534
1-12-84 85 (1)

I.12781

DR# 2040-0

DOE/ID--10117

DE84 005012

HYDROTHERMAL INJECTION RESEARCH
PROGRAM

ANNUAL PROGRESS REPORT
FY-1983

November 1983

Prepared by
University of Utah Research Institute
Earth Sciences Laboratory

EG&G Idaho, Inc.
Earth and Life Sciences and
Special Energy Programs

Under DOE Contract No. DE-AC07-76ID01570

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

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

DISCLAIMER

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

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
NTIS Price Codes: Printed Copy A04
Microfiche A01

DISCLAIMER

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

HYDROTHERMAL INJECTION RESEARCH PROGRAM
ANNUAL PROGRESS REPORT
FY-1983

R. E. Blackett R. G. Capuano
P. T. Kolesar W. R. Sill

University of Utah Research Institute
Earth Sciences Laboratory

D. W. Allman W. F. Downs
L. C. Hull K. N. Koslow
R. M. Large R. E. McAtee
J. D. Miller B. F. Russell
P. A. Skiba

EG&G Idaho, Inc.
Earth and Life Sciences

November 1983

Prepared for the
U.S. Department of Energy
Idaho Operations Office
Under Contract No. DE-AC07-76ID01570

DISCLAIMER

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

CONTENTS

	<u>Page</u>
1.0 Introduction.	1
2.0 Rationale for Research.	3
3.0 Approach.	6
4.0 Discussion of Program Results	8
4.1 Field Test Program	9
4.2 Geology of Raft River.	16
4.3 Geochemistry/Tracer Development.	18
4.4 Geophysical Studies.	28
4.5 Laboratory Fracture Flow Testing	30
4.6 Hydrologic Analysis.	37
5.0 Reservoir Simulation.	51
6.0 Summary	55
7.0 Conclusions	60
References	61

FIGURES

	<u>Page</u>
1. Work breakdown structure for Injection Program.	7
2. Cross-Sectional view of major geological formations and structures of the Raft River KGRA	17
3. Structural features of the southern Raft River Valley . . .	19
4. Raft River Test 2C Fraction of Injectate in Backflow. . . .	21
5. Generalized Mixing Curves - Raft River.	24
6. Mixing curves for Raft River test series 4.	25
7. Calcium/Magnesium recovery - Raft River test series 2C. . .	27
8. Resistivity and self potential trends in long term injection tests	29
9. Schematic of velocity profile in fracture	32
10. Solute travel through the fracture intersection	33
11. Variable volume injection/backflow tests with reservoir flow field.	34
12. Normalized curves showing effect of injection volume. . . .	35
13. Tracer recovery curves for variable quiescence with reservoir flow field.	36
14. Well construction for RRGP-5BF after fracture treatment . .	39
15. Production/receiving zones discharge/uptake as a percentage of flow rate for RRGP-5BF	41
16. Pulse test Q/S_{10} vs Q for RRGP-5BF.	42
17. Generalized mixing curves after normalization	44
18. Test 4B conductivity response as a function of time	46
19. Test 4C conductivity response as a function of time	47
20. Test 4A conductivity response as a function of time	48
21. Test 4D conductivity response as a function of time	49
22. The time to the conductivity shoulder or peak as a function of quiescent time.	50
23. Wellhead temperature vs withdrawal time, Tests 2C and 2D. .	52
24. Conceptual model of RRGP-5BF reservoir in plane of the hydrofracture	53
25. Typical injection/backflow reservoir simulation	56

TABLES

	<u>Page</u>
1 - Supply and Injection Wells, Raft River and East Mesa. . . .	11
2 - Summary - Raft River Test Program	12
3 - East Mesa Injection/Backflow--Test Program Summary. . . .	15
4 - Ratio of the Mass of Tracer Recovered vs Mass Injected Into the Wellbore	23

1.0 INTRODUCTION

The economics of geothermal power development are highly dependent on the efficiency of heat recovery from the resource. In the past, reservoir research has focused on techniques to explore, evaluate reservoir size, and predict longevity of resources. While it has always been recognized that injection of spent fluids is a potential means to increase recovery of resource heat, the cost of injection systems, problems in handling fluids, and uncertainties in reservoir response have delayed practical application of this approach. Operating geothermal fields have considered spent fluid a liability and have disposed of it in the most economical manner, often causing degradation of both the resource and the environment.

As long-term production data are beginning to accumulate in various geothermal fields around the world, it is becoming evident that injection of geothermal fluids may be necessary to effectively recover geothermal heat. The spent fluid is actually a valuable resource whose effective use can markedly increase system efficiency. In many reservoirs, pressures have been declining faster than predicted. Experience at the Broadlands, at Cerro Prieto, and at other locations has strongly indicated the need for injection to maintain pressure. Limited injection experience to date has ranged from success in pressure maintenance to thermal breakthrough.

Injection presents several unique requirements for reservoir analysis. In geothermal production an existing fluid is moved through the rock formations whereas with injection a fluid with modified properties is introduced into the formations. The injected fluids can cause physical and chemical changes in the rock formations and in turn the rocks can induce changes in the injected fluid. These interactions may affect fluid movement by either increasing or decreasing formation permeability.

The Department of Energy Division of Geothermal and Hydropower Technology (DGHT) recognized the need for additional understanding of the complex subsurface interactions. In December of 1981 it established research into the problems

associated with the injection of spent geothermal fluids into fractured reservoirs as a priority area of research. EG&G Idaho and the Earth Sciences Laboratory of the University of Utah Research Institute (ESL/UURI) working for the Idaho Operations Office of the Department of Energy, have been planning and conducting a significant injection research program since its identification as a priority research area by DGHT.

The principal thrust of the joint research effort is a series of highly instrumented field experiments with supporting laboratory and theoretical work. The field experiments are intended to help develop and ultimately to verify new techniques for reservoir analysis when simultaneous injection and production in a common reservoir are planned.

The test program was initiated at the Raft River Geothermal Field in southern Idaho in September of 1982. A series of eight short-term injection and back-flow tests followed by a long-term injection test were conducted on one well in the field. Tracers were added during injection and monitored during back-flow of the well. The principal objective was to determine if tracers could be effectively used as a means to assess reservoir characteristics in a one well test. The test program was completely successful, resulting in a unique data set which shows promise as a means to improve understanding of the reservoir characteristics. In December of 1982 an RFP was issued to obtain an industrial partner to obtain follow-on data on the injection/backflow technique in a second field and to study any alternate advanced concepts for injection testing which the industrial community might recommend. Republic Geothermal, Inc. and the East Mesa Geothermal Field were selected for the second test series. Two wells were utilized for testing, and a series of ten tests were conducted in July and August of 1983 aimed principally at further evaluation of the injection/backflow technique. This test program was also successfully completed.

To support the test program and assure that the techniques which evolve from the work have a sound theoretical basis, laboratory work has been initiated by EG&G Idaho and ESL/UURI. At EG&G Idaho during FY-83, a series of laboratory fracture flow experiments were conducted to obtain basic data for assisting in the analysis of the Raft River mixing and flow data. At ESL/UURI, basic studies were conducted to determine tracers which might be used in the field test and to screen those which reacted adversely with the geothermal fluids.

A significant effort was spent at EG&G Idaho in selecting and adopting computer codes to model the physical processes occurring in the reservoir. These simulations are intended to integrate all of the measured reservoir performance characteristics into a mathematical model which can be used with site specific data to characterize other geothermal reservoirs.

This report describes in detail the analysis conducted on the Raft River data, the supporting work at EG&G Idaho and at ESL/UURI, and gives an overview of the objectives and test program at East Mesa.

2.0 Rationale for Research

The fundamental need guiding the research discussed in this report is that new testing techniques are required to effectively utilize injected fluids in a geothermal reservoir. The current reservoir engineering practice of measuring the reservoir pressure response during flow tests is inadequate. Injected fluids are chemically and thermally altered from native fluids and these factors can lead to both short-term and long-term effects which cannot be properly interpreted with pressure data alone. A body of reservoir data is required which demonstrates the thermal and chemical interactions between the injected fluids, the native fluids, and the reservoir rock matrix. This data, along with traditional flow, pressure, geologic, geochemical, and geophysical data are required to develop the new techniques necessary to predict long-term reservoir performance with fluid injection.

