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Errata for UCID 16954

p. 5 fifth line from bottom of page should read, "... requires a high ratio of tip speed to fluid velocity, V_i ,"

Replace Figure 3 with enclosed corrected Figure 3.

COMPARISON OF PERFORMANCE OF REACTION TURBINE WITH THE IMPULSE TURBINE

The Hero's turbine

$u = \text{Tip velocity} = r\Omega$

$V_o = \text{absolute fluid velocity}$

$V_{REL} = \text{relative fluid velocity}$

$V_i = \text{ideal fluid velocity from a fixed nozzle.}$

$$V_{REL} = \eta \sqrt{V_i^2 + u^2}$$

FIGURE 3

5-76
Capt NTIS

MASTER

UCID- 16954

Lawrence Livermore Laboratory

THE LLL GEOTHERMAL ENERGY DEVELOPMENT PROGRAM
STATUS REPORT: JANUARY, 1975 THROUGH AUGUST, 1975

A. L. Austin, Project Leader
J. H. Howard, Project Geologist
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September, 1975

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

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THE LLL GEOTHERMAL ENERGY DEVELOPMENT
PROGRAM

STATUS REPORT

JANUARY, 1975 THROUGH AUGUST, 1975

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Compiled and Edited by:

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September, 1975

THE LLL GEOTHERMAL ENERGY DEVELOPMENT PROGRAM *

PREFACE

THE LLL Geothermal Energy Development Program was initiated in January, 1974. This report includes significant events during FY75 as well as the activities during the reporting period, and is intended to serve as a status report to summarize program activities, findings, and plans.

It should be noted that these status reports are intended to be informal, and as such, the information presented should be considered as preliminary. Finalized program activities will be published separately as formal reports.

I. INTRODUCTION

The major goal of the LLL Geothermal Program is to develop systems for the recovery and conversion of the energy stored in hot water deposits with particular emphasis on those containing more than 3% total dissolved solids. The current interest in conversion machines and systems designed uniquely for these resources is stimulated mainly because: hot water resources are abundant, economic conditions require development of high efficiency machines to minimize costs, and the range of chemical conditions in the high salinity deposits will require new approaches. Currently, the Flashed Steam System and the Binary Cycle Systems are under consideration for application to the low salinity resources, but problems of precipitation, corrosion, and scale formation may limit their applicability to the high saline resources.

The LLL program is directed toward development of a new approach called the Total Flow Concept. This, in principle, consists of expanding the total wellhead brine-steam mixture directly through a mixed-phase expander to drive an electrical generator. Among the candidate expanders are tangential, axial, and radial flow impulse turbines, reaction devices, and positive displacement devices. These are being considered as individual units or, in combinations, as hybrid concepts.

Thermodynamically the Total Flow process is the simplest and it can be shown to provide the upper bound on cycle efficiency. A detailed analysis indicates that about a 60% increase in power output could be achieved by successful development of the Total Flow concept. As shown in Figure 1, this advantage exists over the expected range of reservoir temperatures. The implication is that although the program is focused on utilization of the high temperature/high salinity resources, the concept, once developed, will find application for all hydrothermal resources.

Development of any conversion system for use with high salinity brines must include resolution of the technical problems of precipitation and scale control, corrosion, erosion, and brine management; i.e.,

* Work performed under the auspices of the U.S. Energy R&D Administration.

handling and disposal. These factors are significant in themselves and do influence the design of the energy conversion system. Hybrid concepts, as mentioned above, may provide improved opportunities to maintain control over the fluid chemistry.

A thorough understanding of the chemical environment requires extensive chemical and materials application development work, both in the laboratory and field. Final system design must be preceded by field testing of materials and components in actual brines under representative operating conditions. Consequently, a major portion of the program effort is devoted to characterizing the precipitation kinetics, scale formation and control methods, and materials behavior coupled with development and testing of brine tolerant energy conversion concepts.

It is important to emphasize the need for advances in utilization technology, especially for application to the high temperature/high salinity (HT/HS) brines.

1. The most significant hydrothermal resource is the Salton Trough geologic province (Imperial Valley, California). It is near large population centers currently dependent on oil and gas for electric generation. It may provide somewhere between 60,000 and one million megawatt-years of electric energy (equivalent to 1.0 to 13 billion barrels of oil, respectively), and consequently can have an important regional impact as well as a national impact by displacement of oil and gas that would otherwise be burned in western power plants.
2. Over half of the stored thermal energy in the Salton Trough hydrothermal resource resides in the form of HT/HS brines. Hence, it is important to develop brine tolerance conversion systems for utilization of this resource.
3. Development of the Total Flow concept has the potential for a 60% increase in conversion efficiency which, in turn, reduces the number of wells and the capital investment, and also increases opportunities for utilizing the HT/HS resource which is not now possible by existing technologies. This latter point is especially important. There are interests in reducing capital investment by development of cheaper, faster drilling techniques and better exploration methods, but there must also be available a means for utilizing the resultant increased availability of noxious brines by advanced drilling and exploration methods.

II. PROGRAM PLAN

Since there is a clear national need to provide alternate commercial energy sources, the program goal is to establish technical feasibility in time to stimulate commercialization within the decade of the eighties. This will require development and testing of a complete system of at least 5 to 10 MW capacity to demonstrate and prove the technology. Concurrent investigations of the resource location and magnitude, productive capacity and lifetime of reservoirs, and environmental impacts must be included to evaluate the reliability of long-term power production. Consequently, the ILL program includes three basic activities: brine chemistry and materials technology; energy conversion and system engineering; and resource assessment. Currently, the division of effort consists of approximately 40%, 40%, and 20%, respectively. A generalized program plan is shown in Figure 2 illustrating the interaction between these three subprograms.

The pacing activity is the development and field testing of the baseline design of a brine tolerant expander at the end of FY77. This will be primarily the result of the combined efforts of the parallel activities of the Engineering and Chemistry Subprograms. Successful field tests would be followed by tests of a 1 MW system which includes addition of condensing, cooling, and injection equipment. In anticipation of successful completion of both activities, design work will start in FY76A toward the ultimate goal of operation of a full-scale (10 MW) experimental power plant system in FY80 as the final step toward demonstration of the feasibility of the Total Flow process.

Within each of the three major technical subprograms there is a continuing activity that can be called "technology transfer". Basically, this means a sharing with industry all pertinent technical information that is developed during the course of the program toward its goal. In fact, the culmination of the program in commercial utilization of a Total Flow process constitutes a transfer of a technology, but within that larger view there are many details that will be useful to all of the geothermal industry, not only that portion concerned with Total Flow or HT/HS or the Imperial Valley.

Technology transfer occurs in three forms, each of which plays a different role at various times in the life of the program. In the following paragraphs we will attempt to define these activities in a general way, and to give some particular examples.

The first, and most obvious, form of technology transfer is in the classic modes of technical communication such as conferences, professional society meetings, publication and distribution of technical reports on status and significant developments of the program. During FY75 we have published 26 reports, as noted in Section V, have participated in several geothermal conferences, and have carried out numerous program briefings of industrial, state, and federal organizations. This level of activity will likely continue throughout the life of the program.

The second area includes involvement with parallel industrial programs as well as detailed technical activities through subcontracts with vendors,

service companies, and those organizations with interests in geothermal developments. Currently, we are establishing a research effort to complement the joint SDG&E/ERDA program, coordinating our existing program with other ERDA and industrial programs, and working with those companies who are engaged in development of components which may find application to the Total Flow process (see section III.A.4, for example). These activities, with their regular interactions among the technical people, will produce a synergistic effect toward the solution of some of the fundamental problems.

A brief digression is in order here to discuss a somewhat less formal aspect of involvement with industry that really does not entirely constitute "technology transfer", but does transmit some information to industry. As often as possible hardware for experimental work is purchased from outside suppliers. In many cases, the requirements are somewhat unique such as in special coatings or machining capabilities, for example. These requests do, in effect, tell industry what the geothermal program is looking for, and indicate the kinds of apparatus that may very likely be needed in the future. Samples of candidate materials for geothermal systems to be tested in early experiments also stimulate the interest of potential suppliers.

The third area is, at this time, the least well defined. In order to attract significant industrial participation, it will likely be necessary to first demonstrate an efficient, small scale (1 MW) brine tolerant Total Flow system by actual field testing. This should result in the necessary confidence in the concept to commit to fielding a 10 MW experimental power plant. At that time, it is expected that sufficient industrial interest will be generated to justify a true joint venture involving cost sharing. Upon completion and operation of the 10 MW plant, it is expected that the industrial partner(s) will play an increasing role in continuing the evolution to pilot plant, then to full-scale demonstration with decreasing involvement by LLL/ERDA.

Demonstration of technical, or thermodynamic, feasibility, by itself, is not sufficient to stimulate commercialization which ultimately will require mass production of system components. An important part of pilot and demonstration power plant development is an activity which we will call production and process engineering. During the evolution from the 100 kw to 1 MW to 10 MW experimental system, there will be a need to develop solutions to special materials, manufacturing, and fabrication problems unique to these one-of-a-kind systems. Production and process engineering involves adapting these specialized solutions to industrial processes necessary for economic production of standardized components and sub-systems. This involves transfer of special process and fabrication techniques developed in the experimental programs to appropriate industries in order to develop the capability ultimately needed for full-scale commercialization of Total Flow conversion systems.

Just as there are numerous suppliers of special equipment for, say, the oil industry, so must there be developed suppliers of specialized equipment for the geothermal industry. As stated earlier, we have not yet formulated precise plans for this activity. Instead, it will likely be an evolutionary process with the technology we develop being transferred by diffusion to industry as we overcome each technical hurdle. We have started this process on a small scale, and expect that it will grow as the program proceeds.

III. ENERGY CONVERSION SUBPROGRAM

A. Total Flow Expanders

The geothermal environment encourages design simplicity and flexibility to allow use of corrosion/erosion resistant materials, incorporation of precipitation and scale control methods, and a means to minimize capital costs. Also, in order to gain the full advantage of the Total Flow process, it is necessary to extract the maximum available energy from the wellhead product by expansion to as low a backpressure as possible. It can be shown that for all reservoir conditions of interest, 40% of the useful work is obtained by expansion below atmospheric pressure to a typical sink condition (49 degrees C, 3.5" Hg). Volume expansion ratios of the fluid range from about 300 (for 300 degrees C fluids) to about 70 (for the 177 degree C fluids). Consequently, the Total Flow expander must be capable of complete expansion to recover the available energy, and must also be able to accommodate large volume flow rates as well. In addition to these requirements, candidate expanders must be able to withstand the presence of significant quantities of dissolved solids. Precipitation of silica during expansion can cause rapid formation of scale, and the corrosive and erosive actions of the brines will be major problems. These will likely require design simplicity, particularly with respect to minimizing the number of moving parts and contacting surfaces, ease of maintenance, and long-term reliability. A single-stage expander is most desirable, but staging may be workable in some cases.

