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THE LLL GEOTHERMAL ENERGY PROGRAM

A Status Report on the Development of the Total-Flow Concept

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FOREWORD

This report summarizes work done at the Lawrence Livermore Laboratory under the auspices of the U.S. Department of Energy to develop the Total-Flow concept and its variations for geothermal energy applications. The development program was terminated at the end of FY 1978. This report describes the status of the program as of the termination date.

To make this report more useful to those interested in the continued development of the Total-Flow concept, we have included some background material previously published. Hence, this last status report is not limited strictly to progress made in FY 1978.

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THE LLL GEOTHERMAL ENERGY PROGRAM

A Status Report on the Development of the Total-Flow Concept

ABSTRACT

This report summarizes the technology development activities of the Geothermal Energy Program at the Lawrence Livermore Laboratory. Industrial support work (i.e., brine chemistry, materials, and earth science activities) will be discussed under a separate cover. Since the technology development program has been terminated as of October 1, 1978, this is the last status report on that phase of the program.

Significant progress toward development of the Total-Flow concept was made during FY 1978. Our results show that the original goal of 70% engine efficiency for the Total-Flow impulse turbine is achievable, that a Total-Flow system is competitive economically with conventional systems, and that the Total-Flow concept offers the benefit of more efficient utilization of geothermal resources for electric power production. Our evaluation of several liquid expanders designed for low-temperature (including geopressured) resources suggests that if development were continued, these expanders could be used in combination with conventional systems to increase overall system efficiency. Although the program was terminated before complete field testing of prototype systems could be carried out, our concepts have been adopted in other countries (Japan and Mexico), where development is continuing.

1. EXECUTIVE SUMMARY

Significant increases in the use of geothermal energy for commercial electric power generation in the U.S. will require exploitation of our relatively abundant water-dominated geothermal resources. Of particular significance are those in the Salton Sea known geothermal resource area (SSKGRA) in California's Imperial Valley. This one area may contain as much as 17% of the total energy recoverable from hydrothermal resources in the United States.

In 1974, the Lawrence Livermore Laboratory's Geothermal Energy Development Program began to address the technical problems involved in recovering energy from the SSKGRA. Early in the program, the decision was made to focus on development of the Total-Flow concept so as to provide an advanced conversion technology with the potential for increased resource utilization efficiency and to broaden the options for energy recovery from high-temperature/high-salinity

(HT/HS) resources. The Total-Flow concept was originated at LLL, and it involves the expansion of the wellhead fluid in its entirety (including water, vapor, and dissolved solids) through a single energy-conversion machine. In principle, this thermodynamic process can provide the highest useful work output per unit mass of geothermal fluid.

To develop a complete working system, significant effort was also devoted to solving scaling, corrosion, erosion, materials, and spent-brine-disposal problems. The following is a summary of our accomplishments over the period FY 1974 to FY 1978.

1.1 TEST FACILITIES

We have designed and operated a laboratory geothermal test facility that can simulate thermodynamic conditions characteristic of any

hydrothermal well output. It has been used to test our expander components, to develop methods for measuring and characterizing two-phase flow, and to test and evaluate Total-Flow expanders with outputs up to about 100 kW. This unique facility has also been made available to industry for tests of their expander designs.

We have also designed and operated a field test station for brine-chemistry and materials studies. At this test station, we have established the technical and economic feasibility of scale control by brine acidification, and have developed and proven a technique for removing solids from spent brine.

Promising corrosion- and erosion-resistant alloys for conversion systems have been identified and field-tested. An extensive series of tests on total-flow turbine blades has been completed; the results indicate that titanium-base alloys have the best combination of resistance to stress corrosion cracking and erosion/corrosion in high-salinity, highly mineralized, acidified, two-phase, high-velocity brine flow.

1.2 ENERGY CONVERSION DEVELOPMENTS

A single-stage total-flow impulse turbine has been developed and tested in the laboratory. The results indicate that the original research goal of 70% engine efficiency is achievable. The existing machine is capable of operating at about 45% engine efficiency. This level of performance was achieved with a conventional nozzle design and an unoptimized blade design. This makes of the Total-Flow concept a near-term rather than a remote technology.

A method of characterizing high-velocity two-phase flow has been developed, and experimental techniques have been devised to determine the droplet size distribution, the droplet spatial distribution, and the mean droplet velocity in low-quality, two-phase flow from a rectangular-cross-section, converging-diverging nozzle. A forward light-scattering technique is used to determine the droplet size distribution; light transmission measurements permit us to detect droplet spatial variations; and a laser-Doppler velocimeter system is used to measure droplet velocities.

The above techniques have been used to characterize two-phase flow through converging-

diverging nozzles with differing throat contours and inlet conditions. The results show that the droplet size distributions had a mass-mean diameter of 2.4 microns. Neither the nozzle throat radius of curvature nor throat height variations affected nozzle exit droplet sizes significantly. (As will be discussed below, this means that to achieve 70% engine efficiency, we must reduce the droplet size by other means.)

A new analytical model capable of predicting droplet breakup in single-component, two-phase flow has been developed. It goes beyond the conventional Weber model of breakup by drag forces, indicating that breakup also occurs as a result of droplet internal boiling. Droplet breakup takes place because the temperature of the droplet is greater than that of the surrounding vapor during the rapid expansion process. Depending on the choice of parameters, the boiling-breakup model predicts droplet diameters between 4.0 and 5.9 microns. This compares with an experimental measurement of 2.5 microns, indicating that the analytical techniques are conservative and therefore useful in nozzle design calculations. The addition of the boiling-breakup mechanism to the droplet breakup model indicates that, with nozzle inlet conditions typical of the higher temperature geothermal resources, droplet sizes as low as 2 microns can be achieved without special designs.

Since, as noted above, the analytical model is conservative by at least a factor of two, production of 1-micron droplets is theoretically achievable. This fact, combined with the possibility of optimizing turbine blade width and spacing, would suggest that a 70% engine efficiency could be achieved if development work were to proceed.

With the existing nonoptimized impulse-turbine-wheel blade width and spacing, a 70% engine efficiency could be achieved if 1-micron droplets were produced. Calculations indicate that a special nozzle designed to separate and remix phases at the throat could reduce the droplet size to below 1 micron. However, this nozzle configuration was not tested before program termination.

A prototype conceptual design of an optimized, full-admission, impulse turbine for field tests was completed.

A cost analysis for a conceptual 50-MW total-flow system was completed and compared with a similar analysis for a conventional double-flash system. The results indicate that capital costs for the

two systems were within 10% and bus bar energy costs within 3%. While the double-flash system was slightly less costly (\$1026/kW, 39.7 mills/kWh), the uncertainties inherent in the cost analyses introduce inaccuracies much greater than 10%. Consequently, the cost analyses, by themselves, are inconclusive. They do serve to indicate, however, that Total-Flow technology, although in its infancy, is currently competitive and has significant potential, especially if resource utilization efficiency is taken into account.

We have designed and tested a unique radial-outflow reaction turbine (RORT) for liquid expansion. It is specifically suited for lower-temperature geothermal resources. Preliminary test results indicate that a 50% engine efficiency is achievable for single-stage saturated or compressed liquid expansion to subatmospheric conditions. A particularly important application of the RORT is to provide additional power by expanding the liquid in the leg between separators in a double-flash system. A rough cost estimate indicates that the RORT can increase the overall power output by 15%, while increasing capital costs by only 3%. This would reduce the bus bar energy costs by about 10%.

The RORT work has led to advanced design concepts that have the potential to increase RORT

engine efficiency to 75%. By tests and by analysis, these unique expanders have been examined for saturated and compressed liquid expansion. They could be very useful in systems designed for lower-temperature resources (including geopressured resources).

A complete series of laboratory tests has been performed on a small (~40 kW) helical rotor expander. The results indicate that a reasonable value for engine efficiency is 55%, but only for two-phase inlet conditions with vapor fractions (quality) ranging from 15 to 25%. The machine exhibits poorer performance for qualities less than 15%. Also, the machine is not suited for complete expansion to subatmospheric conditions. Hence, application of this machine will likely be limited to low power output, noncondensing conditions, or topping cycles in a flash steam system.

The technology developed thus far at LLL has been adopted for industrial applications. Two major Japanese companies are designing and testing versions of the Total-Flow impulse turbine. The main purpose is to commercialize the concept for power production from waste heat contained in hot, pressurized water—a by-product of steel manufacturing.

2. INTRODUCTION

2.1 PROJECT RATIONALE

Significant increases in the use of geothermal energy for commercial electric power generation in the U.S. will require exploitation of our relatively abundant water-dominated geothermal resources. This is the next logical developmental step for the U.S. geothermal industry. Of particular significance are the identified hydrothermal resources in the Salton Trough geologic province. This region contains six known geothermal resource areas (KGRA) in U.S. territory (California's Imperial Valley). Of these, the Salton Sea KGRA (SSKGRA) is best known. Over 23 wells have been drilled there, large amounts of geophysical data have been gathered, and large amounts of private money have already been invested for wells and leaseholdings.

According to the U.S. Geological Survey (USGS Circular 726), the SSKGRA is the hottest and third-largest KGRA in the U.S.; it is capable of producing 83,600 MWe-yr of electric energy, which is 10% of the total capacity of all the large hydrothermal resources in the U.S. (including dry steam resources). The two largest KGRAs (Long Valley and Coso Hot Springs, both in California) are virtually unexplored, and estimates of their energy productivity are speculative at best. If these two are dropped as candidates for early development, the SSKGRA potential amounts to 17% of the total energy recoverable from U.S. hydrothermal resources. Over half the energy recoverable from the six KGRAs in the U.S. portion of the Salton Trough resides in the SSKGRA.

The SSKGRA is a prime candidate for early development because:

- It is the best known KGRA in the U.S.
- It is the hottest (300°C) geothermal resource in the U.S. and hence has the potential for producing the lowest energy costs.
- It has the potential for producing 83,600 MWe-yr of electricity (which is equivalent to 1 billion barrels of oil).
- It is close to major west coast load centers.

More than 90% of the SSKGRA is already under private lease, but the presence of large quantities of dissolved solids in the water (as much as 30% by weight) is a major barrier to rapid commercial development. Since 1975, there has been increasing industrial and governmental interest in development of the SSKGRA, but much more progress remains to be made before commercialization will be a reality. Consequently, the LLL Geothermal Program was directed specifically at solving the problems unique to the SSKGRA and at providing the needed advanced technologies with emphasis on development of the Total-Flow concept.

The Total-Flow process involves the expansion of the fluid from a geothermal well (including water, vapor, and dissolved solids) through a single energy-conversion machine. Three characteristics of the process are especially important:

1. It has the potential for highest resource-utilization efficiency because the available energy of the liquid phase is used.
2. The simplicity of single-stage expansion is an advantage in dealing with the harsh chemistry of geothermal brines.
3. It adds a third basic technology to the repertoire of alternatives (the flashed-steam and binary-cycle concepts being the other two) and will thus broaden opportunities for successful exploitation of HT/HS resources and provide a means of developing more combinations of systems (hybrids) applicable to other resources.

Several decisions were made as the program began in FY 1974: first, that we would focus on the recovery and conversion of energy from the high-temperature, high-salinity (HT/HS) brines of the SSKGRA; second, that the program would be goal-oriented, leading to development and field testing of a complete system capable of efficient, reliable, and economical production of electric power from this important resource; third, that the scheduling would be consistent with the overall national goal (as stated at that time) of developing alternate

energy sources for use early in the decade of the 1980s; fourth, that contacts with industry would be established to accelerate commercialization and technology transfer.

We adopted an interdisciplinary system approach to developing solutions to the problems of brine handling and disposal, scale formation, corrosion and erosion of materials, and conversion-system design. Much of this work has general applicability to other resource-utilization concepts and to other resource areas. Consequently, in FY 1976, the Laboratory established—at the request of the U. S. Energy Research and Development Administration (ERDA)—an Industrial Support Program (ISP) to provide technical assistance to joint ERDA/industry projects in their efforts to recover energy from HT/HS geothermal resources in the Imperial Valley, California. Since then, LLL program emphasis has been shifting from applied research to development and involvement with field demonstration programs.

2.2 PROJECT OBJECTIVES AND SCOPE

Basically, the program has had two objectives: technology development and industrial support.

2.2.1 Technology Development

The Technology Development program has emphasized development of a Total-Flow energy conversion system and its variations. Significant effort was also devoted to solving scaling, materials, and spent-brine-disposal problems. In the energy-conversion area, two major efforts were underway: development of a Total-Flow impulse-turbine system uniquely designed for the HT/HS brines of the SSKGRA, and development of machines and systems designed especially for lower-temperature resources, including geopressured resources.

The program strategy, shown schematically in Fig. 1, called for energy-conversion activities conducted in the laboratory and a parallel brine chemistry and materials program performed largely in the field. It was decided that the basic feasibility of the Total-Flow concept should be demonstrated first under controlled laboratory conditions before expensive and complicated field tests were begun. However, work on scale and solids control, materials behavior, and brine characterization had to be

FIG. 1. Strategy for Total-Flow-system development program.

done with real brines under actual field conditions. This two-pronged strategy was selected to maximize the probability of success. If the conversion work alone proved successful, it could be applied immediately to other areas; if the field work alone were successful, it would be applied to other systems, and if both were successful, field testing and demonstration of a complete, brine-tolerant, Total-Flow system would follow.

The program plan was based on the assumption that both programs would be successful and that it would be possible to field a prototype 2-MWe system by FY 81. To lay the groundwork for commercialization, we planned to involve appropriate industries early, so that we could select partners to participate in the design, fabrication, fielding, and testing of this prototype total-flow system. It was expected that, if the field demonstration were successful, industry would proceed to a full-scale

demonstration. The LLL role would decline as the need for research and development declined.

Development of the Total-Flow concept would have added a third basic technology suitable for water-dominated geothermal resources (the other two being the flashed-steam and binary-cycle technologies). In exploiting economically marginal resources that require combinations of systems or technologies for cost reduction, a third alternative would have been very useful. For this reason, our technology development program included development and testing of concepts for hybrid systems suitable for lower-temperature resources.

2.2.2 Industrial Support

The purpose of the industrial support activity is to provide technical assistance to joint DOE/industry geothermal programs in developing the

SSKGRA. The emphasis is on (1) applying the expertise and results obtained in the technology development activity to operational problems and (2) carrying out complementary applied research to broaden opportunities for solving potential problems. In this manner the technical capabilities developed at LLL can help to stimulate industrial

development of geothermal energy. Currently, we are working on the flash/binary project jointly undertaken by the San Diego Gas and Electric Company and DOE. The results of this and other industrial support work will be reported under a separate cover.

3. DEVELOPMENT OF THE TOTAL-FLOW CONCEPT

The Total-Flow process is defined very simply as the expansion of the fluid from a geothermal well directly to sink conditions through a single machine. The wellhead fluid may be either a liquid or a mixture of liquid and vapor. The range of possible thermodynamic and chemical conditions forces consideration of various different expander concepts.

In the course of the development work, two different types of machines received prominent attention: an impulse turbine designed to accommodate a mixture of liquid and vapor at the inlet, and other expanders designed uniquely for liquid. As shown in Table 1, the impulse turbine is for higher-temperature resources and the other expanders are for lower-temperature resources. Two low-temperature machines investigated were the helical rotor expander and the bladeless turbine. The bladeless turbine tested was not an adequate representative of the concept, and no definitive conclusions could be drawn.¹ The helical rotor expander will be discussed in a later section.

In the course of analysis and testing, several variations on the above concepts came to light:

- There is no obvious reason why the impulse turbine could not be a candidate for fluids with much lower inlet quality,* even for the liquid condition.

- The liquid expander could be effectively used in a hybrid system, i.e., in combination with conventional turbines.

These variations deserve further investigation.

In this section, we will discuss the thermodynamics of total flow and the nature of geothermal fluids, and of the impulse turbine. In a subsequent section, we will discuss liquid expanders and hybrid systems.

3.1 THERMODYNAMIC CONSIDERATIONS

Figure 2 is a temperature-entropy diagram for pure water. The fluid downwell in a geothermal reservoir is actually a compressed liquid, but it is shown for simplicity as a saturated liquid at point 1. In a self-pumping mode of operation, the fluid emerges at the wellhead (point 2) as a two-phase fluid. Expansion through a two-phase expander occurs from point 2 to point 3', and condensation of the vapor occurs from point 3' to point 4. The liquid is discarded in the sink condition at point 4.

*Quality is defined as the ratio of the mass of the vapor divided by the total fluid mass (vapor plus liquid).

TABLE 1. Typical turbine inlet conditions.

	Pressure, psia	Temperature, °F	Quality
Impulse turbine	360	434	19% vapor (by mass)
Radial-outflow reaction turbine	135	350	0% vapor
(Both concepts exhaust to 120°F, 1.7 psia)			

$$\text{Net power out} = \dot{W}(h_2 - h_3)e_e \text{ where}$$

$\dot{W}$ = flow rate

h = enthalpy

e_e = engine efficiency

$$\text{Power lost in spent brine} = 0$$

$$\text{Overall thermal efficiency} = e_e \left(\frac{h_2 - h_3}{h_2 - h_4} \right)$$

$$\text{Engine efficiency} = e_e = \frac{h_2 - h_3}{h_2 - h_3}$$

FIG. 2. Temperature-entropy diagram for the Total-Flow process.

For some resources, especially lower-temperature ones, the wellhead fluid is a saturated or compressed liquid. In this application, the Total-Flow process is essentially the same, with state 2 being on the liquid line. This results in 100% liquid inlet to the expander and imposes a different set of design requirements for a Total-Flow expander. Our development of a radial outflow expander has its roots in design requirements for utilization of the geopressed fluids where the wellhead pressure may be a few thousand psi, far beyond the saturation pressure for brines in the range of 300 to 400°F. As mentioned briefly above, the potential for hybrid systems as well as the more conventional lower temperature resources added further stimulation to the work on an expander for liquids.

All of our expander development work has been done on clean water. However, in system analyses done for purposes of economic comparison, actual brine properties were used.

3.2 WELLHEAD FLUID CHARACTERISTICS

Table 2 lists typical well-flow characteristics as a function of reservoir temperature for the self-pumping mode of operation. In each case the wellhead conditions are for the maximum thermal energy extraction rate. The last line in the table defines conditions chosen for a "typical" HT/HS

TABLE 2. Calculated geothermal well flow characteristics for self-pumping mode of production.^a

Reservoir temperature,		Wellhead characteristics				
°F	°C	Temperature, °F	Pressure, psia	Vapor fraction, %	Flow rate, 10 lb/h	Thermal energy extraction rate, ^b MWt
350	177	281	50	7.4	256.5	17.3
400	204	326	98	8.3	337.5	28.0
500	260	390	220	13.7	427.5	49.0
572	300	434	360	18.9	450.0	62.6

^aWell depth = 5000 ft; production casing = 7.625 in. o.d. × 6.770 in. i.d. (area = 0.25 ft). Calculations based on the thermodynamic properties of pure water, Moody friction factor = 0.04.

^bWith reference to saturated-liquid enthalpy at 120°F.

resource. These conditions were used in designing the impulse turbine.

The original analytical model for these calculations was based on elementary considerations of conservation of mass and momentum for adiabatic flow of pure water up a wellbore.² An approximate general rule is that the maximum energy extraction rate is reduced by about 0.8% for every 1% increase in total dissolved solids (TDS). We have completed a computer program which enables the user to obtain conveniently the thermodynamic properties of brine and water vapor in combination, given a minimum amount of specified information. Parameters included are salt content, temperature, pressure, enthalpy, entropy, density or specific volume, quality, and amount of superheat. The program, called BPROP7, is described in Ref. 3.

3.3 THE TOTAL-FLOW IMPULSE TURBINE

Initially, various machines were considered for the Total-Flow process. The impulse turbine was selected as the most suitable candidate primarily because of its simplicity. All of the pressure and temperature drop occurs in the stationary nozzles. This allows better control of the expansion process and easy access for droplet-size and scale control. In addition, the components downstream of the nozzle, including the highly stressed rotating turbine wheel, operate at a low temperature, say 50°C, which is more conducive to long-term materials reliability. Figure 3 schematically represents the axial-flow impulse turbine and simplistically illustrates the dependence of turbine efficiency on nozzle and wheel energy efficiencies.

The relationships shown in Fig. 3 lead to several conclusions:

1. Overall engine efficiency is strongly dependent on nozzle performance because the velocity coefficient is squared.
2. Wheel efficiency is strongly dependent on momentum transfer from the liquid phase because the liquid is the major fraction of the mass flow in the HT/HS application.
3. The liquid phase must exist in droplets small enough to follow the vapor flow path and not hit the blades; hence efficiency is strongly dependent on the size of droplets in the flow leaving the nozzle.

Analytical efforts for the impulse turbine project were centered on the development of:

1. Models to predict turbine and nozzle performance with two-phase flow.
2. Understanding of the two-phase fluid dynamics of fluid in three-dimensional nozzles and curved blade passages (for design optimization).
3. A realistic droplet-breakup model.

Experimental activities for the impulse turbine included the following:

1. Design and demonstration of efficient supersonic nozzles for expanding a two-phase, single-component fluid.
2. Design and demonstration of the feasibility of the axial-flow impulse-turbine concept.
3. Verification of analytical prediction.
4. Liquid-phase characterization as to droplet size, velocity, and void fraction.
5. Droplet size reduction, including verification of the droplet-breakup model and evaluation of strategies for the reduction.

$$\begin{aligned}\Delta h_{is} &= h_2 - h_3 \\ V_3 &= \sqrt{2(h_2 - h_3)} \\ V_{3'} &= \eta V_3 \\ P_{ideal} &= \dot{W}(h_2 - h_3) \\ P_{out} &= \dot{W}(h_2 - h_3)\eta^2 e_w \\ \therefore e_t &\cong \eta^2 e_w\end{aligned}$$

where

e_w = wheel efficiency

e_t = turbine efficiency

η = nozzle coefficient

FIG. 3. The axial-flow impulse turbine.