Use of tracers to monitor injected fluid dispersion was established as a priority technique for study at the joint DOE/industry meeting in December of 1981. Traditionally, tracers have been used as a means to monitor fluid subsurface movement by adding them to injected fluids and monitoring for their arrival at other locations in the geothermal field. If they arrive at the monitor locations, inferences can be made about how the tracer dispersed in the field and, in general, the reservoir flow conditions. There are many problems with this technique. If the tracer arrives at the monitor well in a reasonable time, the developer has valuable reservoir data, i.e. fluid is short circuiting in the reservoir. If it does not arrive in the monitor wells, little information has been gained about the reservoir. The tracers

could be physically or chemically restrained by the reservoir matrix rocks, the fluid could be moving through locations where there are no monitor wells, or it could be dispersing in an orderly manner, mixing with the native water until the tracers are below detection levels.

The Idaho Operations's Office (IDO) team conceived the concept that a more proper way to initiate use of tracers might be to inject fluid with tracers into a well, backflow the well, and analyze the returning fluid for tracers and chemical reaction products. This approach has the following potential advantages:

- 1) A suite of tracers can be easily evaluated. Those which interact with the formation can be eliminated and conservative tracers can be established.
- 2) With conservative tracers established, the mixing of the injected fluid with native fluids can be studied.
- 3) Analysis of the mixing curves should provide information regarding the reservoir flow system and may be used to determine selected reservoir characteristics.
- 4) If the injected fluid flows from an area of fracture permeability into an area of matrix permeability or visa versa during injection flow, this may be detectable as a change in the tracer concentration in the return flow.
- 5) The chemical reactions between the injected fluid and the matrix rocks and native fluids can be assessed by analyzing the chemicals in the injected and returning fluids.
- 6) Deposition of solids can be assessed by analyzing the solid particles in the injected and returning fluids. This analysis would be integrally related to the chemical reactions which would also affect solids.
- 7) With the temperature of the injected and returning fluids known along with the mixing of the injected and native fluids and the time in the formation, the heat transfer between fluids and the matrix can be assessed. The heat transfer may be related to matrix porosity and this might be an additional means to assess reservoir flow characteristics.

- 8) Natural reservoir flow or drift of fluids in the area of the injection well can be assessed by delaying the backflow from the test well. Loss of tracers or a failure to obtain a mass balance would indicate a substantial natural flow in the reservoir with the tracer moving beyond the well's radius of influence.
- 9) The single well test procedure has great advantages during the early phases of reservoir development when well spacing is at the greatest distances and the chances of tracer breakthrough are least likely.

The strategy of the IDO team has been to first develop the methods for acquiring these single well data with a series of short-term tests. The basic test procedure is to inject a fluid into a well with tracers and then to backflow the well and monitor the return of the tracers. Chemical analyses are performed on the injected and returned fluid, and system pressure, temperature, and flows are closely monitored during the test. From these data information on fluid mixing, chemical reactions, heat transfer and flow within the formation is deduced.

When the single well short-term test techniques are demonstrated, it is planned to expand the field test program to include longer term testing and multiwell tests. In addition, the performance of major operating fields will be reviewed to determine if the new techniques can be applied to the management and continued development of operating geothermal systems. In concert with the field tests, laboratory data are being acquired to assure that analytical techniques which result from the field data are based on theoretically sound principles. At EG&G Idaho, the laboratory work presently consists of developing fundamental data on the flow and dispersion of fluids in fractured systems. At ESL/UURI the work consists of the acquisition of basic data on the interactions of tracers with reservoir fluids and rocks.

New analytic techniques are required to integrate this information. Ideally the desired code or package of codes should be able to integrate the complete body of information obtained from geological studies, geochemistry analyses, geophysical surveys, and reservoir engineering test data including the new information on fluid mixing and chemical reactions.

3.0 Approach

The program has been divided into seven areas of research as shown on Figure 1. The following summarize the principal objectives and accomplishments of the work in each major area:

- 1) Field Testing: The primary objectives of this work are to develop and refine the new field procedures necessary for conducting the injection/backflow tests in conjunction with the use of tracers and to produce field data for analysis. Two test programs were successfully accomplished.
- 2) Geology: The objective of this work is to develop a baseline geological model of the reservoir using existing geological, geophysical, geochemical and well log data. At Raft River much of this work had already been accomplished, and at East Mesa, this work will be initiated in FY-84.
- 3) Geophysics: The principal objective of this work is to conceive and test techniques which might monitor the movement of injected fluids in the reservoir. Self Potential (S.P.) and resistivity surveys were conducted at Raft River and an S.P. survey was made at East Mesa. Encouraging results were obtained at both locations.
- 4) Geochemistry/Tracer Development: The objectives of this task are to identify tracers for use during injection, conduct screening laboratory tests to evaluate the various tracers, and to develop techniques for sampling and analyzing the tracers both in the field and in the laboratory. Analysis of the tracer data was conducted as a part of this task. Conservative tracers were determined, best estimate mixing curves were developed, and chemical reactions between the injected fluid and the rock matrix and native reservoir fluids were studied. A majority of the analyses have been completed on the Raft River data and preliminary analyses have been completed on the East Mesa data.

S3 2205

Figure 1. Work breakdown structure for Injection Program

- 5) Preliminary Reservoir Analysis: The objectives of this work are to evaluate the response of the reservoir to the injection backflow testing. This work included a conventional well test analysis, an interpretation of the reservoir fluid mixing, and a preliminary analysis of the heat transfer. A refined conceptual model of the flow field around the Raft River test well was prepared to assist in the integrated analysis.
- 6) Laboratory Fracture Flow Testing: The objective of this work is to obtain basic data on the flow and mixing of an injected fluid in controlled laboratory experiments simulating the injection/backflow field tests. A fracture model has been constructed of plexiglass and parametric tests have been initiated studying reservoir crossflow and injected fluid volume.
- 7) Reservoir Simulation: The objective of this task is to integrate the various research areas into a unified reservoir characterization. Initial work has been concentrated on finding a computer code with the combined capability of fluid mixing and pressure/temperature response in simulating a reservoir. No one code could be found which had all the desired capabilities. A baseline code has been selected and is in the process of being checked out.

4.0 Discussion of Program Results

In this section a summary discussion is presented on the accomplishments in each of the major work packages. Sufficient detail is presented to give the reader an understanding of the basis for the conclusions from this first phase of the research program. Work was conducted in parallel on each of the research tasks. This has necessitated use of slightly different data in the various analysis. For instance, the best estimate mixing curves were not available while most of the fracture flow analysis work was in process. Interim mixing curves were used and some differences can be noted. These minor discrepancies have not affected the analyses or conclusions.

4.1 Field Test Program

The first objective of the field test program was to assess the feasibility of using tracers in short-term injection/backflow tests. The Raft River Geothermal Field was selected for the preliminary feasibility study.

The field was immediately available for testing, excellent facilities were available, and the moderate temperature of the wells (250-300°F) provided an ideal environment for tracer development. The wide variation in water chemistry between wells (8000 μ S to 2700 μ S) allowed naturally occurring chemical species to be used as tracers. The Raft River reservoir is highly fractured and it is a program objective to develop techniques primarily for fractured reservoir analysis.

Selection of the test well at Raft River was also based on a known pressure connection with another well in the field. It was hoped a series of injection backflow tests could be conducted on the well and then a long-term injection test conducted which would result in a tracer breakthrough between the wells. This objective was not met, as a tracer breakthrough did not occur.