Table I lists the basic classes of expanders which we have considered for use in the Total Flow Process. It is not necessary here to give a detailed description of each, nor is this the only way to classify them. We have completed a survey of the relative merits, where possible, of most of these devices. The following is a summary of our current understanding.

1. Impulse/Reaction Machines

Generally, reaction devices will likely find limited application. Since a pressure and temperature drop is required in the rotating component, scale formation, if it occurs, will be difficult to control or remove. One device which has received considerable attention is Hero's turbine, or lawn sprinkler. This is a pure reaction device, consisting of rotating nozzles, shown in Figure 3, and its performance characteristic is typical of other reaction machines. Figure 3 shows the comparison of the ideal performance with an impulse turbine. The nozzle coefficient chosen for non-ideal performance is taken arbitrarily at 0.9 for the reaction turbine. This may be optimistic since centrifugal separation of liquid and vapor in the rotating passage will likely reduce nozzle performance. Hence, the performance calculated here is optimistic. The basic point is that optimum performance occurs at $u/V_i \approx 1.0$, compared to $u/V_i \approx 0.5$ for the impulse turbine. Consequently, maximum power output requires a high ratio of tip speed to absolute fluid exit velocity which leads to very high speeds and very high stresses. In addition, there are practical problems of maintaining rotating seals, modification of geometry as wellhead pressure drops with time, and other losses associated with windage, friction, etc.

The multiple-disk turbine consists of a series of closely spaced thin disks mounted side by side on a shaft. Fluid enters through nozzles and is injected into the spaces between the disks to follow an inward spiral path to a central exhaust port. During this passage, the fluid exerts a frictional shear stress on the disks resulting in a net torque on the shaft. Since the basic mechanism for transfer of momentum is frictional drag, and since the possibility exists that the entrained liquid droplets will be thrown radially outward by centrifugal forces, one can only speculate that turbine efficiencies may be low. Considerable work has been done to analyze similar machines for operation from single-phase fluids. As yet, no detailed analyses have been made for two-phase flow operation of this device. This is needed as well as laboratory tests before definitive statements can be made relative to performance characteristics and suitability as a Total Flow expander.

2. Positive Displacement Machines

As a class, positive displacement expanders are limited in volume flow-rate capacity relative to the pure impulse-reaction machines. Fundamentally, this is due to internal losses related to sonic velocity in the fluid. Consequently, these expanders must be physically large to produce significant power output. At this time, one device can be considered a serious candidate for geothermal applications.

The helical rotor expander (The Lysholm Engine)* is a positive displacement device which operates by direct expansion of the two-phase fluid through meshing rotors, as shown in Figure 4. The fluid enters through a nozzle control valve into the high pressure pocket at A. As the rotors revolve, the pocket elongates continually, giving rise to a successively increasing volume from B to E where exhaust occurs. This device is mechanically simple, and has the advantage of self-cleaning as a result of rotor-to-rotor and rotor-to-case relative motion. The Hydrothermal Power Corporation has operated a helical rotor machine expanding brines in the Cerro Prieto and East Mesa geothermal fields. They reported that no scale deposition problem had been detected during over 1000 hours of operation. This unit also has recently undergone a series of clean-water tests at the LLL Geothermal Test Facility in order to investigate the mechanical performance under a range of inlet fluid thermodynamic conditions. Results are reported in UCRL-51861.

The performance of the engine was determined by means of speed and torque measurements in conjunction with a waterbrake dynamometer. Water flow rate was measured in the compressed liquid state, just before the system control valve. Inlet pressure to the rotors was varied from 24.4 psia (0.17 MPa) to 76.5 psia (0.51 MPa). Vapor fraction (quality) ranged from 11.6% to 33.3%. In all tests the exhaust pressure was one atmosphere.

* See UCRL-51861

Forty-nine data points are reported in Figure 5, which shows thermal efficiency and engine efficiency versus output power, for output shaft speeds of 3000, 4000, and 5000 rpm. These test results show a maximum engine efficiency of 49% at 16 kW for 3000 rpm, 53% at 23 kW for 4000 rpm, and 55% at 30 kW for 5000 rpm. Thermal efficiency is, for all practical purposes, independent of speed. Performance over much of the speed range is in excess of 50% for pressure ratios as high as 5:1. The lowest water rate measured was 173 lb/kW-hr, which is entirely reasonable considering that this is an experimental engine running with a very small enthalpy drop.

The flatness of the engine efficiency characteristic with respect to speed and power output and pressure ratio has been exhibited by all Lysholm engines and compressors. A flat performance characteristic is advantageous inasmuch as it means that although the engine is designed for optimum performance at one pressure ratio, its behavior under other than design conditions is good. It is important to emphasize that these tests are the first such detailed performance tests on a Lysholm engine operating on a mixture of water and vapor. In fact, no performance characteristic for any engine using low-quality mixtures as working fluids are known. Consequently, comparisons with other tests are not available.

Our conclusion is that the Lysholm engine can operate with a two-phase mixture as the working fluid, and it is a viable candidate machine for the conversion of energy from geothermal fluids by the Total Flow process.

Further work is required and is in progress to more completely investigate the potential of these machines for specific applications. The basic characteristic of large physical dimensions or large numbers of smaller machines, however, will remain as a possible limitation of positive displacement devices in terms of capital costs for central station power generation.

3. Impulse Machines

Based on the present understanding of all requirements, and particularly the need for inherently simple, compact machines, it is concluded that pure impulse devices have significant advantages. Because of geometric considerations the axial flow machine currently appears as the most promising configuration for the Total Flow application. Figure 6 is a simplified view of an axial flow impulse turbine, and also illustrates the basic elements of other impulse machines. Expansion of the two-phase wellhead product through a converging-diverging nozzle converts the brine thermal energy at high wellhead pressures at 2 to kinetic energy in the form of a high velocity fluid stream at the backpressure of 3'. The nozzle velocity coefficient, η , is the ratio of actual velocity output to the ideal velocity from an isentropic expansion from 2-3. The wheel efficiency, e_w , is a measure of the ability of the wheel to convert the fluid kinetic energy to shaft work. It is a complex function of blading geometry, turbulence, fluid friction, entrance and exit losses, fanning losses, etc. The turbine efficiency, e_t , then will be $\eta^2 e_w$ as noted in Figure 6. We can calculate the ratio, P_{TF}/P_{FS} , of power outputs from

Total Flow and a single flash system. Figure 7 illustrates the effect of nozzle coefficient and wheel efficiency. The shaded area indicates that greater than 50% more power output can be achieved if $\eta > .90$ and $e_w > .7$.

Although it is not yet possible to provide a comprehensive comparison of all candidate expanders, physical size is an overriding characteristic since implicitly, at least, it gives a strong indication of relative costs to be expected. Figure 8 gives results of calculations of expander sizes to produce a nominal 10 MW_e output. This is not entirely useful since the positive displacement devices shown will likely have lengths greater than their diameters, while the impulse wheel width is greatly less than its diameter. Further, such a single parameter comparison must be viewed with caution. Site-specific conditions, requirements for hybrid systems or combinations of expanders, and specialized applications will be important factors influencing ultimate choices of expanders. Nevertheless, the size advantage of the impulse turbine along with its mechanical simplicity remain as important considerations. Consequently, we have concluded that the axial flow impulse turbine offers the greatest potential as a Total Flow expander, particularly for use with the high saline fluids. The main emphasis of our program, thus, is on development of this device.

Within the limits of our budget, we are carrying out smaller parallel efforts to understand other candidate machines for Total Flow applications. We have had discussions with the "inventors" of the machines listed below, with plans for test and evaluation in various stages of negotiation. In general, these evaluations are necessary first steps before considering any large sums of money for further development.

BiPhase Engines, Inc.
General Ener-Tech, Inc.
Molecular Kinetics
Keller Corporation
Horst Power Systems, Inc.

4. Turbine Development

As pointed out in the last status report, development and testing of efficient nozzles for two-phase expansion is of prime importance. Consequently, extensive testing has been carried out during the year with details reported by Alger in UCRL-76417. Tests of nozzles with circular cross-sections indicate that nozzle coefficients in the .92 to .96 range are achievable. Recent tests of rectangular nozzles (see Figure 9) of both two- and three-dimensional geometries have indicated that optimum nozzle coefficients in the .92 to .94 range can be obtained. These results also compare with the conical nozzle test results and imply that geometric factors do not cause significant degradation of performance. This further increases confidence in the baseline turbine design configuration shown in Figure 6. The most encouraging point is that achievement of high nozzle coefficients ($> .9$) will allow greater latitude in wheel efficiency, thus extending the shaded area below the $e_w = 0.7$ curve in Figure 7.

This is especially important since one of the main factors contributing to losses in wheel efficiency is the interaction of liquid droplets with the turbine blade during passage of the two-phase supersonic flow. As a result of some preliminary experimental work and analytical studies, we estimated the range of possible wheel efficiencies, as shown in Figure 10. The lower bound represents very conservative conditions, as noted, while the upper bound represents an ideal efficiency based on geometry alone. There is some preliminary experimental evidence that droplet sizes about 2 microns may be typical. The point of Figure 10 is that there is a wide latitude of possibilities, and much experimental work is yet to be done before wheel efficiencies can be more accurately determined. It should be noted in passing, however, that even if the lower bound of 55% cannot be exceeded, reference to Figure 7 indicates that the Total Flow process via the impulse turbine competes favorably. This may have future significance since the Total Flow concept may be the only alternative for utilization of the high salinity brines.

Experimental work has begun on characterizing droplet/blade interactions, and effects on blade efficiency; i.e., the ability of the blade to transfer the momentum of the two-phase flow from the nozzle. Currently, this consists primarily of static blade testing with the apparatus, shown in Figure 11, which allows both blade thrust and pressure distribution measurements. The nozzle is designed to produce a fluid velocity equal to the relative fluid velocity over a moving blade so that the static test system is an approximate kinematic equivalent of the actual conditions. This device will be used for detailed investigations of droplet/blade interactions, blade configurations, and verification of analytical techniques to be ultimately used for turbine design.

