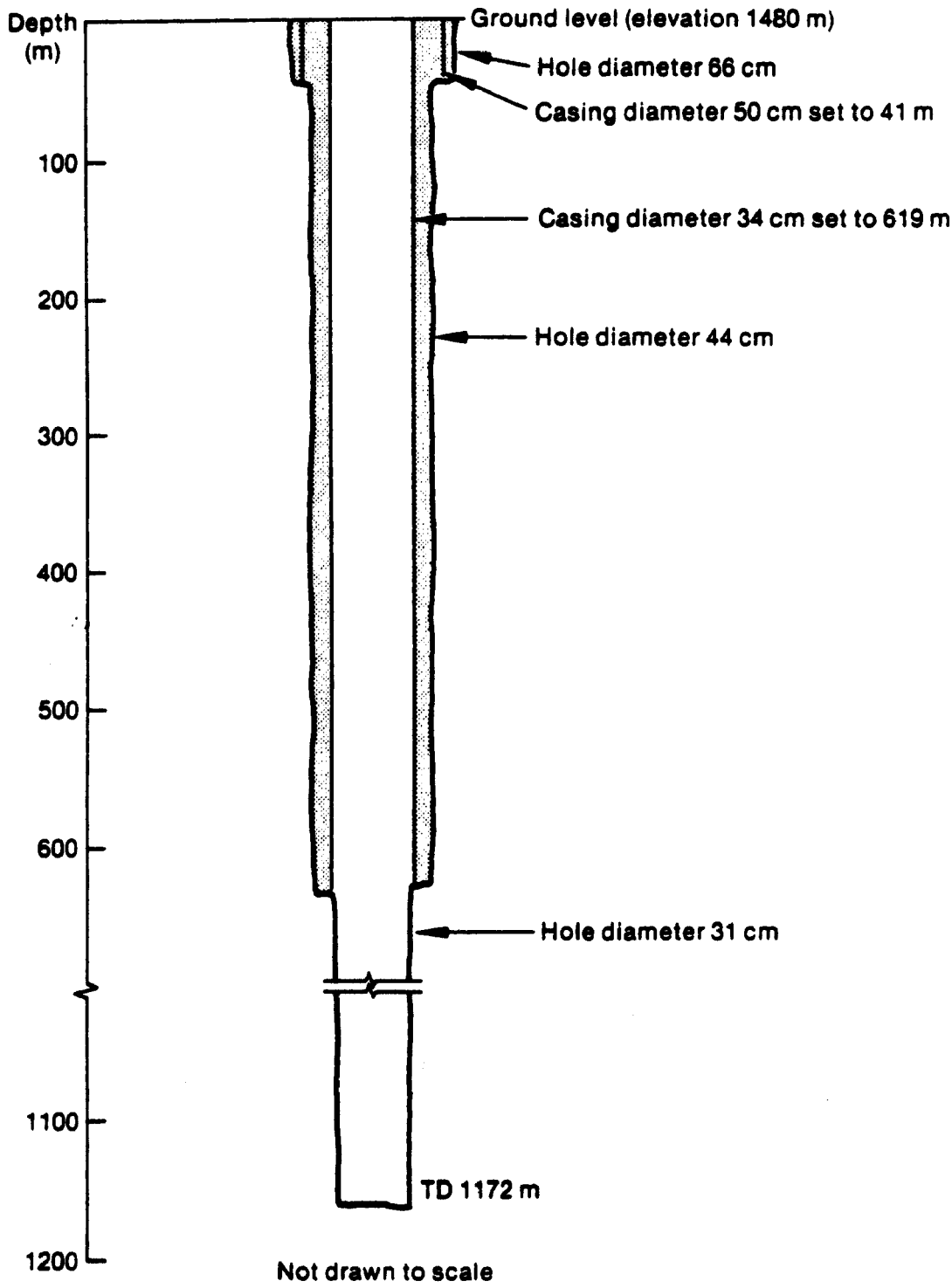


Figure 9. Well Construction of RRGI-7 (from Miller and Prestwich, 1979b).

REVIEW COMMENTS

Note: 1) Selection of intermediate depth disposal

2) Cemented surface casing

3) Casing lubrication on RRGI-6

4) Cemented intermediate casing

5) Geophysical logs

6) Open hole completion - no tubing or packer

7) BOPE and Injection Testing

8) Mud logging service

9) Depths of USDW(s)

1) Two geologic and one economic factor were considered in the selection of using the intermediate zone for disposal. Injection into this zone will minimize ground-water contamination into the surface alluvium and Raft River Formation, the primary sources of ground water in the area. Deep injection below the intermediate depth zone may cool the geothermal heat source and is more costly for drilling and well construction. An increase in formation pressure at depth would also require a higher injection pressure system. The above reasons for intermediate-depth injection into the Salt Lake Formation are valid and reasonable.

2) In both wells, the surface casing has been cemented to prevent any surface contamination from migrating down the annulus. Injection between the well bore and casing is

prohibited in all classes of existing and new injection wells.

3) During the construction of RRGI-6, lubricating agents were used on stuck casing. These lubricants can pose a contamination potential in the well and surrounding area. The exact amount of lubricant and its chemical composition used in the well should be known.

4) The intermediate casing must be cemented beneath the lowermost formation containing a USDW. The casing in both injection wells is of standard weight and size used in the petroleum industry, and is designed for the life expectancy of the well. The American Petroleum Institute (API) approved Class-G cement is a basic cement intended for use to 8,000 feet depth (2,438m) and at high temperature of 200°F (93°C). The cement can be modified with accelerators or retarders to meet a wide range of temperature conditions. Additives were mixed into the Class-G cement to increase strength, temperature rating and decrease porosity. Information about types of cement and its properties may be obtained from Halliburton Services, Duncan, Oklahoma.

5) Numerous resistivity and porosity logs were run in each well before casing was set and cemented. Their purpose was to identify USDWs, injection zones, geothermal production zones and the fresh-saline water interface. Conventional interpretive techniques were used in the upper sedimentary

rock units; however, these techniques were found unreliable in the dense igneous rocks. Further discussion on borehole geophysical analysis is located in Section V of this report.

Question: Can you identify logging methods required by the UIC program and not performed according to this case study? A cement bond, temperature or density log was not performed after cementing to evaluate the bonding between the formation and the casing. Any one of the three above logs is required for all new injection wells.

6) Both Class V injection wells were open hole completion beneath the intermediate casing. Tubing and packers were not used in the completion of the wells which is in accordance with UIC requirements. Class I (except noncorrosive municipal wells) and II wells require tubing and a packer while Class III wells are exempt from this construction requirement.

7) The only known mechanical integrity testing performed on either injection well was a casing pressure test during BOPE operations on RRGI-7. Further mechanical testing of the injection wells may be conducted by monitoring the annulus pressure after completion of the well. Results of such testing should be submitted to the permitting authority periodically.

To monitor for the presence of fluid channels between the casing and well bore, a temperature or noise log should have been run. The volume of cement necessary to fill the annulus between the casing and well bore should be calculated

and compared to the amount used in the well construction. Cementing records may demonstrate that adequate cement had been pumped behind the casing. However, the records may bear little or no relationship to the quality of the cement bonding due to borehole diameter deviations.

8) Although not required by UIC regulations, a mud logging service provides valuable petrophysical and lithological subsurface data. Logs aid in determining the thickness and depth of USDW(s) and confining zones.

9) The base of the lowermost USDW has not been defined and submitted by the permit applicant. No fresh-saline water interface map is included in the report. According to UIC regulations, this significant information must be determined by water sampling or geophysical log analysis and submitted with the additional permit information.

V. WELL LOGGING AND TESTING

Borehole Geophysical Analysis

Introduction

Due to the nature of the project and the subsurface environment encountered, the primary interest attached to the borehole geophysical program was to delineate fractured intervals. Because of the variety of rock types (sedimentary, metamorphic, igneous), the presence of alteration products and the variability of fracturing, conventional interpretive techniques were found to be unreliable. As an example, the log responses to igneous and metamorphic lithologies made it impossible to determine porosities and permeabilities. Therefore, major efforts were performed to use the various interpretive techniques to identify fractures using indicators from the logs, to record characteristic log responses, and to then attempt to define and understand the geologic factors causing these log responses. By cross plotting the various rock types, matrix parameters were able to be determined. These techniques resulted in determining the relevant data necessary to assess a geothermal reservoir and potential injection zones. These methods should be very useful in other injection well applications where igneous and metamorphic environments are encountered.

The Logging Program

The basic suite of logs that were run on each well included: induction, acoustic, density, neutron, caliper,

the spontaneous potential (SP) curve, and temperature. Logs run on Wells 1, 4, 5, 6, and 7 were digitized and stored on magnetic tape.

Induction Log

The induction log is used to measure the resistivity of a formation; values are expressed in ohm-meters. The dual induction log measures three depths of investigation: the shallow reading curve measures the resistance of the invaded zone around the borehole. The deep induction curve measures the entire formation resistivity and must be corrected for borehole size, fluid resistivity, and tool stand-off. The medium induction curve is essentially the same as the deep induction curve but is focused to respond to shallower depths.

The dual induction log indicates the presence of fractures if values obtained from the shallow induction curve are less than those from the deep induction curve. The shallow induction curve is a vertically focused, short spaced resistivity instrument that may respond to thin-bedded formations and/or to vertical fractures when they are filled with filtrate of resistivity lower than that of the formation. The deep induction log reads horizontal conductivity which is presented in the induction log as resistivity. As a result, the presence of fractures in the wall of a borehole

might be detected if the shallow induction curve indicates less resistivity than the deep induction log.

The major drawback to the use of this logging instrument in massive igneous and metamorphic environments is that the natural formation resistivity is usually very high. The high resistance causes the dual induction curves to saturate, and accurate resistivity readings cannot be obtained. In these instances, the dual laterlog resistivity instrument should be used.

SP Curve

The SP method is used to measure natural formation potential and is used to distinguish between sand and shale and to also qualitatively identify porosity and permeability. With the SP as one aid, the resistivity of formation waters can also be determined.