The second reservoir selected for testing was based on a request for proposal (RFP) which was sent to all major geothermal field developers in the U.S. The RFP emphasized that DOE was looking for new and novel techniques for injection testing and a second evaluation of the injection/backflow technique. It was also emphasized that the developer should plan to use the data as a part of his field development planning. Several responses were received and the Republic Geothermal, Inc. (RGI) field in East Mesa was selected for testing. Significant findings from the response to the RFP were that there is considerable industry interest in the injection/backflow technique. No alternate advanced testing techniques were proposed. Based on this response, it is concluded that the injection/backflow technique should be pursued to convert the promising test results into methods and procedures which can be used by industry.

RGI proposed two test wells; one is planned as an injection well and it had no known pressure connections with other wells in the field. The second is planned as a production well and has a known pressure connection with a third

well which was proposed as the supply well for the test program. This well selection gave an opportunity to compare tracer response in an isolated well and in a well with the potential for a subsurface flow bias induced by the production well. The RGI East Mesa field consists of multiple layers of primarily porous homogeneous aquifers. It was concluded that this field could provide basic data for comparison with the fracture flow data obtained at Raft River.

A summary of data on the Raft River and East Mesa test and supply wells are shown on Table 1. The three injection wells provide a strong initial base for developing data on the injection/backflow test technique.

Table 2 summarizes the test program conducted at Raft River. The first test was an operational check to assess any problems which might occur in attempting to use tracers in a short term injection/backflow test. A "cocktail" of tracers was injected and injection flow was continued for sufficient time to fill a large portion of the wellbore but not enter the formation. The test was successful. Approximately 96% of the injected tracers were recovered which indicated excellent operational control for the test program.

Two series of parametric tests were then conducted in conjunction with the evaluation of assorted tracers. In the first test series shown on Table 2, the effect of increased volume of injected fluid was studied. Injection time was varied from two hours to 96.5 hours. Flow was held at 150 gpm and backflow was initiated as rapidly as possible after the completion of injection. Backflow was to be continued until the tracer content had returned to background level as determined by field analyses. Subsequent laboratory analyses showed that the tracer content of the fluid produced had not returned to background level so there were tracer losses. Analyses indicate it would have required approximately eight volumes of backflow for each volume of injectate to fully recover the tracer.

The second series of tests investigated the effect of extended delays between injection and backflow. The quiescent period was varied from two to 50 hours. The final test was a long-term injection test to evaluate two geophysical techniques for monitoring downhole injectate flow and to determine if a tracer breakthrough could be obtained into a second Raft River well. At the conclusion of this test, a series of pulse tests were conducted to gain additional

TABLE 1
SUPPLY AND INJECTION WELLS
RAFT RIVER AND EAST MESA
INJECTION/BACKFLOW TEST PROGRAM

	<u>RAFT RIVER</u>		<u>EAST MESA</u>		
	<u>SUPPLY WELL</u>	<u>TEST WELL</u>	<u>SUPPLY WELL</u>	<u>TEST WELL #1</u>	<u>TEST WELL #2</u>
Well Designation	RRGP-3	RRGP-5	38-30	56-30	56-19
Well Depth (ft)	5,917	4,911	9,009	7,520	4,502
Type Completion	Openhole	Openhole	Slotted liner	Slotted liner	Slotted liner
Temperature	300°F	275°F	339-354°F	315-345°F	231-259°F
Fluid Composition					
TDS (mg/l)	4,575	1,370	2,034	2,100	5,830
Conductivity (μS)	8,000	2,700	3,500	3,000	8,700
Ca (mg/l)	200	38	6.5	6	20.1
Na (mg/l)	1,194	484	605	600	2,005
K (mg/l)	101	28	25	46	53
HCO ₃ (mg/l)	32	50	550	600	1,092
Cl (mg/l)	2,433	666	496	530	2,520
SiO ₂ (mg/l)	151	140	193	180	94

TABLE 2
SUMMARY RAFT RIVER TEST PROGRAM*

<u>TEST DESCRIPTION</u>	<u>TEST NUMBER</u>	<u>INJECTION TIME</u>	<u>QUIESCENT TIME</u>	<u>BACKFLOW TIME</u>
Baseline Tests	2A-1	1 hr (well-bore only)	-0-	-
Parametric Analysis Injection Volume	2A-2	2 hrs.	-0-	10.4 hrs. @ 150 GPM 10. hrs. @ 30 GPM
	2C	46.5 hrs.	-0-	110 hrs.
	2D	96.5 hrs.	-0-	231 hrs.
Parametric Analysis Quiescent Time	4A	.3 hrs.	27.5	8.0 hrs.
	4B	.3 hrs.	2.2	10.5 hrs.
	4C	.3 hrs.	12	8.5 hrs.
	4D	.3 hrs.	50	48.5 hrs.

*Injection and backflow were at a nominal 150 gpm.

TABLE 2 (Cont'd)

<u>TEST DESCRIPTION</u>	<u>TEST NUMBER</u>	<u>INJECTION TIME</u>	<u>QUIESCENT TIME</u>	<u>BACKFLOW TIME</u>
Long Term Injection	5	376 hrs.	80 hrs.	120 hrs.
Pulse Tests	5	<u>Flow Rate gpm</u>	<u>Flow Time Minutes</u>	<u>Recovery Time Minutes</u>
		75	18.3	11.2
		125	15.8	19.4
		175	23.1	10.2
		225	16.9	118.0
		276	32.8	14.6
		325	1.5	6.8
		300	2.8	4.0

pressure response data, and a short backflow test was conducted for comparison with previous injection backflow tests. Self potential and resistivity surveys were made to determine if the injected fluid movement could be detected.

Table 3 summarizes the test program conducted at East Mesa. Well 56-30 was tested first. This well has a known pressure connection with the supply well 38-30, and it was desired to determine if subsequent testing of well 56-19 would disturb an injected volume of tracers around well 56-30. To accomplish this objective, flow tests at two rates were first run at well 56-30 and then a baseline injection/backflow test was conducted. The flow tests were conducted to help select a rate for the injection/backflow test and to obtain the standard well drawdown data. The baseline injection/backflow test was run for comparison with the final test where an identical volume of fluid was injected and left in the reservoir. This fluid will be withdrawn in January or February of 1984 to determine if the subsequent flow testing at well 56-19 and/or long term storage affected the dispersion of tracers.

Baseline flow conditions of 300 gpm for 12 hours were selected for injection and backflow. These conditions were selected for operational convenience, as we presently have no theoretical basis for selecting a standard set of conditions. The baseline testing at East Mesa was conducted with a constant recovery period between injection and backflow whereas baseline tests at Raft River were conducted with a minimum delay between injection and backflow. This change was made to improve the ability to analyze the well drawdown and recovery characteristics.

Testing at well 56-19 was initiated with two flow tests and a baseline injection/backflow test similar to those at well 56-30. Two exploratory injection/backflow tests were then conducted. The first was at a higher flow rate, 500 gpm, and for the second the injection time was doubled (14 hrs. versus 7 hrs.). In the final test, a volume of fluid with tracers was injected and left in the formation to determine the effect of a long quiescent period.

Currently both wells are idle with identical volumes of injectate (with tracers) in the reservoir. It is planned to begin testing again in January or February of 1984. The baseline data will be analyzed in the interim period and a series of parametric tests planned to complete the program in FY-84.

TABLE 3
EAST MESA INJECTION/BACKFLOW
TEST PROGRAM SUMMARY

WELL 56-30					WELL 56-19				
	INJECTION	RECOVERY	BACKFLOW	RECOVERY	INJECTION	RECOVERY	BACKFLOW	RECOVERY	
BASELINE FLOW TESTS									
LOW	-0-	-0-	300 gpm 25 hrs.	17.5 hrs.	-0-	-0-	300 gpm 26.3 hrs.	20.5 hrs.	
HIGH	-0-	-0-	450 gpm 24 hrs.	7 days	-0-	-0-	500 gpm 24.2 hrs.	27.5 hrs.	
Baseline Injection/ Backflow	300 gpm 11.5 hrs.	12 hrs.	300 gpm 67 hrs.	21.7 hrs.	300 gpm 12.5 hrs.	11 hrs.	300 gpm 53.4 hrs.	19 hrs.	
High Rate Injection/ Backflow	-	-	-	-	500 gpm 7.4 hrs.	12.8 hrs.	500 gpm 28 hrs. 450 gpm 20 hrs.	49.8 hrs.	
Increased Volume Injec- tion/Backflow	-	-	-	-	500 gpm 14.5 hrs.	12 hrs.	500 gpm 38.8 hrs. 450 gpm 9 hrs.	18.5 hrs.	
Long Term	300 gpm 12 hrs.	~ 6 mos.	-0-	-0-	500 gpm 7.3 hrs.	~ 6 mos.	-0-	-0-	

Operationally, both the Raft River and the East Mesa tests were extremely successful. Techniques for handling tracers were developed and field procedures for monitoring the return of tracers were successfully accomplished. Excellent baseline data for evaluating the viability of the injection/backflow technique were obtained.