Since the static blade testing does not completely model an actual turbine, there many factors affecting wheel efficiency that can only be investigated by operation and testing of an actual turbine. Consequently, we are developing an experimental turbine for test in the Geothermal Test Facility. This unit is a single stage axial flow impulse turbine, as shown in Figure 6, with a vertical axis of rotation with downward fluid flow. The wheel diameter is about 1 meter, and with a single nozzle will produce about 50 kW at 6000 rpm. All of the housing, chamber, and mounting components have been fabricated and are being assembled. The turbine wheel has been machined from a single blank of 7075-T6 aluminum alloy. The finished wheel is shown in Fig. 12. Final assembly and testing of the complete turbine is now re-scheduled for February, 1976, due to budgetary constraints. However, further delays are developing due to difficulties in finding a vendor who can nickel-coat the blading to our specifications. The nickel coating is required for erosion resistance during testing. It should be noted that this unit will be the first of a series of experimental wheels for laboratory test. Subsequent designs will depend on test results and analytical studies. Only the wheel has been fabricated at ILL; the remaining components of the turbine were fabricated by outside manufacturers.

If testing produces satisfactory results, the may will be field-tested at a higher power output of about 1 MW (about 20 nozzles required) at a well producing low salinity fluid, if sufficient funds are available. As shown in Figure 2, successful completion of this test will be followed by the combined efforts of the Engineering Subprogram and Chemistry Subprogram to produce a brine tolerant system for field testing on a high temperature/high salinity well.

Although we do not yet have sufficient information to completely characterize a Total Flow system, the concept is evolving to the point where we can foresee, at least, the major features. Figure 13 is an artist's rendition synthesizing the technical facts currently available. The basic element is a horizontal axial-flow turbine wheel fed by wellhead fluid expanding through nozzles spaced along the periphery. Condensing would be accomplished by a modified barometric condenser designed to separate the vapor fraction from the liquid in order to isolate the cooling system. This is only one possible scheme, but it represents our current view of the most promising configuration. There are other possibilities for expanders, and also we are considering the value of alternate systems utilizing combinations of expanders or systems, i.e., hybrid systems.

B. Hybrid Systems Studies

We have recognized for some time that a very broad band of site specific conditions makes it unlikely that any single geothermal prime mover will have universal, exclusive applicability. For some site locations it is expected that a hybrid system combining two or more types of expanders will be the logical choice. Among the important factors affecting selection of surface configurations are thermodynamic characteristics of the wellhead fluid, brine chemistry, cost of equipment, availability of cooling water, and a thorough understanding of prime mover characteristics and capabilities.

Our hybrid studies, to date, have mainly involved combinations of positive displacement expanders and turbines. Studies have been made of the helical rotor and oscillating vane positive displacement expanders as well as positive displacement expander concepts developed here at LLL. In addition, a helical rotor prime mover (Lysholm engine) was performance tested at Livermore (Weiss, et al, 1975).

Positive displacement expanders, while possessing many desirable attributes, suffer primarily in ability to expand two phase geothermal fluids to low back pressures. The basic problem arises from expansion ratio limitations and resultant very large expander size at low pressure. Both the need for expansion to low pressure and the resulting effect on expansion ratio and exhaust specific volume are illustrated in Figure 14. This figure, generated from calculations, assumes an expander with an engine efficiency of 70% and a wellhead steam conditions typical of part of the Imperial Valley. Considerable reduction in expansion ratio and exhaust specific volume, with a resulting reduction in expander size, can be achieved by expansion to one atmosphere instead of 1.7 psia. The higher exhaust pressure would allow only about 58% of the available work output, however.

A hybrid system should have a minimum number of components, in order to minimize costs and still be capable of reasonable overall efficiency. A combination meeting this criteria is the helical rotor (H.R.) positive displacement expander and low pressure (L.P.) turbine (System "B", Figure 15). In this system, throttling is done ahead of the helical rotor expander in order to limit the expansion ratio within the machine to 15. The exhaust at one atmosphere is run into a separator where the vapor goes to a low pressure turbine and the liquid is discarded. Fifty eight percent of the work is accomplished in the H.R. expander and 42% in the L.P. turbines.

Figure 15 is a system comparison, for a 40 MW gross output, for three different systems. System "A" illustrates the poor engine efficiency (46%) caused by the excessive throttling required to achieve a 15-to-1 expansion ratio (see Figure 16), and the very large (27-ft) rotor diameter required when using the H.R. expander alone. System "C" is the total flow turbine exhausting to a separator. The design advantage of System "B" over System "A" is apparent in the lower water rate (487 lb/sec versus 721 lb/sec) and reduced H.R. rotor diameter (8 ft versus 27 ft). The System "B" water rate is only 5.4% higher than the System "C" steam rate. If it turns out to be desirable from a design point of view to limit the enthalpy drop across the total flow turbine, then it could be used in a system "B" configuration ahead of the separator.

C. Geothermal Test Facility

Modifications to the facility that were initiated early in the calendar year have been completed. The operation of hot water generator to supply two-phase fluid mixtures has been fully automated. The capability of the facility has been expanded to include three stations for conversion equipment, a station for instrumentation development, and a station for erosion testing of materials. The latter will be used for preliminary screening of materials prior to field testing in brines. A schematic of these developments is shown in Figure 17.

In order to increase the erosion resistance of the 7075-T6 aluminum turbine wheel, a series of tests were undertaken to evaluate resistance of various coatings to water droplet erosion. It was found that .003" of electroless nickel offered a significant improvement over any of the organic or plasma sprayed coatings that were applied to the aluminum surface. Consequently, our first experimental impulse turbine will be nickel coated, as previously noted, to extend the turbine life.

A general description of the two-phase instrumentation to be tested in the Geothermal Test Facility is found in UCID-16806. Test spool No.1 has been fabricated and installed, and preliminary testing completed. This spool contains two pressure transducers, two wall-mounted thermocouples, the quality measurement heat exchanger system, the impact transducer, and the light attenuation experiment with glass windows in the pipe wall. The pressure-temperature recordings were in good agreement with saturation values and quality data gave values reasonably close to the nominal 20% quality steam used in the early testing.

Test spool No. 2 will include the ultrasonic velocity gage, piezoelectric flowmeter, and the five-inch glass spacer pipe section for flow photography. The glass pipe section was safety tested at a temperature of 420 degrees F to 1.5 times the maximum test pressure.

A pulsed ruby laser light source arrangement for nozzle flow photography has been designed, fabricated, and will soon be ready for use. The laser will provide about two Joules of monochromatic light in a pulse with a half-amplitude duration of about 30 ns. Pulsing will be accompanied with a dye cell.

D. Geopressure Program

1. Concept Definition Study

Work on the concept definition study has been completed. Results of the study are contained in UCRL-51813, "Potential Power Generation and Gas Production from Gulf Coast Geopressure Reservoirs". A paper on this subject was presented by P. A. House at the ERDS-sponsored conference, Geopressured Geothermal Energy Resources: Research and Development, held in Austin, Texas, June 2-4, 1975.

2. Prime Mover for Low-Enthalpy Liquid

A preliminary engineering design of a low pressure radial outflow, 80% reaction, turbine has commenced. This turbine, intended for laboratory evaluation, will operate with 300 degrees F, saturated water at the inlet, and 1.8 psia exhaust pressure. The turbine is intended for application with the geopressure resource, as well as others, where reservoir temperatures range from 250 to 350 degrees F. The partial reaction, radial outflow turbine appears, at this point, to be more favorable with low temperature, low quality resources.

IV. CHEMISTRY AND MATERIALS SUBPROGRAM

A. Introduction

The short range goals of the Chemistry and Materials Subprogram are to define processes for scale control and fluid handling and to select materials of construction to facilitate a test of a 100 kW brine tolerant Total Flow turbine by the end of FY77. These goals are being implemented through an integrated program of laboratory activity and field testing. The laboratory activities include 1) reviews and analysis of the chemical reactions which lead to scale formation as well as the saline corrosion/erosion problems and field experiences; 2) design and construction of field test hardware; and 3) analysis of field test results using laboratory analytical facilities. Also, modest laboratory efforts are being carried out to determine the compatibility of polymeric materials with saline solutions and erosion resistance of various materials in the LLL pure water Geothermal Test Facility. It was concluded early in the program that field testing using actual HT/HS brines is necessary to properly identify problems, test various methods of scale control, and evaluate materials. This conclusion resulted from the recognition that laboratory synthesis of HT/HS brines and their dynamic behavior cannot adequately duplicate actual field conditions. However, some limited laboratory investigations of silica chemistry and corrosion mechanisms can be utilized.

B. Review of Field Activities

The results of the field test activities accomplished since the last reporting period will be reviewed in the Results and Discussion section. A review of the field activities is given here to put the field test program into perspective. Access to the Sinclair #4 well located in the Salton Sea Geothermal Field began in May, 1974, through an agreement with the consortium of Southern Pacific Land Company, Phillips Petroleum, and Southern California Edison Company. Use of the well was on a non-interference basis and this resulted in some delays and technical problems. This first period of testing ended in early November, 1974. A second period of exclusive use started April 1, 1975, and ended May 13, 1975. This second period of testing falls within the current status reporting period.

In order to begin testing quickly and with a minimum of cost during the first period of access to the well, an existing retort pressure vessel was fitted with a four-station nozzle test manifold through which the well-head product was delivered to 1/4" diameter throat, 6 degree, converging/diverging nozzles with expansion ratios* of 4:1 (Figure 18a). Wear plates were installed so that the wear characteristics of various materials in a flat plate configuration inclined at an angle to the nozzle exhaust stream could be evaluated (Figure 18b). Various nozzle/wear plate materials, including type 304 stainless steel, titanium, and various polymeric materials were tested.

* Expansion ratio is the ratio of nozzle exit area to throat area.

Several problems were encountered. First, solid debris often entered that test apparatus and clogged the nozzles. Second, since it was required that the discharge pipe be submerged in the ponded brine, back-up of the acidic ponded brine into the retort occurred whenever the well-flow was interrupted by well operators. This occurred often and compromised the value of some of the tests. Third, the nozzles, wear-plates, and retort interior became severely encrusted with scale even after a days operation. Examples of scale deposits after about 100 hrs. of operation are shown in Figure 18. One promising results from this series of tests, as reported in the last Status Report (Ref. 1), was the scaling and erosion resistance exhibited by teflon (PFA). Further tests, as discussed later, showed that this material scales and wears at unacceptable rates when tested under conditions which produce a better approximation to the operation of a Total Flow nozzle (lower exhaust pressure). The former result, however, indicates that teflon (PFA) may provide a scale resistant material for separators and piping where the pressure drop and erosion environment would be less severe than in a supersonic nozzle.

The retort system was replaced with three nozzle test stations exhausting to atmosphere through 18" diameter culverts to the pond as shown in Figure 19. Also included in the system was a gravity separation device to trap the larger solid debris. Two type 304 stainless steel nozzle wear plate assemblies were tested in this system and were severely encrusted with scale and salt after 24 hours operation. Most of this scaling was attributed to splash-back and evaporation of the spent brine. To prevent splash-back, an inner concentric 6" diameter expansion tube was installed within the 18" culvert to jet-pump the brine expansion area.