Reference 4 contains a full description of the design, construction, and testing of the Total-Flow impulse turbine. An engine efficiency of 23% was measured in a single-nozzle test. The numerical model and achievable nozzle thrust coefficients indicate that under full-admission conditions an engine efficiency of between 38 and 48% can be realized with present technology. If maximum liquid removal loss is assumed, the performance range is between 38 and 41%. Droplet size reduction and the development and implementation of enhanced two-phase flow analysis techniques should make it possible to achieve the research goal of 70% engine efficiency.

Nozzle development and testing for the impulse turbine are described in Ref. 5. Nozzle inlet qualities and pressures were varied from approximately 10 to 20% and from 1.8 (260 psia) to 2.8

MPa (406 psia), respectively, to simulate geothermal wellhead products. The optimum nozzle performance for a specific geometry was determined by varying the nozzle back pressure from atmospheric to approximately 14 kPa (2 psia). Experimental thrust coefficients and pressure profiles were compared with theoretical predictions. Observations were made concerning nozzle exit shock and expansion waves for off-design conditions. As anticipated, the optimum nozzle efficiencies were high.

Early experimental work indicated that nozzle velocity coefficients could be over 0.93. Actual measurement of the thrust of the nozzle used in the turbine assembly showed a velocity coefficient of 0.94. However, in the turbine test, some degradation occurred as a result of nearby shrouding.

Figure 4 shows the turbine rotor in preparation for testing. Half of the case and the nozzle are

FIG. 4. Impulse turbine rotor in preparation for testing. (The nozzle and half of the case have been removed.)

removed. The complete assembly with the nozzle in place is shown in Fig. 5. The test results are summarized in Fig. 6, which also gives the predicted performance and the extrapolations to a full-admission design. The test machine with a single nozzle achieved a peak efficiency of 23%. A full-admission design, i.e., 20 nozzles with the same non-optimized blading, would have an efficiency of about 45%.

It should be noted that the design of the machine tested was frozen long before advanced calculational techniques were developed. The extrapolations shown in Fig. 6 are for the existing blade width and spacing, and they require reduction of the droplet diameters to less than 1 micron. Figure 7 shows the effect of increasing blade width

B. As shown, wider blades can accommodate larger droplets. For example, tripling the blade width allows a potential increase in wheel efficiency of about 8%. Hence, a combination of droplet reduction and optimized blading greatly increases the probability of achieving 70% engine efficiency for the Total-Flow impulse turbine. The significance of a 70% engine efficiency in terms of resource-utilization efficiency will be discussed later.

The FY 1978 effort includes a synthesis of the experience and knowledge gained to produce a conceptual design of a full-admission Total-Flow turbine incorporating the most likely candidate scheme for droplet size reduction by means of liquid injection into the nozzle throat. This design would have been built and field-tested had the program continued.

FIG. 5. The complete impulse-turbine assembly (with nozzle and case in place).

3.4 THE STATUS OF DROPLET-REDUCTION EXPERIMENTS

As noted in Fig. 7, it is important to reduce the droplet diameters to less than 2 microns. However, to use the existing wheel design for subsequent laboratory tests, we will need to achieve droplet diameters of 1 micron. To reach this goal, we have been working on a means of nozzle flow visualization, a droplet-velocity-measurement technique, a droplet-size-measurement technique, and analytical methods for flow characterization and advanced nozzle design. A significant effort was expended in FY 1977-78 to develop and prove these techniques.

For detailed information, the reader is referred to Refs. 6 through 9. The following briefly describes the status of these projects.

3.4.1 Flow Visualization

To provide flow visualization and a means of initially testing and verifying the experimental techniques, a specially designed transparent nozzle system was installed as shown in Fig. 8. A schematic of the test setup is shown in Fig. 9. The pulsed ruby laser emits approximately 2 J in a pulse time of 20 ns, which allows a "stop action" picture of the flow. Variation in the light intensity across the nozzle

FIG. 6. Results of testing and performance evaluation for the total-flow impulse turbine.

FIG. 7. Idealized rotor performance as a function of droplet diameter for various blade widths.

flow provides information on the liquid phase distribution and boundary layer mechanics (see Ref. 6).

3.4.2 Droplet Velocity Measurement

It is important to measure droplet velocities for supportive information on nozzle and turbine performance. Knowledge of droplet velocities can be

FIG. 8. Transparent nozzle system specially designed for flow visualization. Variation in light intensity across the nozzle flow provides information on the liquid phase distribution and boundary layer mechanics.

FIG. 9. Schematic of the laser shadowgraph test set-up used with the transparent nozzle shown in Fig. 8.

used in estimating droplet size. Also, the droplet velocity distribution across the nozzle is an important factor governing nozzle performance, and both are crucial to the final design of blade geometry.

Characterization of the droplet phase is difficult because of the high velocities (600 m/s), the small droplet sizes, the high number density, and the requirement that the flow remain unperturbed during measurements. Hence, a passive technique based upon the scattering of light was selected. This method operates on the principle that the light scattered from a moving droplet will experience a frequency shift from that of the incident light, and that the frequency shift is proportional to the droplet velocity. Measurement of this shift was accomplished by a dual-beam, backscatter, laser-Doppler velocimeter (LDV) arrangement incorporating a Fabry-Perot interferometer (FPI). The optical setup is shown in Fig. 10.

The transmitting optics arrangement for this LDV system is identical to that of a dual-beam, heterodyne LDV, i.e., the light beam from a single-frequency argon laser is divided into two identical parallel beams, which are focused to an intersection volume in the flow. The light backscattered from droplets traveling through this volume is collected by means of a scanning confocal Fabry-Perot interferometer (FPI). Because of the dual-beam arrangement, an unscattered or reference beam is not necessary, and the optical alignment ease and stability are greatly improved over similar LDV-FPI systems. For greater detail on this system and on the results of droplet velocity experiments, the reader is referred to Refs. 6 and 8.

The LDV-FPI was used to measure droplet velocity profiles at the exit of a rectangular converging-diverging nozzle with two different operating conditions. The results demonstrated the technique for accurate determination of droplet velocity and velocity distribution across the nozzle exit. A sample measurement, shown in Fig. 11, gives the droplet velocity profile across the nozzle thickness at a location 1 cm from the nozzle exit.

A comparison of the velocity profiles of Fig. 11 shows that there is little change in the profile due to the change in the inlet pressure. This indicates that the boundary layer effects are essentially the same in either case. The two profiles show a difference of approximately 100 m/s (328 ft/s) in the exit velocities. However, a calculation based on isentropic, homogeneous flow indicates that the velocities corresponding to the different nozzle operating conditions should be nearly the same [approximately 600 m/s (1969 ft/s)]. An analysis of the pressure profiles for the two cases shows that for the velocity profile corresponding to the 2.1 MPa (300 psia) inlet pressure [exhaust pressure of 37.9 kPa (5.5 psia)], the nozzle was operating underexpanded, and for the velocity profile corresponding to the 0.7 MPa (100 psia) inlet pressure [exhaust pressure of 17.2 kPa (2.5 psia)] the nozzle was operating overexpanded. Overexpanded operation caused an oblique shock to form in the nozzle jet flow. This caused a velocity decrease before the fluid reached the measurement location 1.0 cm from the nozzle exit. Additional calculations verified that the velocity difference was caused by the overexpanded condition for the 0.7-MPa (100-psia) inlet pressure condition.

Underexpanded nozzle operation at an inlet pressure of 0.7 MPa (100 psia) resulted in exhaust velocities near 600 m/s (1969 ft/s). This is very near the vapor velocity calculated by means of one-dimensional methods. This indicates that in properly designed nozzles there is very little slip between phases.

Although the velocity measurements in Fig. 11 were made with a 0.325-cm jet thickness, the LDV-FPI system can accommodate much thicker nozzle-jet flows. Velocity measurements in two-phase, air-water jet flows with light-transmission characteristics similar to those of steam-water nozzle flows have shown that the dual-beam-backscatter, LDV-FPI arrangement is capable of measuring droplet velocities up to 0.6 cm into the

FIG. 10. Dual-beam backscatter LDV-FPI optical and signal analysis arrangements used to measure the low-quality, steam-water nozzle-jet flow.

flow. Thus, this technique can be used to measure the free-stream velocity of fluids from large-cross-section, two-phase nozzles.

3.4.3 Droplet Size Measurement

Our droplet-size-measurement technique is based on the theory of light-scattering by a single spherical particle. This theory is readily extended to include light-scattering by many particles of different sizes, provided that the light incident on all particles is the same. Thus, by measuring the angular distribution of the scattered light, we can determine the particle size spectrum.

A schematic of the experimental arrangement is shown in Fig. 12a. The technique is based on the

use of a calibrated film to determine the angular distribution of scattered light. Each piece of film is calibrated individually to increase accuracy. The intensity at any angle $I(\theta)$, relative to the central intensity I_0 , the Mie scattering function $i(\alpha, \theta, m)$, and a particle-size distribution function are related as in Eq. 1.

$$\frac{I(\theta)}{I_0} = C \int_0^\infty i(\alpha, \theta, m) f(\alpha) d\alpha \quad (1)$$

By measuring I_0 and $I(\theta)$ and calculating the theoretical Mie scattering function $i(\alpha, \theta, m)$, we can determine the particle-size distribution function $f(\alpha)$

FIG. 11. Droplet velocity measurements across a half-thickness of the jet-flow.

by numerical inversion of Eq. 1. Since $\alpha = \pi D/\lambda$ where D is the droplet diameter and λ is the initial light beam wavelength, the droplet size and distribution can be obtained.

Demonstration and calibration of this technique was done initially with a suspension of glass beads in water. A typical exposure is shown in the

lower inset of Fig. 12b. The exposures across the top of the film supply the film-calibration data. The exposure on the lower right side of the film is the initial laser beam without scattering particles; the exposure on the lower left side of the film is the light after scattering by glass beads. An isometric display of the same film plane is shown in Fig. 13.

FIG. 12. Optical system used to record light-scattering, (a) Schematic; (b) artist's rendering of system and a typical exposure obtained with the system and used to determine the droplet size distribution in the flow.

FIG. 13. Isometric plot of the film plane shown in Fig. 12b.

For final data reduction, the film is scanned by a microdensitometer to obtain accurate readings of the film density. Then, by using the known energy in the calibration exposures, a relationship between film density and energy density can be determined.

By using this relationship, the film density corresponding to the initial and scattered light beams can be converted to energy density or light intensity, after the calibration has been applied. This figure provides the data required for determining the droplet-size distribution by means of Eq. (1). Measurements with glass beads by this technique and by photomicrography agree within 10% for the mean diameter and the mean volume-to-surface-area diameter.

The light-scattering technique was used to measure the droplet size distributions from a series of specially designed converging-diverging nozzles. The dimensions of these nozzles are given in Fig. 14 for reference. These nozzles were operated under nominal inlet conditions of 100 psia and 150 psia with inlet enthalpy of 500 Btu/lbm ($X = 20\%$) and an exit condition of about 2 psia. Actual operating conditions varied somewhat from these nominal values, and the reader is referred to Ref. 6, pp. 95-115 for detailed test results. The results of one test series are given in Fig. 15. This series was selected because it most clearly shows that decreasing the throat radius does reduce the droplet size, but not significantly. The mass-fraction curves associated with the right-hand ordinate show that as throat radius decreases, a greater mass fraction has smaller

droplets, but the variation is not large enough to increase the mass fraction of small droplets sufficiently.

Another important point is that the $f(\alpha)$ distribution on the left indicates that the nozzle-jet flow is dominated by a large number of droplets less than 1 micron, but they constitute only a 20% fraction of the total droplet mass. The mass median droplet diameter is near 2.5 microns. It was concluded that the small droplets (<2.5 microns) are associated with the center core region of the jet flow, while the larger droplets are generated by the boundary layer-liquid film shearing action occurring along the nozzle walls, and particularly near the throat.

It should be mentioned that laboratory droplet measurements made with such small jet widths (0.325 cm) are biased in favor of large droplet sizes because boundary effects are relatively more important in thin nozzles than in full-sized impulse-turbine nozzles. Hence, a greater fraction of the liquid mass in a commercial-sized turbine using similar but larger-cross-section nozzles would be present as small droplets.

The important achievements of our droplet-size-measurement program are as follows: (1) the light-scattering technique for droplet measurement in high-velocity two-phase flow has been developed and demonstrated; (2) it has indicated that the mass median droplet diameter for conventional nozzles is 2.5 microns; and (3) the technique is now proven as a valuable experimental tool for evaluating and optimizing designs of Total-Flow impulse turbines.

3.4.4 Droplet Breakup Mechanisms

The conventional approach to predicting droplet size in a dispersed gas-liquid flow is to use the Weber-number criterion. The Weber number, by definition, is the ratio of aerodynamic forces to surface-tension forces on a liquid droplet. If the aerodynamic drag forces become sufficiently large compared to the surface-tension forces holding the droplet together, the droplet will break up into smaller segments. Experiments show that breakup occurs at Weber numbers between 6 and 10.

With two-phase flow through a converging-diverging nozzle, the liquid droplets are unable to attain the high acceleration of the vapor in the throat region of the nozzle. Consequently a velocity difference develops, and this gives rise to an aerodynamic force sufficient to cause droplet

Nozzle No.	Throat radius of curvature, cm	Throat height, cm	Thickness, cm	Diverging half angle, deg	Exit height, cm
1 [†]	0.635	0.440	1.750	10.0	5.53
2	0.051	0.635	0.325	17.5(10.7) ^{††}	9.53
3	0.318	0.635	0.325	11.1	9.53
4	2.540	0.635	0.325	11.2	9.53
5	0.051	0.318	0.325	17.5(10.7) ^{††}	9.21
6 [†]	0.318	0.635	1.905	11.1	9.53

[†] Transparent sidewalled nozzle.

^{††} Nozzle No's. 2 and 5 had a compound angle divergence section. The divergence half angle was 17.5 degrees just after the throat, which rapidly tapered into 10.7 degrees for the majority of the diverging section length.

FIG. 14. Numerical designations and dimensions of the experimental nozzles.

breakup. Calculations based on the Weber number predict droplet sizes of approximately 5 microns in the nozzles under study.

The fact that the steam-water flow from a geothermal resources is essentially a single-component flow suggests the existence of a different mechanism for droplet breakup. In addition to the velocity difference that develops between the droplet and the vapor, a corresponding thermal lag appears because of the finite heat-transfer rate within the droplet. The internal temperature of the droplet will be higher than that of the surrounding vapor, and internal boiling will lead to droplet breakup unless the surface tension is adequate to prevent it. This mechanism accounts for the non-equilibrium condition in rapid two-phase expansion

processes. A complete analytical treatment of a boiling-breakup model is given (with sample calculations) in Ref. 9. The model has been used to calculate droplet sizes for a representative nozzle under different inlet conditions. As shown in Fig. 16, the droplet breakup is most effective at higher inlet temperatures, but inlet quality appears to have less effect. Over the region shown on the temperature-entropy plane, the maximum droplet sizes are all low. This is evidence that the impulse turbine can be used with a wide range of inlet fluids, including almost pure liquid ($\chi \cong 2\%$), and is contrary to "conventional wisdom," which says that the impulse turbine is only useful at high temperatures and with inlet fluids typical of the HT/HS resource.

Nozzle No.	Actual test conditions				
	Throat radius r , cm	Inlet pressure; MPa (psia)	Inlet enthalpy, MJ/kg (Btu/lbm)	Inlet quality, %	Exit pressure, kPa (psia)
3	0.318	0.80 (116)	1.21 (518)	23.7	16.5 (2.4)
2	0.051	0.75 (109)	1.17 (501)	22.2	15.2 (2.2)
4	2.54	0.70 (102)	1.14 (489)	21.3	14.5 (2.1)

FIG. 15. Measured droplet size distribution and their respective mass fractions.

Predicted droplet diameter from boiling model using typical geothermal operating conditions.

Nozzle entrance condition (supersonic exit)				Predicted maximum diameter of droplet, microns
psia	T, °F	T, °C	X, %	
360	431	222	19	2.4
360	431	222	2	2.8
200	381	194	5	3.6
200	381	194	2	3.8
100	327	164	27	4.9

FIG. 16. Calculations of various nozzle conditions.

To compare the boiling-breakup model with the experimental measurements, the model was applied to the experimental nozzle configuration used to produce Fig. 15; the results are shown in Table 3. The predicted maximum droplet diameter is larger than the measured mass-averaged diameter. The droplet spectrum shown in Fig. 15 indicates droplets as large as 10 microns, but these are believed to be caused mainly by a mechanism unique to the experiment design. Since the nozzles tested were very thin (0.325 cm), boundary layer effects are more prevalent than they would be otherwise, and the calculational model does not include these effects. As previously mentioned, full-sized nozzles would have a much greater nozzle-surface-to-exit-area ratio, which would minimize the boundary effects. Comparison of measured values of mass-averaged mean droplet diameters with those predicted by the boiling-breakup criterion show that the model is conservative. The few large droplets indicated in the measurements can be eliminated by appropriate nozzle design. These results suggest that the Total-Flow impulse turbine may be useful over a large range of representative resource conditions.

The boiling-breakup model provides a better prediction of measured droplet diameter than the empirically dependent Weber-number model. Since

TABLE 3. Experimental and numerically predicted droplet diameters (microns).

Experimental diameters (mass-averaged), microns	Predicted diameters, microns	
	At average droplet temperature	At droplet center temperature
2.5	5.9	4.0

it is derived from first principles, it is a more fundamental method of predicting droplets in single-component, two-phase flows. Based on the comparison of the boiling-model results with experimental measurements, the use of average droplet temperature or the center temperature in the calculational techniques provides conservative (larger than measured) estimates of droplet size (see Table 3).

3.5 THE TECHNICAL POTENTIAL OF THE TOTAL-FLOW IMPULSE TURBINE

Thermodynamically, the Total-Flow process is the most efficient process for producing electric power from geothermal brines, and thus, it has the

potential for the highest output of energy per unit mass of fluid in comparison with other processes. Of all expanders considered, the Total-Flow impulse turbine is the most promising candidate. To achieve the maximum potential of the Total-Flow process, we originally set an arbitrary goal of 70% engine efficiency (see Fig. 2, $e_e = 70\%$). As noted in Fig. 3, the impulse turbine performance is given approximately by

$$e_t \cong \eta^2 e_w = 0.70$$

where

η = the nozzle thrust coefficient

e_w = turbine wheel efficiency.

In the course of the development program, thrust coefficients between 0.93 and 0.95 were routinely achieved in laboratory tests. It has been suggested that these thrust coefficients might be severely reduced by the presence of dissolved solids in real brines, but there is no strong physical justification for this belief. Equation-of-state calculations for brine indicate no significant degradation of nozzle performance. Hence, we have concluded that nozzle thrust coefficients of about 0.94 can be expected. This means that the efficiency of conversion of the thermal energy in the wellhead product to kinetic energy at the nozzle exit will be η^2 , or $(0.94)^2 = 89\%$.

The remaining step is the efficient transfer of momentum from the high-velocity nozzle exit flows to the wheel. The efficiency of this process is represented by e_w , and it is strongly dependent on blade width, blade spacing, and droplet size as shown in Fig. 7. If $\eta = 0.94$, e_w must equal 79% to give the desired engine efficiency e_t of 70%.

The further implication of Fig. 7 is that even if droplets cannot be reduced below 3.0 microns, doubling the blade width will allow an increase of e_w from 55 to about 68%, which alone will yield an engine efficiency of about 60%.

Reduction of droplet size to below 2.0 microns remains as the last step required to achieve the goal of 70% engine efficiency.

3.5.1 Droplet-Size-Reduction Possibilities

The present situation is summarized in Fig. 17, where the mass fraction distribution curves from Fig. 15 are combined in a single solid curve, which

has a mass median of 2.5 microns. As noted earlier, the thin-nozzle experiment produced a greater number of large droplets than would be expected in full-sized nozzles. Calculations indicate that a maximum of 5.0 micron droplets would be possible by preventing a liquid film from forming on the nozzle walls. Hence, the dashed line in Fig. 17 represents the likely distribution for larger size nozzles, and is considered achievable today. To achieve 70% engine efficiency, we must either maintain the existing wheel design and reduce the droplet diameter from 5.0 to 1.0 microns or reduce the droplet diameter from 5.0 to 2.5 microns and redesign the wheel. The effect of doubling the blade width is shown in Fig. 7.

Although numerous methods for reducing droplet size have been proposed, only two were selected for investigation. The first, and most direct, method was to reduce the nozzle-throat radius of curvature. As indicated in Fig. 15, experiments with this concept did not show a significant droplet-size reduction. However, as previously mentioned, boundary-layer effects were prevalent in the thin nozzle used, and consequently, larger scale experiments will be necessary.

The second method for reducing droplet size was to separate the phases upstream and remix them at the nozzle throat. This scheme was conceived for several important reasons:

- It has been established that, for the HT/HS resource, brine acidification will prevent scale formation during expansion. The hydrochloric acid additive (100–200 ppm) will have to be metered to control pH, and it would be advantageous to inject it into the liquid phase near the wellhead. Hence, it will be necessary to separate the phases anyway. This can be done easily at high pressures with a minimum of expensive equipment because it need not be a complete "separation".

- Upstream separation and remixing allows accurate measurement and control of the total brine flow for control of power plant output.

- Introduction of the liquid in the form of many small jets at the nozzle throat would allow control to prevent liquid entrainment in the boundary layer along the walls.

- Also, separation and remixing would provide the maximum difference between liquid and vapor velocities, and this would enhance droplet breakup directly.

- Calculations indicate that separation and remixing would not degrade the thrust coefficient.