In the remainder of this report more detailed discussions are presented on analysis of the Raft River data, supporting laboratory work and on the development of a simulation model to analyze the data. A report on analysis of the East Mesa data will be prepared at a later date.

4.2 Geology of Raft River

The geology of the Raft River Known Geothermal Resource Area (KGRA) has been studied extensively by members of the U.S. Geological Survey (Williams et al, 1976, Covington, 1977, 1980, and 1983), the Idaho National Engineering Laboratory (Dolenc et al, 1981) and the University of Utah Research Institute (Blackett and Kolesar, 1983).

A synopsis of these documents is presented below.

The Raft River KGRA occurs in a downdropped, downwarped basin bounded on the east, west, and south by mountain ranges. The basin stratigraphy, Figure 2, consists of approximately 1900 m of basin fill sediments overlying a series of Precambrian quartzites and schists. The upper 300 m of basin fill is comprised of Quaternary, colluvial and alluvial sediments called the Raft Formation. Underlying these sediments is the Tertiary Salt Lake formation, aluviated and possibly lacustrine deposits of tuffaceous sand, silt and conglomerate up to 1600 m thick. The basement is comprised of the Precambrian yost quartzite, Upper Narrows Schist, Elba Quartzite, and Older Schist, underlain by Precambrian adamellite quartz monzonite which has been partially remobilized and intruded (Armstrong).

The western boundary of the basin is downdropped along a series of listric normal faults called the Bridge and Horse Well Faults. The Bridge Fault trends north-south and extends from the eastern edge of Sheep Mountain to

Figure 2. Cross-Sectional view of major geological formations and structures of the Raft River KGRA.

the south end of the Jim Sage Mountains. These faults dip from 60-80° at the surface flattening with depth to parallel the basement rocks. Numerous vertical fractures associated with these faults extend into the Salt Lake Formation.

The southern terminus of the Bridge Fault zone is a poorly understood structural lineament which strikes in a northeasterly direction from the Narrows at the south end of the Jim Sage Mountains (Figure 3). This structure, the Narrows zone, is not manifested on the ground surface, but can be identified on geophysical surveys. It is not well understood but is thought to be a basement shear possibly related to the Humboldt zone of northern Nevada (Mabey 1978).

4.3 Geochemistry/Tracer Development

Natural and artificial tracers were used to assess fluid movement and mixing in the formation surrounding test well RRGP-5. Natural tracers are those dissolved chemicals which are present in the injected fluids at significantly different concentration levels from the native reservoir fluids. Artificial tracers are compounds which are added to the injected fluids in known concentrations. At Raft River, RRGP-3 was selected as the supply well for the tests at RRGP-5, primarily because of the difference in dissolved solids contents of the two wells (4575 RRGP-3 versus 1370 mg/l RRGP-5). In addition to the natural tracers in the supply water, seven artificial tracers were investigated. These were as follows:

- Sodium Iodide
- Sodium Bromide
- Magnesium Chloride
- Borax
- Disodium Fluorescein
- Rhodamine-B
- Sodium thiocyanate

An ideal tracer is one which is 1) conserved, i.e. unreactive with the geologic formations present in the study area, 2) is not present in the rocks in a form that is readily released into the tracer solution, and 3) whose concentration in the tracer solution can be well documented.

Figure 3. Structural features of the southern Raft River Valley.

Three tracers were determined to be conserved under the conditions encountered at Raft River: sodium, potassium, and chloride. Evidence that these are conservative tracers is based on theoretical considerations for chloride and the results from test 2A-2 for all three tracers.

The natural tracer chloride is highly soluble in natural waters, well above the maximum concentration of 3000 ppm injected during testing. Because chloride is not greatly affected by adsorption, desorption and ion exchange, minor gains and losses resulting from these processes would be relatively small compared to the high chloride concentrations in the injectate. In addition, no chloride minerals were identified in the reservoir rocks in the vicinity of RRGP-5 (Blackett 1983), and therefore chloride gains resulting from mineral dissolution are not a concern.

In test 2A-2, a large volume of fluid was backflowed relative to the volume of fluid injected (10.5/1), and all evidence points to complete recovery of injected fluids. Average recovery in test 2A-2 was 99% for the three conservative tracers Na, K and Cl. Figure 4 shows the percentage of injected fluid in the total backflowing fluid calculated from each of the three conservative tracers as a function of total solution backflowed for test 2C. The excellent agreement further illustrates the reliability of the three tracers. Similar results were obtained comparing the three tracers in other tests.

The effects of chemical reactions and mixing are minimal in solutions confined to the wellbore. Therefore the tracer content of the final solution injected in the wellbore should equal the tracer content of the initial solution removed from the wellbore. This comparison provides a unique opportunity to evaluate the overall quality of data collected for each test. For example, errors in chemical analyses or in estimation of flow rates, mixing in the wellbore and accidental flow during quiescence periods are all potential sources of error that can be evaluated. During injection testing, downhole conductivity surveys were conducted to follow the tracer front into and out of the wellbore. The results showed that little or no mixing occurred between the tracer solution and the reservoir water within the confines of the wellbore. Thus, errors caused by mixing in the wellbore will not be significant.

Figure 4. Raft River test 2C fraction of injectate in backflow

This information was used to monitor each of the tests for errors in test control. The results shown on Table 4 show that the conservative tracers sodium potassium and chloride indicate good test control on tests 2A-2 and 2C. On the remainder of the tests problems are evident. The principal problem was minor wellhead leakage during quiescent periods and/or convection between the wellbore and formation caused by temperature differences.

The artificial tracers generally have poor wellbore recoveries. The poor agreement relative to conservative tracer recoveries suggests errors in the determination of variables other than mixing in the wellbore, flowrate and accidental or convective flow during quiescence. Possible reasons for these poor wellbore recoveries include irregular tracer injection rates, early shutdown of artificial tracer injection, analytic errors and a wide spacing between analyses.

The mass of injected fluid recovered during backflow was calculated for all of the tests conducted at Raft River using the three conservative tracers. The results show that in the long-term injection tests mass recovery was quite low, 63% for the 46.5 hour injection test and 66% for the 96.5 hour injection test. Tracer concentration had not returned to background levels because of insufficient backflow. Analysis of the Test Series 2 data shows that approximately 8 volumes of backflow are required to effect full recovery of injected fluid.

The short 20 minute injection tests in the Test Series 4 were grossly affected by the background tracers left in the reservoir. Recovery averaged from a low of 70% to greater than 120% depending on the background assumption used.

Best estimate mixing curves for the return of injected fluids are shown on Figures 5 and 6. These curves are based on the conservative tracers Na, K and Cl.

TABLE 4
RATIO OF THE MASS OF TRACER RECOVERED
VS MASS INJECTED INTO THE WELLBORE^a

TRACER ^b	TESTS							
	2A-2	2C	2D	4A ^c	4B	4C	4D	5 ^c
Na	0.96	1.01	0.96	0.73	0.78	0.70	0.61	0.70
K	0.98	1.02	0.97	0.72	0.78	0.71	0.62	0.70
Cl	1.03	0.95	1.18	0.76	0.95	0.92	0.58	0.71
Mg		0.73	13.04					
I	0.94			0.81		1.22		
Br							0.91	
SCN					0.72			
Na ₂ Fluorescein		0.96			0.85	0.87		
Rhodamine-B			0.55					

^aWellbore volume is 7.1×10^4 liters.