Initial attempts at sampling the brine for analysis were also made during the first period of testing, but sampling problems were encountered as discussed in the last status report. Also during the first period, a study of the micro-structure of a scale deposit formed inside of a type 304 stainless steel nozzle was carried out. This study indicated that the scale consisted of metal sulfides and silica, as also described in the last status report. The main value of these first series of tests was the definition of problem areas and the evolution of a test facility toward a design which would allow better evaluation of the scaling process and materials performance.

These experiences resulted in the test facility shown in Figure 20, which was used in the second field test period from April 1 to May 13, 1975. The scaling and materials performance of nozzle/wear plate assemblies were evaluated during this period. Nozzles having greater expansion ratios were tested since nozzle performance tests in the laboratory indicated that the ideal expansion ratio was nearer 8:1. The nozzle exhaust was filmed through glass covered ports to observe the physical nature of flow using the lighting and camera arrangement shown in Figure 21. The characteristics of brine flow through piping before expansion was also evaluated by filming through glass-covered ports installed in the pipe, as shown in Figure 22. Other experiments conducted during the second field test period included the measurement of brine enthalpy, CO_2 analysis, brine analysis

via various sampling methods, and an experiment to evaluate the effect of electric potential on scaling. The status of analysis of the results of these various field activities are discussed below. In addition, the results of laboratory studies on methods of scale control and the status of the advanced chemistry test facility is also discussed.

C. Discussion of Results

1. Metallic Material Evaluation

Titanium and type 304 stainless steel nozzle/wear plate assemblies were exposed to the flowing well-head product delivered at about 240 degrees C and pressures between 375 and 425 psi over a period of 24 hours using the experimental set-up shown in Figure 20. The nozzles in these particular tests had expansion ratios of 2:1. Knife edge wear plates with included angles of 11 degrees were located 1/4 inch from the nozzle exhaust with the plane of the plate parallel to the nozzle axis. The exterior portions of these nozzles and wear plates were scaled to a much lesser degree than the assemblies tested using the prior test facility. Still, all surfaces were more or less uniformly coated with black scale approximately 1 to 2 mm thick. Even the impingement area of the wear plates were coated with scale, making valid analysis of wear impossible. Films taken of the nozzle exhaust showed that the brine was very under-expanded at the exhaust (see Figure 23). The exhaust velocity would be expected to be lower and the temperature higher relative to a more completely expanded fluid. Thus, the precipitation process would be expected to be less complete in the case of the under-expanded fluid and the scaling potential of this fluid would, therefore, be expected to be greater. A 8:1 nozzle/wear plate assembly (type 304 stainless steel) was therefore tested for 24 hours to determine if the scaling characteristics would be reduced and the expansion more ideal. Figure 24 shows that the outer surfaces of this assembly accumulated much less scale than any tested previously and that the impingement area on the wear plate was free of scale. This is consistent with the more ideally expanded fluid which exhausted from the 8:1 nozzle, which is shown in Figure 25.

The latter test is the most significant to date and was, therefore, evaluated thoroughly. A longitudinal section of the nozzle was prepared to determine the severity of internal scaling. Figure 26 shows that a scale layer, which varied in thickness from throat to exhaust, formed with a peak thickness of about 2 mm. The scale near the exhaust end chipped off during handling. Nodular growths near the throat on the expansion side of the nozzle are apparent, and if permitted, would reduce nozzle performance. This test indicates that a continuous method of scale removal or prevention is necessary.

The scale build-up on either sides of the wear plate not exposed to the direct impingement of the exhaust is evident in Figure 24 and in the close-up view of the wear plate in Figure 27. This indicates that a scaling tendency remains after exhaust of the relatively ideally expanded fluid and that scaling in the turbine chamber could occur.

This observation suggests that chemical methods to eliminate the scaling tendency should be emphasized. Physical removal of scale only at the nozzle will probably not be effective since the exhausted fluid would likely cause scaling in the chamber or down-stream components. Promising methods of chemical scale control are discussed in another section of this report.

The wear plate erosion (actually corrosion assisted erosion) visible in Figure 10 indicates that type 304 stainless steel does not have adequate resistance to erosion/corrosion in untreated HT/HS brine for conversion machinery. The longitudinal microscopic sections of the worn area of the wear plate shown in Figure 28 show that principle wear mechanism is corrosion. Corrosion processes lead to the tree-like morphology and the re-entrant pitting. Such active corrosion is consistent with the known reduction of stability of the Cr_2O_3 protective film in chloride environments. (Ref. 2) This reduction in the passivation due to chloride is noted on the oxidation potential (E_H or E (V)) vs pH diagrams (Pourbaix diagrams) given in Figure 29. The E_H and pH of the present brine (-.35 v and 5.5, respectively) determined in the present field test activity is plotted in the diagrams and shows that passivation would be expected in solutions not containing chloride, while active dissolution would be expected in chloride environments. Fortunately, the Pourbaix diagrams for titanium and tantalum indicate that these materials should be resistant to corrosion in the HT/HS environments. These materials have yet to be tested in the 8:1 nozzle configuration.

Corrosion of the type 304 stainless steel which occurred prior to the deposition of a layer of scale was observed in the longitudinal section of the 8:1 nozzle near the expansion end as shown in Figure 30.

2. Polymeric Material Evaluation

In the second testing period, our objectives were to verify results from the earlier tests, and screen new materials in the form of nozzles, wear plates, and pipes, as well as to check variables in the testing procedures.

Well brine was delivered to the test stations at about 240 degrees C at pressures between 375 and 425 psi. All nozzles tested acquired some scale, primarily in the exit end. Nozzle throats were not eroded but picked up traces of scale (5 to 30 mils). The nozzles were 2.75 inches long with inlet, throat and exit diamters of 0.975, 0.5, and 0.75, and weighed from 46 to 107 g. The rate of scale acquisition is shown in Figure 31. There is little evidence for a diminishing rate of scale build-up despite continually changing expansion ratios. A rough estimate of the scale build-up rate is about 0.7 g/10 hr. for the three fluorinated polymers (TFE, PFA, and Tefzel), and about 1 g/10 hr. for Ryton PPs and the Haveg composite. Whether these numbers are precise or not, the Ryton and Haveg composite do gather more scale. The fact that the Teflon PFA did not perform as well as in the first field test may be due to the lower exhaust pressure conditions in the second period

of testing. A microscopic evaluation of scaled teflon materials shows that erosion mechanisms probably cause a roughened and pitted surface which allows scale to adhere by mechanical means (ref. 3). Scale deposits ranged in thickness up to 120 mils. Wear plates were also tested at the same time by allowing the expanding stream from the nozzle to impinge directly upon the plate edge. The blade type wear plates were approximately 3x1x1/4" with one 3" edge machined to a 30 degree angle. This wear plate form and method of exposure simulated proposed turbine parts.

Twenty seven wear plates were tested, made of ten different materials. Results are plotted in Figure 32, which show that all of the polymeric materials tested eroded at unacceptably high rates. Also, further investigation indicates that there appears to be no correlation between erosion resistance and material hardness.

Piping is needed in any power plant system which will withstand heat, pressure, corrosion, erosion, and scaling. Five foot sections of 2 inch pipe lined with teflon TFE and with teflon PFA were tested. The two pipes were connected in series to the wellhead brine supply line with pressure being maintained by a 0.5 inch orifice plate immediately downstream. This high pressure/temperature condition was maintained for 20.5 hours, and the pipes examined. The PFA lining had partially collapsed, probably due to the vacuum formed upon cooling as a result of the orifice plate plugging by scale and well debris. Neither lining had suffered otherwise. The test was continued for 21.3 hrs with the teflon TFE alone on the high pressure side, then for 33.7 hrs. on the low pressure side to look for scaling resistance. The TFE lined pipe has developed only a very thin, incomplete lining of black scale.

3. Scale Characterization

Scale samples deposited during the second period of field testing in stainless steel and plastic nozzles and flow line pipe were analyzed. Polished sections and thin sections were prepared for optical examination and subsequent analysis by scanning electron microscopy, microprobe analysis, and x-ray diffraction techniques. The objective of this effort is to develop a better understanding of the chemistry and mechanisms of scale formation. It is believed that this will lead to the insights necessary to better define chemical approaches to scale control.

The scale was found to be primarily composed of an amorphous iron silicate. On a volumetric basis, sulfides are minor constituents. Results of electron microprobe and spectrochemical analyses of scale deposited near the divergent end of a long 1 degree included angle nozzle are summarized in Figure 33, Table II, and Table III, respectively. Silicon, iron, and copper are found to be the most prevalent elements present. A uniform distribution of very fine-grained (<0.05 mm) digenite (Cu_2S), shalcocite (Cu_2S) and bornite (Cu_5FeS_4) was found using the scanning electron microscope. The total accumulation of scale was between 1 and 2 mm in 24 hours. Since the samples are deficient in total sulfur

with respect to both iron and copper as sulfides, it is concluded that iron and silicon co-precipitate as an amorphous iron silicate. A subsequent analysis of sulfide deficient scale from a Haveg composite nozzle confirmed that iron and silicon are precipitating in a mole ratio of about 1 to 1.5 (see Table II). The region analyzed was between copper sulfide segregations in which no other phases were visible other than the silica-iron matrix at magnifications up to 2600 times. The concentration of aluminum in scale is anomalously high with respect to its normal concentration of less than 4 ppm in the brine, suggesting that aluminum may be precipitating as a hydroxide and/or as a silicate.

Tree-like growths of heavy metal sulfides have been observed in the stainless steel 8:1 nozzle and in 2:1 plastic nozzles. They only occur adjacent to the expansion side of the throat in the 8:1 nozzle and comprise no more than about 5% of the total mass of scale deposited in a 24 hr. period. However, sulfides are ubiquitous in the lower expansion ratio polymeric nozzles (i.e., Haveg and Tefzel) and comprise 15 to more than 50% of the total mass of accumulated scale. Curved segregations of sulfides in scallop-shaped cells are possibly indicative of deposition under highly turbulent flow conditions (Figure 34 to Figure 36). SEM analyses indicated that the dominant phases are anhedral to anicular iron sulfides, and native silver in a massive, translucent-appearing iron silica matrix (Figure 37 to 39). These observations suggest that sulfide scaling can be minimized by optimizing nozzle geometry. Furthermore, studies of scale morphology appear to have some potential as a diagnostic tool for nozzle designers.

Chemical methods for controlling silica and sulfide scaling are discussed below. The microstructure and composition of scales from chemically modified brines will be studied and compared to the present results to provide a better basis for developing chemical scale control methods.

4. Brine Sampling and Analysis

The oxidation potential E_H , pH, and brine composition were determined because these parameters are necessary to evaluate the corrosion and scaling characteristics of the brine and to provide a data base necessary for chemical modification experiments. These analyses were made at four intervals during a month of field testing between April 1 and May 13, 1975, to determine if brine properties change with time.