FIG. 17. Droplet reduction requirements.

Other droplet-size-reduction schemes proposed involve combinations of throat-contour changes and remixing and/or addition of surfactants to reduce surface tension. However, the potential of the separation-and-remix technique by itself appeared promising enough to proceed with an experimental design for test and evaluation. Figure 18 is a view of a remix nozzle. The system consisted of a row of ten 0.050-in.-diam tubes spaced along and protruding slightly into the nozzle throat. Each tube

contained a 0.028-in. slot, which produced a thin, sheetlike liquid spray directed downstream. The vapor traveling past this sheet acts to break up the droplets further during the expansion process through the diverging section of the nozzle. The complete apparatus has been fabricated and is ready for testing. The experimental procedure also necessitated substantial modification of the test facility. Much of this work was completed, but the program was terminated before any definitive test results could be obtained.

FIG. 18. Upstream view of an experimental remix nozzle.

Whether or not the concept would produce the results outlined in Fig. 17 must be left to speculation. However, in view of the fact that both droplet reduction and wheel and blade optimization will improve engine efficiency, we conclude that continued development would have produced a 70% engine efficiency for the Total-Flow impulse turbine.

3.5.2 Material Selection

There have always been major concerns over the possibility of serious erosion and corrosion of turbine components subjected to HT/HS brines. The most critical component is the turbine blade itself, which is exposed to high-velocity two-phase flow, centrifugal stresses, and the corrosive action of acidified brine.

As reported in our last status report (Ref. 10), we have performed initial feasibility tests of candidate materials for the Total-Flow impulse turbine. These tests involved expansion of acidified, separated liquid brine through nozzles, with the exit flow directed over turbine blades. The tests established the technical and economic feasibility of acidification for scale prevention, and indicated that the Ti-base alloys were corrosion- and erosion-resistant under the test conditions.

Because of the success of these initial tests, it was important to proceed with a second series of tests more representative of Total-Flow operation, i.e., two-phase flow of wellhead quality at the nozzle

inlet. Of particular interest was the possibility of increased acid consumption due to HCl vaporization and reaction with ammonia. Also, a wider variety of materials needed to be tested over a longer period of time with more extensive post-test measurements and metallographic examinations.

The test setup, shown schematically in Fig. 19, was located at the LLL Field Test Station at the Magmamax No. 1 well in the Imperial Valley. All fluid streams were carefully metered, and each station was fitted with a nozzle, a turbine blade, and a stress-corrosion-cracking specimen of candidate materials. The pH of the outflow stations was monitored hourly. Separation and remixing of the wellhead fluid allowed testing at nozzle inlet qualities of 11 and 33%, with an inlet temperature of about 195°C.

The results of the acid-consumption tests are shown in Fig. 20 along with prior results for 0% quality inlet. As expected, increased acid consumption was observed for the two-phase case because of neutralization of HCl by ammonia in the vapor phase (~ 400 ppm NH_3 in the vapor phase). Typical wells in the Salton Sea Geothermal Field (SSGF) are expected to produce about 10% quality, and fluids from other wells, e.g., IID No. 1, contain about the same ammoniacal nitrogen levels as fluids from Magmamax No. 1. Thus, the acid consumption and cost curves for 11% quality given in Fig. 20 are expected to be typical of SSGF well fluids. HCl

FIG. 19. Schematic of the two-phase-nozzle/blade field test station.

costs for pH reduction will, on the basis of data in Fig. 20, vary between 1 and 2 mills/100 lb of brine, depending on the desired pH.

Following the acid-consumption tests, 60-h materials-performance tests were carried out under the conditions noted in Fig. 19. A wide variety of Ti-, Co-, Ni-, and Fe-base alloys were evaluated for erosion and stress corrosion cracking after exposure to the nozzle exhaust at 104°C. The detailed results of these tests are reported in Refs. 11 and 12 and will not be duplicated here.

Of all the materials tested, the Ti-base alloys appear to have the best combination of resistance to stress corrosion cracking, erosion-corrosion, and scale resistance. The Ti-6Al-4V nozzles were scale-free, except near the exhaust end. This scaling was

FIG. 20. Acid consumption and cost for Magmamax No. 1 brine expanded through nozzle.

due to evaporative concentration of the brine, and it can be eliminated by proper design of the nozzle wall.

Post-test profilometer measurements of the leading edge of the turbine blades indicated 18- and 19-micron erosion for the carbonitrided and uncoated Ti-6Al-4V blades, respectively. A linear extrapolation leads to a rate of about 0.1 in./yr. The tests, however, were not completely definitive because the fluid velocities used were higher than those that would occur over an actual rotating blade. Also, the carbonitride coating on the test specimen could be improved greatly. Stress corrosion cracking was not observed in the Ti-6Al-4V specimens stressed initially to 30,000 psi.

As a result of these tests, it is generally concluded that better blade tip materials will allow turbine operation for periods of years. For example, hard titanium-base alloys applied to the Ti-6Al-4V alloy blade, nitrided Ti-6Al-4V, and possibly ceramics are all very promising materials. Based on published information indicating higher erosion resistance, these materials are expected to allow reliable, long-term turbine operation.

While material selection for erosion/corrosion resistance is an important consideration, it is basically a design problem. There are materials available that will perform in the Total-Flow environment. Hence, material erosion is not con-

sidered a fundamental limitation to development of a reliable Total-Flow impulse turbine.

3.5.3 A Conceptual Design

During FY 1978, plans were underway to build and field-test a complete, 2-MWe, full-admission, Total-Flow impulse turbine. These plans involved a preliminary design incorporating all the necessary features needed for proof-testing a reliable brine-tolerant system. Figure 21 shows the finalized concept, including provisions for separation and remixing for droplet breakup and brine acidification. Specifications were prepared for operating characteristics, materials selection, fabrication, and assembly.

As part of this effort, we contracted with a major U.S. turbine manufacturer to develop a concept definition for a 50-MWe unit incorporating industrial production features, and to estimate the unit cost of commercially produced Total-Flow turbines.

3.6 COMPARATIVE COST ANALYSES

We had planned to carry out cost analyses as part of a broader study of the energy costs of utilization of the HT/HS resource of the SSKGRA. The

FIG. 21. Two-phase Total-Flow turbine.

Total-Flow-system cost studies were to be done consistent with the field demonstration plan (Fig. 1), and, in addition, a concept design study of a 50-MWe Total-Flow turbine was planned to provide the turbogenerator cost information needed for overall system studies.

The sequence was revised, however, since the Division of Geothermal Energy (DGE) required the overall-system-cost analyses by midyear (December). As a result, the cost studies for the Total-Flow system do not incorporate information derived from a concept design and cost analysis of the Total-Flow turbine itself, or from field testing. The DGE's objective was to obtain rough cost projections on the Total-Flow system and other competing systems for energy recovery from the HT/HS resource. The results were an important factor in their decision to terminate support for development of the Total-Flow concept.

The three power-conversion-system (PCS) concepts selected for comparative study were: the double flash system (DF), which is representative of the best available conventional technology, the multi-stage flash binary system (MSFB), representative of the most advanced concept, and the Total-Flow (TF) system, representative of an intermediate advanced concept. Rogers Engineering Company did the basic work on the DF study, and the Bechtel Corporation did the MSFB and TF studies. Overall direction and coordination were provided by LLL. A complete description of these studies is given in Ref. 13. The following is a summary of that work.

The following basic format for each PCS study was developed by mutual consent in an attempt to provide uniformity and standardization: given the study specifications and requirements, a specified system logic, wellhead brine properties, and a computer program for calculation of process brine conditions, (1) calculate system performance and produce a system conceptual design including major equipment and site layout, and (2) estimate capital costs in \$/kW and perform an economic analysis to estimate levelized bus-bar energy costs (BBEC) in mills/kWh. The firms were also asked to perform limited studies of the effect on system performance of variations in parameters such as turbine backpressure and total dissolved solids (TDS). The cost study results are not for optimized systems. That level of detail would have been reached later if the program had continued.

The specifications provided by LLL are summarized in Table 4. Reasonable values for flashed-steam-turbine efficiencies were mutually agreed upon even though performance data was lacking for the intended applications. Also, since no other method of scale control had been demonstrated, LLL specified brine acidification with HCl as a requirement to prevent scale formation. This necessitated additional specifications for special materials and alloys capable of withstanding the acidified brine flow.

The results of system conceptual design studies for the double-flash system, the Total-Flow system (base case), and the multi-stage flash binary system are shown schematically in Figs. 22 through 24, respectively. The Total-Flow-system base case used for the cost studies involved condensation of the vapor fraction (which required a separator downstream from the turbine). It was later found that the performance of the system could be improved by about 17% by eliminating the separator and the associated higher turbine backpressure. Hence, the concept of direct two-phase brine condensation was analyzed. Figure 25 shows the brine condensation case, in which the two-phase turbine exhaust is fed directly into a shell-and-tube condenser, resulting in a lowered condensing pressure, a reduction in exhaust piping, and an exhaust-pressure drop.

The results of the performance analyses are shown in Table 5, which compares the net specific energy outputs (Wh/lb of brine) of each system. In a study assuming 45% engine efficiency (a performance level achievable today), a Total-Flow system produced 9.1 Wh/lb. At this level, it is competitive with a single-flash system but is not competitive with the double-flash or MSFB systems. Hence, further discussion of the 45% Total-Flow system will not be included here.

The results of the cost analyses are summarized in Table 6. Among the systems analyzed, the MSFB is clearly the most expensive. However, the expected accuracy of these studies is no better than $\pm 20\%$, and therefore all systems should be considered the same on the basis of cost alone. Since the Total-Flow and double-flash systems appear to be essentially equal, within the limits of accuracy, further discussion on the nature of the uncertainties in the cost comparisons is necessary.

No attempt will be made here to discuss separately each item making up the cost estimates in

TABLE 4. Power-conversion-system specifications.

1. Plant Performance	5. Environment
50 MWe net output	98% minimum reinjection required
30-year plant life	H ₂ S venting allowed at 130-ft stack height
80% capacity factor	No liquid no solid emissions allowed
2. Turbine Efficiencies	79°F wet bulb temperature
DF 75% low-pressure stage	Minimum usage of makeup water
(steam turbine)	6. Scale and Erosion Control
80% high-pressure stage	Brine acidification required
(steam turbine)	Special vessel and pipe alloys
MSFB 85% (organic vapor turbine)	Hastelloy C-276 above 150°C
3. Resource	1 Cr 0.5 Moly below 150°C
SSKGRA at 290°C (554°F), 25% TDS	Cooling water treatment required
0.5% CO ₂	7. Economic Factors
0.04% NH ₃	Material and equipment at estimated or quoted cost plus 6% sales tax.
0.0015% H ₂ S	Direct labor, 17\$/h
No flow or temperature decline with time	Contractors overhead, 65%
1.6 psia/lb/s drawdown factor	Contractors profit, 4%
350 psia reinjection pressure required	Engineering service, 10%
4. Wellfield	Contingency, 20%
Wellflow production 800,000 lb/h per well	Owners cost, 8%
injection 1,600,000 lb/h per well	Allowance for funds during construction, 8%
4,000 ft depth	Economic analysis methodology
10-3/4 in. diam	
500-yd-square array wellfield	
2 miles between production and reinjection fields	

Table 6. However, summaries are included in Ref. 13 for the reader who is interested. An item-by-item examination of these cost summaries brings into question their consistency and validity for comparative purposes. In retrospect, it probably would have been more useful to have the same firm conduct all three studies or to have several firms carry out all three.

A complete cost analysis must include the cost associated with the achievement of the system reliability required to attain the specified system capacity factor (80% in these studies). These costs include research and development, possible interim life major item replacement (e.g., turbines, pumps, heat exchangers), and possible higher operation and maintenance costs.

TABLE 5. Power-conversion-system performance comparisons.

Conversion system	Net specific energy output Wh/lb brine	Brine flow-rate, 10 ⁶ lb/h
Total flow (70% engine efficiency)		
Steam condensation	13.2	3.79
Brine condensation	15.4	3.24
Multistage-flash binary (85%)	12.8	3.91
Double-flash binary (80/75%)	10.2	4.96

50 MWe net output.

Resource: SSKGRA, 290°C @ 25% TDS, 0.5% NC.

FIG. 22. Schematic of a double-flash steam plant used for power-conversion-system study.

FIG. 23. Schematic of a Total-Flow power-conversion-system steam-condensation case used in the power-conversion-system study.

These PCS studies have not systematically investigated the reliability requirements and associated costs. However, in preparing this report, we have made a qualitative assessment and ranking of the three systems based on the major uncertainties outlined below:

Double Flash

- (1) Brine flow operations. Scaling, erosion, corrosion.
- (2) Steam scrubber effectiveness. The scrubber must clean particles and chemicals (brine, acid, etc.) from the steam to protect the turbines.

TABLE 6. Comparative costs for power-conversion systems with 50 MWe net output.

Conversion system	Capital costs, \$/kW			Levelized bus bar energy costs, mills/kWh		
	Wellfield	Plant	Total	Wellfield	Plant	Total
Double flash	246	780	1026	18.3	21.4	39.7
Total flow						
Steam condensation (base case)	179	956	1135	14.3	26.6	40.9
Brine condensation	156	924	1080	12.9	26.2	39.1
Multistage-flash binary	179	1164	1343	14.3	32.6	46.9

Resource: SSKGRA 290°C @ 25% TDS, .5% NC.

FIG. 24. Schematic of the multistage flash binary power conversion system used in the power-conversion-system study.

While the design approach is known, the actual field operation is unproven.

(3) Turbine blade reliability. Operation and subsequent life of the turbine under upset conditions in the scrubber.

(4) Cost and availability of special turbine blade materials (titanium alloys, for example).

(5) Actual turbine operational efficiencies. The efficiencies of 80/75% used in the LLL PCS study are considered maximum, and are not demonstrated.

Multi-Stage Flash Binary

(1) Brine flow operations. Scaling, erosion, corrosion.

(2) Staging operations. Maintenance of proper interstage differential pressures with the uncondensables and unsteady flow characteristic of the Niland geothermal wells.

(3) MSF-vessel heat exchanger and demister fouling (a major maintenance consideration).

(4) Integrity of binary fluid tubes in the interfaced multi-vessel design at high and/or changing temperatures.

FIG. 25. Schematic of the Total-Flow power-conversion-system brine-condensation case used in the power-conversion-system study.

(5) Binary turbine size. A 50-MWe binary turbine has not as yet been built. The high efficiency postulated (85%) has yet to be proven, and the cost has yet to be verified.

(6) Operation and maintenance requirements associated with safe operation of a binary fluid plant are uncertain.

Total Flow

(1) Brine flow operations. Scaling, erosion, corrosion.

(2) Turbine efficiency. High turbine efficiency has not yet been demonstrated. It will require

droplet size reduction as well as improved blade design and spacing.

(3) Turbine blade reliability. Operation and subsequent life of the turbine under brine flow has not been demonstrated. Static blade tests strongly indicate that titanium alloys are capable of acceptable performance.

(4) Turbine costs. This is the largest single uncertainty in the PCSS. The estimate used in the LLL study was on the high side at \$180/kW, but it is no more than a guess, since no specific design was analyzed. Estimated turbogenerator

costs for the double-flash system were \$128/kW (net, to produce 50 MW) and \$117/kW (gross, to produce 55 MW).

On the basis of these uncertainties and considerations, we rank the three competing processes as follows in terms of the costs of achieving reliability (where 1 denotes lowest expected costs):

<u>DF</u>	<u>70% TF</u>	<u>MSFB</u>
1	2	3

The DF reliability costs are lowest because the greatest uncertainty associated with its development is its ability to handle the flashing brine flow, and this problem is common to all the other systems. The 70%-efficient TF system is ranked second because development, while technically difficult, would require only relatively inexpensive laboratory experiments. If these experiments were successful, a prototype (2-MW) turbine system could be field-tested quickly and at a relatively low cost to determine reliability. The MSFB is ranked most costly because a complete field plant would have to be built and operated to demonstrate its capabilities.

Another major factor to be considered in a complete cost analysis is the indirect cost or benefit coming from effective (or ineffective) utilization of the total energy resource. This cost is based on system-performance results, and, although it is usually expressed as the specific net energy output in Wh/lb of brine, it can also be converted to barrels of oil saved. Performance results for the base case are given in Table 7.

Clearly, if the indirect cost/benefit due to performance is not a significant consideration, the DF

system is the best candidate for the SSKGRA. It is the system with the highest probability of being on-line in the shortest period of time with the lowest probable BBEC. If we stipulate that the system must be on-line in 1983 (with a consequent commitment to plant construction by 1979), the double-flash system is clearly the best choice for this first plant.

If, however, the overall resource-utilization efficiency is included in the total cost, a different conclusion can be drawn. As shown in Table 7, the potentially more efficient 70% TF system could generate as much electricity as 1100 million barrels of oil over the usable life of the resource, whereas the DF system would generate only the equivalent of 830 million barrels. At present (1978), the cost of oil is \$13/bbl. Thus, the TF system offers a 270-million-barrel, \$3.5 billion benefit. This benefit would not be realized directly by the geothermal resource developer. It is instead a national conservation benefit, accrued over a long period of time. The development costs for prototype advanced conversion systems will be no more than a few tens of millions; hence, the benefit/cost ratio is on the order of 1000.

While rough energy-cost estimates indicate that advanced conversion systems offer no clear economic advantage, the lack of system field-test data makes these estimates suspect. As yet, no reliable system for producing electric power from the hypersaline brines of the SSKGRA has been demonstrated. Consequently, it would seem important to continue development of advanced conversion systems in parallel with those that offer the potential for early power on-line.

TABLE 7. Comparison of the performance of the three competing processes for geothermal energy recovery.

	70% TF	MSFB	DF
Specific net energy, Wh/lb brine	13.2	12.8	10.2
Net system thermal efficiency, %	11.7	11.3	9.0
Electric energy from SSKGRA, MW-yr	81,500	78,700	62,700
Barrels of oil saved, ^a 10 ⁶ bbl	1100	1010	830

^aUSGS Circular 726 estimates that 83,600 MW-yr of electrical energy could be produced from the SSKGRA by a system with 12% conversion efficiency.

3.7 CONCLUSIONS

Although the development program was terminated before field tests of a complete Total-Flow impulse-turbine system could be carried out, some conjectures regarding the potential of the turbine can be made. Basically, the Total-Flow concept offers the potential of maximum recovery of available energy, but achievement of this potential depends on the choice of an expander. A research goal of 70% engine efficiency was selected early in the program, and the combined requirements of efficiency, simplicity, and brine-tolerance led to the selection of the impulse turbine as the most promising expander.

The work done to date suggests that the original goal of 70% engine efficiency is achievable, either through droplet size reduction, wheel optimization, or both, and there is reason to speculate that if the droplet diameter could be reduced to less than 1 micron, even higher efficiencies could be achieved.

The comparative cost analysis indicates that the 70% Total-Flow system is competitive with the double-flash system. While there is little doubt that the double-flash system is the prime candidate for early demonstration, its performance remains to be demonstrated as a means of recovering energy ef-

ficiently and reliably from the HT/HS resource. Hence, there remains the need for parallel development of advanced systems that offer the benefits of more efficient utilization of the resource.

Development work at LLL on the Total-Flow impulse turbine has focused strongly on its application to the HT/HS resource. Two major Japanese firms are now working on applications in another context. One is involved in development and testing of a 240-kWe, single-stage, condensing, Total-Flow, impulse turbine for recovery and conversion of waste energy in steel mills. The program also includes nozzle testing, materials-erosion studies, and droplet-velocity and -size measurements. The pilot test turbine is scheduled for completion this fiscal year.

Another large Japanese firm is currently building a 700-kWe Total-Flow impulse turbine that will be used to expand hot water from 240°C (40 atm) to 6 atm, with the exhaust fed to a multistage flash-steam system to give a combined output of 5700 kWe. The intended application here is also waste-heat recovery in steel mills.

Both companies have reported progress in their efforts to expand low-enthalpy fluids efficiently. Hence, the potential of the Total-Flow impulse turbine has broadened considerably, and commercialization is on the near horizon.

4. HYBRID SYSTEMS FOR LOWER-TEMPERATURE RESOURCES

As stated earlier, it is estimated that the high-temperature Salton Sea Geothermal Field contains up to 17% of the energy recoverable from U.S. hydrothermal resources. The remaining water-dominated geothermal resources are generally at low-to-medium temperatures ($<200^{\circ}\text{C}$), which result in low system thermal efficiencies and prohibitive or marginal economics for electric-power production. Consequently, commercial development of about 85% of our geothermal resources will probably lag until sufficient cost reductions can be achieved to bring them into a competitive position.

A recent study¹⁴ done for DOE/DGE concludes that only five prospects presently appear competitive (Salton Sea, Brawley, Puna, Lassen,

and Roosevelt H.S.) and that all other resources areas will require improvements through R&D, including increases in the efficiency of conversion systems. The study is based, in part, on the assumption that resources above 200°C will use the flashed-steam cycle, and that resources below 200°C will use the binary cycle (since the latter is alleged to be more efficient at lower temperatures). Although this view is consistent with the current conventional wisdom and may ultimately be proven by test and demonstration, the basic fact remains that the lower-temperature resources will continue to be of marginal-to-poor economic value for electric-power production until technological improvements and possibly fiscal incentives make them less expensive to recover. At this time, there are insufficient

technical data to categorize and select conversion systems by resource temperature alone. Consequently, it is important to continue development of systems and combinations of systems for more efficient resource utilization.

Although the LLL program has been focused primarily on high-temperature resources, the Total-Flow concept can be applied to lower-temperature resources as well. The basic purpose of our work on expanders for saturated and compressed liquids has been to broaden the application of the Total-Flow concept and two-phase expansion technology to include reliable, low-cost conversion systems for geothermal resources with temperatures below 200°C. The work has consisted generally of system analyses and expander development for specific applications.