^bTracer slugs not included unless injected during the last 7.1×10^4 liters of injection.

^cOperators log indicates during the quiescence portion of this test an unknown volume of solution backflowed from the well.

Figure 5. Generalized mixing curves - Raft River

Figure 6. Mixing curves for Raft River test series 4

Analysis of chemical reactions between the injected fluid and the reservoir rocks and fluids has been initiated. The most obvious reaction noted to date is the depletion of magnesium by approximately 40 mg/liter (1.65×10^{-3} moles/liter) and enrichment of calcium by approximately 64 mg/liter (1.60×10^{-3} moles/liter), as shown on Figure 7. The calcium enrichment gives initial calcium concentration in the backflow solution up to 40 mg/liter higher than calcium measured in either the injected RRGP-3 water plus tracer or RRGP-5 reservoir water. The molar loss of magnesium is almost equivalent to the molar increase in calcium, suggesting exchange of calcium for magnesium within the reservoir rock. The large quantities of cement injected into the formation around well RRGP-5 during drilling and hydrofracturing operations may be responsible for cation exchange and loss of magnesium from the water.

The bicarbonate is also enriched in the backflow solution by approximately 14 mg/liter (2.3×10^{-4} moles/liter). This suggests injection resulted in the dissolution of calcite or cement present in the quartzite reservoir rock. For each mole of bicarbonate added to solution through calcite dissolution an equivalent amount of calcium is added. The resulting calcium increase accounts for less than 15% of the excess calcium in the backflow solution.

Silica in the backflow is depleted by approximately 50 mg/liter (8.3×10^{-4} moles/liter). This decrease may be the result of silica precipitation in response to decreased reservoir temperatures during injection.

In summary it has been shown that conservative tracers can be found which permit a determination of mixing between injected fluids and native fluids in the reservoir surrounding an injection well. Na, K and Cl were found to be conservative at Raft River. The technique of analyzing tracer returns from fluid injected and backflowed from the wellbore is a discriminating means of assessing the overall control on the conduct of tests and can be used to assure valid data are being obtained. Analysis of the chemical content of injected and backflowed fluids shows great promise as a means to assess water-water and rock-water reactions within a geothermal reservoir.

Figure 7. Calcium/Magnesium recovery - Raft River test series 2C

4.4 Geophysical Studies

Two geophysical techniques to monitor the direction of downhole fluid movement were investigated during the injection tests. At Raft River resistivity and self potential surveys were run and a self potential survey was conducted at East Mesa. Detailed reports on the geophysical work at Raft River are presented in the referenced reports by W. R. Sill. The East Mesa self potential data will be analyzed in FY-84.

Responses in all tests were measured which were indicative of the detection of fluid movement. At Raft River, however, the responses were close to the noise level of the instrumentation and it is not possible to make absolute conclusions that the techniques can be used to monitor subsurface fluid movement. The encouraging fact is that both the self potential and resistivity surveys indicate movement of fluid in the same general direction, and the indicated direction of movement is reasonable based on the geology of the area.

Figure 8 shows the layout of the wells in the Raft River field and two pertinent geological features, the Bridge Fault and the Narrows Structure. Well #5 (the test well), is shown in the lower left side of the figure and sits adjacent to the Bridge Fault which runs in a northeasterly direction. The best interpretation of the direction of fluid movement based on the resistivity and self potential surveys is also shown on Figure 8. The self potential data closely follow the direction of the narrows structure, while the resistivity data more closely follow the direction of the Bridge Fault. It is reasonable that the injected fluids would be following a fault system, and this tends to be supported by the observed data.

Modeling studies have been run on the resistivity and self potential data, and these suggest a narrow deep fault that would explain the observed results. However, the fault would have to extend to a relatively shallow depth (100 meters), but no pressure response was observed in monitor wells which penetrated to this depth in the general area of the faults.

Figure 8. Resistivity and self potential trends in long-term injection tests

Definite changes were observed at East Mesa in the self potential measurements, indicating that subsurface movement of fluid was being detected. As mentioned previously these data have not been analyzed, so the soundness of the results cannot be assessed. It is concluded that the resistivity and self potential techniques have considerable potential, but additional testing is required to verify their validity.

At Raft River and at East Mesa, funding constraints prevented optimization of the tests for evaluation of the geophysical techniques. Compromises were made between the need to obtain the geophysical data, the need for geochemical data and the need for conventional reservoir engineering data. In planning the second phase of the test program at East Mesa, studies will be made to determine if an improved test can be developed which will provide a more positive evaluation of the potential for the self potential technique.

4.5 Laboratory Fracture Flow Testing

A series of laboratory models have been constructed at EG&G Idaho to obtain basic dispersion data on water in simulated fracture systems. The work was initiated with a simple Plexiglass model which simulated a single fracture junction; this was expanded to a quarter circle model with multiple fracture junctions; and finally to a rectangular model with 112 simulated fracture junctions.

The 112 junction rectangular model was constructed specifically for the injection program to provide fundamental data on the injection/backflow technique. Experiments are conducted by filling the simulated fracture network with water of one conductivity and color and then injecting water with a second conductivity and color. The model is made of Plexiglass so mixing can be visually studied, and it is fully instrumented with conductivity and pressure probes to quantify the mixing of the fluids. Fluid can be injected and removed from a single location. A cross-flow of fluids can be maintained in the fracture matrix while fluid is injected and removed from the simulated wellbore.

Test runs in the single fracture model demonstrated that at high flow velocities, the injected fluid moved according to the parabolic velocity profile (Figure 9). As time increased, or flow rates decreased, transverse diffusion within a fracture mixed the tracer between adjacent streamlines. This produced a uniform distribution across the fracture, but a concentration gradient persisted along the fracture. Flow rates during injection/backflow testing of the physical model were too high to allow complete mixing within fractures. At fracture junctions, little mixing of tracer occurred between adjacent streamlines (Figure 10). The distribution of tracer entering a fracture from a junction is related to the position of the tracer in the incoming fracture and the hydraulic gradient in the vicinity of the junction.

When backflow is initiated, a reverse process occurs. The native fluid in the reservoir begins to form a thin streamline through the center of the mixture of fluids in existence in the various fracture passages and junctions.

Two injection/backflow test series were conducted with the fracture model. A series of twenty-three runs was made studying the effect of injected volume on the mixing of the two fluids and the effect of reservoir cross-flow on the recovery of the injected fluid.

The results of the injection volume runs are shown on Figure 11. When the injected volume was increased, the apparent dispersion of the fluids increased. However, when the dispersion curves are normalized by dividing the data by the total volume of injected fluid the curves fall on top of each other (Figure 12). This indicates a fairly homogeneous reservoir, where dispersion characteristics do not change significantly with distance.

Nineteen runs were made to study the effect of reservoir crossflow on the dispersion of the returning fluids. As would be expected, the cross-flow caused a lengthening of the tail on the return of the injected fluid. At high cross-flows a portion of the injected fluid was lost. A plot of results is shown on Figure 13.

Figure 9. Schematic of velocity profile in fracture

Figure 10. Solute travel through the fracture intersection

S3 2947

Figure 11. Variable volume injection/backflow tests with reservoir flow field

S3 2944

Figure 12. Normalized curves showing effect of injection volume

Flow Field - 10.8 cc/min

Figure 13. Tracer recovery curves for variable quiescence with reservoir flow field

The fractional tracer recovery is related to the quiescence time in the reservoir by the equation:

$$1-F = \frac{V}{\theta \pi h}^{-1/2} \frac{\bar{v}}{2} t$$

V = injected volume

θ = porosity

h = aquifer thickness

$\bar{v}$ = mean flow velocity in aquifer

t = quiescence time

F = fractional tracer recovery

By combining data from tracer recovery tests with aquifer transmissivity and gradient, the porosity and flow rate can be determined.