Special attention was given to the brine sampling method since it had been determined that flow could be stratified in the pipe. Thus, samples were taken from both the top and the bottom of the pipe. A photograph of brine sampling apparatus in the field is given in Fig. 40. Later analysis indeed showed that, with the well flowing under choked conditions, flow was stratified and that samples from the top of the pipe were predominantly vapor and those from the bottom were almost entirely liquid. The E_H , pH, and major constituents of the liquid phase samples are given in Table IV.

The E_H and pH values reported were measured at ambient temperature but under the high pressure associated with the presence of CO_2 . This is important since analysis of corrosion potential of the brine is very dependent upon accurate knowledge of pH and loss of CO_2 would result in a pH increase. As indicated in Table IV the brine was found to be slightly reducing ($E_H \approx -.35$) and acidic (pH ≈ 5.5) and that neither E_H or pH changed significantly over the test period.

The brine composition represents the composition of the liquid phase samples taken and the values are reconstructed to include solids that precipitated during cooling as well as the solids remaining dissolved in the cooled liquid. A calculation of quality from enthalpy measurements discussed below indicate that the vapor fraction was about 10% at the pressure and temperature conditions during sampling. Thus, the values given in Table 3 must be reduced by about 10% to obtain the concentrations in the unflashed fluid. It has been assumed that the liquid samples did not contain a significant fraction of steam phase. The measurements given in Table IV are relatively consistent, except for the sample taken near the beginning of well operation and indicate that the brine composition did not change significantly over about 15 days of well flow. The total dissolved solids content (relative to the unflashed liquid) from the analysis given in Table IV is about 25%. The sulfur values are necessary to determine the additive requirements necessary for sulfide scale control and are the first available for the Sinclair #4 brine. The data in Table IV give the most complete analysis for Sinclair #4 well fluid yet available. A complete discussion of the methods used for sampling and analysis is given in Ref. 4.

5. Calorimetry

Brine enthalpy and quality are important parameters in the design of field test facilities and conversion systems. To provide this data, enthalpies were measured by collecting samples from the flowing 6-inch line in a sampling bomb immersed in a water bath calorimeter. The enthalpy of each sample collected was determined from the rise in temperature of the water bath and the total weight of the sample. The weight fraction steam in each sample was calculated by equating the measured enthalpy with the steam enthalpy times the weight fraction steam plus the brine enthalpy times the weight fraction liquid. The steam enthalpy was taken from the steam tables and the brine enthalpy was computed (at 22% dissolved solids) from a model developed to take into account the effect of salt (Ref. 5). Knowing the weight of dissolved solids in each sample, the steam fraction collected, and using an assumed value for the total dissolved solids in the unflashed brine, it is possible to compute the quality of the homogenous flow and its enthalpy. The values so computed are given in Table V. A minimum variation resulted among the samples if a value of 22% dissolved solids was assumed. Table V shows that an appreciable increase in the enthalpy of the well fluid occurred after the wellhead flowed for about 20 days. The value of 427 Btu/lb is within 7% of a value computed from a model (ref. 5) taking into account the effect of salt on enthalpy at an assumed reservoir temperature of 300 degrees C.

6. CO₂ Content

Non-condensable gas content is important in conversion systems design and CO₂ in particular is important in determining scaling rates and corrosion because it affects pH. For these reasons the CO₂ content of the well fluid was determined. The total non-condensable gas content of the samples taken in the above calorimetry experiments was determined using a wet test meter. Since mass spectrometric gas analysis data indicates this is greater than 95% CO₂ it is assumed that the measured volume of non-condensable gas was CO₂. A mass balance analysis together with an estimate of the quantity of CO₂ remaining in the quenched liquid was used to compute the content and distribution of CO₂ at the collection temperature and pressure (210 C and 245 psi). The analysis indicates a CO₂ content of 4000 ppm in the well fluid with about 63% of this in the vapor and 37% in the liquid at the above pressure and temperature conditions. Further details of the analysis are given in Ref. 6. The above data were taken after about a month of well operation. The CO₂ level at the beginning of well operation were roughly three times greater (about 1.2%).

7. Dynamic Well Flow Data

During the first test period a pulsating flow condition was noted at the discharge end of a 2" pipe and also from the nozzles during operation. In the second period of testing the flow dynamics were evaluated by monitoring pressure transducers at approximately 100 ft intervals along the pipe from the wellhead to the disposal pond. Data from these transducers showed that the strong pulsations which were observed at 10 second intervals originated at the discharge end of the pipe, much in the same way as a "water hammer". This was probably associated with the development of a "slug" of nearly pure liquid phase and its sudden impact with an orifice or choke in the line. The effect is related to the two-phase flow pattern in the pipe, and it disappears as flow velocities approach 30 m/s. We are continuing to review this data, which was recorded on magnetic tape for direct computer entry.

Filming of the nature of flow in a 2-inch diameter pipe upstream of the exhaust using the apparatus shown in Figure 22 confirmed the existence of stratified flow when the well was operating under choked conditions. The films show a very inhomogeneous flow which mostly consisted of a liquid phase in the bottom of the pipe and mist flow in the top of the pipe. These results show that care must be taken to obtain a representative flow of brine and vapor when well fluid is taken directly from the pipe. The observation that the glass sight ports remained clear of scale for a time suggests that on line analysis using ultra-violet spectroscopy may be possible.

8. Effect of Electrochemical Potential on Scale Formation

In mid-April, 1975, we ran a series of experiments in which stainless steel balls (1 cm in diameter) with varying potentials and polarity were exposed to the flashing fluid from a 6 nozzle at Sinclair #4. The purpose of the experiment was to determine if an electrical potential could be used to either inhibit or to enhance scale formation as a means of control. Balls were selected as the configuration which allowed optimization of the electrical charge on the surface. Experiments were run with positively charged balls at 5 and 30 V, negatively charged balls at 5 V, and neutral (above ground) balls. In all, 24 balls were exposed to the fluid as follows: 3 at +30 V; 5 at +5 V; 5 at -5 V, and 11 neutral. They were exposed to the fluid for two hours and were placed 180 mm from the throat of the nozzle. During this exposure the balls remained intact and exhibited scale formation. The appearance of the balls before and after exposure to the brine is shown in Figure 41 and 42, respectively.

Preliminary observations in the field revealed several significant differences between +5 V charged, neutral, and the -5 V charged balls. The scale formed on the positively charged balls was black when compared to that found on the neutral balls, which appeared brown. Although visual observation indicated no significant difference in the amount of scale among positively charged and neutral balls, subsequent higher oxidation of the material on the positively charged balls could be related to a smaller amount of scale, or to other effects. On the other hand, the negatively charged balls exhibit considerably more scale than either the positively charged or neutral balls. This scale consists, when fresh, of a fuzzy mass of brownish-black material which, in most cases, is distorted by the flow in the system.

As of this date we have obtained preliminary results of both flame spectrometer and x-ray fluorescence analyses (see Table VI). Several patterns have emerged from the combined results. It appears that there is a large increase in the relative amount of lead present in the negatively charged balls. Copper seems to follow lead. Silicon may also be reduced in the negatively charged balls. On the other hand, iron appears to be depleted on the negatively charged balls and enhanced in the positively charged balls. Zinc appears to follow iron. These preliminary results suggest the presence in the brine of lead and copper as a cation but not of iron and zinc. This may indicate that both iron and zinc are complexed in solution, perhaps with hydroxyl ions.

We are presently performing x-ray diffraction and electron microprobe analyses of these scale samples. We will then be in a better position to speculate about silicon and sulfur behavior in these experiments.

9. Silica Chemistry Review and Opportunities for Silica Scale Control

A review of silica chemistry with particular attention to the factors which control the rate of polymerization of silica was carried out to identify silica scale control methods (Ref. 7).

It has been demonstrated, for example, that colloidal silica can be destabilized (precipitated) or restabilized simply by varying the concentration of ferric iron and/or the solution pH. Scaling in converging-diverging nozzles is severe because further cooling of a partially expanded wellhead product produces a solution with a high degree of silica super-saturation under conditions that favor rapid polymerization.

Scale preventive measures will involve varying one or both of the factors outlined above to influence the rate of polymerization of monomeric silica. Acidification may be a viable process for preventing scale deposition because pH is one critical parameter in silica polymerization kinetics that is relatively easy to control (Figure 43 and 44). Super-saturated silica solutions are stable at pH values between 2 and 3. However, silica polymerizes rapidly in the pH interval between 5 and 8, especially in solutions of high ionic strength. Nozzle scaling may be eliminated if brine pH is maintained at values between 3 and 4 by injection of appropriate amounts of hydrochloric acid. A cost estimate for such acidification indicates that the procedure would add less than .2 mil/kW-hr. energy conversion cost.

10. Sulfide Chemistry Review and Opportunities for Sulfide Scale Control

Metal sulfides can form up to half the scale from high saline reducing brines. The possibilities for keeping them in solution were analyzed (Ref. 7). In water solutions, copper and iron sulfide solubilities are controlled by pH and oxidation state. In brines containing large amounts of CO_2 and Cl , other equilibria contribute to solubility.

It was concluded that a partial oxidation process, by reducing the sulfide content and formation of free sulfur before expansion, could help to control precipitation without forming other solids such as sulfates. Acidification, which has been proposed as a silica control measure, will also be useful in increasing sulfide solubilities. It is expected that free sulfur will form and flow through the system as particulates. These may have to be removed to facilitate reinjection over long periods of time.

D. Status of Advanced Test Facility

The FY76 Chemistry and Materials Subprogram emphasizes the testing of various proposed methods of brine modification to control

scale formation. Materials evaluation will be de-emphasized until a scale control method becomes visible. The construction of a facility to test the effects brine modification methods on scaling in expansion nozzles is underway and field testing is scheduled to commence during January, 1976. The test facility includes a separator to provide a non-pulsating, measured flow of brine and vapor which is necessary to define additive quantities. Remixing will provide fluid with various qualities for evaluation of scaling. Metering pumps will deliver acids, bases, and oxidizing agent to the brine at nearly the wellhead temperature and pressure conditions. Sampling stations upstream and downstream of the additive point and three expansion nozzle test stations are included.

It might be pointed out that two industrial chemical modification programs for scale control have been carried out by industry. These have been reviewed and we have established that the acidification and partial oxidation approaches which will receive principal attention in the present program have not, heretofore, been investigated. In addition to the above approaches which are designed to retain the scale forming species in solution, methods designed to precipitate the scale forming species prior to expansion will be investigated.