While igneous and metamorphic rocks do not generally display a self-potential, the SP can be used qualitatively to determine the presence of fractures. The SP curve tends to hachure when a fractured interval is encountered, where each spike most likely corresponds to a streaming potential effect caused by mud filtrate invasion into the fractures.

Acoustic, Density, Neutron Logs

These logs are used to identify the porosity and lithology of a formation. In addition, the use of the litho-porosity cross-plot interpretive technique can also determine the presence of vuggy and/or fractured zones. This technique was originally used to help interpret formations with complex lithologies, handling data from density, neutron, and acoustic logs simultaneously. By analyzing these logs, two porosity-independent parameters, M & N, can be determined using the following equations:

$$M = \frac{t_f - t}{p_b - p_f} \times 0.01$$

$$N = \frac{(\emptyset)_f - \emptyset N}{p_b \quad p_f}$$

In the cross-plot of M versus N, each mineral is represented by a unique point regardless of porosity. For complex lithologies, the position of the data points on the M-N plot helps identify the various minerals in the formation and the approximate percentage of each. Figure 10 presents the locations of prevalent minerals at the Raft River site. The major drawback to the use of these logging instruments in igneous and metamorphic environments is that porosities and permeabilities are difficult, if not impossible, to determine.

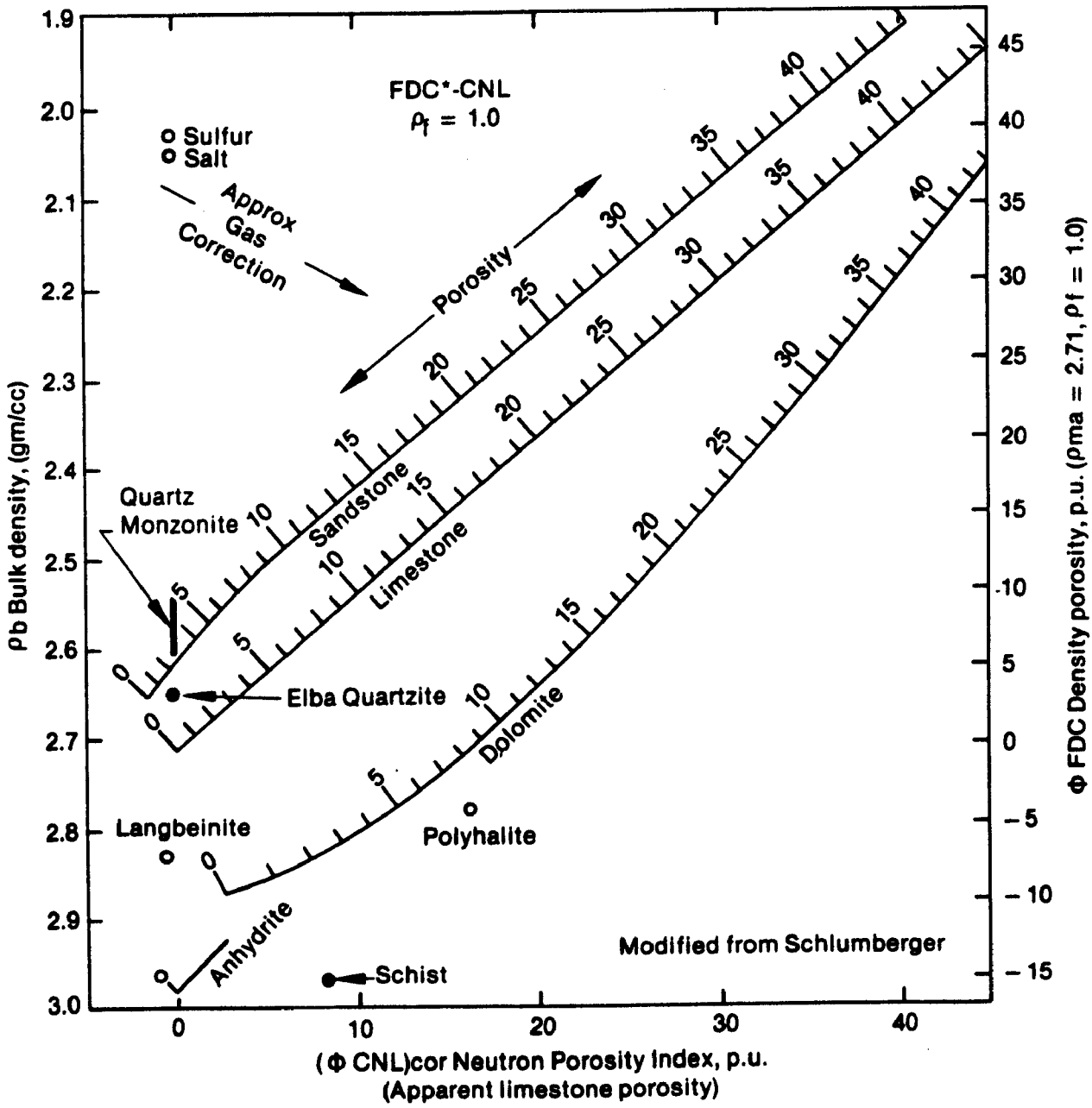


Figure 10. Bulk Density-Porosity Plot from Schlumberger Modified to Show Raft River Rock Types (from Dolenc, 1981).

Other Borehole Tools/Miscellaneous Indicators for Fracture Detection

Other borehole logs, such as the borehole televiewer and the temperature log, can also be used to detect possible fractures. The borehole televiewer takes an acoustic picture with a rotating ultrasonic scanner. The log inspects the borehole and evaluates the formation as it reveals induced and natural fractures and/or vugs. This borehole log is currently in the experimental stage with commercial models expected in the near future.

Temperature logs were used extensively in interpreting fractures at the Raft River site. The temperature log, run under nonequilibrium conditions, also provided useful information about the characteristics and location of the production zones. Finally, traditional indicators of fracturing during drilling operations included: drilling rate, mud circulation data, drill cuttings data, and rock strength.

Tables 1 and 2 indicate the various borehole geophysical logs run in each injection well.

Injection Zone Testing

Pump and Injection Tests

Pump and injection testing have been conducted at most of the Raft River exploration, production, and injection wells. This testing used electric-powered submersible and turbine shaft pumps, restricting the discharge rates to the

design limitations of the particular pump. This prohibited the high production and injection rates required for operating the 5MW(e) power plant during the testing. It was typical to measure drawdown/recovery in a production well by using a bubbler tube and surface gauge and build-up/fall-off by a wellhead gauge. To reduce thermal shock in the transit pipeline, most wells discharged through the pipeline prior to starting the pump test. Wellhead pressure rose and then stabilized as a function of wellbore fluid density. Thus, "initial" cold or hot wellhead pressures are of questionable value. No recovery was accomplished before starting the higher discharge rate pump test.

Well testing, with the primary goal of reservoir evaluation, were conducted for greater than 500 hours duration of pumping and injecting. Recovery data were obtained for a much shorter period of time due to wellbore fluid density changes. Data were obtained in as many observation wells as possible. However, many observation wells were under artesian conditions and had poorly regulated discharge rates for various reasons.

Numerous injection tests at reservoir temperatures, and a few at cooler-than reservoir temperatures were conducted. No reservoir parameters could be calculated from the cool water injection tests due to the short duration and discharge rate control problems. The potential effects of injecting

cooler water should be determined, as the 5MW(e) power plant will cool the injection fluid. However, injection of cool water was used successfully for delineating production zones. Pressure buildup curves and disposal zone parameters determined in RRGI-6 and RRGI-7 are summarized in Figures 11 and 12 and Tables 3 and 4.

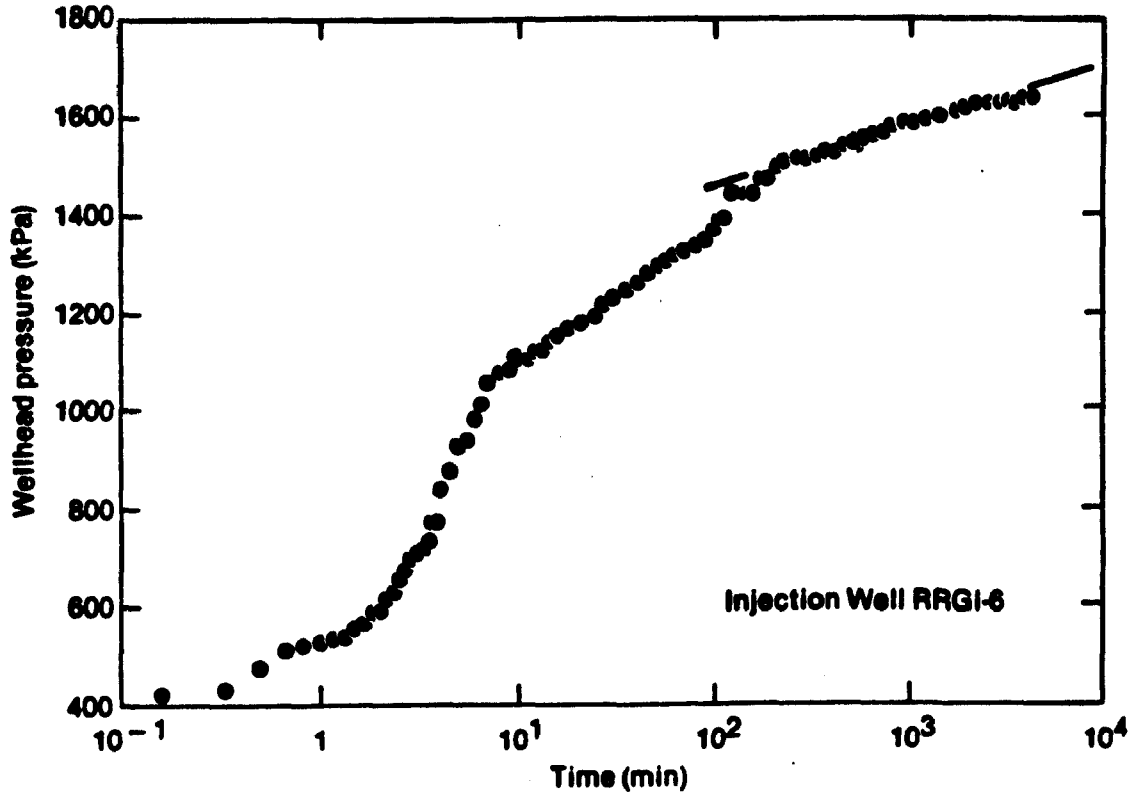


Figure 11. Pressure Buildup During Injection Test of Well RRGI-6 (from Dolenc et al, 1981).