It is concluded the laboratory models are providing good basic data on mixing of fluids in fracture systems. Expanded experimental work is required to get additional basic data on the effect of variables such as surface roughness, fracture dimensions, junction angles, etc. These data are used to develop the models for use in the reservoir simulation codes.

4.6 Hydrologic Analysis

RRGP-5BF, the test well at Raft River, is located in an area of complex fracture flow systems. The well is located close to the Bridge Fault which is in the general vicinity of the Narrows structure, a poorly understood thought to dissect the Raft River valley. Figure 2, a cross-section of the area, shows that the well extends into the basement adamellite through quartzite, schist and breccia. The prime subsurface conduit for the movement of geothermal fluids at RRG-5BF and probably for wells RRG-1 and RRG-2 is believed to be the Schist of the Upper Narrows.

The well had unique completion problems. The first leg drilled was an excellent producer flowing an estimated 1000 gpm. The initial temperature was lower than desired (approximately 275°F) and drilling was continued in an effort to locate higher temperature fluids. The drill stem twisted off during the drilling and in the process of completing the initial leg of the well, 198 tons of salt and 1030 bags of cement were added to the wellbore. When drilling commenced the borehole became offset from the portion of the hole filled with cement and the initial high flows were never regained. The well was then cased to a depth below the major aquifers and then hydrofractured with 215 tons of sand injected into the well. An acoustic televiwer log indicated a new fracture about 140 feet long with a maximum width of 0.6 inches had been formed. A diagram of the well as completed is shown on Figure 14. The well is now capable of short-term 300 gpm artesian flow and it has been pumped several times at approximately 600 gpm. Sand produced by the well limited all pump tests to a short duration. (The sand destroyed the pump impellers.) During the hydrofrac and during previous pump testing, a hydraulic connection was noted between RRGP-5B and RRGE-1. In summary, RRGP-5BF is located close to major faults; it was cased and cemented off from the major aquifers with production partially restored with a hydrofrac treatment. It has many tons of unrecovered sand and cement in the formation around the well.

Four sets of data were analyzed to assess the flow of the fluids in the open borehole and in the aquifers penetrated by RRGP-5BF. These were the borehole geophysical logs, the wellhead pressure response data, the mixing of injected and native fluids, and data on the transfer of heat between the injected fluid and the reservoir.

The well borehole geophysical logging operations conducted before and during the injection/backflow tests included temperature, caliper, spinner, and fluid temperature/conductivity. Temperature data obtained from the logging operation suggest that the major producing zone encountered during the drilling of the first leg was probably encountered by the hydraulic fracture. This aquifer is presumed to be responsible for the essentially constant-head boundary conditions within 5 minutes of initiating/terminating flow. Spinner, borehole fluid temperature and borehole fluid specific conductivity logs

RRGP-5BF Well Construction

Figure 14. Well construction for RRG-5BF after fracture treatment

INEL 3 3924

indicate at least 5 major production/receiving zones in the hydraulically fractured portion of the well. Figure 15 summarizes spinner/temperature/conductivity data obtained during injection and backflow of RRGP-5. This figure shows the five producing zones.

Pressure data were analyzed for each of the injection/backflow tests, for the long-term injection test and for the series of pulse tests run after test #5 was completed. Downhole pressure measurements were not available during most of the injection/backflow tests and this largely negated efforts to analyze the pressure transients during these tests. The wellhead pressure data were significantly influenced by the changing wellbore fluid density with the reservoir drawdown being generally less than the wellhead pressure decline due to wellbore fluid density effects. The pressure would actually drop shortly after the initiation of injection and would rise shortly after initiation of well discharge which is the reverse of expected well performance without the density effects.

The pulse tests provide the best information to assess the hydraulic characteristics of the well. These data clearly show that the hydraulic characteristics of RRGP-5BF are not those expected with a single homogeneous isotropic porous media aquifer of infinite areal extent. This is illustrated on Figure 16 which shows a plot of the discharge rate (Q) divided by the drawdown or recovery of pressure per log cycle of time (S_{10}) since discharge was initiated or terminated for the seven pulse tests. The parameter (Q/S_{10}) should be a constant independent of the flowrate if the flow is into a simple homogeneous porous aquifer with an infinite boundary. As shown on the figure, it changes throughout the range of discharge rates. A definitive explanation for this phenomenon (which has also been observed for RRGE-1 and RRGE-2 data, both multiple aquifer fracture flow controlled wells), is not available, but is probably the result of non-laminar flow in the aquifers and/or comingling effects between aquifers.

A pressure response was not observed at well RRGE-1 during any of the injection/backflow tests on RRGP-5BF. Pressure responses had previously been noted during a 640 gpm pump test of RRGP-5B prior to the hydrofrac and during the hydrofrac when the wellhead pressure was raised in excess of 1800 psi. It is concluded that the flowrates in the injection/backflow tests were too low to significantly affect the pressure at RRGE-1.

Figure 15. Production/receiving zones discharge/untake as a percentage of flow rate for RRG-5BF

Figure 16. Pulse test Q/S_{10} vs Q for RRGP-5BF

The mixing curves developed as a part of the tracer analysis represent another potential means to assess the flow of the injected fluids in the reservoir surrounding RRGP-5. In theory, the percentages of the injected fluid and the native reservoir fluid in the backflow of a well should be related to the physical characteristics of the aquifer into which the fluid is injected. To verify this hypothesis, it is necessary to obtain injection/backflow data in a variety of reservoirs with known hydraulic characteristics or as a minimum to study a variety of systems in the laboratory or by computer simulation. With only RRGP-5 data this cannot be accomplished, but two variables were studied in the Raft River tests series which might give indications of reservoir characteristics. In Test Series 2, the volume of fluid injected was studied, and in Test Series 4, the effect of a time delay between injection and backflow was investigated. To provide a basis for analysis of results, a similar set of tests were conducted in the laboratory.

When the volume of injected fluid was increased, similar results were obtained at Raft River and in the laboratory. As the volume of injected fluid was increased, the mixing of native reservoir fluid and the injected fluid increased. This is shown on Figures 5 and 11. It is significant to note that even after 96.5 hours of injection into the formation (Test 2C), complete displacement of native reservoir fluid had not been accomplished. Almost immediately upon backflow a small percentage of native fluid begins to return. When the RRGP-5 data are normalized by dividing the volume of backflowed fluids by the volume of injected fluids (Figure 17), the curves overlies each other similar to the laboratory data. This similarity suggests the injected fluid is mixing with the reservoir fluid in an orderly fracture system and is in apparent conflict with the pressure data. The pressure data suggest a highly restricted flow area adjacent to the wellbore which opens into a large aquifer with an infinite (undetermined) boundary.

At the present time there is insufficient data to verify how mixing is affected by the various types of fracture systems through which an injected fluid might pass. It is concluded that additional laboratory work and computer simulations are required to assist in the interpretations of the Raft River data.

Figure 17. Generalized mixing curves after normalization

To determine if there is flow in the reservoir surrounding RRGP-5, four tests were run varying the time between completion of injection and initiation of backflow (-4 Series of Tests). The tests were short in duration with only twenty minutes of flow into the formation. The quiescent period between termination of injection and initiation of backflow was varied between 2.2 hours and 50 hours. It was found that there was fluid movement during the quiescent period, but the nature of the movement is difficult to assess. Figures 18 to 21 show plots of the fluid conductivity at the surface of the wellbore. These plots only show the conductivity for the portion of the backflow after the conductivity begins to drop, i.e. prior to this time the flow would consist only of high conductivity water from RRGP-3 which entered the wellbore but did not enter the formation. In each of the plots, the conductivity begins a gradual decline and then there is a knee or local conductivity high in the curve indicative of the return of the tracer slug used during injection. The actual chemical tracer data are difficult to use in analyzing the Test Series 4 results because insufficient samples were obtained to get the smooth curves shown on Figures 18 to 21.