It is interesting to note that acidification and oxidation will generally increase the corrosivity of the brine. Fortunately in the Total Flow system, the principle temperature and pressure drop occurs in the nozzle so that the more expensive corrosion resistant materials needed to resist corrosion by the modified brine must only extend from the point of chemical addition to the nozzle and possibly to within the turbine chamber. The very low temperature effluent from the chamber can be handled by less expensive alloys or polymeric materials. It is also possible, of course, that the spent fluid can be treated to reduce its corrosivity or to otherwise prepare it to facilitate reinjection.

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V. GEOLOGY SUBPROGRAM

A. Test Site Development and Reservoir Characterization

1. Test Site - State No. 1

Currently, the LLL field activities are limited to work at Sinclair #4 on a non-interference basis through an agreement with the well owners. While this arrangement has been very helpful in providing some opportunity for field work, there are limitations. At the present time, an agreement for field testing in November, 1975, is being finalized for this fiscal year, pending review and acceptance of LLL's proposed experimental program for the well.

In order to insure future opportunities for field work at an accelerated pace, and to provide the necessary space, well flow, and facilities for a 10 MW plant in 1980, we are negotiating to acquire a field test site to accommodate the needs of the program. A location in the center of Salton Sea Geothermal Field, which lies directly over known deposits of high temperature/high salinity brines, has been identified. The site is shown in Figure 45. The property contains 550 acres and an existing well known as State No. 1, which has produced brine and vapor at about 100 lb/sec with a TDS of about 22%. Other nearby geothermal wells, such as IID 1, IID 2, Sinclair 4, Sinclair 3, and River Ranch have been flowed at comparable rates. This property and well site are currently leased by Imperial Thermal Products (Morton Salt Company) from the State of California. LLL is currently negotiating a contract with the help of ERDA/SAN for assignment of this lease to ERDA.

The current version of the lease calls for LLL to have rights to the property for research purposes for up to 8 years. Annual rental for the property is expected to be about \$25,000. The well will cost \$50,000 per year for five years, and the total cost of the well could be as high as \$250,000. Estimated cost of a new well is at least \$400,000. The agreement can be terminated by LLL (or ERDA) at the end of any year period.

In anticipation of construction of facilities for LLL at this site, Design Sciences, Inc., of El Centro, California, have, under contract to LLL, carried out a topographic survey of the site and have drawn up a design for a field site with associated ponds. These drawings by DSI form the basis for calling for bids for construction.

At this time, the situation at State No. 1 site is muddled. Problems exist in several important relations: between owners of surface rights and mineral rights, and between the State and the lessee of the property. The existence of these problems in no way affects LLL's attitude about the importance of this property to the LLL program. With the strong support of ERDA, these problems should be resolved. Figure 45 also illustrates the type of test site development that would follow once the property has been acquired.

2. Salton Sea Geothermal Field Resource Assessment

No new assessments have been made as of the last report. It still appears that the Salton Trough geothermal province will probably yield at least 100,000 MW yrs. of electrical energy - see UCRL-51851.

A terminology for resource assessment (see Table VII) has been adopted, based on recommendations of the U.S. Geological Survey and the U.S. Bureau of Mines. In brief, certain key words have been defined which reflect: a) confidence in understanding of the geologic parameters which describe the resource, and b) economic feasibility of schemes to exploit the resource. Opinions about geology and economic feasibility vary a great deal, owing to lack of geologic data and to lack of specific experience bearing on economic feasibility. LLL has also had to accept these inadequacies in making resource estimates for the Salton Trough.

The identified, demonstrated and inferred, paramarginal subeconomic resource of the Salton Trough is estimated to be of the order of 100 GWY. This resource is roughly equal to 20 times the 1972 Southern California consumption of electrical energy. Under extreme assumptions regarding the existence and recovery of the resource, the resource could be as large as 1300 GWY (4×10^{17} BTU).

A report was also completed on the economics of geothermal resources, in general, as a fuel (UCRL-77031). These costs are important, inasmuch as the size of a resource is dictated in part by the cost of alternative fuels, such as natural gas (as contrasted with simply technical parameters, such as temperature). The report reaffirms the widely held conclusion that geothermal resources can compete with other fuels in generating electricity and in non-electrical uses as well.

3. Well Data Acquisition

Data on wells outside the Salton Sea Geothermal Field have been acquired with a view to developing a better understanding of the regional geology. Steps have been taken to acquire core and cuttings from wells within the property presumably held by San Diego Gas and Electric and from the Sinclair 3 and 4 wells and from the State No. 1 well. Much of this material is currently at the University of California, Riverside.

Attempts to acquire well flow data from the SSGF have been unsuccessful so far. Imminent ERDA/industry contracts for developments in the area that include measures to make these data available will be very helpful in facilitating information exchange.

4. Subsurface Geologic Studies

A summary of the salinities seen at the wellheads in the SSGF was prepared. Salinities as low as 32,000 ppm and as high as 356,000 ppm have been reported. A series of maps showing the distribution of temperatures in the field have been completed. A partial composite (Fig. 46) of these maps has been included in this report in order to communicate an image of the geothermal reservoir. The reservoir has been arbitrarily defined by the 230 degree C isothermal surface and a horizontal plane at a depth of 6,500 feet. Were the reservoir defined differently (e.g., the 100 degree C isothermal surface, if brines at that temperature could produce competitively priced electricity), the estimated size of the geothermal resource would increase correspondingly because the volume included within that isothermal surface would be larger. It should be noted that the above resource estimates (Section 2.) is based on the assumption that only fluids at greater than 230 degrees C can be economically utilized for electrical power production.

Well-to-well log correlations have been done as a part of a task of developing and understanding of the stratigraphy of the reservoir. This work is important because it leads to a refined understanding of the recoverable resource. An understanding of the stratigraphy reveals the distribution of porosity and permeability, and these functions are important to valid reservoir analysis.

5. Geochemistry

Work on silica geochemistry and scale morphology is reported previously in this report. Work on the spatial variation of the chemistry of the fluid and solid phases of the reservoir has been planned and will begin when support is available. This task is important since it provides a guide to the quality of brine that must be accepted at a plant entrance, and also because it is necessary for planning a reinjection program.

6. Geophysics

A geophysical program to evaluate the extent and availability of the geothermal resource in the Salton Sea KGRA has been initiated. The program is designed to supplement previously published magnetic, gravity, heat flow, and resistivity data which lead to the definition of the KGRA, as well as to complement data from electric well-logs from deep wells in the region.

The geophysical program has four parts, with the following objectives:

- (a) Seismic Refraction Survey - to define the basement depth and slope in order to remove the effect of the basement from the gravity and magnetics anomalies, and to examine layering within the geothermal system.

- (b) Electrical Resistivity Surveys - to determine the lateral extent, depth, and thickness of low resistivity regions. (Low resistivity implies rocks saturated with hot and/or relatively more saline fluids.)
- (c) Temperature Gradient Survey - to determine if regions of low resistivity are hot (cf. highly saline) and to estimate temperatures at depth.
- (d) Examination of Well Logs - to produce one or more models of "known" regions in order to substantiate and aid interpretation of geophysical data measured at the surface of the earth.

The field work for both the seismic refraction survey and the electrical resistivity survey has been completed by subcontract. The electrical resistivity survey was performed by Geonomics, Inc., and included nearly thirty equatorial dipole soundings, 40 km of dipole-dipole soundings, eight scalar magnetotelluric stations with frequencies up to 100 seconds, and 10 dipole sounding with receivers in the Salton Sea. A low resistivity region extends farther to the southeast than was expected, and appears to be terminated to the northeast by a fault.

The seismic refraction survey was performed by Prof. Shawn Biehler of UC/Riverside and included two 20 km reversed refraction profiles extending north and east from the Obsidian Buttes, and three several-hundred-pound shots from the north and west of the Salton Sea into the Buttes region. Several layers of different velocity have been mapped, indicating that the base of permeability (in a sense, the bottom of the reservoir) lies below 6500 ft as has been accepted in resource assessment calculations. A detailed examination of later arrivals is being performed by Prof. Biehler, and evidence is seen for a major fault between Obsidian Buttes and Red Island.

Well logs, temperature data, and cuttings descriptions from 12 deep holes in the Salton Sea geothermal field have been interpreted to produce graphs of sand percentage, sand layer thickness, sand resistivity, shale resistivity, amplitude of sand self-potential and interval temperature gradients. These data will be used with assumptions about the physical properties of brine, sand and shale, to map the distributions of resistivity, porosity, seismic velocity, and thermal conductivity within the drilled portion of the geothermal field. Knowledge of those distributions will improve understanding of the meaning of surface geophysical measurement and will also lead to a better understanding of heat transport (e.g., generation of convection cells) and storage capability of the entire geothermal system. It should be emphasized that, owing to the availability of some well control, the Salton Sea Geothermal Field provides an unusual opportunity for evaluating the resolving power of geophysical methods applied to the understanding of geothermal resources.

B. Reservoir Engineering

The culmination of all earth science tasks is the reasonable assurance that brine of certain quality can be provided to a power plant at acceptable rates for a given period of time (e.g., 20 years). Reservoir engineering includes, among other things: 1) the design of a system of wells to provide appropriate amounts of brine to and from a power plant; 2) an assessment of specific properties of the fluid (e.g., viscosity) and of the rock (e.g., permeability) which control fluid flow in porous media; 3) the modeling of transport of brine from the bottom of a well to the wellhead; and 4) methods of stimulation of wells to increase their rates of flow. Progress has been made on several tasks bearing on these items.

1. Flow Within the Reservoir

Reviews of the literature on the completed mathematical formulation of fluid transport in porous media and of the literature on analytical models of flow analysis in petroleum reservoirs that has applicability to geothermal reservoirs have been completed. It appears that elementary analytical models predict well performance in the range of accuracies that can actually be measured with present monitoring methods.

A hydrologic model entitled GEOTHERM has been developed and programmed for use in computer simulation of geothermal reservoirs (UCON-75-30). It will handle multiple well, single phase, isothermal, liquid flow. The program has certain graphical display techniques included in it. An example is Figure 47, which shows an unconfined four-spot injection/recovery system. In this example the wells are 500 m apart with the central well injecting relatively cooler fluid and surrounding wells recovering hot brine. Contours represent lines of constant head.

A review of the capabilities of other geothermal reservoir modeling groups outside the laboratory has been initiated in order to determine the extent to which their capabilities would be useful to the LLL geothermal program. Despite claims and implications to the contrary, it appears that their computer programs simulating two-phase multi-dimensional geothermal reservoirs are not sufficiently developed to provide dependable answers to some of the obvious problems such a code should be able to handle.