Our interest in lower-temperature resources has led us to evaluate hybrid systems (i.e., combinations of energy-conversion systems) and expanders for saturated liquids. Our efforts have been concentrated on two types of devices for these applications: the helical rotor expander and specialized expanders for liquid at saturation pressure or above.

In the development work at LLL, two designs have evolved. The first is a radial outflow reaction turbine taking saturated liquid at inlet. The second (a later version) is similar in outward appearance, but it has an inner (second) rotor.

The original research goal was to develop a liquid expander with an engine efficiency as high as 60%. However, in studying the applications, we found that a 40% efficiency would be attractive in many cases. Actual test results of a small laboratory model of a radial outflow turbine indicate that 50% efficiency is achievable. Thus, additional development and testing are important and clearly justified.

In the following sections the radial outflow reaction turbine (RORT) is described in some detail and its applications discussed. The velocity-pump reaction turbine (VPRT) is then described, and finally, the performance and potential applications of the helical rotor expander are described.

4.1 DESIGN AND TESTING OF THE RADIAL OUTFLOW REACTION TURBINE (RORT)

After considerable study and applications analysis, we concluded that the radial outflow reac-

tion turbine was best suited for expansion of saturated liquid. A unique and versatile two-stage nozzle design was developed and tested for efficient energy conversion over a wide range of pressure ratios.

We then designed and tested an experimental radial outflow reaction turbine, which incorporates a 16-in.-diam disk with four nozzle sets. Liquid enters the center of the rotating disk through a seal and then flows into radial passageways to the two-stage nozzles (Fig. 26). The work done on the fluid by the rotor during the radial flow appears as pressure at the end of the passage. Liquid nozzles then reduce the pressure back down to the saturation value, thereby recovering work added to the liquid. The two-phase steam nozzles, integral with the rotating disk, convert a portion of the available thermodynamic energy into shaft power. Figure 27 shows the complete test set-up, with one side of the turbine case removed to show the rotor.

Test conditions are listed in Table 8. Inlet hot water temperatures ranged from 346 to 371°F with exhaust pressures from 2.6 to 3.7 psia. Operating speeds ranged from 4062 to 8066 rpm.

4.2 RORT TEST RESULTS AND IMPLICATIONS

Efficiency, defined as measured brake power output divided by isentropic expansion power for each set of conditions, is listed in Table 8 and plotted in Fig. 28. The highest measured value is 32.7% at 8066 rpm.

Engine efficiency was based on the power at the eddy-current brake. Since losses in the power-transmission belts, pulleys, and jackshaft bearings are not accounted for, the actual engine efficiency is slightly higher than that listed.

It is clear from Fig. 27, however, that the engine efficiency peak had not been reached at 8066 rpm. A characteristic of the RORT is that the mass flow rate increases with rotor speed, and, unfortunately, we reached the maximum test-facility flow capability on the two highest-speed runs. The lower performance of the turbine near 7500 rpm (Fig. 27) was probably due to leakage past the inlet seal. The design concept has been proven with the present experimental turbine. This means that the original goal of 50% engine efficiency for the RORT is credible, and could be achieved if development were to continue on larger, improved designs.

FIG. 26. Nozzle configuration.

FIG. 27. RORT test configuration.

TABLE 8. RORT performance data from test runs on 18 July 1978.

Point	Inlet conditions			Case pressure, psia	Turbine speed, rpm	Brake power, hp	Brake engine efficiency, %
	Temperature, °F	Pressure, psia	Flow-rate, lb/sec				
1	345.6	191.5	1.37	2.57	4161	13.36	22.11
2	361.6	200.1	1.33	2.54	4062	14.10	20.75
3	366.3	195.5	1.42	2.64	4489	16.65	22.46
4	367.3	188.2	1.44	2.64	4602	17.07	22.44
5	369.0	196.2	1.53	2.68	4927	19.59	24.02
6	369.7	191.1	1.54	2.77	5046	19.98	24.55
7	369.7	191.7	1.70	2.90	5587	23.74	26.74
8	369.7	195.5	1.71	2.90	5524	23.44	26.36
9	370.4	195.1	1.83	2.99	6022	26.42	27.82
10	370.8	195.8	1.85	3.00	6022	26.35	27.54
11	369.9	193.0	1.98	3.13	6552	29.18	28.99
12	370.0	193.2	1.99	3.16	6586	29.44	29.41
13	370.6	193.2	2.13	3.30	7085	32.34	30.42
14	370.2	194.3	2.14	3.31	7080	32.28	30.19
15	369.3	194.7	2.29	3.44	7549	34.25	30.76
16	369.3	193.2	2.29	3.47	7545	34.15	30.67
17	369.9	192.9	2.30	3.67	8043	36.05	32.59
18	370.6	193.6	2.30	3.67	8066	36.24 ^a	32.71

^aPerformance for Run 18 = 3.265 Wh/lb.

FIG. 28. Engine efficiency of the RORT.

A liquid expander efficiency of 40% or higher is very respectable. At that level, a hybrid system composed of the RORT, a separator, and one vapor turbine, will exceed the performance of the conventional two-stage flashed-steam system in expanding a saturated liquid source. Thus, the measured engine efficiency of 33% for the small experimental reaction turbine is very encouraging, especially in view of the fact that this does not represent the maximum possible efficiency of that particular machine.

The basic nature of this design is such that its cost per kilowatt may be considerably lower than that of a conventional turbine. Previous analyses indicate that a 50%-efficient RORT would improve the efficiency of a conventional double-flash plant operating from a high-temperature fluid by about 15%. A rough cost estimate for a 7.5-MW RORT is 0.5 to 1.5M\$; hence, a 15% increase in overall plant output can be achieved for less than 3% in additional capital costs, if we assume a total cost of \$50 million for a 50-MW plant. If perfected, the radial outflow reaction turbine would be a significant addition to geothermal-energy-development technology, and to other technologies involving expansion of hot liquids.

4.3 REACTION TURBINE APPLICATIONS

Figure 29 compares the radial outflow reaction turbine, used as a Total-Flow expander for water at 300°F, with the single-stage flashed-steam system. With a RORT efficiency of 40%, the two systems

Total flow operation — effective engine efficiency = 46.6%

Single-stage flashed steam — effective engine efficiency = 37.4%

FIG. 29. The radial outflow reaction turbine (RORT) in the Total-Flow mode compared with the single-stage flashed-steam system.

are comparable; with an efficiency of 50%, the effective engine efficiency of the RORT system (system expander work divided by isentropic work between sources and sink) is 25% greater than that of the flashed-steam system. Further gains in conversion efficiency for low-temperature resources can be realized by the systems shown in Fig. 30. The effective engine efficiency of a reaction turbine teamed up with a vapor turbine is 12% greater than that of the two-stage flashed-steam system.

Figure 31 represents an advanced flashed-steam system for use with high-energy-reservoir systems (e.g., HT/HS geothermal wells with two-phase steam at the wellhead). The reaction turbine is used to expand liquid from the first separator to the second. Although a detailed economic study has not been made, the advanced system is expected to pay for itself because the additional cost of the reaction turbine would be balanced by lower well costs (reduced mass flow rate) and extended reservoir life for a given power output. The effective engine efficiency over a broad range of reservoir temperatures is shown in Fig. 32. Three curves are

shown as a function of the two-phase expander efficiency. The conventional two-stage flashed-steam system is represented by the curve marked 0%. Specific energy outputs for the three curves at the low- and high-temperature ends are 5.2, 5.8, and 6.1 Wh/lb and 20, 21.7, and 23.2 Wh/lb, respectively. A significant improvement in performance is obtained by adding the reaction turbine to the two-stage flashed-steam system. System performance remains good over a broad range of wellhead conditions, including low temperature and low steam quality.

One point to consider is that the RORT can be added easily to an otherwise standard system, either single- or double-flash. Depending on the size, it may be desirable to integrate its output into the main plant output or use it within the plant. In an add-on mode, the gains would not be as great because the main system would be designed to operate without the RORT, but this initial type of application would still pay for itself because of the low cost of the RORT.

Hybrid system — effective engine efficiency = 53.3%

Two-stage flashed steam — effective engine efficiency = 47.7%

FIG. 30. Hybrid system containing the radial-outflow reaction turbine compared with a conventional double-flash system.

FIG. 31. The radial outflow reaction turbine added to a double-flash system.

FIG. 32. Performance of an advanced double-flashed-steam system.

4.4 THE VELOCITY-PUMP REACTION TURBINE (VPRT)

The encouraging results of the RORT development have led us to design a more advanced velocity-pump reaction turbine (VPRT). This design has the potential for increasing RORT efficiency by about 50%. Variations of the VPRT specifically suited for application to geopressured resources have been conceived. Thus, a family of expanders designed uniquely for liquids has been created to produce shaft work at potential engine efficiencies in the 50-70% range. Unlike the usual reaction turbine, the VPRT reaches its highest efficiency level at rotor speeds compatible with available materials.

The VPRT concept, shown schematically in Fig. 33, uses an inner rotor (driven by an external power source) as a velocity pump. A detailed analysis has been carried out to determine the performance characteristics of the VPRT.¹⁵ The engine efficiency is given by

$$e_{VPRT} = \left(\frac{r^2}{R^2} - 2 \right) \beta^2 + 2\beta\eta_2 \sqrt{1 + \left(1 - \frac{r^2}{R^2} \right) \beta^2} \quad (2)$$

where:

- r = the inner rotor radius
- R = the outer rotor radius
- η_2 = the outer nozzle velocity coefficient
- β = the velocity ratio = v/v_{is}
- U = the outer rotor tip speed = $R\Omega$
- V_{is} = the isentropic nozzle velocity from expansion of the fluid from inlet to exit through a fixed nozzle resulting from the ideal enthalpy drop Δh_i .

FIG. 33. Schematic of the velocity-pump reaction turbine (VPRT) concept.

(Note that Eq. (2) implicitly assumes a perfect inner nozzle, $\eta_1 = 1.0$. Since the working fluid remains liquid through the inner rotor, this does not introduce a significant error or loss of generality.) It is of interest to note that when $r = 0$, the configuration in Fig. 33 reverts to the RORT concept, and Eq. (2) will reduce to the performance model of the RORT, as it should. Also, Eq. (2) gives the gross engine efficiency. The internal losses from fluid friction and velocity-pump performance are not included because they are not known at this time (nor can they be determined without evaluation by test).

The unique feature of the VPRT is that it allows peak performance at a reduced β which, in turn, allows a reduced tip speed and reduced rotor stresses. Figure 34 shows typical performance curves for $r/R = 0.8$ and a range of nozzle coefficients that illustrate the range of velocity ratios for peak performance.

To exhibit the advantage of the VPRT, Fig. 35 shows the locus of peak efficiencies. The dashed line represents the upper bound on performance, but,

FIG. 34. Effect of nozzle performance on the output of the velocity pump reaction turbine (VPRT).

FIG. 35. Performance of the velocity-pump reaction turbine (VPRT).

obviously, $r/R = 1.0$ is not a practical design condition, nor is it likely that nozzle coefficients greater than 0.9 can be achieved in the rotating nozzle (even though coefficients greater than 0.9 are achieved in fixed impulse-turbine nozzles). These curves were developed from Eq. (2), and they clearly illustrate the increase in gross engine efficiency offered by the VPRT as opposed to the RORT ($r/R = 0$). For example, with a nozzle coefficient of 0.8 and $r/R = 0.9$, the gross engine efficiency of the VPRT is about 60% (as compared to 40% for the RORT). Hence, the VPRT concept provides a potential means of achieving a significant improvement in the technology of liquid expanders, particularly for lower-temperature geothermal resources.

4.5 APPLICATIONS TO GEOPRESSURED RESOURCES

Geopressured geothermal resources are potentially very large. Generally, these hot water

deposits, at depths up to about 15,000 ft, are subjected to overburden pressures up to about 10,000 psia, and they may contain large quantities of dissolved methane. Previous studies have shown that because of high well costs, and generally low temperatures [$\sim 150^\circ\text{C}$ (300°F)], central-station generation of electric power from the thermal and hydraulic energy components of geopressured resources will probably not be economically competitive unless significant quantities of associated methane can be obtained. Geopressured resources should be thought of as fossil energy resources primarily; the geothermal energy is merely a by-product. Thus, it will be important to develop a low-cost, efficient energy-conversion system uniquely suited for low-temperature geothermal-energy and hydraulic-energy components. The applicability of the VPRT to this specific application is discussed in Ref. 15.

The geopressure velocity-pump reaction turbine (GVVRT) is identical to the VPRT in operating principle, and it is represented conceptually in Fig. 33. The only difference is that the additional hydraulic head H at the wellhead (caused by the geopressure) provides additional energy and a higher absolute spouting velocity from the inner rotor. The design of the unit allows simple separation of the gas coming out of solution as the pressure drops.

Hence, the total amount of available energy is the sum of the thermal and hydraulic components. The actual power out is

$$P = \frac{\dot{m}V_{is}^2}{2} \left[\frac{2gH}{V_{is}^2} + \left(\frac{r^2}{R^2} - 2 \right) \beta^2 + 2\beta\eta_2 \sqrt{1 + \left(1 - \frac{r^2}{R^2} \right) \beta^2} \right], \quad (3)$$

where

$\dot{m}$ = the mass flow rate, and
 H = the geopressure hydraulic head.

The ideal available energy is

$$P_i = \frac{\dot{m}V_{is}^2}{2} + \dot{m}gH,$$

and if we define Z as the ratio of the available thermal energy to the available hydraulic energy,

$$Z = \frac{\Delta h_{is}}{H} = \frac{V_{is}^2}{2gH} \quad (4)$$

then the engine efficiency of the GVPRT is

$$e_{GVPRT} = \frac{1}{1+Z} + \left(\frac{Z}{1+Z} \right) (e_{VPRT}) \quad (5)$$

where e_{GVPRT} is given by Eq. (2).

Clearly if $H = 0$, then Eq. (5) reduces to Eq. (2), and if the thermal component is zero ($V_{is}^2 = 0$), then $e_{GVPRT} = 1.0$ as it should for a hydraulic turbine, since we have already implicitly set $\eta_1 = 1.0$.

Thus, the performance of the GVPRT is directly proportional to that of the VPRT, and any increase in output is due directly to the added available hydraulic head H . This is shown graphically in Fig. 36 for various values of Z .

A special case of the GVPRT is obtained by fixing the inner rotor as shown in Fig. 37. This is inherently a simpler device and may prove better suited for gas removal. The performance of this

FIG. 36. Performance of the geopressure velocity-pump reaction turbine (GVPRT).

FIG. 37. Geopressure combination turbine.

machine is not significantly different from that of the GVPRT, except that operation is limited to a range of $Z > 5$ because of the restriction that $0 < r/R < 1.0$. This point is discussed in some detail in Ref. 15.

4.6 THE HELICAL ROTOR EXPANDER

Over the last few years there has been some interest in the use of positive-displacement machines

for expansion of the total geothermal wellhead product. The helical rotor expander (HRE) has emerged as the only likely candidate from that class of devices. However, as compared to pure impulse or reaction machines, positive-displacement expanders are limited in volume flow rate capacity. This is due fundamentally to internal losses related to sonic velocity in the fluid. Consequently, the HRE must be physically very large to produce significant power output from the complete expansion of geothermal fluids to subatmospheric conditions.

A detailed analysis of this device¹⁶ indicates that single-stage expansion (to subatmospheric pressure) of self-pumped geothermal fluids from reservoirs at 180°C (356°F) to 300°C (572°F) would require an HRE with rotor diameters from 11 to 42 ft for a range of outputs of 5 to 40 MW. This means that the total machine size would be roughly equal to twice the diameter in width (to accommodate the two meshing rotors) to about 1.5 times the diameter in length. By comparison, a single-stage impulse turbine system would require a rotor diameter about one fourth as large, with two rotors per shaft. Since the impulse rotors are essentially thin disks, the total impulse machine is very much smaller than the HRE. Thus, the size factor will be an important economic limitation on the application of the HRE in central-station generation of power from geothermal resources.

The HRE will probably be used only as part of a hybrid system or possibly in a noncondensing, low-power-output system, and in the latter application, it would produce only about 50% as much electrical energy per unit mass of wellhead fluid as a condensing system (e.g., a double-flash system). Table 9 compares estimates of the specific electrical energy outputs (in Wh/lb) of various systems. Test data on the HRE indicates that a 55% engine efficiency is reasonable. At this level, the noncondensing HRE produces the least output of all the systems listed. Even the simple single-flash system offers better performance as a wellhead generator.

TABLE 9. Estimated performance comparison (gross electrical output of Total-Flow and flash-steam systems.^a

System	Specific energy output, ^b Wh/lb
Single flash (75% engine efficiency)	14
Double flash (75% engine efficiency), both stages	18
Total-Flow impulse-turbine system	
Existing design full admission (38-48% engine eff.)	12-15
Advanced design - full admission (70% engine eff.)	21
Helical rotor expander - atmospheric exhaust (noncondensing, 55% engine eff.)	10

^aCalculations based on: Inlet conditions, 370 psia, 14% quality; condensing condition, 2 psia (126°F); thermodynamic properties of pure water (0% TDS). For presence of dissolved solids, reduce energy output by 0.85% for each 1% TDS.

^bGross outputs only (in-plant parasitic losses not included).

As a result of the size requirement and the fact that the HRE is limited to noncondensing operations, this expander is probably best suited to applications involving relatively low expansion ratios and exhaust pressures above atmospheric. Thus, it could probably only be used as an element in a hybrid system.

To evaluate the characteristics of the HRE and to identify the range of possible operating conditions, we have designed and tested a small (~40 kW) unit at the LLL geothermal test facility. The unit, the test procedure, and test results are described fully in Ref. 17. Inlet pressures were varied from 179 kPa (26 psia) to 1.4 MPa (198 psia), inlet qualities (vapor fraction) from 6-7 to 27.3%, and inlet enthalpy from 387 to 537 Btu/lbm. Back pressures were varied from 34 kPa (4.9 psia) to 234 KPa (34 psia). The results indicate that under the test conditions the HRE can operate well with a two-phase mixture as a working fluid and that it seems to perform best at inlet qualities (vapor fractions) between 15 and 25%. An optimum quality was not determined, nor was it determined that an optimum exists. The maximum observed engine efficiency was 53% at 800 rpm, with an inlet pressure and quality of 1.3 MPa (190.6 psia) and 22.2%, respectively, and an exhaust pressure of 211 kPa (30.6 psia). These conditions are for a pressure ratio of 6.23 and a volume ratio of 7.75. Engine operation was poorer for qualities below 15%, and, as expected, performance was poor for low exhaust pressures [especially below 48 kPa (7 psia)]. The HRE is apparently not suited for liquid expansion, and this tends to further limit its applicability in hybrid systems.

The most obvious application of the HRE is in a topping cycle associated with a single-flash system. In this context, the HRE would produce shaft work by expanding the wellhead product to an intermediate pressure, where the vapor fraction would be separated and used to drive a conventional condensing steam turbine.

At this point, it can be speculated that an HRE/single-flash hybrid system might have performance equal to or better than that of the conventional double-flash system and that the greater simplicity might lead to lower costs. Consequently, detailed system analyses should be conducted to determine the potential advantages. All of the necessary testing of the HRE has been done.

5. CONCLUDING REMARKS: THE POTENTIAL OF THE TOTAL-FLOW CONCEPT

The potential of the Total-Flow impulse turbine has already been discussed in Secs. 3.6 and 3.7 in terms of its usefulness as an element of the Total-Flow process. In a broader context, the Total-Flow process adds a third approach to geothermal resource utilization. Our original concept focused primarily on the use of the concept in single-stage expansion (see Fig. 2). However, the concept is obviously not limited to this function. It may well turn out that the more important application of the Total-Flow concept will be as part of a hybrid system, i.e., Total-Flow systems in combination with other systems. The Japanese have already used a Total-Flow turbine in a topping stage to a multistage system, and analyses presented in Sec. 4.3 of this report indicate that inclusion of a Total-Flow expander in the liquid leg of a double-flash system can increase overall performance significantly.

The LLL program has also produced new expander concepts (RORT, VPRT, GVPRT) specifically designed for liquid expansion. All will serve to broaden the usefulness of the basic Total-

Flow concept. They may, for example, be applied to geopressured resources. Since the primary energy product in this case is the dissolved natural gas, inexpensive systems will be needed for recovery of the low-temperature geothermal-energy and hydraulic-energy components. Another important application may be recovery and utilization of waste heat in industrial processes involving streams of hot, pressurized liquids. In these cases, the liquid must be expanded through relatively simple, reliable devices that can be easily incorporated into an existing plant.

The LLL program was aimed only at the recovery of geothermal energy, but it is now evident that the concepts developed have the potential for broader applications. Both technical and economic feasibility of the Total-Flow concept have been established. However, with the termination of the LLL program, no further development is currently foreseen in the U.S. toward demonstration of the concept as the last step in the process leading to commercialization.

6. REFERENCES

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APPENDIX A. REPORTS

CHEMISTRY AND MATERIALS

Calder, C. A., *Flow-Regime Characterization for Horizontal Two-Phase Steam Flow*, Lawrence Livermore Laboratory, Rept. 52186 (1976).

The reliable characterization of the flow regime, given the fluid properties, flow rate, and piping configuration, would be a significant help in the design of instrumentation, energy-conversion machinery, and piping for two-phase geothermal flow. A relatively simple model, using Baker parameters, is described and applied to flow-regime data generated by high speed photography of two-phase steam flow. The experiments were conducted at the Geothermal Test Facility (GTF) at Lawrence Livermore Laboratory. Although results depend somewhat on the personal judgment and interpretation of the observer, the model was found to give a reasonable prediction of the flow regime for the flow ranges available at the GTF in 1- and 2-in.-diam pipes.