The time displacement of the conductivity peak is a function of the quiescent period between completion of injection and initiation of backflow. This is shown on Figure 22 on which the time delay from the start of conductivity drop to the secondary peak in the conductivity is plotted versus the quiescent period. This curve suggests there was fluid movement which displaced the tracer slug relative to the initial interface between the pure well RRGP-3 fluid and the mixture of RRGP-3 and RRGP-5 fluids. The laboratory data in which a pure reservoir cross flow was studied, gave different results (Figure 13). In these data the increased cross flow gave a smooth reduction in the percentages of injected fluid in backflowed solutions. The highest cross-flow, 14 min. (Figure 13) did give indications of a discontinuity and this might be representative of the Raft River data.

The clouding issue in the Test 4 Series at Raft River is the wellbore flow. It is known that small leaks were detected at the surface during quiescence and also that there is a shrinkage of fluid in the wellbore due to cooling. A third possible factor is convection between the hotter fluid in the formation

Figure 18. Test 4B conductivity response as a function of time

Figure 19. Test 4C conductivity response as a function of time

Figure 20. Test 4A conductivity response as a function of time.

Figure 21. Test 4D conductivity response as a function of time

Figure 22. The time to the conductivity shoulder or peak as a function of quiescent time

and cooler fluid in the wellbore. The net result of these considerations is that we cannot positively state that evidence of a reservoir crossflow has been established. In retrospect more fluid should have been injected into the formation so that wellbore effects would have been insignificant. At Raft River where time was limited this would have required a compromise with other test objectives.

Figure 23 shows a plot of the temperature of the backflowing fluid at the wellhead from tests 2C and 2D. These are the long term injection tests where fluid was injected into the formation for 46.5 and 96.5 hours. The slow return of the temperature to equilibrium suggests the injected fluid was still cool when leaving the formation surrounding RRGP-5. It was hoped the heat transfer from the formation to the injected fluid could be calculated using this data. Unfortunately, downhole temperature measurements were not made and a transient wellbore model was not available to calculate bottomhole temperatures. Attempts to use steady state wellbore temperature gradient data gave implausible results. It would appear as though there was little heat transfer to the injected fluid but positive conclusions are not possible. At East Mesa, downhole temperature and pressure data were obtained during all transients and it should be possible to obtain good heat transfer data for the tests on both wells in this field.

Figure 24 was prepared as a best estimate for the formation around RRGP-5. The five flow zones are shown with two contacting a lower temperature aquifer and three contacting the upper aquifer. The fracture is shown to be filled with sand but no cement in the immediate area. The cement is postulated to be primarily in the aquifers. This model will be used as input to the reservoir simulation computer model when it is ready.

5.0 Reservoir Simulation

Key to proper interpretation of injection/backflow testing is the utilization of a computer code which is capable of simulating the mixing of fluids along with the flow and heat transfer of fluids in a mixed fractured permeable system. The geothermal industry presently does not utilize such codes. The mixing of fluids is not simulated and only fluid bulk thermodynamic properties are tracked in a reservoir.

Figure 23. Wellhead temperature vs. Withdrawal time, Tests 2C and 2D

Figure 24. Conceptual model of RRGP-5BF reservoir in plane of the hydrofracture.

A survey of codes in use in the U.S. which have this capability was made and a part of the work accomplished in FY-83. There are a large number of codes in use which have the capability to simulate the transport of contaminants or "dispersion" in underground aquifers. They have been developed for use in studying the underground disposal of hazardous wastes. However, none of the codes had all of the features necessary for geothermal injection analysis. The injection program is not funded for a large code development effort, and an effort was made to find a combination of codes which had the features necessary to begin analysis of the injection/backflow data.

The primary requirements for selecting codes were, ease of operation, documentation available, fracture and porous media flow models, heat transfer and a fluid mixing model.

Two codes were initially selected for analyses; the SALE code to study basic flow in fractures and the FTRANS code to simulate reservoir matrixes surrounding test wells. The SALE code (Simplified Arbitrary Lagrangian-Eulerian) was written at Los Alamos in 1980 to solve a variety of fluid dynamics problems based on numerical solution of the Navier-Stokes equations in two dimensions. It was selected on the basis of its capability for incompressible low speed flow, its current usage at LASL and numerous other sites, the existence of a 3-D version, its operational status on the INEL CYBER system, its excellent structure, length and documentation and specific recommendations by its author for the subject application. The code did not contain a dispersion calculation, and a marker particle routine which has been successfully used in other codes to calculate dispersion was added to the SALE code. The modified code has been checked out by simulating flow dispersion in a pipe and between parallel plates. Good agreement has been obtained with analytic solutions, and studies are in process comparing results in the fracture flow model with SALE predictions.

The FTRANS (Fracture Flow and Transport of RAdioactive NuclideS) code was selected for reservoir analysis because it had the best simulation of multiple discrete fractures and was extensively documented. The code was written at

GeoTrans under DOE funding through the Battelle Office of Nuclear Waste Isolation. The results of an extensive evaluation of the code were disappointing in that the documentation did not match the Fortran coding and the flow calculation was not stable. In addition, the solute transport calculation was distorted by numerical diffusion.

A new code was built out of the hydrologic background developed in reviewing and testing FTRANS, along with the marker particle capability added to SALE and experience in developing dynamic simulations using a problem solver code named ACSL (Advanced Continuous Simulation Language). The resulting code, named FRACSL, has been partially checked out by solving the complex fracture system shown on Figure 25. A preliminary injection withdrawal marker particle calculation has been completed and is being reviewed.

Work to date may be summarized as methods development, partial checkout and demonstration. Further work is required in fracture geometry characterization and fracture element flow and dispersion studies before specific flow and dispersion models of the Raft River or East Mesa reservoirs can be developed. Further extensions are required to simulate heat transfer and rock-water reaction effects.

6.0 Summary

Prior to the initiation of the injection/backflow test program, there was a very poor understanding of the flow system around well RRGP-5 (primarily because of the inability to get a long-term pump test after the hydrofrac). The predominant theory was that the cement had permeated the fracture system surrounding the well, the hydrofrac had opened a fracture leading to a large aquifer but flow was still restricted, probably by sand. Because of the completion difficulties, the well is not a typical geothermal well and the completion complications have also made analysis of the flow system more difficult.

The well was selected for testing primarily because of the known pressure connection between the test well and well #1 (approximately one mile to the northeast). It was hoped with a series of injection/backflow tests to obtain

Figure 25. Typical injection/backflow reservoir simulation

an understanding of the flow system in the immediate area and then with a long term injection test get a tracer breakthrough to well RRGE-1 which would enable a complete analysis of the flow system. Tracer breakthrough to well RRGE-1 was not obtained which is representative of the problem of using tracers in this manner.

The conventional reservoir engineering analysis summarized in the prior section shows that the fracture controls flow into the well, that the flow is restricted within the fracture and that the fracture is probably intersecting at least two aquifers. The only conclusion possible relative to the main aquifer(s) is that they are large relative to the fracture and that no boundaries have been encountered. The conventional analytical techniques based on an infinite homogeneous reservoir are invalid and it is impossible to assess the long term longevity of the well either as a producer or as an injector using these techniques.

The postulated advantage of the injection/backflow technique in analyzing a well such as RRGP-5, summarized in the rationale for research section, is that the additional information on tracer dispersion, chemical reactions, measurement of the direction of fluid flow and heat transfer should improve on the ability to understand the flow system surrounding a well. The following summarizes the status of these investigations on well RRGP-5.

Fluid Mixing

The preliminary analysis of the fluid mixing data as discussed in the prior section suggests that the injected fluid flowed in a continuous system without discontinuities. The best estimate model of the system based on traditional reservoir engineering data indicates flow should initiate in a fracture and then at some point make a transition into a larger aquifer, presumably also a fracture system, but with a greater fluid capacity. However, the length of the fracture from the wellbore to the larger aquifer adjacent to the well of RRGP-5 can only be speculated upon and we currently do not have sufficient understanding of mixing phenomena to rigorously interpret the Raft River mixing curves. A preliminary look at the mixing curves obtained at East Mesa suggest different

characteristics and the Raft River data may be telling us more than we can presently interpret. Additional laboratory data and computer analysis using the model described later in this section are required to resolve these issues.