2. Flow Up the Wellbore

Understanding of flow up the bore from the producing interval to the wellhead is important because of the changes in thermodynamic quality that can occur during passage. Such changes in quality may affect the mechanisms of scaling and corrosion via changes in salinity in the liquid phase and may also have significance for the method of energy conversion. Inasmuch as different methods of energy conversion, e.g., flashed

steam versus total flow, may gain advantages in having brine of different qualities delivered to the front end of the energy conversion cycle, knowledge of the transformations of state that occur in the bore are important. Liquid flow changes to bubble flow and evolves to fully developed mist flow under appropriate conditions. Depending on particular operating conditions (including especially length of bore), transformations might progress no farther than froth flow, for instance, at the wellhead. If the total flow process is used, such a flow condition could be more difficult to use than mist flow might be, for example. We have synthesized existing analytical techniques into a calculational program for characterizing well flow. The program predicts flow rate, energy extraction rate, and flow regime for given reservoir conditions.

C. Environmental and Regulatory

Progress on environmental and regulatory aspects of the geothermal program since the last status report has included the following: a) an environmental assessment for the LLL's planned activities at State No. 1 (UOPKE 75-24) and a request for a negative assessment, therefore, from ERDA; b) major involvement in planning an ERDA-sponsored environmental baseline study for the entire Trough (UOPKE 75-29); and c) a technical report on atmospheric dispersion of pollutants and noise in the vicinity of the SSGF. The LLL Geothermal program has worked closely with the LLL Division of Biomedical and Environmental Research to define the proposed baseline study. The Earth Sciences Group has contributed especially to planning for work on induced seismicity and subsidence and has developed a plan to coordinate this entire portion of the program and carry out part of it in-house, if appropriate.

D. Geopressure Program

The Earth Sciences Group of the geopressure program has included work on: a) resource assessment; b) monitoring geologic investigations carried out by the Univ. of Texas at Austin; and c) monitoring work by DSS Engineers, Inc., on the non-electrical applications of this resource. (The latter work was done in part because of LLL's CCMS non-electrical program.) Details of these works can be found in a) UCRL-51813, b) reports by UT/A, Bebout et al. (Contract No. At-(40-1)-4882, in press); and c) UCRL-13633 by DSS Engineers.

E. Miscellaneous and Other Earth Sciences Work

LLL has had roles in several short term projects. These have included: 1) help with the II United Nations Conference on Geothermal Resources; 2) coordinating the CCMS Non-Electrical Project; and 3) help with formulating a national non-electrical plan.

1. II U.N. Conference

The LLL geology group led two field trips to the Salton Trough in May in connection with the Conference. Based on comments received from the participants, these trips were considered highly successful. A guide book was prepared for distribution to trip participants (UCRL-51775) and it has been in popular demand as an introduction to learning about geothermal resources development in the Trough.

2. CCMS Non-Electrical Project

The goal of the CCMS non-electrical project has been to assess the status of non-electrical applications of geothermal resources throughout the world. A preliminary report on the subject was issued as UCRL-76408 and presented to the II United Nations Conference. The proceedings will be issued no later than at the end of their calendar year. LLL has formally concluded its roll in this project as of June 30, 1975, when J. H. Howard ended his term as coordinator for the project.

UCRL-13633: "Geothermal Resource Utilization - Pulp and Cane Sugar Industries" is a report that resulted from LLL's involvement in the CCMS Non-electrical Project. This report, which was completed early this summer, concludes that utilization of thermal energy from the geothermal-geopressure resource in pulp and paper mills and new sugar refineries is technically sound and economically viable provided that the other energy in the fluid (natural gas and pressure) is recovered concurrently. Studies on specific sites and plants are reported to be needed in order to refine and verify assumptions in this regard made in the report.

VI. PUBLICATIONS

Total Flow Concept Development

1. "An Estimate of the Geothermal Energy Resource in the Salton Trough, California, by D. Towse, UCRL-51851 (June, 1975).
2. "The Economics of Geothermal Heat as an Alternate Fuel," by D. Towse, UCRL-77031 (September, 1975).
3. "Regulatory Considerations in the Development of Geothermal Resources," J. J. Cohen, N. B. Crow, Kathy A. Tonnesen.
4. "Environmental Aspects of Geothermal Energy Development in the Salton Sea/Imperial Valley Area," by K. Tonnesen, UCID-16717 (March, 1975).
5. "Some Comments on the Total Flow Method for Conversion of the Energy in Geothermal Hot Water Deposits," by A. L. Austin. Presented at the Conference on Research for Development of Geothermal Energy Resources sponsored by National Science Foundation, California Inst. of Tech., Pasadena, CA., September 23-25, 1974.
6. "A Comparison of Methods for Electric Generation from Geothermal Hot Water Deposits," A. L. Austin and A. W. Lundberg., Presented at the Winter Annual Meeting of ASME, November, 1974 (Paper No. 74-WA/ENER-10.
7. "Prospects for Advances in Energy Conversion Technologies for Geothermal Energy Development," A. L. Austin, Presented at II U.N. Symposium, UCRL-76532 (May, 1975).
8. "The Performance of Two-Phase Nozzles for Total Flow Geothermal Impulse Turbines," T. W. Alter, presented at II-U.N. Symposium, May, 1975, UCID-16417.
9. "Geothermal Two-Phase Flow Test Facility," H. Weiss. Presented at II U.N. Symposium, May 1975, UCRL-76409.
10. "A Waste-Heat Reinjection System for the Total-Flow Turbine Concept Using Hot Geothermal Brines, R. Quong, UCID-16694.
11. "The Effect of Salinity on Geothermal Well Performance," by J. Grens, May 1975, UCID-16791.
12. "The LLL Geothermal Energy Development Program - A Status Report," by A. L. Austin, UCID-16721, February, 1975.
13. "Performance Test of a Lysholm Engine," H. Weiss, et al., UCRL-51861, July, 1975.
14. "Solution Technique for Two-Phase Turbine Flow," W. J. Comfort, UCIR-909, July, 1975.
15. "Present Status of the Polymeric-Materials Screening Program for the LLL Geothermal Project," L. E. Lorensen, C. M. Walkup, E. T. Mones, UCRL-51843, July, 1975.

16. "Precipitation of Amorphous Silica from High-Temperature Hyper-saline Geothermal Brines," L. B. Owne, UCRL-51866 (June, 1975).
17. "Vapor Droplet Flow Equations," C. T. Crowe, UCRL-51877, Aug., 1975.

Geopressure Resource Development

1. "Potential for Utilizing Geothermal Resources in the Pulp and Paper and Cane Sugar Industries," DSS Engineers, Inc.
2. "Geothermal Resources Frio Formation, South Texas," Bureau of Economic Geology, UT/Austin, Geol. Circ. 75-1, by D. G. Bebout, M. H. Dorfman, and O. K. Agagu.
3. "Potential Power Generation and Gas Production from Gulf Coast Geopressure Reservoirs," P. A. House, P. M. Johnson, and D. F. Towse, UCRL-51813.

International

1. "Klamath Falls Hot Water Wells Study," by G. Gene Culver, J. W. Lund, L. S. Svanevik (contract with Oregon Inst. of Technology), UCRL-13614, October, 1974.
2. "Analysis for Potential Non-Electrical Applications of Geothermal Energy and Their Place in the National Economy," Gordon M. Reistad, UCRL-15747, March, 1975.
3. "Present Status and Future Prospects Non-Electrical Uses of Geothermal Resources," by the Non-Electrical Project Working Committee, J. H. Howard, Chairman, June 1975. UCRL in preparation.
4. "Principal Conclusions of the CCMS Geothermal Pilot Study Committee on Non-Electrical Applications," J. H. Howard, Presented at II U.N. Symposium, May, 1975.
5. "Geothermal Development of the Salton Trough, California, and Mexico," T. D. Palmer and D. L. Lande. Report for the II U.N. Symposium, May, 1975.
6. "Conceptual Design of 5 MW Wellhead Located Geothermal Steam Turbine Driven Electrical Generating Plant," Prepared by Rogers Engineering Co., Inc., for the Lawrence Livermore Laboratory.

CLASSES OF EXPANDERS FOR TOTAL FLOW APPLICATIONS

- p) stainless-iron matrix with fine-grained (<0.02 mm) copper sulfide
 a) sulfide deficient matrix: no other phases visible in matrix after metallographic etching

1. Impulse/reaction machines

Axial flow — Curtis/Rateau steam turbine

Radial inflow — Francis turbine and multiple disc drag turbine

Radial outflow — rotating nozzle (pure reaction). Hero's turbine

multiple disc turbine — bladeless impulse or reaction drag turbine.

2. Positive displacement machines

Helical screw expander

Rotating oscillating vane machine

3. Impulse machines

Tangential flow — Pelton wheel, Re-entry turbine

Axial flow — DeLaval, Curtis turbine

TABLE I

TABLE II ELECTRON MICROPROBE ANALYSES OF SCALE DEPOSITED IN THE DIVERGENT END OF A 1° NOZZLE
AND IN THE EXPANSION PORTION OF A HAVEG NOZZLE ADJACENT TO THE THROAT REGION

1° Type 304 Stainless Steel Nozzle a)				HAVEG Nozzle b)		
Element	Concentration (weight %)	Moles	Mole Ratio	Concentration (weight %)	Moles	Mole Ratio
Fe	21.23	0.0038	Fe/Si 1.46	17.31	0.0031	Fe/Si 0.72
Si	7.17	0.0026	Fe/S 633	12.02	0.0043	Fe/S 10
Al	1.39	0.0005	Cu/S 6	0.83	0.0003	Cu/S 2
Ca	1.26	0.0003		0.61	0.0002	
Cu	0.24	0.000038		3.49	0.0006	
S	0.02	0.000006		0.93	0.0003	

a) Sulfide deficient matrix. No other phases visible in matrix at a magnification of x 2600.

b) Silica-iron matrix with fine-grained (<0.05 mm) copper sulfides.

TABLE III SPECTROCHEMICAL ANALYSIS OF SCALE

FROM THE DIVERGENT END OF TYPE 304 STAINLESS STEEL NOZZLE

(Values are approximate ppm by weight for the elements listed)

Fe	> 100,000
Si	> 50,000
Cu	> 10,000
Ag	3,000
Al	3,000
Ca	3,000
Mn	3,000
Na	3,000
B	1,000
Sb	1,000
Co	300
Be	200
Pb	200
Sr	200
Mg	100
Mo	100
Ba	50
Ni	20

The following elements were not detected:

< 300	As, W
< 100	P
< 30	Hg, Nb, Zr, Tl
< 10	Ge, V, Zn
< 3	Bi, Cd, In, Sn, Ti
< 1	Cr

TABLE IV. "LIQUID" PHASE SAMPLES (RECONSTRUCTED ANALYSIS)*

Date of Sample	April 3	April 9	April 14	April 23
Pressure and Temperature	210°C	239°C	247°C	255°C
Condition at Time of Sample	220 Psi	430 Psi	440 Psi	445 Psi
$E_H(V)$	-.31	-.35	-.22	-.32
pH	5.3	5.6	4.8	5.2
Element				
Na	74,000 mg/l	64,000 mg/l	61,000 mg/l	70,000 mg/l
Mg	80	90	71	71
Al	3	2	2	2
Si	277	257	234	249
S	11	6	6	4
Cl	185,000	166,000	161,000	165,000
K	16,700	15,300	14,000	15,000
Ca	31,500	28,700	28,200	29,000
Mn	1,340	1,200	1,180	1,230
Fe	1,550	1,490	1,490	1,450
Cu	6.2	3.9	3.9	2.7
Pb	110	102	92	101
Ag	0.7	0.7	0.6	0.5
Total Solids (g/l)	310	277	267	283

* Analysis are reconstructed and include dissolved solids as well as precipitated solids.