Durbin, P. F., *Radiographic Inspections at the Calipatria Geothermal Test Site*, Lawrence Livermore Laboratory, Rept. UCID-17734 (1978).

The Lawrence Livermore Laboratory (LLL) Nondestructive Evaluation (NDE) section of the Materials Engineering Division is making radiographic inspections to estimate the extent of corrosion and scale buildup at the Geothermal Test Site in Calipatria, California. This study, begun in early 1976, is continuing. The NDE section developed the radiation exposure techniques using 60 and 192 isotopes; Hazards Control and NDE established radiography safety procedures. Five radiographic evaluations were made of the Geothermal Test Site from May 1976 to February 1977. Estimations of scale buildup from radiographs of operating plant pipes, valves, and tanks correlated closely with our actual scale measurements from used plant sections.

Feiereisen, W., *A Numerical Study of Boundary Layer Injection as a Scale Control Method*, Lawrence Livermore Laboratory, Rept. UCID-16909 (1975).

A boundary layer injection method of controlling scale-buildup in geothermal two-phase flow nozzles is studied. The object of this study is to set an upper limit on the ratio of the injected mass flow rate to the free stream mass flow rate that is necessary to isolate the scale carrying free stream flow from the nozzle wall. In order to develop a numerical model of the boundary layer flow, assumptions are made which reduce the results to order-of-magnitude approximations.

Two configurations of nozzles with various injection flow rates are tried. It is found by numerical experiment that a nozzle with injection through a 1-mm-thick ring near the inlet is more efficient at isolating the free stream than a porous nozzle. A mass flow rate ratio of 0.173% was necessary to achieve this effect. It may be concluded that an upper limit on the mass flow rate ratio is about 2.0% with injection through a ring near the inlet, and that boundary layer injection is a reasonable method of controlling scale-buildup.

Goldberg, A., *Comments on the Use of 316L Stainless Steel Cladding at the Geothermal Niland Test Facility*, Lawrence Livermore Laboratory, Rept. UCID-17113 (1976).

Report discusses the possibility of corrosion in geothermal brine-steam separator drums made of carbon steel and clad with 316L stainless steel. Although the brine is reducing, some oxygen is likely to be ingested into the system. Such ingestion must be carefully monitored, for in the presence of chlorides, even trace quantities of O_2 (<1 ppm) can cause stress corrosion cracking (SCC) of austenitic stainless steels. An example is given of intergranular corrosion in 304 stainless steel exposed to brine from Sinclair No. 4 well located in the Salton Sea area. Measures to prevent SCC are suggested, and new grades of stainless steels, which appear less susceptible to SCC in chlorides than conventional austenitic grades, are described.

Goldberg, A., *Quarterly Report: Geothermal Materials Studies*, Lawrence Livermore Laboratory, Repts. UCID-17261-76-1, UCID-17261-76-2, and UCID-17262-76-3 (1976).

Since its inception in 1974, the LLL Geothermal Program has evolved into two basic activities:

- To provide advanced technologies for hydrothermal systems with emphasis on the *Total Flow Process*.

- A recently initiated *Industrial Support Program* to provide technical assistance to joint ERDA/industry projects.

The Metallurgy Division is carrying out a materials effort in support of both activities.

Goldberg, A. and Kershaw, R. P., *Evaluation of Materials Exposed to High-Velocity, High-Salinity, Highly Mineralized Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCRL-80755 (1978).

Using surface traces, scanning electron microscopy, and light microscopy, Ti-, Co-, Ni-, and Fe-base alloys were evaluated for erosion and stress corrosion cracking (SCC) after exposure at about 104°C to the nozzle exhaust from acidified geothermal brine. Examples of erosion, SCC, and corrosion are shown. Results are evaluated in terms of synergism between erosion, corrosion, and stress. Repassivation kinetics might play a key role in the formation and growth of erosion cavities. Of the materials tested, the Ti-base alloys appear to have the best combination of resistance to SCC and erosion/corrosion in high-salinity, highly mineralized, acidified, two-phase nozzle exhaust.

Goldberg, A., McCright, R., Garrison, R., and Harrar, J., *Quarterly Report: Geothermal Materials Studies*, Lawrence Livermore Laboratory, Repts. UCID-17261-76-4 and UCID-17261-77-1 (1977).

The LLL Geothermal Program provides advanced technologies for hydrothermal systems and technical assistance for joint ERDA/industry projects. The materials group at LLL has responsibility for the testing, evaluation, and selection of materials in support of both activities.

In the present report we describe the results of materials testing in a field experiment in which acidified brine was expanded through nozzles to atmospheric pressure. A variety of materials was tested as erosion/corrosion wearblades, bent-beam stress-corrosion specimens, and corrosion electrodes.

Results show that Ti-6Al-4V has promise for total-flow turbine applications and that low-alloy steels may be useful as plant materials in low-temperature applications for acidified brine. We discuss the analysis of several component failures.

Goldberg, A. and Owen, L., *Pitting Corrosion and Scaling of Carbon Steels in Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCRL-79508 (1977). (This paper was prepared for the 150th Fall Meeting of the Electrochemical Society in Las Vegas, Nevada.)

An evaluation was made of pitting corrosion failures of surface pipeline and wellhead casing exposed to hypersaline brine in the Salton Sea Geothermal Field. Uniform corrosion, pitting corrosion, and various forms of highly localized, selective attacks were observed. The corrosion product (Fe was covered with a transition zone of mixed corrosion product-scale that graded into a scale-rich deposit. The scale, consisting of heavy metal sulfides dispersed in an Fe-rich amorphous silica matrix, was deposited as the brine cooled. The possible roles of the outer scale deposit, the intermediate transition zone, and the inner corrosion product on either abetting or deterring corrosion are discussed. We propose that cracks, resulting from thermal stresses induced during periods of intermittent operation, form in the scale permitting the infusion of oxygen during shutdown intervals. This contributes to localized accelerated pitting resulting in perforation of the pipe and casing walls. The importance of environmental (pH, E_h , composition, heterogeneity) and material (composition, casting, thermomechanical history, microstructure, surface condition) variables that influence the formation of different morphologies is discussed and compared with related observations cited in the literature.

Grens, J. Z., *The Effect of Salinity on Geothermal Well Performance*, Lawrence Livermore Laboratory, Rept. UCID-16791 (1975).

The effect of varying concentration of dissolved solids on the wellflow characteristics and energy yield of geothermal wells is considered. Increasing salinity is found to have an adverse effect on well production and on the energy content of the fluid produced. This effect may reach 0.8 to 0.9% reduction in available energy for each 1.0% dissolved solids. Simple techniques for estimating the physical and thermodynamic properties of brines as functions of composition and temperature are also presented.

Grens, J., *Preliminary Tests Using a Laser Particle-Size Analyzer on Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCID-17637 (1977).

A laser light-scattering particle-size analyzer was used for a two-day period under limited field conditions to observe the occurrence and growth of particles in geothermal brines. Tests were conducted under conditions where both pH and rate of cooling to room temperature strongly influence the size and nature of the particulate population, with a low (4.5) pH and rapid quenching favoring slow growth rates. A method for estimating particulate mass in time periods shorter than 6 h from quenching is presented. Some implications for sampling and solids analysis are discussed.

Grens, J. Z., Owen, L. B., and Tardiff, G. E., "Field Evaluation of Scale Control Methods: Acidification," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Harrar, J. E. *et al.*, *Determination of the Rate of Formation of Solids from Hypersaline Geothermal Brine as a Function of pH*, Lawrence Livermore Laboratory, Rept. UCID-17596 (1977).

This report is a preliminary description of the results obtained in the analysis of the effluent brine from the LLL four-stage flash system. Of principal interest was the rate of formation of suspended solids and the rate of decrease of dissolved silicon (or silica) in the solution as a function of the pH of the effluent brine. The experiments were conducted using Magmamax No. 1 brine at the LLL Test Facility near Calipatria, California. The wellhead brine (having a pH of 5.7) was acidified in the flash system to pH values of 5.0, 4.0, and 3.0, ± 0.2 pH unit, and the solids and silica in the effluent at 90°C were measured, respectively, by filtration and atomic absorption spectrophotometry. Changes in solids and silica concentration were determined after holding the brine at 90° $\pm 5^\circ$ C for periods of time up to one week.

Harrar, J. E., Lorensen, L. E., Otto, C. H., Jr., Deutscher, S. B., and Tardiff, G. E., *Effects of Organic Additives on the Formation of Solids from Hypersaline Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCRL-80970 (1978). (This paper was prepared for submission to the Geothermal Resources Council Meeting, Hilo, Hawaii, July 25, 1978.)

The effect of 49 chemical additives, including organic polymer additives, on the rate of the silica precipitation from geothermal brine was investigated. Hypersaline geothermal brines from the Salton Sea geothermal field were used. Nine additives were found to be effective in inhibiting the silica precipitation process. These as well as other additives will be tested to determine their effectiveness in inhibiting silica scale deposition.

Harrar, J. E., McCright, R. D., and Goldberg, A., *Field Electrochemical Measurements of Corrosion Characteristics of Materials in Hypersaline Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCRL-52376 (1977).

A flow cell (with appropriate accessories) was developed for use in short-term testing of the corrosion behavior of materials in 100°C, hypersaline geothermal brine. We designed the apparatus to accommodate commercial (Petrolite) corrosion measurement equipment and conducted experiments on-line at the Lawrence Livermore Laboratory Test Station in the Salton Sea Geothermal Field. The apparatus also permitted direct readings of corrosion potentials, solution redox potential (E_h), brine flow rate, pH, and temperature. We obtained estimates of general corrosion rates by the linear polarization resistance technique and from measurements of complete potentiodynamic polarization curves. The latter also afforded predictions of pitting susceptibilities of active-passive type materials. Twenty-two alloys (with various heat treatments) were tested and readily grouped according to general corrosion resistances in acidified hypersaline (~4 M chloride) brine. Especially promising in regard to corrosion resistance-vs-cost is the series of low Cr-Mo steels. Prescaling of materials in unacidified (pH ~5.7) brine prior to exposure to acidified (pH 2-4.5) brine was found to be beneficial in reducing corrosion rates at 100°C.

Harrar, J. E., McCright, R. D., and Goldberg, A., "Materials Evaluation for Geothermal Applications: Plant Materials," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Hill, J. H. and Morris, C. J., *Sampling a Two-Phase Geothermal Brine Flow for Chemical Analysis*, Lawrence Livermore Laboratory, Rept. UCRL-77544 (1975).

This report describes an experiment designed primarily to define the problems associated with sampling the two-phase flow in a pipeline of geothermal brine. Analyses reported for 26 samples include chemical composition, oxidation potential, pH, density, and total solids. Changes in brine composition as the well operated during a four-week period are evaluated. The apparatus and techniques used for sampling are described and evaluated.

Hill, J. H. and Otto, C. H., Jr., *Sampling and Characterization of Suspended Solids in Brine from Magmamax No.1 Well*, Lawrence Livermore Laboratory, Rept. UCRL-79007 (1977). (Prepared for submission to the Proceedings of the 2nd Workshop on Sampling and Analysis of Geothermal Effluents, February 15-17, 1977, Las Vegas, Nevada.)

When high-temperature, high-salinity geothermal brines are cooled, appreciable quantities of solids precipitate. These suspended solids can cause extensive erosion and plugging in power-plant components. In addition, there is considerable concern that reinjection of these solids with spent brine may plug the geologic formation adjacent to the reinjection wells. This report describes work done to sample these solids and characterize them so that processes can be devised for their removal or control.

Suspended solids produced in brine from Magmamax No. 1 well consist primarily of an iron-rich amorphous silica gel. A sampling apparatus to filter these solids out of high-temperature, high-pressure brine streams is described. Their chemical composition and physical description is discussed. Rates of production of suspended solids are given for brines flashed through nozzles and flashed in steam separators. Control of solids production by acidification to a pH of 4.5 is described. At this time, control by acidification seems to offer an attractive alternative to conventional methods (filtering, settling, etc.) for removing suspended solids from spent brine prior to reinjection.

Hill, J. H., Otto, C. H., Jr., and Morris, C. J., "Solids Control for High Salinity Geothermal Brines," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Jackson, D. D., *Computation of Gas-Liquid Equilibria in High-Saline Geothermal Fluids*, Lawrence Livermore Laboratory, Rept. UCRL-79043 (1977). (This paper was prepared for submission to the 1977 SPE International Symposium on Oilfield and Geothermal Chemistry, Dallas, Texas, June 27-29, 1977, Society of Petroleum Engineers of AIME.)

The Lawrence Livermore Laboratory is actively engaged in the development of energy-extraction processes for high-temperature, hypersaline brines, such as those found extensively in the Salton Sea Geothermal Field of California. A computer-assisted chemical modeling study of equilibria in flowing brine systems has been undertaken as part of the LLL program. Equilibria between liquid and volatile components of two-phase fluids have profound effects on such important phenomena as corrosion, scale formation, environmental quality, and the economics of energy extraction. The principal reactions considered are those involving volatiles naturally present in the fluid, including NH_3 , H_2S , and CO .

A computer code is described which performs stepwise equilibrium computations at 1°C intervals for a unit mass of fluid, between reservoir and reinjection temperatures. The data base used is the quality-temperature function for the brine, the chemical composition, and equilibrium constants for the solubility reactions of gases and dissociation of their aqueous species. Chemical changes that take place during cooling and expansion are illustrated by distribution diagrams. Although the computations were developed for application to the high-saline resource, they are not fluid- or system-specific, and should be of general usefulness where a chemical composition and temperature history can be specified.

Jackson, D. D. and Hill, J. H., *Possibilities for Controlling Heavy Metal Sulfides in Scale from Geothermal Brines*, Lawrence Livermore Laboratory, Rept. UCRL-51977 (1976).

Heavy metal sulfides form a substantial part of the scale deposition from high-temperature, high-saline geothermal brines. An assessment has been made of the prospects for controlling this deposition by chemical modification of the brine.

The types of reactions influencing sulfide precipitation are outlined. It is suggested that two factors affecting sulfide solubility—oxidation state and pH—may be amenable to chemical modification of the brine. A partial oxidation process can be used to convert aqueous sulfide species to free sulfur, a process favored by thermodynamics and kinetics. Some oxidizing agents are suggested for this purpose.

The possibility of precipitating other solid phases after extensive oxidation is discussed. It is concluded on the basis of the available data that this possibility exists, but that uncertainties in reaction kinetics, unavailable data, and solution complexity make an exact analysis difficult. The usefulness of a field evaluation of chemical modification processes is indicated.

Locke, F. and Grens, J., "LLL Geothermal Field Laboratory," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Lorensen, L. E. and Walkup, C. M., *Polymeric and Composite Materials for Use in Systems Utilizing Hot, Flowing Geothermal Brine. II*, Lawrence Livermore Laboratory, Rept. UCRL-81019 (1978).

Further progress is reported on a continuing experimental program designed to select high-performance polymeric materials for use in geothermal power plants. In field tests 12 nozzles, 27 wear plates and 2 types of polymer-lined pipe were tested. Nozzles made of Teflons TFE and PFA, Tefzel, Ryton PPS, and H-Resin/carbon cloth were little changed except for some scaling. The fluorocarbons scaled least rapidly. All blade type wear plates eroded, those based on Tefzel, PPQ, and PPS the least. Fluorocarbon-lined pipes were little affected by exposure.

In laboratory tests samples were heated at 250 and 300°C in brine. Several materials including fluorocarbon and unhydrolyzable aromatic or cross-linked aliphatic, thermally stable polymers survived for periods up to 1300 h. In erosion tests, coatings based on epoxy resins and a fluorocarbon were most resistant; good adhesion was required.

Lorensen, L. E., Walkup, C. M., and Mones, E. T., *Present Status of the Polymeric-Materials Screening Program for the LLL Geothermal Project*, Lawrence Livermore Laboratory, Rept. UCRL-51843 (1975).

As a result of the difficulty of handling hot high-pressure brines, LLL has been searching for high-performance polymeric materials to be used in the construction of down-hole brine delivery pipes, nozzles, turbines, condenser parts, and brine reinjection pipes. LLL has tested 29 polymeric materials in a 300°C static brine. Seven polymers have withstood up to 555 h with less than 10% weight loss.

Owen, L. B., "Properties of Siliceous Scale from the Salton Sea Geothermal Field," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Quong, R., *A Waste-Heat Rejection System for the Total-Flow Turbine Concept Using Hot Geothermal Brines*, Lawrence Livermore Laboratory, Rept. UCID-16694 (1974).

A waste-heat rejection system, for use in a total fluid flow method proposed for producing electrical power from high-saline geothermal brines, is described. Because of the unique conditions imposed by the total-flow concept, major design modification will be necessary in conventional heat rejection equipment if it is to be used. These changes are technically feasible without adding significantly to either total capital or operating costs. Design parameters, equipment choice, and costs are discussed for a waste-heat rejection system for a plant module size of 220 MW.

Quong, R., *Scaling Characteristics in the Geothermal Loop Experimental Facility at Niland, California*, Lawrence Livermore Laboratory, Rept. UCRL-52162 (1976).

The San Diego Gas and Electric Company-U. S. Energy Research and Development Administration joint Geothermal Loop Experimental Facility (GLEF), located at Niland in the Imperial Valley, California, began operation in May 1976. The GLEF incorporates a sequential four-stage flash process to successively lower temperatures and pressures with a binary fluid energy-conversion cycle. Approximately 300-h of intermittent operation were logged before shutdown of the facility on June 16 for inspection and maintenance. Samples of the brine, suspended solids, and scale deposits were analyzed for bulk composition and mineralogy, but correlation with temperature and pressure is vague.

In general, a galena-rich scale is observed in valves and piping ahead of the first-stage separator, becoming much less abundant beyond that point. The bulk of the scale consists of an increasing proportion of an iron-rich amorphous silica with process progression. Trace crystalline phases, such as akaganeite, kutnahorite, and sphalerite and/or wurtzite, have been detected or are strongly suspected in the scales. Halite and sylvite are found primarily as a result of numerous facility shutdowns and subsequent cooling of the retained brine in the equipment. Barite is frequently present when irrigation water (used for priming the wells) containing SO_4 is mixed with the brine. Calcite and/or aragonite is also found whenever separated steam condensate in contact with CO_2 is recombined with the brine. Corrosion products, magnetite and hematite, form an integral part of the scale adjacent to steel walls. The scales are layered with bands of widely differing material. The color, texture, hardness, and thickness of the deposits also vary considerably within location in the GLEF.

A new method of in-process scale buildup surveillance based on radiography was successfully verified.

Quong, R., *The LLL Geothermal Industrial Support Program in Chemistry and Materials for FY76T and FY77*, Lawrence Livermore Laboratory, Rept. UCID-17209 (1976).

This report describes work to be done at the ERDA/SDG&E site relative to scale characterization, brine and effluent characterization, assessment of solids control methods, and materials test and evaluation.

Quong, R. et al., *Processing of Geothermal Brine Effluents for Injection*, Lawrence Livermore Laboratory, Rept. UCRL-80945 Rev. 1 (1978).

The handling of brine effluents for injection is a critical part of any geothermal conversion process. Brine effluents from the San Diego Gas and Electric/Department of Energy Geothermal Loop Experimental Facility were characterized for particulate concentration and chemical composition. Bench scale tests were conducted with inorganic and organic coagulants as a means of enhancing the sedimentation process for separation and removal of suspended solids, principally amorphous silica. The effects of temperature, retention time, and pH on the precipitation of supersaturated silica, subsequent floc settling properties, and supernatant clarity were determined. A pilot-sized clarifier with mixed-media sand or precoat-pressure filtration has been successfully tested as a means of producing injectable brine effluents. Preliminary cost estimates range in the vicinity of 20¢/1000 gallons.

Quong, R., Bishop, H. D., and Hill, J. H., "Scale and Solids Deposition in the SDG&E/U.S. ERDA Geothermal Loop Experimental Facility at Niland, California," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Quong, R., Schoepflin, F., and Stout, N. D., *Conditioning of Geothermal Brine Effluents*, Lawrence Livermore Laboratory, Rept. UCID-17716 (1978).

This report describes the use of various chemical coagulants and flocculants with spent geothermal brine for enhancing the removal of colloidal solids prior to injection. Brine at 80-85°C was obtained from the injection line of the SDG&E/DOE Geothermal Loop Experimental Facility during a period of operation with Magmamax No.1 fluid. The solids consist primarily of an iron-rich amorphous silica and heavy metal sulfides, principally lead. Standard jar testing equipment was used to carry out the tests.

Ryon, R. W. and Hill, J. H., *Removal of Silica from Spent Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCID-17702 (1977).

This report is based on preliminary survey experiments conducted at the LLL Salton Sea Geothermal Test Site in April and May 1977. The addition of caustic to raise the brine pH to 6 precipitated silica and other materials. The addition of flocculating agents, such as ferric hydroxide, aids settling and filtration. Small-scale pilot plant studies are recommended.

Schock, R. N. and Duba, A., *The Effect of Electrical Potential on Scale Formation in Salton Sea Brine*, Lawrence Livermore Laboratory, Rept. UCRL-51944 (1975).

Field experiments were carried out at a flowing well in the Salton Sea Geothermal Field to study the influence of electrical potential on scale deposition. The scale is composed mainly of silicon, iron, copper, silver, and aluminum. Significantly more scale formed on negative than on either positive or neutral electrodes. The scale on the cathode contained up to 1000 times more lead than the scale on the other electrodes. It may also have contained slightly increased amounts of copper. Although the amount of scale on positive and neutral electrodes appeared to be the same, the scale on the positive electrodes were richer in iron and zinc. X-ray powder diffraction revealed the presence of lead as Pb(OH)Cl and of iron as FeOOH. No crystalline silicon forms were detected. Collectively, the results suggested that both iron and lead are present in complex ionic forms in solution.