Geophysical Measurements

The geophysical measurements, resistivity and self potential, while at the limit of their resolution capability suggest the fluid is moving in a north-easterly direction possibly along the Bridge Fault or the Narrows Structure. The indications extend for a considerable distance from well RRGP-5 and if true might indicate a substantial "short circuiting" potential for Raft River. The resistivity in particular would indicate movement of the injected fluid for a substantial distance. This technique measures a conductivity difference between the injected fluid and the native fluid, in other words it determines the actual location of the injected fluid. S.P on the other hand measures all fluid movement and with an inelastic system it would also detect the movement of reservoir fluids (indicative of pipe flow or flow along a narrow fracture).

Chemical Analysis

Chemical analysis of the Raft River data is in the preliminary stages and there is considerable work still to be done in this area.

The ion exchange between calcium and magnesium clearly indicates that the injected fluid is in contact with some of the cements which sealed off the high flow aquifer originally producing from well RRGP-5. This information suggests an acid frac might restore the original high production rate of the well. The ability to use tracers to detect chemical reactions and to monitor mixing would also be useful in planning the acidification and monitoring its effectiveness.

Deposition of Solids

The particulate content of the fluids entering and leaving the wellbore was not checked in the test series at Raft River.

an understanding of the flow system in the immediate area and then with a long term injection test get a tracer breakthrough to well RRGE-1 which would enable a complete analysis of the flow system. Tracer breakthrough to well RRGE-1 was not obtained which is representative of the problem of using tracers in this manner.

The conventional reservoir engineering analysis summarized in the prior section shows that the fracture controls flow into the well, that the flow is restricted within the fracture and that the fracture is probably intersecting at least two aquifers. The only conclusion possible relative to the main aquifer(s) is that they are large relative to the fracture and that no boundaries have been encountered. The conventional analytical techniques based on an infinite homogeneous reservoir are invalid and it is impossible to assess the long term longevity of the well either as a producer or as an injector using these techniques.

The postulated advantage of the injection/backflow technique in analyzing a well such as RRGP-5, summarized in the rationale for research section, is that the additional information on tracer dispersion, chemical reactions, measurement of the direction of fluid flow and heat transfer should improve on the ability to understand the flow system surrounding a well. The following summarizes the status of these investigations on well RRGP-5.

Fluid Mixing

The preliminary analysis of the fluid mixing data as discussed in the prior section suggests that the injected fluid flowed in a continuous system without discontinuities. The best estimate model of the system based on traditional reservoir engineering data indicates flow should initiate in a fracture and then at some point make a transition into a larger aquifer, presumably also a fracture system, but with a greater fluid capacity. However, the length of the fracture from the wellbore to the larger aquifer adjacent to the well of RRGP-5 can only be speculated upon and we currently do not have sufficient understanding of mixing phenomenae to rigorously interpret the Raft River mixing curves. A preliminary look at the mixing curves obtained at East Mesa suggest different

characteristics and the Raft River data may be telling us more than we can presently interpret. Additional laboratory data and computer analysis using the model described later in this section are required to resolve these issues.

Geophysical Measurements

The geophysical measurements, resistivity and self potential, while at the limit of their resolution capability suggest the fluid is moving in a north-easterly direction possibly along the Bridge Fault or the Narrows Structure. The indications extend for a considerable distance from well RRGP-5 and if true might indicate a substantial "short circuiting" potential for Raft River. The resistivity in particular would indicate movement of the injected fluid for a substantial distance. This technique measures a conductivity difference between the injected fluid and the native fluid, in other words it determines the actual location of the injected fluid. S.P on the other hand measures all fluid movement and with an inelastic system it would also detect the movement of reservoir fluids (indicative of pipe flow or flow along a narrow fracture).

Chemical Analysis

Chemical analysis of the Raft River data is in the preliminary stages and there is considerable work still to be done in this area.

The ion exchange between calcium and magnesium clearly indicates that the injected fluid is in contact with some of the cements which sealed off the high flow aquifer originally producing from well RRGP-5. This information suggests an acid frac might restore the original high production rate of the well. The ability to use tracers to detect chemical reactions and to monitor mixing would also be useful in planning the acidification and monitoring its effectiveness.

Deposition of Solids

The particulate content of the fluids entering and leaving the wellbore was not checked in the test series at Raft River.

Heat Transfer

Transfer of heat between injected fluids and the reservoir was difficult to determine because of transient wellbore heat transfer effects. Downhole temperatures were not available. The substantial delay in reaching equilibrium temperature at the surface suggests, however, that the fluid emerging from the formation was still quite cool. Attempts to estimate quantitative heat transfer rates were unsuccessful because of measurement uncertainties.

The poor heat transfer, if verified, suggests flow situations as noted in the laboratory data may be in existence in the well RRGP-5 flow system, i.e. small streamlines of injected fluid are penetrating through the native fluid with a relatively slow diffusion of the two fluids. This might cause the native fluid to act almost like an insulator with a large boundary layer effect. Assuming these insulating properties are a function of the surface to volume ratio, the heat transfer may be a very discriminating parameter in assessing the porosity of the rocks around a well. Considerable laboratory data, field data, and analytical studies are required before an assessment of the true potential of these measurements can be made.

Reservoir Flow System

The results of the Test Series 4 are inconclusive on the presence of a reservoir flow system. There clearly was fluid movement but it may have been into the wellbore. The relatively long distances, Figure 2, noted with the geophysical tests may indicate fluid movement toward the north. If it had not been necessary to leave the Raft River geothermal area, additional testing could most likely have resolved the issue of reservoir fluid movement around well RRGP-5.

7.0 Conclusions

In conclusion, the injection/backflow tests have provided positive information on the physical mixing of the injected fluids, the chemical reactions with the formation, the heat transfer from the formation and indications of the direction of subsurface movement. These data are powerful tools for use in reservoir analysis and ultimately will greatly enhance the capability of industry in planning injection strategies. A major analytical effort is required to develop the techniques for interpreting these new data.

It is also concluded that the FY-83 test program has successfully proven the feasibility and usefulness of the injection/backflow technique. In FY-84 work will continue on the interpretation of existing test data, and new tests will be designed to explore promising concepts.

REFERENCES

- Blackett, R. E. and Kolesar, P. T., 1983, Geology and Alteration of the Raft River Geothermal System, Idaho: Geothermal Resource Council Transactions, Vol. 7, in press.
- Covington, H. R., 1977, Deep Drilling Data, Raft River Geothermal Area, Idaho: U. S. Geological Survey Open File Report 77-616.
- Covington, H. R., 1980, Subsurface Geology of the Raft River Geothermal Area: Geothermal Resources Council Transactions, Vol. 4, pp. 113-115.
- Covington, H. R. 1982, Structural Evolution of the Raft River Basin: unpublished report, 23 pp.
- Dolenc, M. R., Hull, L. C., Mizel, S. A., Russell, B. F., Skiba, P. A., Strawn, J. A., Tullis, J. A., and Garber, R., 1981, Raft River Geoscience Case Study: EG&G Idaho, Inc., Report No. EGG-2125, Vol. 44, No. 6.
- Sills, W. R., Earth Sciences Laboratory, University of Utah Research Institute, 1983, Final Report Interpretation of Self Potential Measurements During Injection Tests at Raft River, Idaho.
- Sills, W. R., Earth Sciences Laboratory, University of Utah Research Institute, 1983, Final Report Resistivity Measurements Before and After Injection Test 5 at Raft River KGRA.
- Williams, P., L., Mabey, D. R., Zohdy, A. A. R., Ackerman, H., Hover, D. R., Pierce, K. L. and Oriel, S., S., 1976, Geology and Geophysics of the Southern Raft River Valley Geothermal Area, Idaho, U.S.A. (1976): Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, CA, May 20-29, 1975, Vol. 2, pp. 1273-1282.