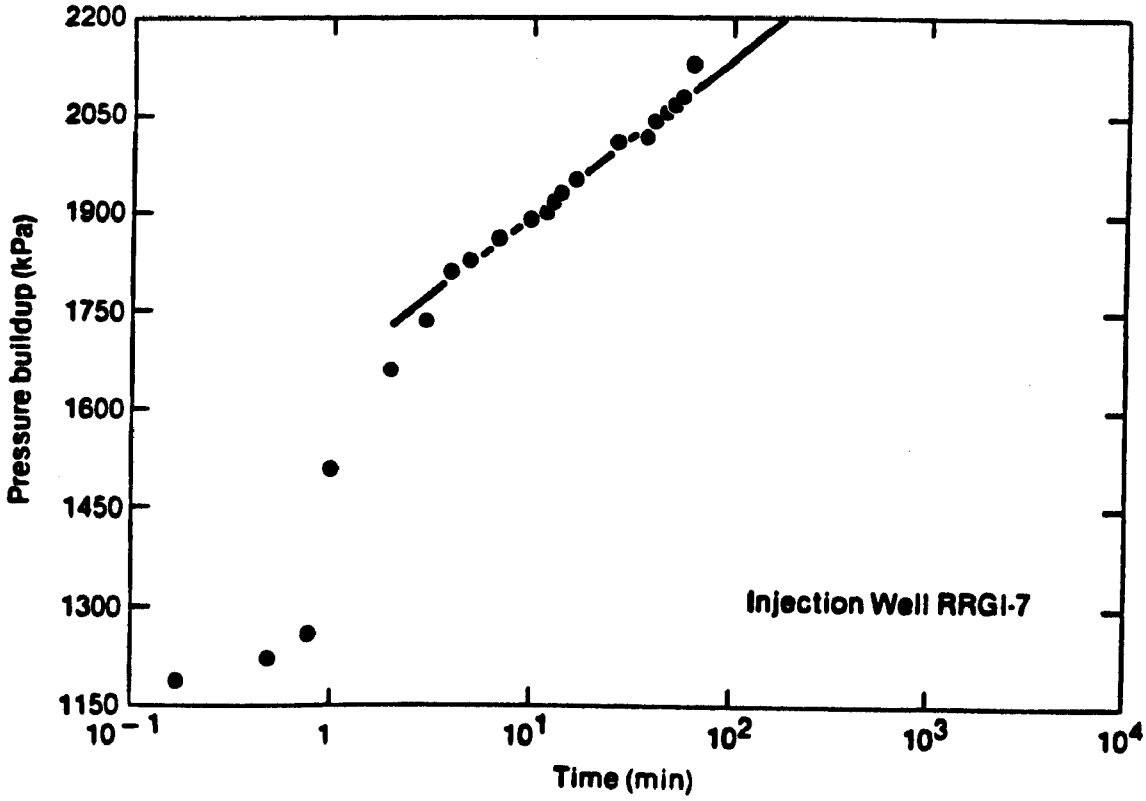


Figure 12. Pressure Buildup During Injection Test of Well RRGI-7 (from Dolenc et al, 1981).

Table 3. Summary of Well RRGI-6 Parameters (from Dolenc et al, 1981).

Date	Q (L/s)	Q/s_{10} (L/s/kPa)	kH_a (mD•m)	T_a (m^2/s)	Type
01/10/79	44.2	0.39	1.6×10^4	2.1×10^{-4}	Injection (wellhead)
01/10/79	44.2	0.40	1.7×10^4	2.1×10^{-4}	Injection (610 m)
03/10/79	37.8	0.34	1.4×10^4	1.8×10^{-4}	Injection
03/10/79	37.8	0.27	1.1×10^4	1.4×10^{-4}	Recovery
05/16/79	40.4	0.34	1.4×10^4	1.8×10^{-4}	Injection
05/16/79	40.4	0.24	1.0×10^4	1.3×10^{-3}	Recovery
05/14/80	45.7	0.29	1.2×10^4	1.5×10^{-4}	Recovery
08/19/80	56.8	0.28	1.2×10^4	1.5×10^{-4}	Injection
08/19/80	56.8	0.24	1.0×10^4	1.3×10^{-4}	Recovery

Table 4. Summary of Well RRGI-7 Parameters (from Dolenc et al, 1981).

Date	Q (L/s)	Q/s_{10} (L/s/kPa)	Kh (mD·m)	T_a (m^2/s)	Type
08/10/79	39.1	0.50	2.1×10^4	2.6×10^{-4}	Injection
08/10/79	39.1	0.35	1.5×10^4	1.9×10^{-4}	Recovery
08/11/79	28.4	0.48	2.0×10^4	2.6×10^{-4}	Injection
08/11/79	28.4	0.33	1.4×10^4	1.7×10^{-4}	Recovery
08/11/79	28.4	0.59	2.5×10^4	3.1×10^{-4}	Injection (1130 m)
08/11/79	28.4	0.37	1.6×10^4	2.0×10^{-4}	Recovery (1130 m)
10/15/80	63	0.75	3.2×10^4	4.0×10^{-4}	Injection
08/19/80	60	0.25	1.0×10^4	1.2×10^{-4}	Injection
08/19/80	60	0.32	1.2×10^4	1.6×10^{-4}	Recovery
09/10/80	56.8	0.30	1.2×10^4	1.5×10^{-4}	Recovery

REVIEW COMMENTS

In the following discussion of injection test interpretation, a textbook injection test and an injection test of well RRGI-7 will be interpreted. The equation used to determine formation transmissivity is Jacobs equation:

$$T = {}^{2.3\ Q}/_{4\pi\ \Delta h}$$

Any consistent units can be used in the above equation. The change in head is measured in one log cycle.

<u>First Case</u>

An injection test was run at 75 gpm (14,434 ft^3/day) for 25 hours. The plot of the pressure buildup data from the injection test is given in Figure 13. After converting gallons/minute into ft^3/day where one cubic foot equals 7.481 gallons and psi into feet (psi x 2.31), the above equation equals:

$$T(ft^2/day) = 2.3(14{,}434\ ft^3/day)/4\pi\,(2136\ ft\ water\ head\ change)$$
$$= 1.24\ ft^2/day$$

The injection test can further be used to determine the formation storage coefficient from:

$$S = {}^{2.25\ T\ t_o}/_{r^2} \quad \text{(dimensionless)}$$

where:

t_o = Intercept of extraploated test curve with time axis in days.

r = radius of well bore in feet.

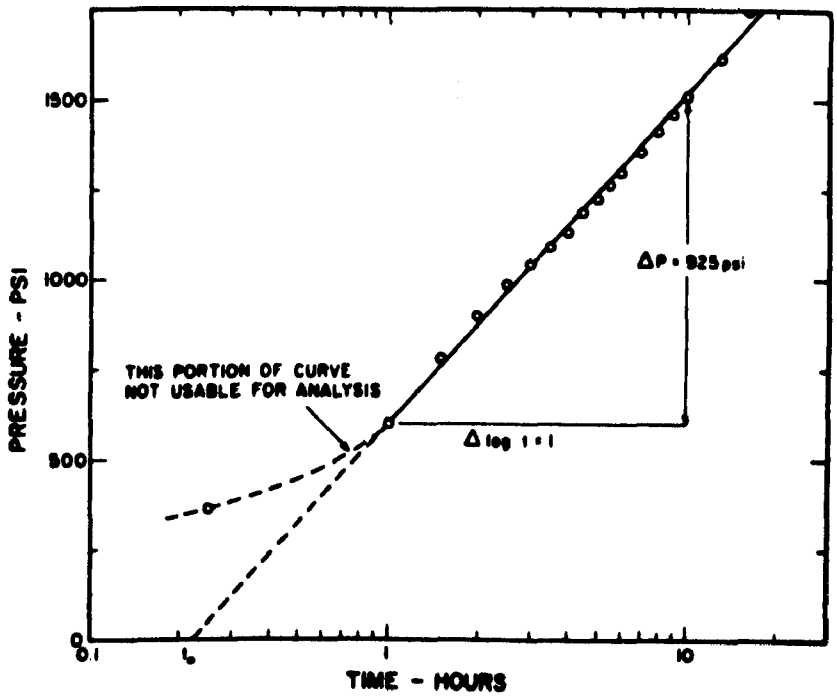


Figure 13. Plot of Pressure Buildup Data from an Injection Test of the Mt. Simon Formation in Ohio (from Everett, 1980).

In Figure 13, t_o = 0.22 hour (0.0042 days) and

$$S(\text{dimensionless}) = 2.25(1.24\ ft^2/day)(0.0092\ days)/(0.396)^2$$
$$= 0.16$$

Note that the storage coefficient calculation defines "r" as the wellbore radius as opposed to an observation point radius. Typical field studies usually never attempt to estimate the storage coefficient on the basis of observations taken at the injection/pumping well during a constant rate test. The step-drawdown test, which allows estimations of S when using only one well, is considered not as accurate as a two-well test.

Well RRGI-7

The injection test duration of well RRGI-7 was 35 hours at an injection rate of 60 L/sec. The injected fluid was from well RRGE-1 at reservoir temperature (150°C). Using Figure 12), the change in head (Δh) over one log cycle is determined to be 240 kPa. For fresh water at 20°C, the kPa value can be converted into meters of head change by dividing the kPa value by 9.807; however, the conversion for steam is approximately 2.6 since steam is about one-fourth of the specific weight of water. After changing liters/sec into m^3/sec (1 m^3 = 1,000 liters), we obtain:

$$T = {}^{2.3(.06)}/_{4\pi(92)}$$

$$= 1.2 \times 10^{-4}\ m^2/sec$$

Note that hydraulic conductivity is a temperature dependent parameter since it is a function of the density and viscosity of the fluid moving through a formation. Hence, the hydarulic conductivity value determined by injection or pump testing a formation with fluid at one temperature will differ to the value obtained with a quite different temperature fluid. For the geothermal case study, a higher hydraulic conductivity value would be obtained when testing with hot geothermal waters than would be obtained when testing with cooled waters. The higher conductivity value so obtained would lead to smaller calculated pressure build-ups and areas-of-review.