Tardiff, G. E., Ed., *LLL Total Flow Geothermal Program: Summary of Two-Phase Nozzle Tests for Scale Control and Materials Performance*, Lawrence Livermore Laboratory, Rept. UCID-17636 (1977).

A series of nozzle and wearblade tests to evaluate scale control and materials performance under Total Flow nozzle inlet conditions and simulated turbine blade environments have been completed using Magmamax No. 1 well fluid. Brine acidification was effective in preventing scale in nozzles and on wearblade

flow surfaces. Acid consumption measurements indicate that acid cost will be less than 2 mills/100 lb brine. Measured erosion rates were low and the results indicate that available materials will allow successful turbine operation for many years. Stress corrosion cracking was not observed in specimens of the leading candidate turbine material (Ti-6Al-4V) after up to 60 h operation at stresses similar to those expected in an operating turbine system.

Tardiff, G. E., *Using Salton Sea Geothermal Brines for Electrical Power: A Review of Progress in Chemistry and Materials Technology—1976 Status*, Lawrence Livermore Laboratory, Rept. UCRL-79468 (1977). (Presented at the 12th Intersoc. Energy Conversion Engineering Conf., Washington, D. C., August 28 to September 2, 1977.)

Geothermal energy development research at the Lawrence Livermore Laboratory through 1976 has been aimed at solving the problems associated with the use of high-temperature, high-salinity brines found in the Salton Sea Geothermal Field for their practical conversion to electrical energy. Specifically, part of the program has been oriented toward solving the problems of scale and solids deposition and corrosion of system components that are exposed to the highly mineralized brines. Brine acidification was found to be a promising method for controlling scale and solids deposition. Titanium, zirconium, and chromium-molybdenum alloys were shown to be the best economical corrosion-resistant materials for use in various parts of a total-flow turbine system. Scale and solids control and materials tests for conversion systems based on brine flashing are currently being evaluated. Some initial results and test plans are discussed.

EARTH SCIENCES

An Electrical Resistivity Survey of the Salton Sea Geothermal Field Imperial Valley, California, Lawrence Livermore Laboratory, Rept. UCRL-13690 (1976).

An extensive electrical resistivity survey was conducted in the Salton Sea geothermal field, Imperial Valley, California, on behalf of the Lawrence Livermore Laboratory. Very high energizing power (upward of 200 A) was employed to determine the extremely low resistivities (less than 0.5 ohm-meters) which were expected, to depths of 3–6 km. A combination of Schlumberger, equatorial, and dipole-dipole sounding techniques was employed and ultra-low commutation periods were used to avoid skin depth effects. Some depth soundings were extended into the sea by means of the equatorial sounding approach.

The findings of the resistivity survey are combined with a previously reported marine seismic survey of the Salton Sea. They indicate that the Salton Sea geothermal field is an expression of active crystal spreading presently taking place along the southern shore of the sea. More than one epoch of plutonism and volcanism has occurred in the area; one is presumed to have taken place about 170,000 years ago and the other about 16,000 years ago. Other volcanic epochs are possible. The existing volcanic domes are minor surface expressions of a plutonic activity that has caused about 35 billion tons of molten rock to protrude into the upper crust. The presently known Salton Sea geothermal field is an expression of that tectonic activity.

The resistivity survey revealed the existence of six significant faults in the area. These are named here as the Wister, Calipatria, Red Hill, Brawley, Fondo, and Westmoreland Faults. Of these, two (Brawley and Calipatria) were previously known from resistivity studies further south, and one (the Brawley Fault) has been recently identified through seismological observations. The discovered faults act as either aquicludes or aquitards, probably with varying degrees of sealing effectiveness along their length.

Comparison of existing isothermal maps, structural maps, and the iso-resistivity data leads us to conclude that sharp salinity gradients must exist in the area. The existence of additional geothermal reservoirs of much lower salinity than those encountered near Obsidian Buttes is possible if these salinity gradients are supported by subsequent drilling.

Chan, M. and Tewhey, J. D., *Subsurface Structure of the Southern Portion of the Salton Sea Geothermal Field*, Lawrence Livermore Laboratory, Rept. UCRL-52354 (1977).

Subsurface correlation of sedimentary strata has been attempted among ten geothermal wells in the southern portion of the Salton Sea Geothermal Field. The spontaneous potential (SP) log has been the principal tool used for correlation purposes. The structure that emerges from the correlation diagrams is a shallow plunging syncline with an east-west axis perpendicular to the axis of the Salton Trough.

Dengler, L. and Piwinskii, A. J., *A Study of Core Chips from the State of California Well No. 1 in the Salton Sea Geothermal Field Using Petrographic, X-ray Diffraction, and Scanning Electron Microscopy Techniques*, Lawrence Livermore Laboratory, Rept. UCID-17184 (1976).

Rock chips from depths of 1380 and 1478 m from the State of California Well No. 1 in the Salton Sea Geothermal Field were examined using conventional petrographic, x-ray-diffraction, and scanning-electron-microscopy techniques. Mineral composition, pore configuration, and the nature of the fine-grained matrix materials were determined.

Hearst, J. R., Kasameyer, P. W., and Owen, L. B., *Potential Uses for a High-Temperature Borehole Gravimeter*, Lawrence Livermore Laboratory, Rept. UCRL-52421 (1978). (This paper was prepared for submission to the Third Workshop Geothermal Reservoir Engineering, Stanford University, December 14-16, 1977.)

It is possible to design a canister to cool a borehole gravimeter for use in geothermal and high-temperature (up to 350°C) gas wells. Repeat surveys with such a gravimeter could (1) help estimate the extent of reservoir plugging in a geothermal injection well after one year of operation and (2) detect compaction of a geothermal aquifer if the change in thickness of the aquifer exceeds 1 m. The instrument could be used together with conventional logging tools to evaluate radial dependence of density around a well, or to estimate gas-filled porosity around wells drilled with mud. A high-temperature borehole gravimeter could also be used to evaluate structure and stratigraphy around geothermal and high-temperature gas wells.

Howard, J. H., *Industrial Low Temperature Utilization of Geothermal Resources*, Lawrence Livermore Laboratory, Rept. UCRL-78271 (1976).

This brief presentation on industrial utilization of low-temperature geothermal resources will first consider an overview of what has been achieved in using geothermal resources in this way and, second, will consider potential, future industrial applications.

The outstanding industrial achievements to date have been the Tasman Pulp and Paper Mill in Kawerau, New Zealand, and the Kisilidjan Corporation diatomaceous filter aid plant at Lake Myvatn in Northern Iceland. Together these activities represent a power use equivalent to about 150 MW of a total industrial nonelectrical usage of perhaps 200 MW throughout the world. Other industrial uses include a variety of projects, most of which, unfortunately, are not well documented in the open literature (see Fig. 1 and Table 1). Examples are brewing and distilling in Japan, salt recovery and palay and grain drying in the Philippines, calcium chloride recovery in the United States, and boric acid production in Italy. Updated statements for many existent and potential applications are to be included in the Proceedings of Second United Nations Symposium on the Development and Use of Geothermal Resources.

Howard, J. H., Ed., *Present Status and Future Prospects for Nonelectrical Uses of Geothermal Energy*, Lawrence Livermore Laboratory, Rept. UCRL-51926 (1975).

This report, which is part of a study initiated by the NATO Committee on the Challenges of Modern Society (CCMS), describes the current status of nonelectrical uses of geothermal resources. Such resources are defined as geothermal fluids between the temperatures of 50 and 160°C. Current and potential uses of these resources including residential and commercial, agricultural and industrial applications are described. Also discussed are exploration and drilling; extraction and distribution; environmental impact; and economic and

regulatory problems. Applications in a number of countries are described. Among the report's conclusions are:

- Geothermal resources are widely distributed throughout the world.
- The extraction of these resources presents no serious technical problems.
- A wide variety of economically viable applications for these resources currently exists.
- Current nonelectrical applications have a favorable economic structure compared with those of other energy sources.
- Disposal of spent fluids has a significant ecological impact. Reinjection appears to be the most likely alternative.
- The legal and institutional framework surrounding these applications needs both clarification and simplification.

Howard, J. H., House, P. A., Johnson, P. M., and Towse, D. F., *Geology and Potential Uses of the Geopressure Resources of the Gulf Coast*, Lawrence Livermore Laboratory, Rept. UCID-17163 (1976).

The United States Energy Research and Development Administration has supported efforts to evaluate the potential contribution to the national energy supply of geopressed geothermal resources in the Gulf Coast. Efforts include a program of resource assessment and programs to examine utilization of the resource for the production of electricity and as a source of industrial process heat.

Resource assessment work has suggested the presence of perhaps as much as 6000 MW-centuries of recoverable electric energy and of 200 Tcf of methane. This program has emphasized finding significantly large sand bodies within the geopressed stratigraphic pressures and formation temperatures. Regional sand facies analyses conducted thus far indicate five locations in the Frio formation, Central and South Texas, where adequately large geopressed geothermal resources may be present.

Engineering studies of energy-conversion systems based on total-flow, flashed-steam, and binary-cycle concepts show that development of electric power from the Gulf Coast geopressure resource is technically feasible. However, such recovery is only marginally economical in view of the relatively low temperatures involved (less than 300°F or 149°C), and especially if dissolved methane is not present at saturation levels. Under favorable circumstances, investment in exploitation of the complete geothermal resource can produce rates of return of 15 to 30%. Rates of return as large as 10% appear unlikely under present and near-term future circumstances if only electric energy is recovered from the resource.

Study of use of the resource as process heat in pulp and paper mills and new sugar refineries has shown that these uses also are technically sound. The thermal content of a barrel of geothermal brine can cost as little as 9 mills when credited for recoverable hydraulic energy and methane. The value of heat approached 50 mills per bbl for certain applications. Again, under favorable circumstances, the use of geopressure resources for these nonelectric applications is economically attractive.

All programs have pointed out clearly the need for better specific understanding of the resource, especially its dissolved methane content and its ability to produce for tens of years.

Kasameyer, P. W., *Preliminary Interpretation of Resistivity and Seismic Refraction Data from the Salton Sea Geothermal Field*, Lawrence Livermore Laboratory, Rept. UCRL-52115 (1975). (Summary of a talk presented at the New Mexico State University Symposium on Geothermal Resources, October 1975.)

Seismic refraction and electrical resistivity surveys were used to study the Salton Sea geothermal field. The resistivity data are used to infer the boundaries of a reservoir of saline fluid. One lateral boundary coincides with a fault located by seismic refraction.

Kasameyer, P. W. and Schroeder, R. C., *Application of Thermal Depletion Model to Geothermal Reservoirs with Fracture and Pore Permeability*, Lawrence Livermore Laboratory, Rept. UCRL-79108 (1977).

The useful lifetime of a geothermal resource is calculated by assuming the fluid will be produced from and reinjected into a uniform porous medium. However, most geothermal systems are found in fractured rock. If so, the reinjected fluid may cool the production wells much sooner than would be predicted from calculations of flow in a porous medium.

We have developed a "quick and dirty" method for calculating how much sooner that cooling will occur. In this paper, we discuss the basic assumptions of the method, and show how it can be applied to the Salton Sea Geothermal Field, the Raft River System, and to reinjection of supersaturated fluids.

Kasameyer, P. W. and Schroeder, R. C., *Thermal Depletion of a Geothermal Reservoir with Both Fracture and Pore Permeability*, Lawrence Livermore Laboratory, Rept. UCRL-77323 (1976).

The useful lifetime for a geothermal resource is often calculated from the volume of available hot water. The lifetime may actually be increased if reinjected fluid is heated by the rock matrix and produced again. That extended lifetime has been discussed for reservoirs containing only porous material and for reservoirs in porous rock where the injection and production wells intersect the same fracture system. Equations are derived for the pore-fluid and fracture-fluid temperature average over macroscopic regions of the geothermal field, ignoring such problems as incomplete areal sweep and interfingering of cool and hot fluids. Approximate expressions relating average temperatures to the heat flowing from rock to fluid are verified by comparing our results to solutions of the exact equations. The resulting equations for the temperature decline can be solved quickly, and solutions for as few as 10 regions are sufficient to produce useful results.

Kasameyer, P., Thorson, L., and McKee, C., "Modeling Thermal and Flow Fronts for Arbitrary Well Arrays," submitted to the Geothermal Resources Council Meeting held May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 94616.)

Morse, J. G., *Well Interference Study of the Multi-Layered Salton Sea Geothermal Reservoir*, Lawrence Livermore Laboratory, Rept. UCRL-80385 (1977). (This paper was prepared for submission to the 3rd Workshop Geothermal Reservoir Engineering, Stanford University, December 14-16, 1977.)

A well interference testing program of the Salton Sea geothermal reservoir is being conducted as part of a resource evaluation study by the Earth Sciences Geothermal Industrial Support Program of the Lawrence Livermore Laboratory. Studies to date indicate that the reservoir rock is composed of layered sequences of shales and sands. Wells involved in the testing program are being used in support of, or are in the vicinity of, the MAGMA-SDG&E Geothermal Loop Experimental Facility (GLEF), located in the Salton Sea Geothermal Field (SSGF). Between these wells, a shale layer has been correlated which appears to divide the reservoir into an upper and lower portion. Other thick sand and shale sequences may provide additional stratification. This report describes work in progress on a well testing program designed to determine the horizontal and vertical transmissivity and storage parameters between wells in the vicinity of the GLEF. These tests are being conducted with the cooperation and support of Magma Power Company and San Diego Gas and Electric Company.

Netherton, R. et al., *Viscosity of Brine from the Salton Sea Geothermal Field, Imperial Valley, California*, Lawrence Livermore Laboratory, Rept. UCRL-52344 (1977).

We measured the viscosity of chemically analyzed brines from the Salton Sea Geothermal Field from 5 to 90°C at 100 kPa. Data indicate that these multicomponent solutions are slightly more viscous than a 3.5 molar NaCl solution in this temperature interval.

Owen, L. B., *Precipitation of Amorphous Silica from High-Temperature Hypersaline Geothermal Brines*, Lawrence Livermore Laboratory, Rept. UCRL-51866 (1975).

A serious problem associated with the conversion of the energy content of hypersaline geothermal systems to electrical power is precipitation of amorphous silica and other phases that can ultimately cause scaling of power plant equipment. The rate of polymerization of monomeric silica is dependent on pH, temperature, salinity, silica concentration, and the presence of solids. At the Salton Sea Geothermal Field, silica precipitation is promoted by cooling and depressurization. Evolution of CO₂ and H₂S causes an increase in residual brine pH, and, as a consequence, monomeric silica polymerizes more rapidly and is co-precipitated with sulfides and hydroxides. However, it may be possible to stabilize silica in geothermal brines by acidification with hydrochloric acid.

Radical changes in vertical and lateral resistivity distributions suggest that a complex stratigraphic-temperature-salinity pattern exists in the area. Hence, several geotechnical techniques followed by extensive exploration drilling will be required to resolve the complex thermal-hydrogeological structure.

Owen, L. B. *et al.*, *Predicting the Rate By Which Suspended Solids Plug Geothermal Injection Wells*, Lawrence Livermore Laboratory, Rept. UCRL-80529 (1977). (This paper was prepared for submission to the 3rd Workshop Geothermal Reservoir Engineering, Stanford University, December 14-16, 1977.)

Standard membrane filtration tests have been used by the oil industry for more than 20 years to evaluate injection well performance. Published analytical models are also available for relating filtration data to injector lifetimes. We have utilized these techniques to evaluate injection at the Salton Sea Geothermal Field, Southern California. Results indicate that direct injection into reservoir zones with primary porosity is not feasible unless 1 m or larger particulates formed during or after the energy conversion process are removed.

Owen, L. B. and Palmer, T. D., *Chemical Geothermometry: Accuracy of Subsurface Temperature Estimates for the Salton Sea Geothermal Field*, Lawrence Livermore Laboratory, Rept. UCRL-78289 (1976).

The accuracy of subsurface temperature estimations by Na-K-Ca and silica geothermometers has been investigated. Data from wells in the Salton Sea Geothermal Field have provided a comparison between the estimated and observed maximum bottomhole temperatures. The advantages of problems encountered with each technique are discussed.

Palmer, T. D., *Characteristics of Geothermal Wells Located in the Salton Sea Geothermal Field, Imperial County, California*, Lawrence Livermore Laboratory, Rept. UCRL-51976 (1975).

We have summarized the geophysical, geochemical, and geothermal characteristics of wells located in the Salton Sea Geothermal Field. Based on the geothermal characteristics of the wells, we have developed a subsurface heat profile for the entire geothermal field. We have also drawn maps of temperature contours for specified depths throughout the field.

Palmer, T. D., Howard, J. H., and Lande, D. P., Eds., *Geothermal Development of the Salton Trough, California and Mexico*, Lawrence Livermore Laboratory, Rept. UCRL-51775 (1975).

A geological description of the Salton Trough is given, followed by the history of attempts to exploit the area's geothermal resources. Presently existing geothermal projects in the area are described in detail.

Piwinskii, A. J. and Netherton, R., *An Experimental Investigation of the Permeability of the Kayenta and St. Peter Sandstones to Hypersaline Brine in the Temperature Interval 70 to 90°C at 10.3-MPa Confining Pressure*, Lawrence Livermore Laboratory, Rept. UCRL-52382 (1977).

Permeabilities of 10.2-cm-long, 2.5-cm-diam Kayenta (porosity $20.7 \pm 1.66\%$) and St. Peter (porosity, $13.6 \pm 0.13\%$) sandstone samples to Magmamax No. 1 brine containing suspended solids were

determined from 70 to 90°C at a 10.3-MPa confining pressure. We performed measurements without filters, with one 10- μ m filter, and with two 10- μ m filters inserted upstream of the core sample. In all cases, there was a dramatic decrease in permeability within the first hour of flow or few hundred pore volumes of flow through the core. Experiments conducted without filters or with one filter yield permeabilities that represent both the rock and the 2- to 3-mm amorphous silica-iron layer on the top face of the core. The experimental results show that if the Salton Sea Geothermal Field (SSGF) were composed of porous, sedimentary formations similar to Kayenta sandstone, long-term injection of unmodified Magmamax brine would not be feasible. In the case of acidified brine, most of the permeability decline may result from the mobilization of calcite.

Schroeder, R. C., *Reservoir Engineering Report for the Magma-SDG&E Geothermal Experimental Site near the Salton Sea, California*, Lawrence Livermore Laboratory, Rept. UCRL-52094 (1976).

A description of the Salton Sea geothermal reservoir is given and includes approximate fault locations, geology (lithology), temperatures, and estimates of the extent of the reservoir. The reservoir's temperatures and chemical composition are also reviewed. The flow characteristics are discussed after analyses of drillsteam tests and extended well tests. The field production, reserves, and depletions are estimated, and the effects of fractures on flow and depletion are discussed.

The reservoir is believed to be separated into an "upper" and "lower" portion by a relatively thick and continuous shale layer. The upper reservoir is highly porous, with high permeability and productivity. The lower reservoir is at least twice as large as the upper but has much lower storativity and permeability in the rock matrix. The lower reservoir may be highly fractured, and its temperatures and dissolved solids are greater than those of the upper reservoir. The *proven* reserves of heat in the upper reservoir are about 1/4 GW·yr (in the fluid) and 1/3 GW·yr (in the rock). In the lower reservoir, the *proven* reserves of heat are 5-3/4 GW·yr (in the fluid) and 17 GW·yr (in the rock). *Unproven* reserves greatly exceed these numbers. Injection tests following well completion imply that hydraulic fracturing has taken place in two of the SDG&E wells and at least one other well nearby.

Tewhey, J. D., *Geologic Characteristics of a Portion of the Salton Sea Geothermal Field*, Lawrence Livermore Laboratory, Rept. UCRL-52267 (1977).

Petrographic analysis of drill cutting samples from the Magmamax Nos. 2 and 3 and Woolsey No. 1 well in the Salton Sea Geothermal Field has resulted in the categorization of the sedimentary sequence. The cap rock extends to 325 m and unaltered reservoir rocks occur to approximately 900 m. The lowermost sequence is hydrothermally altered reservoir rocks. Laboratory measurements of core samples indicate a reduction in porosity with depth, and fracture porosity appears to contribute to the total porosity of the system. The geologic picture that emerges from SP log correlation is that of a structural basin whose axis lies to the northwest of Magmamax No. 2.

Tewhey, J. D., *The Effect of Hydrothermal Alteration on Porosity and Permeability in the Salton Sea Geothermal Field, California*, Lawrence Livermore Laboratory, Rept. UCRL-79623 (1977).

On the basis of studies of drill cuttings, core samples, and geophysical logs from geothermal wells, the sequence of sedimentary rocks in the Salton Sea geothermal field can be divided into three categories: cap rocks, reservoir rock, and hydrothermally altered reservoir rock. The cap rock is a zone of low porosity and permeability consisting of anhydrite-rich evaporite deposits in a carbonate-clay matrix. Permeable reservoir rocks have been subjected to hydrothermal alteration as a result of their interaction with hot, saline brine. The principal effect of alteration, in particular the epidote-producing reaction, has been the reduction of porosity and permeability with depth. The porosity of westward-dipping sandstone aquifers is 20% above the eastward-dipping epidote isograd and 10% below the isograd. The isograd corresponds approximately to the 285°C isotherm. Intergranular porosity in reservoir rocks is subject to irreversible self-sealing due to alteration,

whereas fractures can be considered as "renewable porosity" in that they can be reactivated subsequent to being sealed. Fractures are common in shales, with fracture porosity estimated at 10%. Cathodoluminescence of calcite-filled fractures commonly reveals two or more episodes of fracturing and sealing. This suggests that the seismicity in the Salton Trough may play a role in maintaining fracture permeability in the reservoir.