Quality was about 15% for sample taken on April 3 and about 7.5% for others. Concentrations given in table must be reduced by these amounts to obtain concentration in unflashed brine.

TABLE V SINCLAIR #4 ENTHALPY DATA

(CORRECTED TO 0.22 TDS)

Sample #		Enthalpy (BTU) LB	Quality (.22) % Vapor	
1		353	4.3	
2	Taken April 3, 1975	355	4.5	$\bar{H}_{(.22)} = 363 \frac{\text{BTU}}{\text{LB}}$ $\sigma = 23$
3		397	6.7	
4		347	3.6	
5		413	11.7	
6	Taken April 24, 1975	412	11.5	$\bar{H}_{(.22)} = 427 \frac{\text{BTU}}{\text{LB}}$ $\sigma = 19$
7		433	14.2	
8		450	16.2	

Table VI Preliminary X-Ray Fluorescence Analyses of Charged Balls

Relative Amounts Referred to Ca

Element	0	-5V	+5V	0	-5V	+5V
Si	6.00	4.00	4.00	7.00	2.00	4.00
S	≤0.10	≤0.20	≤0.10	≤0.40	≤0.03	≤0.06
Cl	2.40	0.82	3.70	1.60	1.60	2.50
K	0.30	≤0.04	0.40	0.40	0.07	0.40
Ca	1.00	1.00	1.00	1.00	1.00	1.00
Fe	2.63	0.23	20.00	19.00	0.84	7.30
Cu	0.55	0.84	1.20	2.70	2.10	0.35
Zn	-	-	0.10	-	-	0.10
Pb	0.004	2.56	0.06	0.02	10.00	0.01

SALTON TROUGH TOTAL RESOURCES

		Identified			Undiscovered	
		Demonstrated		Inferred	Hypothetical	Speculative
		Measured	Indicated		(In known districts)	(In undiscovered districts)
Economic		Reserves				
Subeconomic	Paramarginal	5 GWY		100 GWY		+
	Submarginal		+	+	+	+
				500 GWY		1300 GWY

Resources

← Increasing degree of geological assurance →

↑ Increasing degree of economic feasibility

TABLE VII

RELATIVE PERFORMANCE CHARACTERISTICS OF GEOTHERMAL ENERGY CONVERSION CONCEPTS

Note: Binary system assumes down hole pumping. Others work from self-pumped well (flashing flow). All systems work to 49°C sink condition.

FIGURE 1

LLL GEOTHERMAL PROGRAM OVERVIEW - HT/HS

FIGURE 2

COMPARISON OF PERFORMANCE OF REACTION TURBINE WITH THE IMPULSE TURBINE

The Hero's turbine

$u = \text{Tip velocity} = r\Omega$
 $V_i = \text{absolute fluid velocity}$
 $V_{REL} = \text{relative fluid velocity}$

FIGURE 3

HELICAL ROTOR EXPANDER

Plan section view

Side section view

FIGURE 4

FIGURE 5

THE AXIAL FLOW IMPULSE TURBINE

FIGURE 6

COMPARISON OF POWER OUTPUTS OF THE TOTAL FLOW SYSTEM WITH THE FLASHED STEAM SYSTEM

FIGURE 7

**RELATIVE SIZES OF TOTAL FLOW EXPANDERS WORKING TO
49°C (3.5" Hg) SINK CONDITION (10 MW CAPACITY)**

FIGURE 8

FIGURE 9

ESTIMATED RANGE OF POSSIBLE WHEEL EFFICIENCIES FOR AN AXIAL FLOW IMPULSE TURBINE

FIGURE 10

FIGURE 11

FIGURE 12

THE TOTAL FLOW CONCEPT FOR GEOTHERMAL ENERGY DEVELOPMENT

FIGURE 13

THE EFFECT OF EXIT PRESSURE ON EXPANDER WORK OUTPUT

FIGURE 14

SYSTEM COMPARISON FOR A 40 MW OUTPUT

Helical rotor expanders: Expansion ratio 15:1,
Tip speed, 300 ft/sec, L/D ratio = 1.5.
Expander efficiency, 70%.

FIGURE 15

THE EFFECT OF THROTTLING ON EXPANSION RATIO AND WORK OUTPUT

Steam is throttled from P_1 to P_2

FIGURE 16

FIGURE 17
Interior Test Area of the Facility Showing Recent Additions

a. View of 2 Nozzles After Test

b. Wear Test Plates and Fixtures In Place

FIGURE 18

Retort Test Assemblies Used in First Period
Of Testing at Sinclair No.4

**FIELD TEST APPARATUS USED FOR NOZZLE TESTING DURING
LATTER PART OF FIRST PERIOD OF TESTS AT SINCLAIR NO. 4**

FIGURE 19

FIGURE 20

Field Test Facility Used in Second Test Period
at Sinclair No.4

FIGURE 21
Lighting and Camera Arrangement for Filming of Nozzle Flow

FIGURE 22

Camera Arrangement for Filming Brine Flow Through Piping

FIGURE 23

Frames from Films Taken of Underexpanded Exhaust from 2:1 Nozzle
Tested at Sinclair No. 4 Showing Extremes in Observed Behavior

FIGURE 24

Type 304 Stainless Steel, 8:1 Nozzle/Wearplate Assembly
After a 24 Hour Test at Sinclair No.4

FIGURE 25

Frames From Films Taken of Exhaust from 8:1 Nozzle
Tested at Sinclair No.4 Showing Extremes in Observed Behavior

FIGURE 26

Longitudinal Section of Type 304 Stainless Steel
8:1 Nozzle After a 24 hour Test at Sinclair No.4

FIGURE 27

Close-Up View of Type 304 Stainless Steel Wear Plate
After 24 Hour Test of 8:1 Nozzle at Sinclair No. 4

50X

100X

FIGURE 28

Longitudinal Section Through Type 304 Stainless Steel Wear Plate
From 8:1 Nozzle Showing Corrosion Damage

(a) Figure established considering Cr(OH)_3 .

(b) Figure established considering $\text{Cr(OH)}_3 \cdot n\text{H}_2\text{O}$.
In solutions containing chloride.

FIGURE 29

Conditions for Corrosion, Immunity and Passivation of Chromium,
at 25°C. After Pourbaix, M. Atlas of Electrochemical Equilibria,
Pergamon Press, 1966, P. 265

Type 304
Stainless Steel

Epoxy Mounting
Material

Scale Separated
From Steel During
Mounting

FIGURE 30

Longitudinal Section of Type 304 Stainless Steel 1° Nozzle
Showing Scale Filled Corrosion Crevices Near Exhaust End

SCALE BUILDUP ON EXIT END OF NOZZLE

FIGURE 31

WEAR PLATE EROSION

FIGURE 32

ELECTRON MICROPROBE ANALYSIS OF SCALE DEPOSITED NEAR THE DIVERGENT END OF A LONG 1° NOZZLE

FIGURE 33

Epoxy

Scale

Interface

8:1 Stainless
Steel Nozzle

FIGURE 34

Sulfide-rich segregations in the expansion portion of the throat (x 30). Note the sharp separation of scale from the nozzle and the uncorroded appearance of the metal surface.

Epoxy

Scale

Haveg Nozzle

FIGURE 35

Tree-like growths of sulfides in a HAVEG nozzle. Note the scallop-shaped cells in which sulfides have segregated and the absence of sulfides in the metal-scale interface region (x 50; middle of the expansion portion of the nozzle).

Epoxy

Scale

HAVEG Nozzle

FIGURE 36

Sulfide segregations in a silica-iron matrix
(expansion portion of the nozzle; x 200).
Note the absence of sulfides at the scale-
nozzle interface.

(x26)

(x260)

FIGURE 37

SEM backscattered image from carbon-plated polished section from the expansion portion of a TEFZEL nozzle. Numbers refer to higher magnification images in Figures 21 and 22.

Region #1. Iron sulfides in a silica-iron matrix (black areas between grains).

Region #2. Native silver and copper sulfides in an iron-silica matrix (x 2600)

FIGURE 38

SEM backscatter images from a carbon-plated polished section. Mineralogy was established by energy dispersive x-ray analysis.

Region #3. Acicular sulfides in an iron-silica matrix (x 2600)

Region #4. Native silver (white) and copper sulfides (gray) in an iron-silica matrix (black) (x 2600)

FIGURE 39

SEM backscatter images from a carbon-plated polished section. Refer to Figure 7 for location of images.

FIGURE 40
Brine Sampling Mechanism Showing Adjustable Probe and Sample Bottle

FIGURE 41

Arrangement Used to Test the Effect of Electric Potential or Scaling

FIGURE 42
Appearance of Balls Charged at +5V, -5V,
and Neutral After 2 Hour Exposure to Expanding Brine

SOL STABILITY: RELATION BETWEEN LOG (GEL TIME) VS. pH (From Iler, 1955)

FIGURE 43

THE POLYMERIZATION OF SILICIC ACID IN ACIDIC AND BASIC SOLUTIONS

FIGURE 44

FIGURE 45
Test Site Development

Scale 1:48,000
Vert. Excg. 4x

FIGURE 46

Isothermal contours of a portion of the Salton Sea Geothermal Field. The reservoir has been arbitrarily defined by the 230°C isothermal surface and a horizontal plane at 6500 feet. This volume is indicated by vertical ruled pattern.

FIGURE 47

An unconfined four spot injection-recovery system under steady state fluid flow conditions. The central well is an injection well which lies 500 meters from the surrounding production wells. The isobaric contours show pressures either greater than or less than the original pressure of the reservoir. The zero difference contour lies essentially at the contour marked "zero". Maximum positive pressure difference contour shown is 160 psi and lies adjacent to the injection well. Maximum negative pressure difference is 32 psi and lies adjacent to the production wells. These values apply only to withdrawal rates of 714,000 pounds per hour per production well and an injection rate of approximately 214,000 pounds per hour with a reservoir transmissivity of 24 Darcy-meters. These results can be scaled to other patterns when the ratio of production to transmissivity is given.