VI. AREA OF REVIEW CALCULATIONS

Potential Injection Formulation

The pressure response of each well to production, or injection in that well and each of the other wells that penetrate the same zone of the reservoir were tested. Pressure response at the end of one year and three years of 85 percent usage is predicted for the assumed flow rates as indicated in Table 5.

Pressure response in each well, due solely to that well's use in production or injection of geothermal fluids, was obtained from the reservoir testing data. The listed values represent the worst case response prediction made for each well for the specific time period and pumping rate.

The pressure response in Table 5 that reflects interference between wells were calculated at different radii from:

$$s = \frac{Q}{4\pi T} \ln \left(\frac{4Ts}{r^2 s}\right)$$

This is the nonequilibrium or Theis equation of pressure response at any point as a function of reservoir properties and flow rate. In this equation: Q is flow rate (L^3/T): T is reservoir transmissivity (L^2/T); S is the storage coefficient of the reservoir (dimensionless); r is the distance from the

Table 5. Predicted Pressure Response (kPa) at the end of 1 Year (t_1) and 3 Years (t_3) of Operation, at 85% Usage, in Each Well[1] (from Dolenc et al, 1981).

		RRGE-1			RRGE-2			RRGE-3			RRGP-4			RRGP-5		
Well	Q (L/s)	Radius (km)	t_1	t_3	Radius (km)	t_1	t_3	Radius (km)	t_1	t_3	Radius (km)	t_1	t_3	Radius (km)	t_1	t_3
RRGE-1	76	0	3222[a]	3379[a]	1.21	295	342	1.86	258	305	0.48	374	421	0.76	335	382
RRGE-2	63	1.21	244	283	0	9800[a]	10 100[a]	2.22	201	240	1.66	222	261	1.89	212	252
RRGE-3	44	1.86	149	177	2.22	140	168	0	5716[a]	6308[a]	1.31	167	194	2.35	138	165
RRGP-4	--	0.48	--	--	1.66	--	--	1.31	--	--	0	--	--	0.69	--	--
RRGP-5	63	0.76	277	317	1.89	212	252	2.35	197	236	0.69	284	226	0	1690[a]	1760[a]
Total	246		3892	4156		10 447	10 862		6372	7089		1047	1102		2375	2559

		RRGI-6			RRGI-7		
Well	Q (L/s)	Radius (km)	t_1	t_3	Radius (km)	t_1	t_3
RRGI-6	123	0	3883[a]	3990[a]	0.49	339	378
RRGI-7	123	0.49	339	378	0	3 984[a]	4 064[a]
Total	246		4222	4368		4 323	4 442

a. Worst case observed.

flowing well to the point at which s is to be found (L); t is the time, measured from the start of pumping, when s is desired (t). When these inputs to the equation for s are in consistent units, the pressure response at a distance r after a given time t, will be obtained in units of length; i.e., pressure response is given in height of a column of water. Pressure in height of water can easily be converted to true pressure units of weight per unit volume if the specific gravity of water at the temperature of interest is known.

Interference testing is an injection test method where the pressure response from a production/injection well is measured in some distant observation well(s). Data collected from an inactive observation well produce data unavailable by other techniques. The data is not thermally affected and can be used to calculate the average transmissivity of a large aquifer volume. However, if the observation wells are under artesian conditions, as in the Raft River testing area, the data may be erroneous. Transmissivity values were obtained by taking a geometric mean of the transmissivity estimated from interference testing. As a result, $T = 1.3 \times 10^{-3} m^2/s$ in the production zone and $T = 2.6 \times 10^{-3} m^2/s$ in the injection zone. No information is available to estimate the storage coefficient, so $S = 1 \times 10^{-4}$ was assumed. The apparent temperature of the production zone, 132°C, leads to

a specific gravity of 58.81 lb/ft^3. Injection fluids are anticipated to be 66°C and thus gives a specific gravity of 61.19 lb/ft^3.

Within the production zone, the greatest amount of pressure drawdown will occur in RRGE-2 where, after three years of 85 percent usage, pressure will have decreased by 10,862 kPa. The least amounts of pressure drawdown will occur in the vicinity of wells RRGE-1 and RRGP-5; pressure in RRGP-5 will decrease 2,559 kPa and pressure in RRGE-1 will decrease 4,156 kPa. Note that the assumed production program does not include production at RRGP-4; this is because of low flow capabilities identified during testing. Thus, the 1,102 kPa pressure decrease shown for RRGP-4 results exclusively from production at other wells.

Pressure buildup in the injection zone is fairly uniform because both injection wells are assumed to flow at the same rate. Since there are only two wells and they flow at the same rate, the interference effect of each well on the other is assumed to be identical.

REVIEW COMMENTS

Note: 1) Errors in pressure response equation.

2) Usage of the modified Theis equation.

3) Fracture pressure calculation.

1) Several errors exist in the given pressure response equation of this case study. Since accurate results are obtained for Table 5, the errors appear to be typographic in nature. The pressure response equation should be listed as:

$$s = \frac{Q}{4\pi T} \ln \left(\frac{2.25Tt}{r^2 S}\right)$$

This equation is actually Jacobs equation measuring the change in head pressure. A small "r" value and large "t" value are required to obtain a small well function "u" value so that the series terms in the Theis equation becomes negligible after the first two terms.

2) The UIC program's modified Theis equation for calculating the radius of endangering influence is a rearranged Jacob equation with variables concerning the specific gravity of the injection zone fluid and hydrostatic head difference between the injection zone and USDW zone. The modified Theis equation is given below:

$$r = (2.25\ kHt/S\ 10^x)^{1/2}$$

where

$$x = 4\pi\ kH\ (h_w - h_{bo}\ SpG_b)/2.3\ Q$$

and

h_w = hydrostatic head of USDW measured from the base of the lowest USDW.

h_{bo} = observed original hydrostatic head measured from the base of the lowest USDW.

SpG_b = specific gravity of fluid in the injection zone.

In the Raft River Valley, the shallow aquifer system is unconfined although some wells are locally under confined conditions. Nearly all water encountered below the base of the Raft River Formation (990 ft) is confined. Piezometric levels in the deep aquifers and injection zones range from 100 feet (30m) to more than 330 feet (100m) above the land surface. The modified Theis equation may be used in the Raft River project area only if the hydrostatic head of the lowermost USDW zone is higher than the injection zone's hydrostatic head. However, in most areas of the Raft River Valley, the head value increases with depth. Because the radius of influence is that portion of the aquifer which is affected by pressure changes, any injection in the Raft River Valley would increase the flow potential between the injection zone and USDW. The radius of the influence would be a finite value representing a distance beyond which pressure changes resulting from injection would no longer be discernable. In addition, the fracturing in the Salt Lake Formation distorts the general Theis assumptions that the

formation is isotropic and homogenous. The permitting authority should know the applicability and limits of the modified Theis equation.

3) The maximum wellhead injection pressure must be calculated to prevent the formation of new fractures and propagation of existing fractures in the injection zone. Besides stimulation injection, it is prohibited to exceed the maximum injection pressure in an injection operation. The fracture gradient of the injection zone must be determined and used in the injection pressure equation given below:

$$P_m = (X - 0.433\ Sg)d$$

where

P_m = injection pressure (psi)

X = fracture gradient (psi/ft)

Sg = specific gravity of injection fluid (unitless)

d = injection depth (ft)

Significantly, in most cases, the fracture gradient of the confining zone is higher than the potential injection zone fracture gradient. The injection zone and confining zone fracture gradients should be determined by the permitting authority if no value is submitted by the permit applicant. The permit applicant must determine or calculate the fracture pressure of the injection formation for new Class I, II and III wells.

VII. GEOTHERMAL FLUID CHARACTERISTICS AND COMPATIBILITY TESTS

In order to determine the potential for injection problems arising from suspended solids and chemical precipitates, filter studies were carried out to determine the quantity and size distribution of suspended solids in well water samples, and batch experiments were run to determine the potential of chemical precipitation occurring during mixing of injected fluids from several different wells and with the native formation fluid. As injection was to occur into a fracture dominated zone, an incompatible reaction between the injection fluids and formation matrix was not expected to be a problem.

Water Chemistry

As each of the geothermal wells were completed, it was developed, tested for its yield, and water samples were collected for chemical analysis. Additional samples were collected from the wells during pump tests or during production runs. Seven monitoring wells were also drilled to determine water levels and the changes in ground water in the vicinity of the project. Water quality data are shown in Table 6.

All the deep geothermal wells have sodium chloride type waters, based on the predominant cation and anion in terms of milliequivalents per liter (meq/l). The sodium concentrations range from 83 to 99 percent of the cations, and chloride

Table 6. Selected Physical and Chemical Data from the Raft River Project Wells (from Dolenc et al, 1981).