Towse, D., *An Estimate of the Geothermal Energy Resource in the Salton Trough, California*, Lawrence Livermore Laboratory, Rept. UCRL-51851 (1976).

The geothermal energy resource in the Salton Trough is estimated based on measured geologic parameters, extrapolation of data from geophysical surveys, and current research in energy-conversion systems. The total resource is estimated at 2×10^{19} J contained in 15×10^{12} kg of water, the quality of which varies up to more than 25% dissolved minerals. More than half of the resource is in the high-salinity deposit near the Salton Sea. It is estimated that 8×10^8 MWh of electric energy, equivalent to 5000 MW for 20 yr, could be generated from the Salton Sea deposit. This is a substantial part of the present electric power requirements of Southern California and is the energy equivalent of 1.3 billion barrels of oil.

Towse, D., *The Economics of Geothermal Heat as an Alternate Fuel*, Lawrence Livermore Laboratory, Rept. UCRL-77031 Rev. 1 (1975).

Geothermal energy is a potential resource that is being studied more closely now that conventional fossil fuels are becoming scarcer and more expensive. This paper examines the economic aspects of geothermal energy in comparison with conventional fuels. It appears that geothermal energy may be economically feasible for electric power generation, and a source of medium-temperature process steam ($\sim 250^\circ\text{C}$) for industrial use, and for heating and cooling residential and commercial buildings. In these uses it could substitute for petroleum fuels and would be competing with such fuels as coal and nuclear reactors.

Towse, D. F. and Palmer, T. D., *Summary of Geology at the ERDA-Magma-SDG&E Geothermal Test Site*, Lawrence Livermore Laboratory, Rept. UCID-17008, (1976).

Lithologic and geophysical well logs and production data were analyzed. The reservoir is a series of sandstone beds below a shaly sequence. The reservoir can be separated into two permeable intervals separated by a shale barrier. Faulting is suspected, but not proved, by well data. Sandstone development is variable, and the reservoir becomes deeper north of the site, where the upper permeable zone is missing. Production at the site has been from both permeable zones.

Yunker, L. W. and Tewhey, J. D., *The Influence of Magmatic Convection on the Development of Contact Metamorphic Aureoles*, Lawrence Livermore Laboratory, Rept. UCRL-79622 (1977).

The dimensions and thermal history of a contact aureole are controlled by the size of the intrusive pluton and the maximum temperature developed at the contact. Basic intrusions typically are characterized by smaller contact aureoles than those surrounding more acidic intrusions of similar size. This is paradoxical in the light of the higher temperatures of the basic intrusions. To test the assertion that this difference is due to intensity of convection in the magma chambers, simple analytical solutions to heat-transport equations have been used. Heat transfer from a 1-km-thick gabbroic body with initial temperature 1000°C and viscosity 10 poise has been compared to heat transfer from a 1-km-thick granitic magma body with initial temperature 800°C and viscosity 10 poise. Calculations indicate that both chambers will undergo convection, however the gabbroic body has a much higher rate of vertical transport of heat (5.0×10^{-3} cal/cm²·s) than the granitic chamber (1.6×10^{-4} cal/cm²·s). This high rate of heat transfer produces extremely high contact temperatures above the gabbroic intrusion. Heat lost at the upper and lower contacts is in the ratio 995:622. With less intensive convection in the granitic chamber heat loss is roughly uniform. These results are consistent with field observations. Erosional slices through granitic and diapiroically-emplaced ultramafic intrusions typically reveal

narrow baked aureoles with evidence of fusion in roof rocks. The assimilation of fused roof rock can account for the greater-than-expected granophyre abundances that have been reported for some gabbroic intrusions. These diverse thermal effects can be attributed to differences in convection intensity within magma bodies of varying composition.

Yunker, L. and Kasameyer, P., *A Revised Estimate of Recoverable Thermal Energy in the Salton Sea Geothermal Resource Area*, Lawrence Livermore Laboratory, Rept. UCRL-52450 (1978).

We have made a revised estimate of the recoverable thermal energy in the Salton Sea Known Geothermal Resource Area (KGRA) using the strong correlation between the temperature distribution and the magnetic anomaly. Our estimates of the power-generating potential range from 1300 MW-20 years (for indicated resources) to 8700 MW-20 years (for hypothetical resources). These figures are compatible with previously published estimates.

Comparison of various estimation procedures reveals major differences in techniques used to assess reservoir volume. However, authors agree generally on parameters used to convert reservoir volume to recoverable energy. Our conservative estimates justify continued research and development to solve the technical problems that stand in the way of commercialization of the Salton Sea resource.

ENERGY CONVERSION

Alger, T. W., *Droplet Phase Characteristics in Liquid-Dominated Steam-Water Nozzle Flow*, Lawrence Livermore Laboratory, Rept. UCRL-52534 (1978).

An experimental study was undertaken to determine the droplet size distribution, the droplet spatial distribution and the mean droplet velocity in low-quality, steam-water flow from a rectangular-cross-section, converging-diverging nozzle. A unique forward light-scattering technique was developed for droplet-size-distribution measurements. Droplet spatial variations were investigated using light-transmission measurements, and droplet velocities were measured with a laser-Doppler velocimeter (LDV) system incorporating a confocal Fabry-Perot interferometer. Nozzle throat radius of curvature and height were varied to investigate their effects on droplet size.

Droplet-size-distribution measurements yielded a nominal Sauter mean droplet diameter of $1.7 \mu\text{m}$ and a nominal mass-mean droplet diameter of $2.4 \mu\text{m}$. Neither the throat radius of curvature nor the throat height were found to have a significant effect upon the nozzle exit droplet size. The light transmission and LDV measurement results confirmed both the droplet size measurements and demonstrated high spatial uniformity of the droplet phase within the nozzle jet flow. One-dimensional numerical calculations indicated that both the dynamic breakup (thermal equilibrium based on a critical Weber number of 6.0) and the boiling breakup (thermal nonequilibrium based on average droplet temperature) models predicted droplet diameters on the order of $7.5 \mu\text{m}$, which are approximately equal to the maximum stable droplet diameters within the nozzle jet flow.

Alger, T. W., *The Performance of Two-Phase Nozzles for Total Flow Geothermal Impulse Turbines*, Lawrence Livermore Laboratory, Rept. UCRL-76417 (1975).

The Total Flow impulse turbine concept requires the efficient conversion of thermal energy into kinetic energy for momentum transfer to an appropriately designed turbine wheel. For this reason, the flow of high-pressure steam-water mixtures at low quality through converging-diverging nozzles was investigated.

Nozzle inlet qualities and pressures were varied from approximately 10 to 25% and 1.8 to 2.8 MPa, respectively, to simulate geothermal wellhead products. The optimum nozzle performance for a specific geometry was determined by varying the nozzle back pressure from atmospheric to approximately 14 kPa. Experimental thrust coefficients and pressure profiles are presented and compared to simple theory. Observations were made concerning nozzle exit shock and expansion waves when operating at off-design conditions. As anticipated, the optimum nozzle efficiencies were high.

Alger, T. W., Crowe, C. T., and Giedt, W. H., *A Laser-Doppler Velocimeter for Measuring Droplet Velocities in Two-Phase Liquid-Dominated Nozzle Flows*, Lawrence Livermore Laboratory, Rept. UCRL-80790 (1978).

A new laser-Doppler velocimeter (LDV) arrangement for measuring droplet velocities in high velocity, liquid-dominated two-phase nozzle flows was developed. The transmitting optics arrangement for this LDV system is identical to that of a dual beam heterodyne LDV, i.e., the light beam from a single frequency argon laser is divided into two parallel identical beams, which are focused to an intersection volume in the flow. The light backscattered from droplets traveling through this volume is collected for analysis using a scanning confocal Fabry-Perot interferometer (FPI). Because of the dual beam arrangement an unscattered or reference beam is not necessary, and the optical alignment ease and stability are greatly improved over similar LDV-FPI systems. Results of droplet velocity measurements in high velocity, high droplet concentration nozzle jet flows are presented.

Alger, T. W. and Giedt, W. H., *A Light Scattering Technique for Determining Droplet Size Distributions in Two-Phase Liquid-Dominated Nozzle Jets*, Lawrence Livermore Laboratory, Rept. UCRL-79647 (1978). (This paper was prepared for submission to the 1st International Conference on Liquid Atomization and Spray Systems, August 1978, Tokyo, Japan.)

A method for determining the droplet size distribution from measurements of the scattered light intensity in the forward scattering lobe has been developed for two-phase, single-component, liquid-dominated nozzle jet flows containing small droplets (diameters $10\text{ }\mu\text{m}$ for visible light wavelengths). The technique is based upon matching the measured scattered light intensity profile with a summation of the intensity contributions of a series of appropriately spaced narrow band size distributions. A numerical optimization technique is used to determine the strength of the individual bands. Application of the technique to the determination of the droplet size distribution (Sauter mean diameter near $1.8\text{ }\mu\text{m}$) in a low-quality steam-water nozzle jet is described.

Austin, A. L. *An Overview of the Geothermal Energy Development Program at the Lawrence Livermore Laboratory*, Lawrence Livermore Laboratory, Rept. UCRL-79340 (1977). (Written testimony presented at hearings held by the State of California Geothermal Task Force, April 29, 1977, San Diego, California.)

This testimony is submitted at the request of the State Geothermal Task Force for presentation at a hearing in San Diego, California on April 29, 1977. It is an overview of the status of the Geothermal Development Program at the Lawrence Livermore Laboratory sponsored by the U. S. Energy Research and Development Administration. Consequently, the testimony is necessarily limited to our area of expertise, and relates specifically to section I.C. of the topical guidelines issued by the Taskforce as an enclosure (OPR:SJB:4-6-77) to the letter of invitation. This section is titled Status of Geothermal Development and Technology: Conversion Technology.

Austin, A. L., "An Overview of the Geothermal Program at the Lawrence Livermore Laboratory," submitted to the Geothermal Resources Council Meeting, May 9-11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 95616.)

Austin, A. L., *The LLL Geothermal Energy Development Program Status Report, January 1974-January 1975*, Lawrence Livermore Laboratory, Rept. UCID-16721 (1975).

Austin, A. L., *Prospects for Advances in Energy Conversion Technologies for Geothermal Energy Development*, Lawrence Livermore Laboratory, Rept. UCRL-76532 (1975).

Events during the last few years have focused worldwide attention on the increasing need for clean, inexpensive energy supplies, with particular emphasis on development of nonfossil sources. In the U.S.,

geothermal energy is now receiving wide attention as one such alternative energy source, particularly for electric power generation. Geothermal energy is thermal energy stored underground in natural deposits of dry steam, hot water, and hot dry rock. Dry steam deposits are technologically the easiest to exploit, but they are estimated to occur only about 5% as frequently as hot water deposits. And while there may be immense amounts of energy stored in hot dry rock, no technologies yet exist for recovery of this energy nor has significant exploration been done to determine if and where exploitable deposits exist. Consequently, during the next decade geothermal energy development in the U.S. will likely emphasize exploitation of hot water deposits. Although these deposits constitute a significant energy resource, there are two major constraints that will influence their rate of development. First, the range of chemical conditions encountered will likely require special energy-conversion systems which are only now beginning to be developed and have yet to be proved feasible for economically utilizing some of the known deposits of very hot and salty brines—fluids that are extremely hostile to mechanical equipment. Second, economic considerations require development of energy-conversion machines with high efficiencies in order to minimize the number of wells per unit of electrical capacity. In the U.S. an accelerated effort is now under way to develop such new energy-conversion systems in an attempt to increase opportunities for utilization of hostile fluids and for improved economics.

Austin, A. L. *et al.*, *The Total Flow Concept for Recovery of Energy from Geothermal Hot Brine Deposits*, Lawrence Livermore Laboratory, Rept. UCRL-51366 (1973).

This report describes a new method for producing electrical power from the energy stored in hot brine deposits. Of the three forms of geothermal energy, the hot brine resource has the greatest potential for development of a viable long-range geothermal energy supply. It is a large energy source with recovery and conversion requiring only moderate extensions of existing technologies.

The proposed method is developed specifically for application to the brines of the Salton Sea geothermal area, where enough energy is stored to provide at least 100,000 MW of electrical generation capacity for more than 20 years. These brines contain up to 30% dissolved salts and are very corrosive. Once developed, the proposed method, then, will certainly be applicable to other geothermal deposits.

The method uses the total flow concept. Hot brine is allowed to expand (from 300°C, 2200 psia, at ~5000 ft) to the surface where the wellhead product contains 20% vapor by weight and ~560 Btu/lb at ~400 psia. This thermal energy is converted to kinetic energy by expansion of the mixture through a converging-diverging nozzle. The high-velocity output is used to drive a modified hydraulic impulse turbine operating at ~3.5 in. Hg (120°F). Theoretically, this method should produce 60% more power than other systems, either operational or proposed, for the hot brine application. The basic advantage is that the total flow is used, allowing recovery of energy in the liquid that otherwise would be lost. The use of hydraulic impulse turbine concepts is attractive since much of the needed technology exists, the devices are inherently rugged, and fabrication with corrosion- and erosion-resistant materials is possible.

We estimate that an electrical power generation station using this concept will require a capital investment of \$200/kW and should produce power at a cost of about 3 mills/kWh. For a power sales price of 8 mills/kWh, we estimate the internal rate of return to be between 10 and 20% depending on the method of taxation and royalty charges.

Austin, A. L. and House, P. A., *New Concepts for Conversion of the Energy Contained in Low to Medium Temperature Liquids with Emphasis on Geothermal Applications*, Lawrence Livermore Laboratory, Rept. UCRL-52583 (1978).

As part of work at the Lawrence Livermore Laboratory to develop the total-flow energy conversion process for utilization of high-temperature water-dominated geothermal resources, several unique expanders have been designed and tested. This report describes recent advances and concepts for efficient, low-cost turbomachinery designed especially for expansion of low- to medium-temperature (~180°C) liquids.

A unique radial outflow reaction turbine (RORT) has been designed and laboratory tested. The results indicate that a 50% engine efficiency is achievable. This work has led to the development of a new concept called the velocity-pump reaction turbine (VPRT). An analysis is presented which shows that the VPRT

has the potential for increasing the gross engine efficiency of the RORT by about 50%. Other variations are discussed which are specifically suited for application to utilization of geothermal geopressed resources. This family of expanders has been created uniquely for expansion of liquids to produce shaft work at potential engine efficiencies in the 50-70% range. These machines are especially important to development of low-temperature energy sources such as those encountered in geothermal deposits, solar heated fluids, and waste heat sources from industrial processes.

Austin, A. L., Howard, J. H., Lundberg, A. W., and Tardiff, G. E., *The LLL Geothermal Energy Development Program Status Report: January 1975 through August 1975*, Lawrence Livermore Laboratory, Rept. UCID-16954 (1975).

The LLL Geothermal Energy Development Program was initiated in January 1974. This report, describing significant events during FY75 as well as activities during the reporting period, serves as a status report summarizing program activities, findings, and plans.

Please note: This report is intended to be informal; therefore, information presented in it should be considered preliminary. Finalized program activities are published separately in formal reports.

Austin, A. L. and Lundberg, A. W., "Electric Power Generation from Geothermal Hot Water Deposits," *Mech. Eng.* **97**, 19 (1975).

Water-dominated geothermal systems are an energy resource from which a quantity of clean, low-cost electrical energy can be extracted. Three conversion concepts—the flashed-steam system, the binary-cycle system, and the Total-Flow system—are analyzed for typical wellhead characteristics found in hot-water geothermal resources. Of the three, the Total-Flow concept is the most promising, with a potential for 60% greater efficiency than either of the other systems.

Austin, A. L., Lundberg, A. W., Owen, L. B., and Tardiff, G. E., *The LLL Geothermal Energy Program Status Report January 1976–January 1977*, Lawrence Livermore Laboratory, Rept. UCRL-50046-76 (1977).

The Lawrence Livermore Laboratory's Geothermal Energy Development Program, funded by the U.S. Energy Research and Development Administration, was initiated in January 1974. This report, which is the third major status report, describes significant events and detailed results obtained from January 1976 through January 1977. The timing is purposely chosen to coincide with the completion of several significant laboratory and field experiments. Furthermore, this report serves as documentation of the material presented at a major program review meeting held at Livermore on December 14–16, 1976, and attended by more than 80 industry representatives. The purpose of the meeting was (1) to provide detailed current information on the LLL program content, technical results, and goals; (2) to seek participation from industry in helping review program direction; and (3) to encourage greater industry participation in future work toward the commercialization of our results. It is hoped that this report will further these objectives.

Beadle, C. W., *Detachable Blade Configurations for a Total Flow Geothermal Turbine*, Lawrence Livermore Laboratory, Rept. UCID-17554 (1977).

The feasibility of using a simple tee-slot configuration to attach removable titanium turbine buckets to a geothermal turbine disk operating at 6000 RPM is considered. A finite element stress analysis was utilized and a possible design configuration with maximum tensile stresses of about 30,000 psi was found. Further reduction in this stress level could be made by optimizing the blade-disk geometry. No consideration was given to dynamic stresses caused by vibration.

Comfort, W. J., *Applicability of the Hero Turbine for Energy Conversion from Low-Quality, Two Phase, Inlet Fluids*, Lawrence Livermore Laboratory, Rept. UCRL-80751 (1978).

The Hero turbine is frequently said to be particularly suited for two-phase geothermal-energy conversion. Its functional simplicity makes it an obvious candidate for use of a very low-quality steam-water mixture as a working fluid. The performance characteristics for the single-phase expander derived are extended to address two options for handling the two-phase mixture in the Hero turbine. The Hero turbine is found to be best suited to fluids that are single-phase at the entrance to the turbine and to expansions that involve low enthalpy change. The turbine appears well suited to saturated liquid expansion in which the fluid becomes two-phase after entering the turbine.

Comfort, W. J., *The Design and Evaluation of a Two-Phase Turbine for Low-Quality Steam-Water Mixtures*, Lawrence Livermore Laboratory, Rept. UCRL-52281 (1977).

A new two-phase turbine has been designed, and built for testing in the laboratory, using a low quality steam-water mixture as a working fluid. This expander has been successfully tested in the laboratory as a part of the Lawrence Livermore Laboratory Geothermal Energy Development Program. The measured performance compares well with performance predictions of a numerical model of the expander.

This report describes: (1) the details of the selection of the type of expander, (2) the design of an experimental expander for use in a clean two-phase flow laboratory experiment, (3) the development of a numerical model for performance analysis and extrapolations, (4) experiments including static cascade performance with two-phase fluid, disk friction and windage measurement, and two-phase performance measurements of the experimental expander, (5) comparisons of the numerical model and experimental results, and (6) the prediction of the performance of an advanced design, indicating how performance improvements can be achieved.

An engine efficiency of 23% for a single-nozzle test was measured. Full-admission performance, based upon the numerical model and achievable nozzle thrust coefficients indicate that an engine efficiency of between 39 and 48% can be realized with present technology. If maximum liquid removal loss is assumed, this performance range is predicted to be 38 to 41%. Droplet size reduction and the development and implementation of enhanced two-phase flow analysis techniques should make it possible to achieve the research goal of 70% engine efficiency.

Comfort, W. J., *Interim Report on Performance Tests of a Total Flow Impulse Turbine for Geothermal Applications*, Lawrence Livermore Laboratory, Rept. UCID-17411 (1977).

A new two-phase expander has been successfully tested in the laboratory. The expander is a part of the energy-conversion effort of Lawrence Livermore Laboratory's Geothermal Energy Development Program. This report: (1) briefly describes the machine, (2) presents the experimental results, (3) compares a numerical performance model to the results, (4) presents predictions of the same rotor with full-admission, and (5) indicates how performance improvements can be made.

An engine efficiency of 23% for a single-nozzle test was measured. Performance predictions of a numerical model agree well with experimental results. The numerical model and achievable nozzle thrust coefficients indicate that full admission engine efficiency between 38 and 48% can be realized with present technology. Droplet size reduction and enhanced two-phase flow analysis techniques should make it possible to reach the research goal of 70% engine efficiency.

Comfort, W. J., *Modeling the Performance of a Two-Phase Turbine using Numerical Methods and the Results of Nozzle, Static Cascade, and Windage Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-80749 (1978).

Performance models for a two-phase turbine were developed to verify our understanding of the loss mechanisms and to extrapolate from the single-nozzle test condition to a full-admission turbine. The numerical models for predicting the performance of the nozzle and the combined nozzle and rotor are described. Results from two-phase, static cascade tests and disk-friction and windage experiments are used to

calibrate the performance model(s). Model predictions are compared with single-nozzle prototype-turbine test results, and extrapolations are made to a full-admission design. The modeling also provides predictions of performance for turbines with various blade geometries, inlet conditions, and droplet sizes. Thus the modeling provides insight into design improvements.

Comfort, W. J., *Performance of a Total-Flow Impulse Turbine for Geothermal Application*, Lawrence Livermore Laboratory, Rept. UCRL-79325 (1977). (Presented at the 12th Intersoc. Energy Conversion Engineering Conf., Washington, D. C., August 28 to September 2, 1977.)

A new, axial-flow impulse turbine was tested at LLL as part of the geothermal energy development program. Engine efficiency of this single-stage, two-phase expander was measured at 23% during a single-nozzle test. Performance predictions of a numerical model agree with these results. Full-admission performance (based on the numerical-model and attainable nozzle thrust coefficients) indicates that engine efficiency can reach between 38 and 40% with present technology. Improved techniques for analyzing two-phase flow and further reduction of droplet sizes should provide 70% engine efficiency.

Comfort, W. J., Alger, T. W., Giedt, W. H., and Crowe, C. T., *Calculation of Two-Phase Dispersed Droplet-in-Vapor Flows Including Normal Shock Waves*, Lawrence Livermore Laboratory, Rept. UCRL-78426 (1976).