Well	Well Depth (m)	Casing Depth[a] (m)	Temperature (°C)	Specific Conductivity (µs)	Chemical Concentrations (mg/L)												Calculated Temperatures (°C)	
					pH	Ca^{+2}	Mg^{+2}	Sr^{+2}	Na^{+}	K^{+}	Li^{+}	HCO_3^{-}	SO_4^{-2}	Cl^{-}	F^{-}	SiO_2	SiO_2	Na-K-Ca
Geothermal																		
RRGE-1	1521	1105	141	2 800	7.3	56	0.6	1.4	455	14	1.6	41	36	776	7.9	121	148	173
RRGE-2	1994	1289	144	2 500	7.1	42	0.1	1.2	441	38	1.1	41	53	708	8.7	131	153	183
RRGE-3	1789	1293	149	8 000	6.9	224	0.5	5.2	1194	105	3.1	44	60	2260	4.9	158	164	187
RRGP-4	1654	1054	142	4 050	7.2	86	--	6.4	753	--	3.1	42	--	1400	6.3	104	136	--
RRGP-5	1497	1039	135	2 700	7.5	41	0.1	1.2	484	31	1.6	35	40	800	7.2	133	154	169
RRGI-6	1176	509	71	10 800	7.2	171	1.4	8.0	2200	32	5.1	73	60	3640	5.7	94	114	114
RRGI-7	1185	623	78	12 000	--	350	1.5	--	2200	--	--	32	64	4000	4.9	83	127	--
Monitor																		
MW-1	399	369	--	11 400	7.6	215	0.4	6.3	2200	30	3.7	25	66	3680	3.4	80	125	110
MW-2	174	154	106	4 400	7.4	125	0.5	3.6	1000	25	2.5	26	57	1740	5.4	86	130	128
MW-3	153	140	71	6 200	7.5	155	6.3	1.9	1400	65	3.0	47	60	2460	5.4	60	111	160
MW-4	305	225	98	7 800	7.7	160	0.6	1.4	1520	31	3.7	27	53	2610	5.6	67	116	123
MW-5	152	124	29	2 200	7.6	107	25	0.9	280	14	0.3	120	27	610	0.6	34	--	--
MW-6	305	274	44	7 600	7.3	207	2.4	1.4	1570	56	3.1	50	73	2270	4.9	85	--	--
MW-7	152	140	35	2 300	7.6	95	20	0.9	333	14	0.6	125	33	650	1.1	40	--	--
USGS Monitor																		
USGS-1	336	--	28	7 400	7.8	230	2.5	1.7	1500	200	0.9	100	45	2800	3.2	85	--	--
USGS-2	243	64	55	1 960	7.7	51	4.0	0.3	170	34	6.6	216	55	520	2.5	88	130	182
USGS-3	434	60	89	5 900	7.7	57	0.5	2.0	1270	14	1.7	77	54	2040	4.8	54	105	103
Other Geothermal[b]																		
BLM[c]	126	--	93	3 000	7.4	41	0.7	1.5	577	21	1.4	49	65	890	7.6	74	120	144
CROOK[d]	165	--	97	5 800	7.7	130	0.8	2.8	1020	32	2.6	34	56	1750	6.2	86	127	138
Private																		
15S-26E 23ABD1	110	--	29	4 500	7.6	97	5.0	--	766	20	1.9	155	96	1270	5.1	61	--	--
15S-26E 23DDD1	78	--	42	3 900	7.1	104	8.0	--	644	18	1.1	168	57	1100	4.5	58	--	--

a. Depth to bottom of casing or to first perforations.

b. Temperature measured at surface.

c. This well was drilled in the 1920's and is called the Bridge well by the USGS.

d. This well previously owned by Crank, and is referred to by that name in earlier publications.

concentrations vary from 92 to 99 percent of the anions. The waters are all low in alkalinity, ranging from 26 to 60 mg/l as $CaCO_2$. A high level of variation was noted in dissolved solids concentrations between the wells.

Wells RRGE-1, 2, and RRGP-5 are similar in the content of dissolved solids, temperature, and chemical character. Contents of dissolved chemical species are relatively low, with specific conductivity ranging from 2,500- 2,800 umhos. These wells have the highest fluoride levels, greater than 7 mg/l in all three.

Wells RRGI-6 and 7 have very high dissolved solids concentrations, predominantly sodium and chloride, and are relatively low in fluoride, having 5.7 and 4.9 mg/l for RRGI-6 and 7, respectively. The temperature of these wells is much lower than that of the others; RRGI-6 is one half the temperature of RRGE-3.

Wells RRGP-3 and RRGP-4 are the wells along the Bridge Fault in the central valley. Well RRGE-3 has maintained the highest temperature of all the production wells, approaching 300°F (149°C).

Water Compatibility Test

Experiments were conducted at two temperatures to simulate two injection scenarious: at 68°F (20°C) to simulate injection of water from holding ponds, and at 158°F (70°C) to simulate injection of water directly from the power

plant. Water samples were collected from RRGE-1, 2, 3, RRGP-5, and RRGI-6 and filtered through 0.45u membrane filters to remove any suspended solids. Mixtures were prepared by mixing all possible combinations of well water samples. A final sample volume of one liter was made up of equal portions of each water in the mixture. Control samples of unmixed water from each well were also included. As samples could not be collected from RRGP-4 and RRGI-7, they were not included in the analysis.

After 24 hours at 68°F (20°C) or 158°F (70°C), the mixtures were filtered through tared 0.45u filters, and the filters were dried at 203°F (95°C) for one hour. Residue and filter were then weighed on an analytical balance to determine the amount of residue.

The quantity of precipitate expected in the mixed samples, assuming no synergistic effects, was calculated by summing the products of the solids formed in control samples multiplied by fraction of the sample in the mixture. If there are no synergistic effects of mixing, the measured and calculated amounts of precipitate should be equal. Results of the actual versus calculated values are shown in Table 7.

If a significant positive or negative difference resulted between the actual and calculated values, an enhancement or inhibition of precipitate formation would be indicated. For the 25 mixtures held at 68°F (20°C), the average difference

Table 7. Water Compatibility for Geothermal Wells RRGE-1, RRGE-2, RRGE-3, RRGP-5 and RRGI-6 (from Dolenc et al, 1981).

	Samples Collected Through A Condensor			
	Temperature 20°C		Temperature 70°C	
Sample Mixtures	Calculated (mg/L)	Actual (mg/L)	Calculated (mg/L)	Actual (mg/L)
1	---	0.6	---	0.0
2	---	1.2	---	0.0
3	---	2.4	---	0.5
5	---	0.1	---	0.0
6	---	4.1	---	2.4
1-2	0.9	0.1	0.0	0.0
1-3	1.5	1.1	0.3	0.0
1-5	0.4	1.1	0.0	0.0
1-6	2.4	0.9	1.2	0.0
2-3	1.8	0.5	0.3	0.0
2-5	0.7	0.2	0.0	0.0
2-6	2.7	2.6	1.2	1.2
3-5	1.3	0.1	0.3	0.0
3-6	3.3	3.6	1.5	--a
5-6	2.1	2.3	1.2	0.6
1-2-3	1.4	1.9	0.2	0.0
1-2-5	0.6	0.7	0.0	0.0
1-2-6	2.0	1.2	0.8	0.0
1-3-5	1.0	0.7	0.2	0.0
1-3-6	2.4	1.6	1.0	0.0
1-5-6	1.6	1.6	0.8	0.0
2-3-5	1.2	---	0.2	0.0
2-3-6	2.6	0.0	1.0	0.0
2-5-6	1.8	1.1	0.8	1.2
3-5-6	2.3	1.5	1.0	1.0
2-3-5-6	2.0	2.5	0.7	0.2
1-3-5-6	1.8	0.9	0.7	0.0
1-2-5-6	1.5	2.6	0.6	0.0
1-2-3-6	2.1	1.7	0.7	0.5
1-2-3-5	1.1	0.0	0.1	0.0
1-2-3-5-6	1.7	0.7	0.6	0.0
Mean[b]	---	1.25	---	0.19
Standard deviation[b]	---	0.94	---	0.39
Sample size[b]	---	25	---	25

a. Missing sample
b. Of mixtures only

was -0.44 mg/l with a 95 percent confidence interval from -0.78 to -0.10 mg/l. There is a significant inhibition effect due to mixing, with mixed waters producing an average of about 0.4 mg/l less precipitated solids than expected from the amount of solids precipitated from the unmixed waters.

Examination of the amounts of solids precipitated from the unmixed samples showed that RRGE-1, 2, and RRGP-5 produce relatively little precipitate. Wells RRGE-3 and RRGI-6 produced from two to three times as many solids as the other wells. Hot waters injected into RRGI-6 directly from the power plant could be expected to form about 0.2 mg/l of solids on the average.

Based upon these experiments, it was concluded that mixing of water from wells RRGE-1, 2, 3, RRGP-5, and RRGI-6 did not result in incompatibility problems. In fact, the mixing of waters from these wells appeared to inhibit precipitate formation. Samples held at 158°F (70°C) showed significantly less precipitate formation than those held at 68°F (20°C). Therefore, it was concluded that injecting water directly from the plant could minimize the formation of precipitates. Even with only 0.2 mg/l of chemical precipitates formed, 2.2 kg/day (4.8 lbs/day) of solids would be injected, assuming an average flow of approximately 7,564 L/m (2,000 gpm).

Filter Studies

Studies were also conducted to determine the amount and particle size distribution of the suspended solids in the geothermal waters. In addition to determining the potential for clogging the reservoir, an analysis of the particle size distribution also permitted the sizing of the filter screens for the injection system. Particle size distributions were determined for water samples from RRGE-2 and RRGE-3. Total solids were monitored during two additional tests.

The filtering apparatus used in the tests consisted of a series of stainless steel filters in the following sizes and order: 230, 140, 90, 60, 15, and 2u. A 0.45u membrane filter was also used. The 230 and 140u filters were used in only one test. For determining total suspended solids, the 2.0u filter was used alone. The filter screens were placed in stainless steel filter holders and from 20 to 100 liters of water passed through the series. The filters were dried at 220°F (105°C) for three hours and weighed on an analytical balance to determine the quantity of suspended solids.

The distribution of particle size shows that almost all of the particles from the well water samples are less than 90u in diameter. Curiously, more particulate matter originated in the distribution system when compared with the wells. The particulate matter from the pipelines generally exceeds 90u grain size.

To test for temporal effects, RRGE-2 was tested for total suspended solids once every 24 hours for five days during an injection test of RRGI-6. There was a generally increasing trend in solids form 0.17 mg/l the first day to just over 1 mg/l on the fifth day. The concentrations were in the same range as an earlier test, but due to the limited duration of the test, it was impossible to predict the eventual steady-state solids concentration. Suspended solids were determined during a fourth test when water from a holding pond near RRGE-1 was injected into RRGI-7. The average concentration of suspended solids in this water was 34.8 mg/l, much higher than that produced from either RRGE-2 or 3.

In RRGE-3, 35.5 percent of the suspended solids ranged between 2.0 and 15.0u in grain size. About 94 percent of the solids measured before injection into RRGI-4 apparently were picked up in the pipeline network. Without removal of these suspended solids, approximately 800 kg (1,764 lbs) per day would be injected into the receiving formation. Even with the installation of 90u filters, however, approximately 245 kg (540 lbs) of solids per day would be injected, assuming an average flow of 7,564 L/m or 2.9 mgd. The ultimate impact of this suspended solids loading on the receiving formation could not be determined based on the testing completed. A possible mitigating factor to the contribution of the pipeline would be to periodically flush the lines to remove the particulate matter.

REVIEW COMMENTS

Note: 1) Chemistry of production well and injection well formation fluids

2) Water compatibility testing of injection fluids with formation fluids and matrix, and confining zone matrix

3) Preinjection treatment requirements

4) Special injection practices

1) The chemical characteristics of a waste fluid and the injection zone fluid and mineralogy are extremely important in determining the suitability of the waste for subsurface disposal. Although the UIC regulations do not state any requirements for wastewater compatibility studies, the permit applicant must submit information on the chemical analysis of the waste and formation fluids to the permitting authority.

All the geothermal wells contain formation water with less than 10,000 mg/l TDS which designates the production zones as potential underground sources of drinking water (USDW). However, these aquifers are exempted from a USDW classification due to their geothermal energy-producing characteristics. The chemical constituents in the formation water are primarily sodium and chloride with small concentrations of calcium and sulfate. The permitting authority should be aware of the potential for geothermal waters to be classified as a hazardous waste. Some geothermal wastes,

such as those from the Imperial Valley, California, could be classified as hazardous in one or more categories of pH, radioactivity and EP toxicity. Chemical analysis of the Raft River geothermal waters should evaluate the geothermal waste against hazardous waste criteria.

2) An extensive water compatibility test was conducted on the waste and injection zone fluids at the Raft River project. Accurate experiments were performed on wastewater from low temperature holding ponds and high temperature power plant wastewater. All combinations of well water samples were mixed and studied. Filter studies were also conducted to estimate the amount of injected suspended solids into the reservoir.

An incompatible reaction of the waste and injection formation fluids is not expected to be a problem due to their similar composition and properties. However, reservoir and injection conditions should be simulated for accurate compatibility results.

The reactions between noncompatible fluids cause the formation of precipitates which decrease the porosity and hydraulic conductivity of the reservoir. These precipitates are typically:

1) precipitation of alkaline earth metals (calcium, barium, strontium and magnesium) as relatively insoluble carbonates, sulfates, orthophosphates, fluorides and hydroxides;

2) precipitation of metals such as iron, cadmium, zinc and chromium as insoluble carbonates, hydroxides, orthophosphates and sulfides; and

3) precipitation of oxidation-reduction reaction products.

(Selm and Hulse, 1960)

Corrosion or scale inhibitors used in the well annulus may also cause the formation of precipitates.

Although the injection zones exhibit a fracture dominated porosity which decreases the precipitate formation potential, a compatibility test between the injection fluids and formation matrix should be conducted. The injection of corrosive or acidic fluids into incompatible formations may result in adverse environmental and health conditions such as an explosive build-up of carbon dioxide generated between the injected fluid and formation rock. Similarly, injection of compounds yielding oxygen as breakdown products could clog the formation with iron and manganese oxides and injection of less saline water, as in the Raft River Geothermal Project, could result in clay swelling which may clog the formation. In addition, compatibility testing of the injected water with the confining zone should be conducted. Chemical reactions could occur between the injected water and the confining zones which could reduce their ability to confine the waste fluid.

3) The preinjection mixing of well waters actually inhibited the formation of precipitate. It was also discovered wastewater from the power plant reduces precipitate formation.

Filtering is necessary to remove suspended solids in the injection water to help prevent reservoir plugging.

4) A proposed injection procedure must be submitted to the permitting authority for review. This procedure plan would include any pretreatment requirements and special injection practices such as pressure and volume rates, filtering, and additives.

VIII. MONITORING WELL PROGRAM

The Raft River monitoring well program was designed to evaluate and predict the impact of geothermal development on the intermediate ground-water aquifers. Seven intermediate monitoring wells (MW-1 through MW-7), drilled in 1978, are located near the geothermal production and intermediate depth injection wells. The depth and location of each well was designed to detect any response to geothermal injection before a response is noticeable at irrigation or domestic wells. The wells were drilled to varying depths designed to ensure that short- and long-term effects could be made. The locations of the monitoring wells and their relationship to the production and injection wells are shown on Figure 1. Table 8 summarizes the characteristics of the monitoring wells at the project site.

The monitoring wells are equipped with continuous reading water level recorders. MW-1 and MW-2 have digital-readout quartz pressure transducers installed at the wellhead for monitoring wellhead pressure. MW-3 through MW-7 have standard water level recorders. Water samples for chemical analyses are collected each quarter with either a submersible pump or downhole samplers to detect changes in water chemistry caused by geothermal development.

General Ground-Water Trends and Test Responses

Water levels in the shallow aquifer near the Raft River have declined over the past 30 years due to extensive irrigation

Table 8. Monitoring Well Summary
(from Dolenc et al, 1981).

Well Number	Ground Level Elevation (ft/m)	Ground-Water Level Elevation (ft/m)	Well Depth (ft/m)	Bottom Hole Temperature (F°/C°)	TDS (ppm)
MW-1	4839/1475	4940/1506	1309/339	----	6270
MW-2	4820/1469	4859/1481	570/174	221/106	5190
MW-3	4829/1472	4780/1457	501/153	160/ 71	4300
MW-4	4816/1468	4810/1466	1000/305	207/ 97	4370
MW-5	4810/1466	4741/1445	499/152	82/ 28	1229
MW-6	4820/1469	4747/1447	1000/305	111/ 44	4820
MW-7	4836/1474	4757/1450	499/152	95/ 35	1380

pumping. In addition, analysis of five years of water level data from USGS-2 (790 feet) suggests that there has been a corresponding decline in shallow ground-water levels in the injection area. Two years of ground-water records from the monitoring wells are inconclusive to support this trend.

Seasonal water level changes are apparent in several of the monitoring wells. A rise in water levels occurring in the spring appear to result from shallow recharge. These levels tend to drop during the period from mid-spring to the end of the irrigation season. With the termination of irrigation pumping, however, the following annual fluctuations have been noted:

Well	Seasonal Fluctuation (m)	
	1979	1980
MW-1		2.07
MW-2		2.60
MW-3	2.44	1.83
MW-4	3.05	2.10
MW-5	5.98	4.76
MW-6	2.84	2.04
MW-7	2.74	2.16

Individual Monitoring Well Responses

Water level responses at MW-1 and MW-2 indicate direct hydraulic connection with the geothermal resource. The lowered water levels indicate a direct relation to geothermal

production activity rather than injection or irrigation pumping. The continued production of geothermal fluids in this area could result in a decrease in local upward geothermal fluid leakage. This decrease would result in declining water levels in MW-1, MW-2, and the BLM and Crook wells. On the basis of the responses noted to date, it is not expected that injection activities will have any effect in this area.

MW-3, MW-5, MW-6 and MW-7 appear only to respond to seasonal fluctuations and irrigation pumping. The magnitude of the response varies, apparently due to the varying distances from the irrigation wells. Geothermal fluid production or injection is not expected to have any significant effects in this area.

MW-4 responds rapidly to geothermal injection activities. The nature of the hydraulic communication is postulated to be via soft-sediment fractures. Fracture injection activities are expected to cause water levels in MW-4 to continue to rise. Unfortunately, due to the lack of sufficient data on the nature of these shallow fractures, it is impossible to predict the total expected impact of injection activities on the shallow aquifer system.

Specific recommendations have been developed to attempt to better understand the nature of the monitoring well responses to geothermal fluid production and injection activities. In order to minimize the variables affecting

the response interpretations, future production and injection testing should be conducted during the months of December through March to eliminate the effects of irrigation pumping on the shallow aquifers. In addition, quarterly chemical analyses and temperature logging of all monitoring wells will be conducted to more precisely define the effects of geothermal production and injection activities on the shallow aquifer system.

REVIEW COMMENTS

Note: 1) Evaluation of only intermediate depth aquifers

2) Location of monitoring wells

3) Water sampling on a quarterly basis

4) Response of MW-4

5) Further recommended testing

1) The monitoring well program evaluates and samples only the intermediate depth zone. No monitoring wells were constructed within the surface alluvium aquifers. Although upward leakage from the injection zone could be detected in the monitoring wells, a defect in the casing or cement near the surface may allow injected fluids to migrate into the upper aquifer undetected. Because information on the monitoring well construction and completion methods has not been obtained in this case study, an evaluation on the design of the monitoring wells and the efficiency of the monitoring system cannot be completed. The number, location, and construction of monitoring wells shall be based on several criteria including location of USDWs, affected population, injection well density and the proximity of the injection location to drinking water withdrawal areas, and must be approved by the permitting authority.

According to UIC regulations, only Class III injection wells are required to have a monitoring well program unless

required for other classes by the EPA. If injection occurs into a formation containing less than 10,000 mg/l TDS as in the Raft River case, monitoring wells must be completed into the injection zone and into any USDW(s) above the injection zone. Injection into a formation containing water of greater than 10,000 mg/l TDS requires no monitoring wells in the injection zone.

2) To advise in the design of a monitoring well program, several questions must be answered about the location of the monitoring wells:

a. Are the monitoring wells sited downgradient from the injection zones? The direction of ground-water flow must be known to determine the downgradient direction.

b. Do any upgradient monitoring control wells exist? What effect will injection have on the direction of ground-water flow?

c. Are the monitoring wells sited to evaluate both porous media flow and fracture flow in the intermediate zone?

d. What is the proximity of the injection well and monitoring wells to domestic and public water supply wells? Does the monitoring program delineate an area to be protected?

e. Does the location of the monitoring wells create an early warning detection system?