A method has been developed for calculating quasi-one-dimensional, steady-state, two-phase dispersed droplet-in-vapor flow. The technique is applicable to both subsonic and supersonic single-component flow in which normal shock waves may occur and is the basis for a two-dimensional model. The flow is assumed to be inviscid, except for droplet drag. Temperature and pressure equilibrium between phases is assumed, although this is not a requirement of the technique. Example calculations of flow in one-dimensional nozzles with and without normal shocks are given and compared with experimentally measured pressure profiles for both low and high quality two-phase steam/water flow.

Comfort, W. J. and Beadle, C. W., *Design Considerations for a Two-Phase Turbine*, Lawrence Livermore Laboratory, Rept. UCRL-80750 (1978).

A two-phase turbine, using a low-quality steam-water mixture as a working fluid, has been designed, built, and tested in the laboratory. Two-phase fluids are found naturally in most geothermal fields throughout the world and can also be used in the conversion of waste heat from industrial sources. The thermodynamic and fluid-dynamic properties of such fluid mixtures are reviewed, with specific reference to the selection and design of an appropriate expander. Various types of practically realizable expanders are considered, and the choice of a single-stage, axial-flow, impulse turbine is explained. Also the basic design parameters, including sizing and blade and nozzle geometry, are described.

Comfort, W. J. and Crowe, C. T., *Dependence of Shock Characteristics on Droplet Size in Supersonic Two-Phase Mixtures*, Lawrence Livermore Laboratory, Rept. UCRL-80748 (1978).

In a dispersed two-phase flow, the mixture chokes at a velocity well below the vapor choking velocity, as shown by the velocity at the throat of a converging-diverging, two-phase, supersonic nozzle. The formation and abruptness of a normal shock wave in a two-phase mixture depends strongly on the coupling between phases, particularly upon droplet size. As droplet size becomes small, the mixture behaves as a continuum, and sharp discontinuities can occur at velocities above the two-phase choking velocity but below the vapor sonic velocity. An approximate analysis is performed to indicate the droplet size at which continuum behavior might be expected to occur. A numerical model, which includes the drag, buoyancy, Basset force, and the force associated with the virtual mass effect, is used to show droplet-size dependence in two-phase normal shock waves. For the examples presented, continuum behavior apparently is approached at droplet diameters between 1 and 2 μm , even through normal shock waves.

Crowe, C. T., *Conservation Equations for Vapor-Droplet Flows Including Boundary-Droplet Effects*, Lawrence Livermore Laboratory, Rept. UCRL-52184 (1976).

The governing equations for a flowing vapor with suspended burning, evaporating, or condensing droplets are derived in a straightforward manner using the control volume, or Reynolds transport, approach. The equations demonstrate how mass transfer at the droplet surface contributes to the momentum and energy of single droplet, a cloud of droplets, and the vapor phase. The inclusion of boundary droplets gives rise to a droplet heat transfer term omitted in previous derivations. These equations provide a starting point for the development of viable numerical and analytic models for vapor-droplet flows.

Crowe, C. T., *On Soo's Equations for the One-Dimensional Motion of Single Component two-Phase Flows*, Lawrence Livermore Laboratory, Rept. UCRL-79053 (1977).

Soo (1976) presents a set of equations for the one-dimensional adiabatic motion of two-phase single-component flow. The purpose of this note is to examine the validity of these equations in a specific application and to offer an explanation of the resulting inconsistencies.

Crowe, C. T., *Vapor-Droplet Flow Equations*, Lawrence Livermore Laboratory, Rept. UCRL-51877 (1975).

This report discusses the general features of a vapor-droplet flow and derives the equations expressing the conservation of mass, momentum, and energy for the vapor, liquid, and mixture using the control volume approach. The phenomenological laws describing the exchange of mass, momentum, and energy between phases are also reviewed. The results can be applied to the development of water-dominated geothermal resources.

Crowe, C. T. and Comfort, W. J., *Atomization Mechanisms in Single-Component, Two-Phase, Nozzle Flows*, Lawrence Livermore Laboratory, Rept. UCRL-79656 (1978). (This paper was prepared for submittal to the Proceedings of the 1st International Conference on Liquid Atomization and Spray Systems, Fuel Society of Japan, August 29-31, 1978, Tokyo, Japan.)

A new model is presented for droplet breakup in single-component, two-phase mixture flows. It is shown that breakup occurs as a result of internal boiling. This boiling model, unlike the Weber-number breakup model, depends only upon fundamental calculable variables and known fluid properties and requires no empirical parameters. The boiling-atomization model lends itself well to both approximate and numerical solution techniques for two-phase flow in nozzles. Results of typical calculations are shown. Droplet sizes are calculated as a function of nozzle-inlet conditions (temperature and quality), and the role of surface tension is investigated. Comparisons of numerically predicted and experimentally measured droplet diameters show that the boiling-breakup model is conservative.

Crowe, C. T. and Weiss, H., *Metering Low-Quality Steam-Water Flows*, Lawrence Livermore Laboratory, Rept. UCRL-52271 (1977).

The simultaneous measurement of mass flow rate and quality of low-quality steam-water flows is of primary interest in evaluating and monitoring the flow from geothermal resources. This report relates the experience acquired at LLL in attempting to perform such measurements with a double flash (meter-valve-meter) arrangement using orifices and venturis. The mass flow correlations proposed in the literature are reviewed and a new correlation based on the energy equation is introduced. The data are presented and evaluated in light of these correlations. Directions for future research in this area are suggested.

Dittman, G. L., *Calculation of Brine Properties*, Lawrence Livermore Laboratory, Rept. UCID-17406 (1977).

Simple analytical expressions are presented for estimating geothermal brine thermophysical properties above 80°F and for salt contents between 5 and 25% by weight.

Linear regression by the method of least squares is used to curve-fit saturated liquid enthalpy and density data on simulated brines. Brine saturation pressure is calculated as a percentage of the pure water saturation pressure at the same temperature. Saturated liquid brine entropy is determined from an approximation to the differential equation for entropy change using the previously determined relationships for the other property values needed.

Brine vapor properties are assumed equal to steam properties at the same temperature and pressure and are obtained from the ASME equation of state for pure water. This report was summarized and submitted to the Geothermal Resources Council Meeting held May 9–11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 94616.)

Dittman, G. L., *Wellflow for Geothermal Wells—Description of a Computer Program Including Effects of Brine Composition*, Lawrence Livermore Laboratory, Rept. UCID-17473 (1977).

A computer program entitled WELLFLOW is presented for calculating wellhead flow and fluid conditions for a self-flowing geothermal well of constant diameter. The calculational model was developed by Elliott and has been modified to incorporate a more accurate analytical procedure for calculating brine thermophysical properties. An additional modification establishes the mass flow rate needed to just produce sonic liquid velocity at the wellhead (if the specified flow rate exceeds this value) in order to characterize the entire range of flow conditions for the well geometry and reservoir characteristics.

Reservoir values of temperature, depth, salinity, mass flow rate and drawdown pressure factor must be specified. Wellbore parameters of casing inside diameter, Moody friction factor, gas/liquid velocity ratio, and the overall heat transfer coefficient between the casing and ground must also be supplied. The calculated wellhead conditions consist of temperature, pressure, vapor mass fraction, enthalpy and entropy of the two-phase mixture, liquid velocity, and vapor and liquid mass flow rates for either pure water or brine.

Giedt, W. H., *The Geothermal Binary Fluid Cycle: Heat Exchanger Area Requirements and Initial Costs*, Lawrence Livermore Laboratory, Rept. UCRL-51912 (1975).

The basic elements of a geothermal binary-fluid energy-conversion cycle are reviewed. The role of the heat exchanger in the overall cycle performance is examined and the extent to which it influences plant cost is evaluated. It is shown that to achieve optimum operating conditions for the system, it is necessary to consider the performances of both the heat exchanger and the energy-conversion cycle.

The purpose of this paper is to examine some of the prospects for advances in energy-conversion technologies specifically suited to development of hydrothermal resources. The discussion emphasizes technical aspects and makes no attempt to produce explicit economic evaluations; any reliable economic analysis requires design data and proven system components (which do not yet exist). We attempt here to take a broad view in order to illustrate the spectrum of prospects for technological advances.

Giedt, W. H., *Investigation of Heat Exchanger Flow Arrangement on Performance and Cost in a Geothermal Binary Cycle*, Lawrence Livermore Laboratory, Rept. UCRL-78390 (1976). (Presented at 11th Intersoc. Energy Conversion Engineering Conf., State Line, Nevada, September 12–17, 1976.)

The performance of an idealized geothermal binary-fluid-cycle energy-conversion system is shown to be a function of the temperatures of the brine and working fluid leaving the heat exchanger. System power output, heat-exchanger area required, and initial well and heat-exchanger costs are determined for counterflow, and single and multi-pass parallel-counterflow exchangers. Results are presented graphically as functions of the brine and working fluid exit temperatures from the exchanger. Use of this system analysis is illustrated by showing quantitatively the advantage of counterflow over the other flow arrangements considered.

Goldberg, A. and Garrison, R. E., "Materials Evaluation for Geothermal Applications—Turbine Materials," submitted to the Geothermal Resources Council Meeting, May 9–11, 1977, San Diego, California. (Available from the Geothermal Resources Council, P. O. Box 98, Davis, CA 94616.)

House, P. A., *Analysis of a Radial-Outflow Reaction Turbine Concept for Geothermal Application*, Lawrence Livermore Laboratory, Rept. UCRL-52480 (1978).

Described herein is the radial-outflow reaction turbine, a pure-reaction turbine designed to improve the conversion efficiency of geothermal energy into electrical power. It also has potential as a total-flow turbine for low-temperature water. We can use the principle of incomplete expansion to obtain a reduction in turbine size when the turbine exhausts into a low-pressure condenser. And, by adding this turbine to single- and two-stage flashed-steam systems, we can improve the conversion efficiency of systems utilizing low- and high-energy wellhead sources, respectively. The Appendix outlines our analysis of the radial-outflow reaction turbine and leads to an expression for engine efficiency.

House, P. A., *Helical-Rotor Expander Applications for Geothermal Energy Conversion*, Lawrence Livermore Laboratory, Rept. UCRL-52043 (1976).

The helical-rotor expander is one of numerous candidates for the direct "total flow" expansion of geothermal fluids. The potential exists for expansion efficiencies as high as 70%. Engine efficiencies will generally be below 70%, however, because of an expansion-ratio limitation of 15 and a maximum pressure differential of 110 psi.

Single-stage expansion of self-pumped geothermal fluids from reservoirs at 350 to 572°F gives engine efficiencies ranging from 57.3 to 43.1%. Calculated rotor diameters range from 10.5 to 42.6 ft for outputs of 5 to 40 MW.

Two-stage expansion of fluid from a 572°F reservoir gives an engine efficiency of 62.3% and reduces the diameter of the larger rotor by 21%. Rotor diameters can be held to more reasonable sizes by using the expander in combination with a vapor turbine. To expand 572°F reservoir fluid (360 psia at the wellhead with 18.9% quality) to helical-rotor-expander exhaust pressures (from 66 to 14.7 psia), requires estimated rotor diameters of 4 to 8.5 ft for a 40-MW combined-system power output. Corresponding system engine efficiencies vary from 58.7 to 55.3%.

The impulse contribution to the total work of the expander ranges from 7.7 to 8.5%, when 572°F reservoir fluid is expanded to backpressures from 1.69 to 14.7 psia, respectively.

The helical-rotor expander is best applied to noncondensing, low-power-output uses or to a hybrid system with helical-rotor exhaust pressures greater than 1 atm.

House, P. A., *Performance Tests of the Radial Outflow Reaction Turbine for Geothermal Applications*, Lawrence Livermore Laboratory, Rept. UCID-17902 (1978).

A unique pure reaction turbine, for geothermal applications, has been developed at the Lawrence Livermore Laboratory. This radial-outflow reaction turbine (RORT) is designed specifically to produce power from the expansion of saturated or compressed liquid at temperatures of less than 180°C.

In the tests reported here the highest efficiency measured was 32.7%, clearly below the peak efficiency for this small machine. Extrapolations to larger machines indicate that an efficiency near 50% is a credible goal, an attractive performance as either a Total-Flow expander for liquid or in conjunction with conventional flashed steam systems. A rough cost estimate indicates that a 7.5-MW RORT would cost somewhere between 0.5 and 1.5 M\$, and could add about 15% to the power output of a conventional 50-MW plant. This means that for less than a 3% increase in capital cost the bus bar energy cost can be reduced by about 10%. Another important result is that the RORT is uniquely suited for conversion of the thermal and pressure energy components in geopressured resources. The development and proof of feasibility of efficient liquid expanders broadens the opportunities for economic power production from lower-temperature geothermal resources, and possibly utilization of waste heat in industrial processes.

House, P. A., Johnson, P. M., and Towse, D. F., *Potential Power Generation and Gas Production from Gulf Coast Geopressed Reservoirs*, Lawrence Livermore Laboratory, Rept. UCRL-51813 (1975).

Extensive onshore and offshore geopressed water reservoirs are found in the Texas and Louisiana Gulf Coast region. Energy in these reservoirs is present as natural gas in solution, as thermal energy, and as hydraulic energy. Reservoir depths generally range from 5000 to 20,000 ft; corresponding temperatures range from below 200 to above 350°F. This report gives a brief description of the geology, an estimate of recoverable energy, an engineering evaluation of the net power and gas production for various operating conditions, an economic analysis, and a discussion of the steps required for developing the resource.

Three types of thermal energy conversion systems are investigated: Total Flow, flashed steam, and binary cycle. Of these, the Total-Flow system is selected for use in a detailed power-plant systems analysis in which net power output as a function of wellhead pressure is determined for the two wastewater disposal methods considered—surface disposal, and injection into an underground formation. The output of electricity and gas from a 7-in. well as determined by this analysis ranges from 0.36 MW and 6.4 scf/s for shallow reservoirs with wastewater disposal by injection to 6.2 MW and 39.3 scf/s for the deepest reservoirs with surface disposal of wastewater.

Economic analyses are made on the basis of peak power outputs determined in the systems analysis. The relatively shallow reservoirs are found not to be profitable for combined gas production and electrical power generation, but they might be marginally profitable for gas production alone. Intermediate-depth reservoirs would be profitable for such combined production, and might be marginally profitable for electrical power generation alone. Profitability of combined gas and power production from intermediate and deeper reservoirs depends on natural gas being present at near saturation levels.

Lundberg, A. W., *Technology Development for High-Salinity Geothermal Resources*, Lawrence Livermore Laboratory, Rept. UCRL-79903 (1977). (This paper was prepared for submittal to the 70th Annual AIChE Meeting, New York, November 14, 1977.)

The accomplishments of the geothermal program at the Lawrence Livermore Laboratory (LLL) during the last year have done much to bring the large geothermal resources of California's Imperial Valley closer to the point of commercial utilization. Successful testing of a specially-designed turbine and verification of chemical methods for scale control are the two main advances. However, they are both supported by a strong base in support capabilities such as the analysis of two-phase flow and in methods for conducting meaningful experiments in chemistry and material science in real brine. In addition, studies are continuing on other energy-conversion concepts and detailed knowledge is being developed for definition of a strategy for resource utilization. Current activities are directed toward the remaining problems in effluent treatment for disposal and toward the refinement of our knowledge of this large, hostile geothermal resource.

Miller, A. B., *A Brine Steam Properties Computer Program for Geothermal Energy Calculations*, Lawrence Livermore Laboratory, Rept. UCRL-52495 (1978).

We have written a computer program called BPROP7 that enables the user to obtain conveniently the thermodynamic properties of brine and water vapor in combination, given at least three of nine parameters. The parameters included in this program are two types of salt content, temperature, pressure, enthalpy, entropy, density or specific volume, quality, and amount of superheat.

Rogers Engineering Company, *Conceptual Design of 5 MW Wellhead Located Geothermal Steam Turbine Driven Electric Generating Plant*, Lawrence Livermore Laboratory, Rept UCRL-13635 (1975).

This report summarizes a design concept for a standardized wellhead geothermal steam-turbine-driven electric generating plant, including budget cost estimates and the time required to manufacture, deliver, and commission such a plant at a site approximately fifty (50) miles from a port. The turbine is capable of

operating either condensing or noncondensing and is designed for an inlet pressure of 80 mm Hg absolute or atmospheric pressure. When operating at design conditions, the generator produces 5000 kW in the condensing mode, and when exhausting to atmosphere, maximum output is approximately 2220 kW.

Rogers Engineering Company, *Modular 5-MW Geothermal Power Plant Design Considerations and Guidelines*, Lawrence Livermore Laboratory, Rept. UCRL-13684 (1976).

This report is essentially a specification for conventional components needed to operate a single flash steam system. This provides the potential user with a set of guidelines to help in equipment selection.

Steidel, R. and Weiss, H., *Performance Test of a Bladeless Turbine for Geothermal Applications*, Lawrence Livermore Laboratory, Rept. UCID-17068 (1976).

The bladeless or Tesla turbine literally has no blades. Through the mechanism of shear, the angular momentum of the entering fluid is transmitted to a number of thin, smooth, flat, parallel disks arranged normal to a shaft. Speed, flow rate, and power output were measured for a number of inlet conditions. Flow rate, specific water rate, and engine efficiency were all determined as parameters of power output. The specific speed and diameter at each operating point were also determined. All work was performed at the LLL Geothermal Test Facility.

Successful bladeless pumps have total admission and optimum blade spacing. We have every reason to believe that this statement would also be true for the bladeless turbine. The turbine tested had neither, and its measured performance was poor.

Steidel, R. F., Jr., Weiss, H., and Flower, J. E., *Performance Characteristics of the Lysholm Engine as Tested for Geothermal Power Applications in the Imperial Valley*, Lawrence Livermore Laboratory, Rept. UCRL-80151 (1977).

The paper describes recent performance tests of the Lysholm engine conducted at the Lawrence Livermore Laboratory. The Lysholm engine is a rotary displacement engine, which can and does use the total flow of the geothermal fluid as it comes from a well.

Generally, geothermal fluids at the wellhead are a mixture of liquid and vapor, with quality (vapor fraction) up to 40%. For most liquid-dominated geothermal resources, the vapor fraction is considerably less than 40%. The Total-Flow process consists of using a mixed-phase expander to expand the total brine-steam mixture from wellhead conditions to atmospheric or condensing conditions to drive an electrical generator. As a thermodynamic process, Total Flow has the potential for using significantly more of the available energy output per pound of fluid, as contrasted with other processes that either transfer heat energy to a second fluid, or use only the vapor fraction and discard the liquid. In our test, the quality was varied between 8 and 27%.

Our results indicate that the Lysholm engine can operate well with a two-phase mixture as a working fluid. The maximum observed engine efficiency was 53% at 8000 rpm, with an inlet pressure of 190.6 psia, 22.2% quality, and an exhaust pressure of 30.6 psia. The best results were observed at the higher speeds and with exhaust to an above-atmospheric back pressure.

Weiss, H., and Shaw, G., *Geothermal Two-Phase Flow Test Facility*, Lawrence Livermore Laboratory, Rept. UCRL-76409 (1975).

A new facility at the Lawrence Livermore Laboratory provides steam-water mixtures of variable pressure, temperature, and quality for mechanical testing of turbine nozzles and blades designed to operate in two-phase flow from geothermal brine reservoirs. Experimental stations in this facility are instrumented to accommodate static tests of nozzle and blade designs, dynamic tests of turbines, tests of materials resistance to water-droplet erosion, and tests of equipment and techniques for characterizing working fluids in the field.

Weiss, H., Steidel, R., and Lundberg, A., *Performance Test of a Lysholm Engine*, Lawrence Livermore Laboratory, Rept. UCRL-51861 (1975).

The Geothermal Energy Program at the Lawrence Livermore Laboratory emphasizes energy conversion by means of the Total-Flow process. One candidate for energy conversion is the Lysholm engine (also known as the helical rotary screw expander).

Recent performance tests conducted by LLL in its Geothermal Test Facility on a Lysholm engine yielded 49 data points. Maximum engine efficiencies were 49% at 16 kW for 3000 rpm, 53% at 23 kW for 4000 rpm, and 55% at 30 kW for 5000 rpm. A steam-water mixture was examined that varied in vapor fraction from 11.6 to 34%.

It is concluded that the Lysholm engine can operate effectively on a two-phase mixture approximating that from a geothermal resource, and that it is a viable candidate for the Total Flow energy conversion process.

Wright, G. W., *Comparative Cost Analyses: Total Flow vs Other Systems for the Salton Sea Geothermal Resource*, Lawrence Livermore Laboratory, Rept. UCRL-52589 (1978).

Cost studies were done for Total-Flow, Double-Flash and Multi-Stage Flash Binary systems for electric energy production from the Salton Sea Geothermal Resource. The purpose was to provide the Division of Geothermal Energy of the Department of Energy with information by which to judge the merits of continuing the development of the Total-Flow system. Results of the studies indicate that the Total-Flow and Double-Flash systems are estimated to have capital costs of 1135 and 1026 \$/kW respectively, and energy costs at 40.9 and 39.7 mills/kWh respectively. Considering the fact that no system has been tested in the Salton Sea resource with its high content of dissolved minerals, the accuracy of the cost estimates cannot be much better than $\pm 20\%$. Thus, the Total-Flow and Double-Flash systems are not distinguishable on a cost basis alone. The Multi-Stage Flash Binary system with capital cost of 1343 \$/kW and energy cost at 46.9 mills/kWh, is within the expected error range, but is significantly more expensive.

Furthermore, if resource utilization and the resultant savings of oil are relevant topics in the total analysis of costs, the Total-Flow system, if fully developed, could save 30% more oil than the Double-Flash system, worth \$3.5 billion at 1978 prices for oil.

This report also includes a discussion of some of the pitfalls in comparing cost estimates and the resultant costs of electrical energy.