3) Ground-water sampling for water quality determinations are taken on a quarterly basis at the Raft River site in accordance with the UIC regulations. However, the UIC regulations for Class III wells state that semi-monthly

monitoring of fluid levels in the injection zone and chemical parameters to determine water quality are required.

4,5) Increased water levels in MW-4 to geothermal injection activities indicate a hydraulic communication via fractures in the Salt Lake Formation. The permitting authority should suggest further investigations on the fracture systems in the injection zone and USDW(s). Shallow monitoring wells should be sited near the MW-4 to monitor the impact of injection on the upper Raft River and surface alluvium aquifer system.

IX. SUMMARY

Deep well injection of most types of nonhazardous and hazardous waste is a safe method of waste disposal if the systems are properly located, designed, operated and regulated. The planning and operation of an effective injection system is a multidisciplinary effort involving geological, engineering, chemical, biological and legal expertise. Detailed geologic investigations must be conducted at each injection system site. A reservoir so chosen will have the capability to store and contain injected waste. Proper well design and construction is necessary to adequately handle the injected waste and protect any source of uncontaminated water. Operating limitations must be established for every well to ensure that the limits of the equipment and the reservoir are not exceeded. Research is needed to provide the physical, chemical and biological effects of injection into subsurface zones. Finally, industry should be familiar with the UIC program to ensure proper implementation of construction, operation, monitoring and reporting requirements.

This case study of the Raft River Geothermal Project injection system is intended to advise the permitting authority of important injection well technology and UIC concepts through the evaluation of individual elements of the project. Although only a portion of the available documentation of this project was presented in this manual, the selected

information provided a sufficient background to discuss many technical and regulatory criteria of an injection well system.

The assessment of the contamination potential of Class V wells is an important issue facing the permitting authority. Because the Raft River geothermal wells are Class V wells, this manual should be of primary assistance to a permit writer. In general, the main concern of a Class V well assessment is whether injection occurs into or above a USDW. A well which injects into or above a known and used USDW should be closely monitored for adverse environmental effects. Additional considerations for assessing the contamination potential of a Class V well includes the nature and volume of injected fluids, proper construction specifications, the compatibility of injected fluids with the formation fluids and matrix, and the well density in a specific area.

In conclusion, to aid the permitting authority in the acquisition and review of required data for an injection well system, application checklists for Class I, II, and III wells are provided in Appendix B.

REFERENCES

Algermisen, S. T. 1969. Seismic Risk Studies in the United States, Fourth World Conference on Earthquake Engineering (Santiago, Chile, January 14, 1969); Preprint, 10p.

Covington, H. R. 1976. Deep Drilling Data, Raft River Geothermal Area; USGS Open-File Report 76-665.

Dolenc, M. R. et al. 1981. Raft River Geoscience Case Study; EG&G Idaho, EGG-2125, Volume 1, 145p.

Everett, L. G. 1980. Groundwater Monitoring; General Electric Company, Schenectady, NY, 440p.

Miller, L. G. and S. M. Prestwich. 1979a. Completion Report: Raft River Geothermal Injection Well Six (RRGI-6); U.S. Department of Energy, IDO-10083, 12p.

Miller, L. G. and S. M. Prestwich. 1979b. Completion Report: Raft River Geothermal Injection Well Seven (RRGI-7); U.S. Department of Energy, IDO-10084, 12p.

Reeder, L. R. et al. 1977. Review and Assessment of Deep Well Injection of Hazardous Wastes; EPA-600/2-77-029a, Volume 1, 187p.

Selm, P. R. and B. T. Hulse. 1960. Deep Well Disposal of Industrial Wastes"; Chem. Eng. Prog., Volume 56, No. 5, pp 138-144.

Walker, E. H. et al. 1970. The Raft River Basin as of 1966: A Reappraisal of the Water Resources and effects of Groundwater Development; USGS and Idaho Department of Water Resources Water Information Bulletin No. 19.

APPENDIX A

CONVERSION FACTORS

CONVERSION FACTORS

Length:

1 meter--1.0936 yards
--3.2808 feet
--39.370 inches

1 foot--0.3048 meter

1 mile--1.6094 kilometers
--5,280 feet

1 kilometer--0.62137 mile

Area:

1 cm^2--0.1550 in^2

1 in^2--6.452 cm^2

1 m^2--10.764 ft^2

1 ft^2--929.0 cm^2

1 acre--43,560 ft^2
--2.471 acres

1 hectare--10,000 m^2
-- 4,047 m^2

1 mi^2--2.590 km^2
--640 acres

Volume:

1 m^3--1,000 liters

--35.314 ft^3

--264 gal (U.S.)

1 ft^3--28.320 liters
--7.481 gal (U.S.)

1 gal--3.785 liters

1 acre foot--43,560 ft^3

--3,259 x 10^5 gal

--1,234 m^3

APPENDIX B

PERMIT APPLICATION CHECKLISTS

UIC CLASS I INJECTION WELL APPLICATION CHECKLIST

NEW _____ OR EXISTING _____

(For Existing Well Actual Data Shall Be Used in Lieu of "Proposed", "Expected", "Planned", Etc.)

APPLICATION NO. _____

APPLICANT _____

STATE/COUNTY _____

REVIEWED BY _____

DATE _____

A. Justification

____ 1. Treatability studies of alternative methods of waste disposal
____ 2. Indicate whether this waste is currently being produced
____ 3. Current method of disposal
____ 4. Manufacturing processes
____ 5. Products

B. Well Location

____ 1. Plant location map
____ 2. Well location in relation to plant and survey lines
____ 3. Surface ownership map
____ 4. Waiver from subsurface owner
____ 5. Area of review with basis

C. Water Well Data

____ 1. Water well map (plant and adjacent property).
____ 2. Tabulation of water well data
    ____ a. Depth
    ____ b. Water level
    ____ c. Owner
    ____ d. Chemical analyses
____ 3. Piezometric map of the water table using wells from C.1
____ 4. Base of usable quality water (USDW)

D. Artificial Penetrations

____ 1. Map showing all artificial penetrations within study area, along with name and location of all surface bodies, springs, mines, quarries, and other pertinent surface features including residences and roads with the scale equal on D.1 and C.1.
____ 2. Tabulation of artificial penetrations
    ____ a. Operator
    ____ b. Lease or owner
    ____ c. Distance
    ____ d. Well construction data
        ____ 1) casing
        ____ 2) setting depth
    ____ e. Cementing data
    ____ f. Well number
    ____ g. Plugging data for abandoned wells
    ____ h. Corrective actions
____ 3. Mineral permit/drilling permit
____ 4. Schematic sketches of penetrations
____ 5. Other subsurface disposal operations in the area (names, distance from the proposed well, injection interval)
____ 6. Hydrologic implications of proposed subsurface disposal operations to existing injection operations

E. Geology

____ 1. USGS topographic map
____ 2. Regional geology
    ____ a. Surface geologic map
    ____ b. Cross-sections
    ____ c. Structural contour map
____ 3. Local geology
    ____ a. Cross-sections with log control, geologic units and lithology from surface to lower confining zone or major structure
    ____ b. Description of upper and lower confining strata (lithology, permeability, etc.)
    ____ c. Description of faulting, lineations, and fracturing in the area
    ____ d. Depositional, structural and tectonic history of the area
    ____ e. Lithology of all units overlying injection zone
    ____ f. Hydrology of all units overlying injection zone
    ____ g. Structural contour map of injection zone
    ____ h. Isopach map of the injection zone (each one, if more than one)

F. Characteristics of Injection Interval - For existing well provide results of all and any tests relating to the following:

____ 1. Depth
____ 2. Porosity
____ 3. Permeability
____ 4. Temperature
____ 5. Reservoir pressure or hydrostatic head
____ 6. Fluid saturation and chemical characteristics of formation and formation fluids
____ 7. Location, extent and effects of faulting, fracturing, and/or solution channels
____ 8. Fracture gradients or formation breakdown pressure (show calculations and methods used)
____ 9. Piezometric surface map or static fluid level and regional gradient

G. Characteristics of Waste Streams - For existing well provide historical data and sampling frequencies

____ 1. Description of chemical and physical characteristics
____ 2. Analysis of final waste stream
____ 3. Analysis of individual waste streams and percentage of total waste volume
____ 4. Toxicity and degradability rates and levels
____ 5. Compatibility of final waste stream, formation, confining zone and formation fluids at expected pressures and temperature
____ 6. Corrosion tests on all materials to be in contact with waste fluids including long string casing
____ 7. Volume of the waste
    ____ a. Percentage of each stream to total effluent
    ____ b. Average and maximum injection rates
    ____ c. Monthly and yearly volume
    ____ d. Anticipated life of the project

H. Proposed Well Completion (all materials must be new unless approved by Department)

____ 1. Total depth
____ 2. Type of completion (including perforating or screen setting depths)
____ 3. Surface casing: size, type, weight, grade and setting depth
____ 4. Long string casing: size, type, weight, grade and setting depth
____ 5. Liner or other casing: size, type, weight, grade and setting depth
____ 6. Number and location of centralizers, scratchers, etc.

____ 7. Logging program
- a. deviation checks (frequency) Yes ___ No ___
- b. surface casing; open hole
  - i) resistivity Yes ___ No ___
  - ii) spontaneous potential Yes ___ No ___
  - iii) caliper Yes ___ No ___
- c. surface casing; cased hole
  - i) cement bond log Yes ___ No ___
  - ii) temperature or density Yes ___ No ___
- d. intermediate or long string casing; open hole
  - i) resistivity Yes ___ No ___
  - ii) spontaneous potential Yes ___ No ___
  - iii) gamma ray Yes ___ No ___
  - iv) porosity Yes ___ No ___
  - v) fracture finder logs Yes ___ No ___
- e. intermediate or long casing; cased hole
  - i) cement bond log Yes ___ No ___
  - ii) temperature or density Yes ___ No ___

____ 8. Proposed bottomhole testing and coring

____ 9. Cement program (for all casing strings)
- ____ a. Service company recommendations plus studies to determine suitability of selected cements
- ____ b. Volumes including percent excess (to surface + 20% excess)
- ____ c. Types of cement and additives
- ____ d. Slurry weights and yields
- ____ e. Cementing equipment (guide shoes, float collars, D.V. tools, etc.)

____ 10. Proposed well stimulation program

____ 11. Description of proposed injectivity tests

____ 12. Size and type of tubing and setting depth

____ 13. Size and type of packer and proposed setting depth

____ 14. Diagramatic sketch of well

____ 15. Diagramatic sketch of wellhead facilities including annulus monitoring system

I. Surface Installations (must meet requirements from application instructions)

____ 1. Description of injection pressure and volume monitoring system

____ 2. Description of annulus monitoring system

____ 3. Filter types and location including capacity and capability

____ 4. Description of injection pumps including type and capacity

____ 5. Detailed description of pretreatment processs and facilities
____ 6. Flow diagram with each waste stream identified
____ 7. Plat of plant showing all waste flow lines and pre-injection system
____ 8. Tank size, capacity, and construction materials
____ 9. Plans for disposal of sludges or solids
____ 10. Emergency storage facilities

J. Injection Well Operation

____ 1. Expected maximum and average injection pressures
____ 2. Formation pressure increase calculations
____ 3. Minimum fluid front calculations including dispersion of injected fluids
____ 4. Provisions for insuring proper well maintenance, mechanical integrity, and qualifications of personnel who will supervise well operation
____ 5. Proposed well abandonment procedure in the event of well failure of expiration of the life of the project (including plugging and abandonment cost estimate)
____ 6. Existing operating permit

K. Other

____ 1. Contingency plan and description of facilities to cope with well failures or shut-in. If one well system is used, then a minimum of 30 days above ground storage system is necessary

REMARKS AND COMMENTS OF REVIEWER:

UIC CLASS II INJECTION WELL APPLICATION CHECKLIST

NEW _____ CONVERSION _____

APPLICATION NO. _____

APPLICANT _____

STATE/COUNTY _____

REVIEWED BY _____

DATE _____

A. Well Location

____ 1. Plant location map
____ 2. Area of review and basis
____ 3. Number, name, location of:
  ____ producing wells
  ____ injection wells
  ____ abandoned wells
  ____ dry holes
  ____ water wells
____ 4. USGS topographic map or map showing bodies of waters, mines, quarries, residences, roads, faults, surface features

B. Penetrations

____ 1. Tabulation of wells penetrating injection zone within area of review
____ 2. Tabulation of wells penetrating formations affected by injection pressure(s) greater than fracture pressure
____ 3. Corrective actions

C. Operating Data

____ 1. Average and maximum daily rate of injection
____ 2. Average and maximum daily volume of injection
____ 3. Average and maximum injection pressure

____ 4. Demonstration of mechanical integrity
____ 5. Waste stream physical and chemical analyses and characteristics
____ 6. Source of sample(s)
____ 7. Monitoring of injection fluids, pressures, volumes, rates

D. Geology-Hydrology
____ 1. Geological data on injection zone, including lithology, name, thickness, depth, permeability, porosity
____ 2. Geological data on confining zone, including lithology, name, thickness, depth, permeability
____ 3. Geologic-hydrologic name of all underground sources of drinking water (USDWs) affected
____ 4. Depth of base(s) of USDWs
____ 5. Faults
____ 6. Chemical nature of formation fluids and materials

E. Well Construction/Completion
____ 1. Schematic or other appropriate drawings of surface and subsurface construction details
____ 2. Total depth and/or plug-back depth
____ 3. Type of completion, packer, packerless, etc.
____ 4. Surface casing: size, type, weight, grade, depth
____ 5. Long string casing: size, type, weight, grade, depth
____ 6. Liner or other casing size, type, weight, grade, depth
____ 7. Centralizers location, etc.
____ 8. Cementing quantities, class
____ 9. Hole size
____10. Tubing-packer: size, type, weight, grade, depth

F. Well Logs/Surveys
____ 1. Deviation checks
____ 2. Surface hole (open) electric and caliper logs
____ 3. Surface casing cement bond, temperature
____ 4. Intermediate - long string hole (open) - electric, porosity, gamma ray, fracture finder
____ 5. Intermediate - long string casing cement bond, temperature

G. Reservoir Properties
____ 1. Formation pore (fluid) pressure
____ 2. Estimated fracture pressure
____ 3. Proposed formation testing
____ 4. Proposed stimulation program

H. Contingency Plans
____ 1. Shut in
____ 2. Failure

I. Plugging and Abandonment
____ 1. Plan
____ 2. Performance bond or other assurance of financial responsibility

REMARKS AND COMMENTS OF REVIEWER:

UIC CLASS III INJECTION WELL APPLICATION CHECKLIST

NEW _____ OR EXISTING _____

(For Existing Well Actual Data Shall Be Used in Lieu of "Proposed", "Expected", "Planned", Etc.)

APPLICATION NO. _____

APPLICANT _____

STATE/COUNTY _____

REVIEWED BY _____

DATE _____

A. Justification

_____ 1. Treabability studies of alternative methods of waste disposal
_____ 2. Indicate whether this waste is currently being produced
_____ 3. Current method of disposal
_____ 4. Manufacturing processes
_____ 5. Products

B. Well Location

_____ 1. Plant location map
_____ 2. Well location in relation to plant and survey lines
_____ 3. Surface ownership map
_____ 4. Waiver from subsurface owner
_____ 5. Area of review with basis

C. Water Well Data

_____ 1. Water well map (plant and adjacent property)
_____ 2. Tabulation of water well data
    _____ a. Depth
    _____ b. Water level
    _____ c. Owner
    _____ d. Chemical analyses
_____ 3. Piezometric map of the water table
_____ 4. Base of usable quality water (USDW)

D. Artificial Penetrations

_____ 1. Map showing all artificial penetrations within study area, along with name and location of all surface bodies, springs, mines, quarries, and other pertinent surface features including residences and roads with the scale equal on D.1 and C.1.

_____ 2. Tabulation of artificial penetrations
- _____ a. Operator
- _____ b. Lease or owner
- _____ c. Distance
- _____ d. Well construction data
  - _____ 1) casing
  - _____ 2) setting depth
- _____ e. Cementing data
- _____ f. Well number
- _____ g. Plugging data for abandoned wells
- _____ h. Corrective actions

_____ 3. Mineral permit/drilling permit

_____ 4. Schematic sketches of penetrations

_____ 5. Other subsurface disposal operations in the area (names, distance from the proposed well, injection interval)

_____ 6. Hydrologic implications of proposed subsurface disposal operations to existing injection operations

E. Geology

_____ 1. USGS topographic map

_____ 2. Regional geology
- _____ a. Surface geologic map
- _____ b. Cross-sections
- _____ c. Structural contour map

_____ 3. Local geology
- _____ a. Cross-sections with log control, geologic units and lithology from surface to lower confining zone or major structure
- _____ b. Description of upper and lower confining strata (lithology, permeability, etc.)
- _____ c. Description of faulting, lineations, and fracturing in the area
- _____ d. Depositional, structural and tectonic history of the area
- _____ e. lithology of all units overlying injection zone
- _____ f. Hydrology of all units overlying injection zone
- _____ g. Structural contour map of injection zone
- _____ h. Isopach map of the injection zone (each one, if more than one)

F. Characteristics of Injection Interval - For existing well provide results of all and any tests relating to the following:

_____ 1. Depth
_____ 2. Porosity
_____ 3. Permeability
_____ 4. Temperature
_____ 5. Reservoir pressure or hydrostatic head
_____ 6. Fluid saturation and chemical characteristics of formation and formation fluids
_____ 7. Location, extent and effects of faulting, fracturing, and/or solution channels
_____ 8. Fracture gradients or formation breakdown pressure (show calculations and methods used)
_____ 9. Piezometric surface map or static fluid level and regional gradient

G. Characteristics of Injection Fluid - For existing well provide historical data and sampling frequencies:

_____ 1. Description of chemical and physical characteristics
_____ 2. Volume of injected fluid
    _____ a. Average and maximum injection rates
    _____ b. Monthly and yearly volume
    _____ c. Anticipated life of the project

H. Injection Fluid Changes

_____ 1. Expected changes in injection fluid movement
_____ 2. Native fluid displacement
_____ 3. Direction of injected fluid movement

I. Proposed Well Completion

_____ 1. Total depth
_____ 2. Type of casing and tubing
_____ 3. Type of completion (including perforating or screen setting depths)
_____ 4. Logging program
    _____ a. Deviation checks (frequency)
    _____ b. Geophysical logs
        _____ 1) resistivity
        _____ 2) spontaneous potential
        _____ 3) caliper
        _____ 4) cement bond
        _____ 5) temperature
        _____ 6) density
_____ 5. Cement program (for all casing strings
    _____ a. Types of cement and additives
    _____ b. Volumes including percent excess
    _____ c. Cement waiver

_____ 6. Proposed well stimulation program
_____ 7. Diagrammatic sketch of well

J. Design of Monitoring Well System

_____ 1. Chemical Analysis
  _____ a. Injection zone fluid
  _____ b. USDW
_____ 2. Map of mining area and collapse structures
_____ 3. Map of potential catastrophic collapse area
_____ 4. Subsidence surveying
_____ 5. Subsidence control methods and calculations
_____ 6. Monitoring well construction
  _____ a. Total depth
  _____ b. Type of casing and completion
_____ 7. Environmental concerns
  _____ a. Affected population
  _____ b. Proximity of injection operation to drinking water withdraw points
  _____ c. Injection well density

K. Injection Well Operation

_____ 1. Expected maximum and average injection pressures
_____ 2. Formation pressure increase calculations
_____ 3. Minimum fluid front calculations includingdispersion of injected fluids
_____ 4. Proviions for insuring proper well maintenance, mechanical integrity, and qualifications of personnel who will supervise well operation
_____ 5. Proposed well abandonment procedure in the event of well failure of expiration of the life of the project (including plugging and abandonment cost estimate)
_____ 6. Existing operating permit

L. Other

_____ 1. Contingency plandand description of facilities to cope with well failures or shut-in.
_____ 2. Performance bond or other assurance of financial responsibility

REMARKS AND COMMENTS OF REVIEWER: