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Lawrence Livermore Laboratory

AN OVERVIEW OF THE GEOTHERMAL ENERGY DEVELOPMENT PROGRAM AT THE LAWRENCE LIVERMORE LABORATORY

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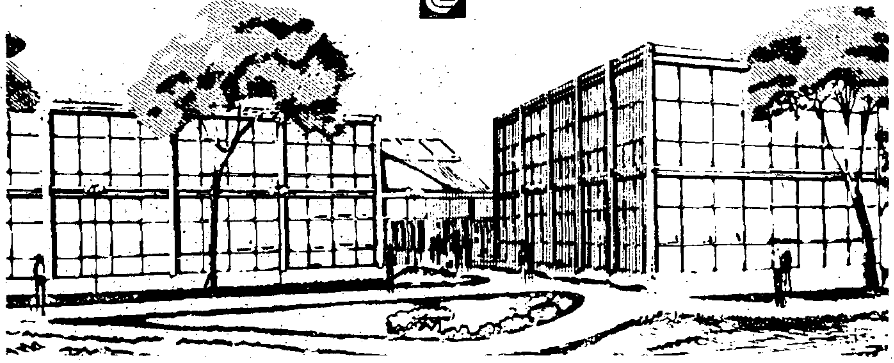


DISCLAIMER

Preface

This testimony is submitted at the request of the State Geothermal Task Force for presentation at the April 29, 1977, hearing in San Diego, California. The subject matter enclosed is an overview of the status of the Geothermal Development Program at the Lawrence Livermore Laboratory and 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.

I. Background

At the Lawrence Livermore Laboratory (LLL), interest in geothermal energy started in the early 1960's as part of the Plowshare Program and because of associated work in the Earth Sciences. In 1972, LLL established programs to develop new non-nuclear energy technologies in response to urgent national needs to develop alternate energy supplies to achieve energy independence in the 1980's. As part of this effort, the LLL Geothermal Development Program began in the latter half of CY1973 for development of Advanced Technologies with specific application to the high-temperature, high salinity (HT/HS) resource in the Imperial Valley of California. The program is currently supported by the U. S. Energy Research and Development Administration (ERDA).

This program consists generally of development of advanced conversion systems, with strong emphasis on a system approach to find solutions of the problems of scale formation, corrosion/erosion of materials, spent brine disposal and solids handling, and development of reliable, efficient energy conversion systems with emphasis on development of the Total Flow concept.

Much of this work has general applicability to other resource utilization concepts and possibly to other resource areas. Consequently, in late CY1975, LLL established - by ERDA request - an Industrial Support Program to provide technical assistance to joint ERDA/industry projects to utilize the HT/HS resources in the Imperial Valley, California. The LLL program is now in transition from emphasis on applied research to one of development of and involvement with field programs.

II. Project Rationale

A key element in the rapid commercialization of geothermal energy is the early development of the hydrothermal resources. They are abundant, their exploitation represents the next technological step, and systems developed for hydrothermal utilization will likely find application to other potentially larger resources such as the geopressured and hot, dry rock forms.

Of particular significance are the identified hydrothermal resources in the Salton Trough geologic province. In this region there are six identified known geothermal resources areas (KGRA) in the U. S. territory alone (Figure 1). The entire region is, perhaps, the best known and characterized water-dominated hydrothermal resource in the North American Continent. Among the six U. S. KGRA's, the Salton Sea Geothermal Field (SSGF) in the Salton Sea KGRA (SSKGRA) is the best known - 23 wells have been drilled and produced, geophysical data have been gathered, and considerable private funds have already been invested in terms of capital for wells and costs of lease holdings. Hence, in terms of setting priorities for accelerating development of geothermal energy, the Salton Trough resources appear to be prime candidates with the SSGF leading as potentially the largest recoverable energy source.

According to the U.S. Geological Survey, Circular 726, published in 1975, the SSKGRA is the highest temperature, third largest, and capable of producing 83,600 MWe-yrs of electric energy. This is 10% of the total of the large high temperature hydrothermal resources in the U.S. However, the two largest (Long Valley and Coso Hot Springs) are undrilled, and estimates of their energy productivity are, by comparison, more speculative. If these two are dropped from the list of candidates for early development, then the SSKGRA could provide up to 17% of the recoverable energy from the total U. S. hydrothermal resources. Further, it is estimated that over half of the recoverable energy from the Salton Trough resides in the SSKGRA.

It should be recognized that these estimates, like all estimates, are speculative at this time. However, the order of magnitude is generally accepted as representative of the resource potential. There are many site specific factors such as presence of dissolved solids, available condensing temperatures, system conversion efficiencies, and costs which will influence the ultimate energy production. In summary, the reasons for interest in the SSKGRA are:

- Resource is best known, and located close to major West Coast load centers.
- Has the potential for producing 83,600 MWe-yrs of electric energy.
- Highest temperature (300C) resource; hence, potentially lowest energy costs.

- R&D and new technologies are needed for utilization due to presence of high content of dissolved solids, as much as 30% by weight in some areas.

This latter point is especially important since it provides one of the main reasons for LLL involvement. Probably over 90% of this region is already under private lease, but one of the major barriers preventing rapid development is the serious technical difficulties posed by the presence of large quantities of total dissolved solids (TDS). An example of the amounts and complexity of the TDS are shown in Figure 2. Scale formation and control, corrosion, solids handling and control, efficient reliable conversion methods, and spent brine disposal are all problems compounded by the presence of high temperature and high TDS and the resultant constraints on choices of conversion systems for utilization of this important resource.

Objectives

The LLL Geothermal Energy Program is directed specifically toward solution of these problems unique to the SSKGRA. Hence, the basic objective of the program is to carry out the research and development necessary to produce the needed advanced technologies, and to reduce the technical risks sufficiently to encourage and accelerate commercial development. Hence, the program is structured to include strong industrial involvement through technology transfer and joint ventures in time to stimulate commercialization in the 1980's. To accomplish this, the program consists of two basic activities (Figure 3).

1. Technology Development

This consists of an interdisciplinary approach to develop efficient, reliable, brine tolerant conversion systems uniquely designed for utilization of the high temperature brines of the SSKGRA where the TDS may be as high as 30% by weight. The emphasis is on development of the Total Flow conversion system coupled with solution of the problems of scale formation, corrosion/erosion, and brine management.

2. Industrial Support

The purpose is to provide technical assistance to joint ERDA/industry geothermal utilization programs to develop the SSKGRA. Emphasis is on applying the expertise and results in the technology development activity to provide technical support, as needed, to help solve operational problems, and to carry out complementary applied research to broaden opportunities for solution of potential problems. Current involvement consists of working with the San Diego Gas and Electric Co./ERDA flash/binary project. A summary of some of the activities are shown in Figure 4.

III. Program Status

A. Technology Development

The three basic conversion methods are shown schematically in Figure 5. The Total Flow System (TFS), in principle, consists of expanding the total wellhead brine-steam mixture directly through a mixed phase expander to sub-atmospheric condensing conditions for maximum energy extraction to drive an electric generator. Based on fundamental thermodynamic principles, a direct expansion from wellhead to sink condition has the potential for conversion of the greatest fraction of the available energy. For example, regardless of the number of stages of separations used in the Flashed Steam System, there will always be some useful energy discarded with the separated liquid in the last flash stage. The fourth method consists of combinations of the first three basic methods. Hence, the term hybrid system. Since several combinations are possible a single example is not shown. One example is the flash/binary system currently under test by the joint ERDA/San Diego Gas and Electric Company project. Another example will be discussed later.

Although the Total Flow concept is simple, and is the most direct means of geothermal energy conversion, it will require development of efficient, reliable machines for two-phase expansion of the wellhead fluid. If successfully developed, however, it has the potential for the highest electrical energy output per unit mass of wellhead fluid. This will result in a corresponding reduction in number of wells and, hence, initial capital costs. In addition, because of inherent design simplicity, there are increased opportunitites for solution of the serious scaling and chemistry problems associated with high

TDS brines, and perhaps more importantly, reduction in capital costs of conversion systems.

Recognized at the start as a high risk activity, but with this potentially high payoff, four problem areas can be identified: (Figure 6)

- the chemistry of the brine with regard to scale and solids formation and disposal of cooled fluid
- the materials required for successful performance of the conversion system in the brine environment
- the energy conversion system
- establish economic feasibility and transfer of technology to industry to accelerate commercialization

The LLL Geothermal Program is an interdisciplinary effort consisting of conversion engineering, brine chemistry and materials, and earth sciences to provide an integrated approach to resolve these technical issues. The basic program strategy is shown in Figure 7. Thus far, development and testing of conversion devices has been purposely limited to laboratory work while scale control and materials work has been primarily carried out in the field using real brines. As shown, the plan is to join these two activities to produce a 2 MW prototype brine tolerant machine for field testing. Note that we plan strong industrial involvement as a start toward early technology transfer. If tests are successful, the next step would be the fielding of a pilot sized plant (probably about 10 MWe). At this point, LLL involvement would decline to a role of industrial support and finally phase out as commercialization proceeds. The following describes the work done to date in the two separate areas of brine chemistry and materials and conversion engineering.

1. Brine Chemistry and Materials Developments

With the exception of conversion engineering activities, the majority of the work is performed in the field using real brines for test and evaluation of scale control methods, materials for conversion systems, and solids and spent brine disposal techniques. Consequently, the results of this field test program will find broad application to all candidate systems for utilization of the HT/HS brines. For this reason, the current results are particularly significant.

Figure 8 shows a sample of the type of scaling that occurs when the HT/HS brines experience a temperature drop typical of that which would occur in a conversion device. The scale consists largely of silica interspersed with concentrations of heavy metal sulfides. There are several approaches to solving this problem: periodic cleaning, boundary layer treatment, and chemical modification of the brine. The approach we have selected to pursue is brine modification by acidification. Since it is known that acidification inhibits silica precipitation and also helps inhibit formation of the sulfides, addition of acid to the brine prior to the temperature drop through a conversion system should prevent scale deposition. The important unknowns are the effects of other elements, temperature, and the amount and type of acid needed. In order to investigate the feasibility of this approach, we are operating a test station (Figure 9), designed to test and evaluate acidification of the brine output from the well Magmamax #1 located at the San Diego Gas and Electric Company Geothermal Loop Experimental Facility near Niland, California. The LLL test station is used to test brine modification methods and evaluate materials resistance to erosion and corrosion.

During the last year we have established that scale deposition can be eliminated by acidification. Dropping the pH from 5.6 at the wellhead to 4.5 and below by addition of between 100-200 ppm of hydrochloric acid completely eliminates scaling in nozzles expanding brine from about 200°C to atmospheric conditions. Figure 10 shows one example of sectioned nozzles (made from Teflon) subjected to unmodified and modified brine. The control nozzle as shown, scaled rapidly at a rate of about .03 mm/hr while the other test nozzle subjected to acidified brine remained scale free.

Other test nozzles of titanium alloy (Ti-6A-4V) also remained clean with no signs of corrosion or erosion over the test period. A preliminary cost analysis shows that acidification by HCl costs about 1-2 mils per 100 lbs. of brine. This would be roughly equivalent to 1-2 mils/KW-hr added cost to the production of electric energy. These experiments are very encouraging and indicate that brine modification for scale control is technically feasible and appears also to be economically feasible.

It is also worth noting that acidification prevented scaling in the tubing leading up to the nozzles. Figure 11 shows sectioned tubing subjected to modified and unmodified brine. The tube carrying modified brine remained scale free. We are planning additional experiments to evaluate the effectiveness of acidification for keeping brine heat exchanger tubes from scaling, and hence, as a means for broadening the applicability of the Binary Cycle concept for utilization of those HT/HS brine reservoirs which may contain large amounts of non-condensable gases. In addition we will also evaluate acidification effectiveness on a small scale double flash system.

Another beneficial result of acidification is shown in Figure 12. Experimental evidence now exists that acidification delays the formation of and stabilizes the colloidal suspension of silica in the cooled brine. The bottle on the left is a sample of cooled unmodified brine showing a cloudy suspension of particulate solids. The other sample is of cooled acidified brine. The clarity of the fluid indicates that acidification has delayed the production of suspended solids. The important implication is that acidification has the potential for preventing plugging of reinjection wells by normally occurring suspended solids over long-term operation of a power plant.

Concurrent field tests of turbine blade materials subjected to high velocity acidified brine streams exiting from the test nozzles indicate that titanium alloys, particularly Ti-6Al-4V, are corrosion/erosion resistant. Figures 13 and 14 shows, respectively, a scaled model turbine blade subject to unmodified brine, and a scale free blade subject to modified brine. The latter also exhibited no signs of corrosion or erosion. Although the test durations were generally less than 100-hours, the results are encouraging since they indicate that the titanium alloys are promising corrosion/erosion resistant materials for Total Flow turbine applications.

Corrosion rate tests have been run on iron based alloys for general power plant use. The results (Figure 15) indicate that alloying with chromium and molybdenum can reduce the corrosion rate significantly. The relative cost index shows that the costs of raw materials would, however, increase as expected.

An alternative approach being investigated is the use of prescaling a small amount prior to acidification. Essentially, this amounts to purposely allowing a thin layer of scale for form on plant piping and brine handling equipment to act as a protective coating. Figure 16 shows some preliminary measurements on corrosion rate on iron specimens before and after acidification.

As shown, the corrosion rate can be reduced by prescaling. Yet another alternate approach is the use of liners in the brine handling piping.

Further work needs to be done to more precisely evaluate these approaches, but all the work done to date indicates that long-term utilization of the HT/HS brines may be possible. Scale control by acidification is technically feasible and appears to be economically feasible as well, we have identified promising corrosion/erosion resistant materials for turbine applications, and there appears to be promising approaches to reducing corrosion to acceptable limits in the balance of a plant. In addition, acidification is a possible means of reducing suspended solids production in the cooled brine and thereby a means to insuring the viability of long-term reinjection. These conclusions are based on the limited field tests completed to date, and may change as more data is gathered. Additional field tests are planned to explore, in more detail, acidification and materials response under a wider range of conditions to further verify these initial results or to define limits of applicability.

2. Total Flow Expander Development

The potential performance of a Total Flow process is shown in Figure 17. It should be emphasized here that this comparison is based only on thermodynamic considerations, and the assumptions used for the respective engine efficiencies of the systems shown. To gain the full performance advantage shown, Total Flow expanders should have engine efficiencies of 70% - a

performance as yet unrealized. Even if this 70% goal cannot be reached, the Total Flow concept remains promising because of its simplicity, and hence potentially lower capital costs. It should also be noted that Figure 17 illustrates comparison of processes, not machines. It is not yet known if the same Total Flow expander can work at 70% efficiency over the working fluid temperature/enthalpy range shown. It may be that different expanders will be needed at the lower temperature range than that at the higher range. At this time, more research and testing of candidate expanders over all working fluid conditions needs to be completed before this basic question can be answered.

In order to gain the full advantages for the Total Flow process, it is also necessary to extract the maximum available energy from the wellhead product by expansion to as low a backpressure as possible. It can be shown that 40% of the useful work is obtained by expansion below atmospheric pressure to a typical sink condition of 49°C (3.5" Hg). Volume expansion ratios of the fluid range from about 300 (for 300°C fluids) to about 70 (for the 177°C fluids). Consequently, the Total Flow expander must be capable of complete expansion to recover the available energy, and must also be able to accommodate large volume flow rates as well. In addition to these physical and thermodynamic requirements, candidate expanders must be able to withstand the presence of significant quantities of dissolved solids. Precipitation of these solids during expansion can cause rapid formation of scale, and the corrosive and erosive actions of the brines will be major problems. These will likely require design simplicity, particularly with respect to minimizing the number of moving parts and contacting surfaces, ease of maintenance, and long-term reliability. A single stage expander is most desirable, but staging may be workable in some cases. Figure 18 lists the basic classes of expanders which we have considered for use in the Total Flow process.

Based on our present understanding of all requirements to utilize the HT/HS brines, and particularly the need for inherently simple, compact machines, pure impulse devices have significant advantages. Because of geometric considerations the axial flow machine currently appears as a promising configuration for the Total Flow application. Figure 19 is a simplified view of an axial flow impulse turbine, and also illustrates the basic elements of other impulse machines. Expansion of the two-phase wellhead product through a converging-diverging nozzle converts the brine thermal energy at high wellhead pressures at 2 to kinetic energy in the form of a high velocity fluid stream at the backpressure 3'. The nozzle velocity coefficient, η, is the ratio of actual velocity output to the ideal velocity from an isentropic expansion from 2-3. The wheel efficiency, e_w, is a measure of the ability of the wheel to convert the fluid kinetic energy to shaft work. It is a complex function of blading geometry, turbulence, fluid friction, entrance and exit losses, fanning losses, etc. The turbine engine efficiency, e_t, then will be $\eta^2 e_w$, as noted. The factor η^2 represents the nozzle efficiency, or its ability to convert thermal energy into kinetic energy. The wheel efficiency, e_w, represents the ability of the turbine rotor to efficiently transfer the momentum of the high velocity fluid stream exiting from the nozzle to produce shaft work. When viewed in this manner, it is clear that the basic problem of designing an efficient Total Flow impulse turbine is twofold: development of efficient nozzles for expansion of two phase fluids, and development of efficient blading for momentum transfer. Considerable work has already been completed in the laboratory to develop and test nozzles and to test blade configurations. We have achieved the necessary nozzle efficiencies and the next step is to develop a technique for water droplet reduction from the present range of about 6 microns to less than 2 microns. This is necessary for efficient transfer of momentum through the blades.

We have recently completed laboratory tests of a Total Flow impulse turbine system. A single stage, axial flow, impulse turbine (Figure 20) has been designed and tested at reduced output, since only a single nozzle was used - about 5% admission. A single nozzle was used for the machine because of limited flowrate capabilities of the test facility.

In order to simplify construction, shorten development time, and to minimize costs, the rotor was designed with integral blades and was fabricated from a 7075-T6 aluminum forging. Aluminum was chosen for its high strength-to-weight ratio and machinability. An electroless nickel plating was applied to the blade surfaces for water droplet erosion protection. The plated rotor is not intended for brine exposure. It was designed to have sufficient life only for the laboratory testing program.

The operating conditions used for the performance testing were selected to be representative of the thermodynamic conditions of well outputs from the reservoirs of the SSKGRA (Figure 21). The basic purpose of the test was to provide operating performance data to verify analytical methods for design of a full admission machine and for predicting the effects of droplet size on performance. Figure 22 shows the comparison of the test data with the prediction for single nozzle performance. Excellent agreement was obtained, and the analytical model can now be used to estimate the performance of a full-admission machine. As shown, the existing design performance lies between 38% to 48%. Most significant, however, is the conclusion that the original research goal of 70% engine efficiency remains credible, and is achievable if water droplet sizes can be reduced to less than 1 micron. The power output with a single nozzle was equivalent to 33 KW, the full admission machine would produce about 1400 KW; and based on this test data, an advanced design would produce about 2300 KW.

A useful manner of viewing system effectiveness is to express the performance in terms of the resource utilization rate (water rate). This is the number of pounds of wellhead fluid to produce a kilowatt hour of electric energy, (i.e., lb/KW-hr). Figure 23 lists the performance potential of the Total Flow process as tested, and compared with the calculated performance for the Flashed Steam System operating over the same set of inlet and exit thermodynamic conditions. Note that all systems are compared on a gross output basis - i.e., exclusive of plant parasitic loads. As shown, the Total Flow impulse turbine is already thermodynamically competitive with a single flash system, but an advanced design has the potential for significant improvements. There are two important implications. First, a decrease in water rate allows a corresponding decrease in number of wells, which in turn, decreases the capital investment for well costs. Second, the simpler Total Flow system offers the additional potential for reduced costs of the conversion equipment.

3. Hybrid Systems

It is recognized, however, that because of the wide variation of reservoir and site specific conditions, it is unlikely that any one concept or system will find general application. Instead, the future will probably see several different conversion systems, each tailored to the specific site conditions. Consequently, combination of the basic concepts of flashed steam, binary cycle, and Total Flow will also be needed. Specifically, we are investigating the use of Total Flow expanders in combination with the double flash system (Figure 24) to produce a greater net power output. Some preliminary calculations, and some initial component tests, indicate that it may be possible to increase the gross power output by about 15%. This work is only in the initial stages; but by this time next year, if support is continued, we should have sufficient data to draw more definitive conclusions.

IV. Commercialization and Technology Transfer Plans

As noted earlier, the HT/HS reservoirs of the Salton Sea Geothermal Field, are a large energy resource, but not yet commercially useful because of the technical problems largely associated with the chemistry of the brine. The LLL program is specifically directed toward solution of these problems by carrying out the necessary applied research, and to develop and field test small-scale prototype advanced conversion systems. The basic purpose is to prove technical feasibility by gathering sufficient supporting data to encourage industrial participation as a start toward commercialization of the concepts. This involves several elements.

The first is transfer of information as it is developed through publications, participation in technical conferences, hosting industrial visitors to LLL to see our work, and through LLL hosted program reviews. We publish, for wide distribution, about 30 publications per year. Attached is a list of publications released during FY77 to illustrate the breadth and type of information flow. Note the inclusion of papers recently accepted for presentation at the upcoming meeting of the Geothermal Resources Council. In addition, we host, on the average, about two industrial visitors per week for informal briefings and site visits. Recently, we held our first large program review on December 14, 15, 16, 1976, during which about 80 representatives of industry attended to hear detailed technical briefings on the program status and results. Their comments and participation in the program were encouraged.

The second is directed participation of industry through subcontracts to help with the program by carrying out technical and economic studies, design and fabrication of components for test, and involvement in our field test activities. During FY76, we spent approximately 17% of our budget in outside procurements of this type. This activity is a form of technology transfer in the sense that industrial suppliers become directly aware of some of the advanced concepts under development. This activity will continue throughout the program.

The third will be the involvement of industrial partners to take on the design, fabrication, and field testing of the small-scale prototype advanced systems. We are currently starting preliminary discussions with turbine manufacturers and engineering firms to lay out plans for design and development of a 2 MW brine tolerant systme for field testing. Depending on the results of our FY77 tests, this first step toward transferring the technology to industry will begin in FY78. Industrial development schedules indicate that a complete 2 MW system might be fielded by FY80.

The fourth, and most important, element is the final step toward commercialization. If field tests of the 2 MW prototype are successful, the option of proceeding with a 10 MW size pilot plant is opened. This, of course, should be primarily an industrial acitivity with the LLL role diminished to one of technical support and assistance. Successful pilot plant operation should then lead to full commercialization by the industrial sector.

Summary

A summary of the major program results are listed below:

- Designed and operated a Geothermal Test Facility at LLL to simulate the thermodynamic conditions of any hydrothermal well output. This facility is used to test expander components, develop methods for measurement and characterizing two-phase flow, and is available for testing of Total Flow expanders with outputs up to about 100 KW.

- Developed and tested a single stage Total Flow impulse turbine system with subatmospheric condensing conditions. The results indicate that the existing design is capable of working at 38-48% engine efficiency. Analysis of the performance also indicates that the original research goal of 70% engine efficiency remains credible and may be achievable. In our opinion, this moves the Total Flow concept from a far-out to a near-term technology.
- Designed and operated a Geothermal Field Test Station for brine chemistry and materials studies under field conditions at Magmamax No. 1.
- Established technical and the potential economic feasibility of scale control by acidification of the HT/HS brines.
- Established that brine acidification can stabilize the colloidal suspension of solids in cooled brine, preventing particulate precipitation. This has important implications regarding long-term viability of reinjection without plugging the formation.
- Identified and field tested promising corrosion/erosion resistant alloys for use in conversion systems, and specifically that titanium alloys are promising corrosion/erosion resistant turbine blade materials.
- Established and developed techniques for brine sampling, brine characterization, scale surveillance, and field tests of materials.
- Developed analytical techniques for advanced two-phase turbine design, two-phase flow, brine chemistry modeling, and multi-well reservoir modeling for production/injection reservoir management.

These results are encouraging, and lead to the conclusion that the Total Flow process will emerge as a reality in some form for utilization of water dominated resources. Figure 25 is one possible conceptual configuration based on the impulse turbine as the conversion element. The above results indicate that this method, as originally conceived, is moving from the conceptual stage toward reality.

Publications Released in FY76T and FY77

1. "Investigation of Heat Exchanger Flow Arrangement on Performance and Cost in a Geothermal Binary Cycle", W. H. Giedt, June 1976. (Presented at the Eleventh Intersociety Energy Conversion Engineering Conf., State Line, Nevada, Sept. 12-17, 1976.
2. "Helical-Rotor Expander Applications for Geothermal Energy Conversion", P. A. House, UCRL-52043, April 1976.
3. "Calculation of Two-Phase Dispersed Droplet-In-Vapor Flows Including Normal Shock Waves", W. Comfort, T. Alger, W. Giedt, C. Crowe, UCRL-78426, July 1976. Also presented at the Winter Annual Meeting of ASME, Dec. 5-10, 1976.
4. "Performance Test of a Bladeless Turbine for Geothermal Applications", R. Steidel and H. Weiss, UCID-17068, March 1976.
5. "Modular 5-MW Geothermal Power Plant Design Considerations and Guidelines", Rogers Engineering Company, UCRL-13635, May 1976.
6. "The LLL Geothermal Industrial Support Program in Chemistry and Materials for FY76T and FY77", R. Quong, UCID-17209, July 1976.
7. "Comments of the Use of 316L Stainless Steel Cladding at the Geothermal Niland Test Facility", A. Goldberg, UCID-17113, April 1976.
8. "Geothermal Material Studies", A. Goldberg, UCID-17261-76-1, March 1976.
9. "Geothermal Material Studies", A. Goldberg, UCID-17261-76-2, June 1976.
10. "Geothermal Material Studies", A. Goldberg, UCID-17261-76-3, Sept. 1976.
11. "The Economics of Geothermal Heat as an Alternate Fuel", D. Towse, UCRL-77031, Revision 1, June 1976.
12. "Preliminary Interpretation of Resistivity and Seismic Refraction Data from the Salton Sea Geothermal Field", P. W. Kasameyer, UCRL-52115, Sept. 1976.
13. "Thermal Depletion of a Geothermal Reservoir with Both Fracture and Pore and Pore Permeability", P. W. Kasameyer and R. C. Schroeder, UCRL-77323, August 1976. Submitted for publication in Journal of Geophysical Research
14. "Reservoir Engineering Report for the Magma/SDG&E Geothermal Experimental Site Near the Salton Sea, California", R. C. Schroeder, UCRL-52094, July 1976.
15. "Scaling Characteristics in the Geothermal Loop Experimental Facility at Niland, California", R. Quong, UCRL-52162, November 1976.
16. "Preliminary Interpretation of Resistivity and Seismic Refraction Data from the Salton Sea Geothermal Field", P. W. Kasameyer, UCRL-52115, Sept. 1976.

17. "On Soo's Equations for the One-Dimensional Motion of Single Component Two-Phase Flows", C. T. Crowe, UCRL-79053, January 1977. Submitted for publication in Journal of Multiphase Flow.

18. "Flow Characterization for Horizontal Two-Phase Flow", C. A. Calder, UCRL-52186, October 1976.

19. "Conservation Equations for Vapor-Droplet Flows Including Boundary-Droplet Effects", C. T. Crowe, UCRL-52184, December 1976.

20. "Interim Report on Performance Tests of a Total Flow Impulse Turbine for Geothermal Applications", W. J. Comfort, UCID-17411, March 1977.

21. "Status Report on the LLL Geothermal Program Results", A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff. To be published, April 1977.

22. "An Electrical Resistivity Survey of the Salton Sea Geothermal Field Imperial Valley, California", Geonomics, Inc. UCRL-13690, May 1976.

23. "Chemical Geothermometry: Accuracy of Subsurface Temperature Estimates for the Salton Sea Geothermal Field", L. B. Owen and T. D. Palmer, UCRL-78289, June 1976.

24. "Application of Thermal Depletion Model to Geothermal Reservoirs with Fracture and Pore Permeability", P. W. Kasameyer and R. C. Schroeder, UCRL-79108, January 1977.

25. "Petrologic Characteristics of a Portion on the Salton Sea Geothermal Field", John D. Tewhey. To be published, March 1977.

26. "Calculation of Brine Properties", G. L. Dittman, UCID-17406, February 1977.

27. "Geology and Potential Uses of the Geopressure Resources of the Gulf Coast", J. H. Howard, et al. UCID-17163, June 1976.

28. "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", L. Dengler, A. Piwinskii, UCID-17184, August 1976.

The following papers were submitted to the Geothermal Resources Council Meeting to be held May 9-11, 1977, San Diego, California.

29. "An Overview of the Geothermal Program at the Lawrence Livermore Laboratory", A. L. Austin, April 1977.

30. "Field Evaluation of Scale Control Methods: Acidification", J. Z. Grens, L. B. Owen, G. E. Tardiff, April 1977.

31. "LLL Geothermal Field Laboratory", F. Locke, J. Grens, April 1977.

32. "Properties of Siliceous Scale From the Salton Sea Geothermal Field", L. B. Owen, April 1977.

33. "Scale and Solids Deposition in the SDG&E/U.S. ERDA Geothermal Loop Experimental Facility at Niland, California", R. Quong, H. K. Bishop, J. H. Hill, April 1977.

34. "Calculation of Brine Properties", G. L. Dittman, April 1977.

35. "Chemical Modeling of Geothermal Systesm", D. D. Jackson, Aoril 1977.

36. "Solids Control for High Salinity Geothermal Brines", J. H. Hill, C. H. Otto,Jr., C. J. Morris, April 1977.

37. "Materials Evaluation for Geothermal Applications: Plant Materials", J. E. Harrar, R. D. McCright, A. Goldberg, April 1977.

38. "Materials Evalution for Geothermal Applications: TUrbine Materials", A. Goldberg, R. E. Garrison, April 1977.

39. "Geologic Characteristics of a Portion of the Salton Sea Geothermal Field", J. D. Tewhey, April 1977.

40. "Modeling Thermal and Flow Fronts for Arbitrary Well Arrays", P. Kasameyer, L. Thorson, C. McKee, April 1977.

SALTON TROUGH GEOTHERMAL PROVINCE

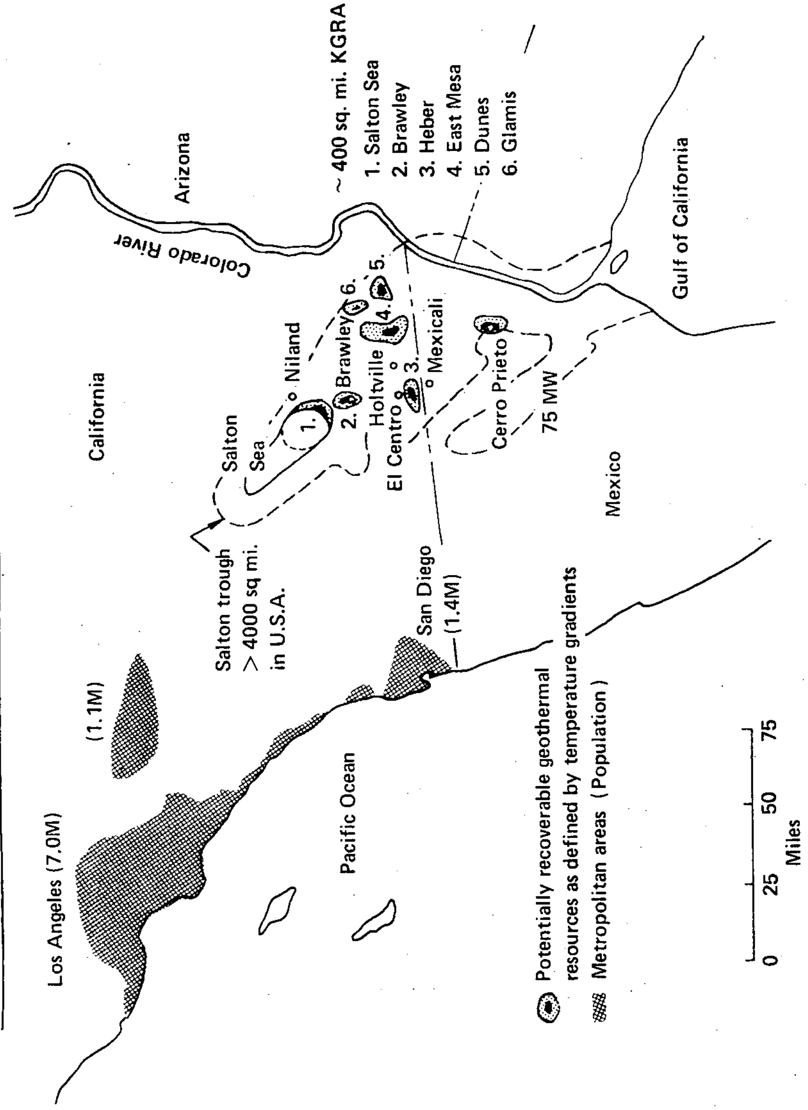


FIG. 1

FIGURE 2

TYPICAL BRINE COMPOSITIONS FOR THE SALTON SEA GEOTHERMAL FIELD

ANALYSIS	IID #1 (WHITE, 1968)	SINCLAIR #4 (HILL & MORRIS, 1975	MAGMAMAX #1 (HILL, 2976)
	CONCENTRATION (PPM)		
Na	50,400	58,650	37,800
K	17,500	13,345	7,740
Ca	28,000	26,308	18,000
Cl	155,000	154,700	108,900
Si	187	234	182
Fe	2,290	1,339	230
Mn	1,400	1,127	621
Zn	540	510	325
Pb	102	94	70
Cu	8	4	0.9
Ag	1.4	.6	- -
Al	4	3	<1
Ba	235	- -	106
Sr	400	- -	349
Li	215	- -	127
Rb	135	- -	58
Mg	54	66	72
Others I,B,Br,etc.)	<600	- -	- -
TOTAL SOLIDS:	258,973	265,630	187,000
NH_3	409	- -	300-600
CO_2	>150 (as HCO_3)	- -	1-2 WT%
H_2S	16	>13	10-30
RESERVOIR TEMP.	340°C	290°C	260°C

THE LLL GEOTHERMAL PROGRAM CONSISTS OF:

I. Development of advanced technologies for hydrothermal systems:

- Total flow concept
- Hybrid systems

II. Industrial support program:

- Technical support to specific joint ERDA/industry projects
- Applied research on potential problem areas
- Hybrid systems

FIG. 3

INDUSTRIAL SUPPORT PROGRAM

- Involvement with and technical assistance to joint ERDA/SDGE project near Niland
- Working in field and lab to help with:
  Brine characterization
  Effluent handling
  Plant operational surveillance for scale control and materials evaluation
  Data handling
  Reservoir production and reinjection strategies
- Opportunities to directly apply results of R&D produced on base program

FIG. 4

METHODS FOR ELECTRIC POWER GENERATION FROM GEOTHERMAL HOT WATER DEPOSITS

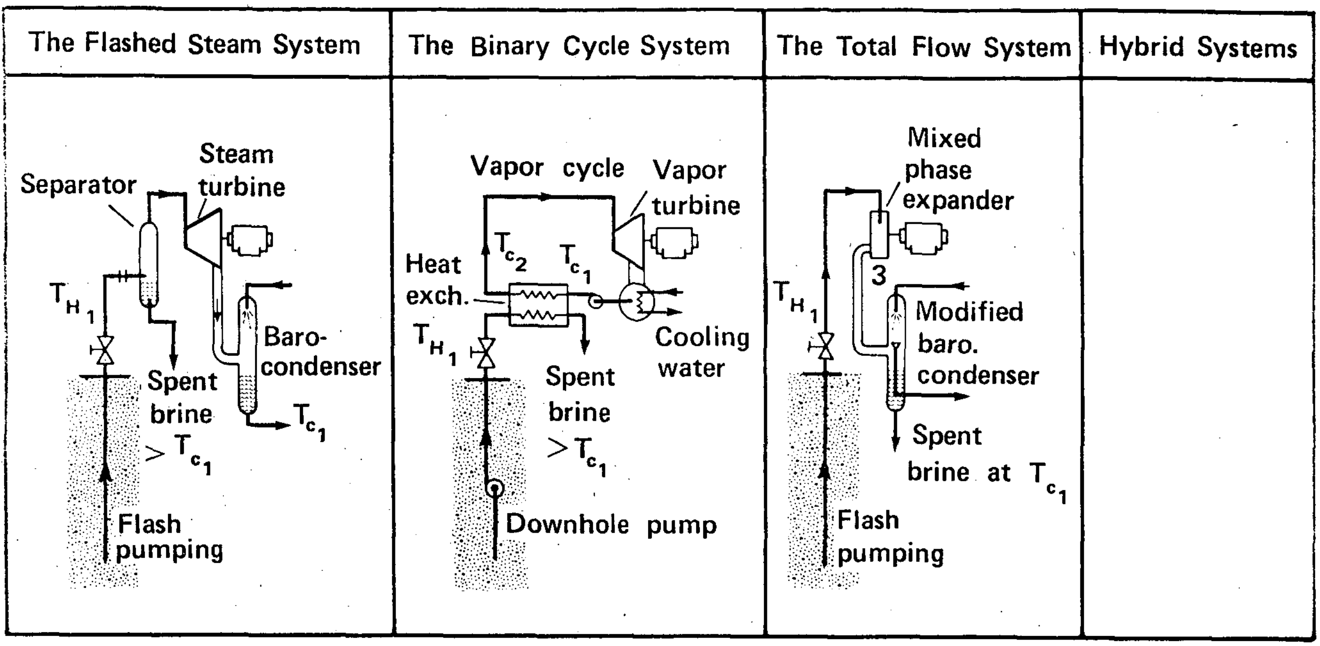


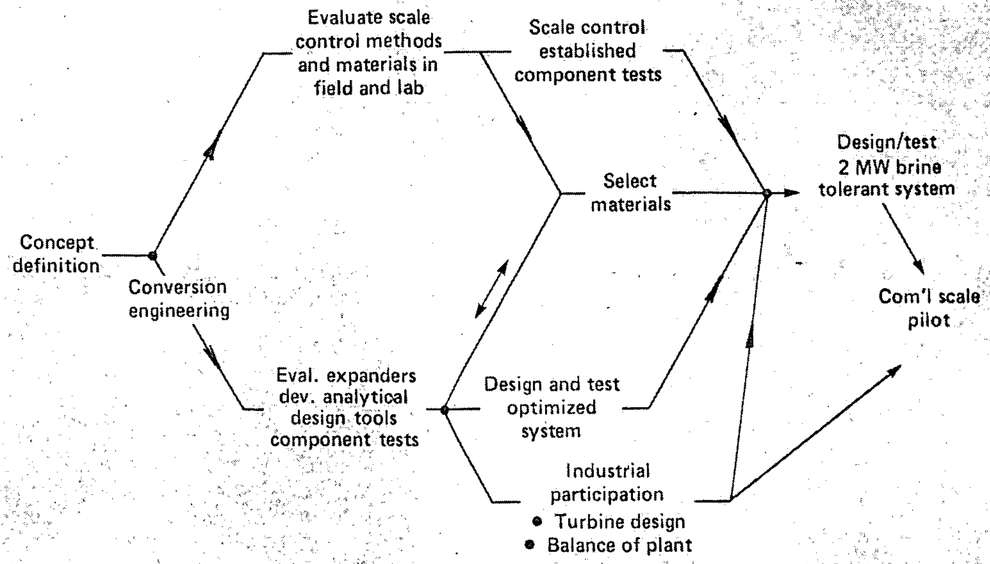
FIG. 5

KEY ISSUES

- Control of scaling
- Development of suitable energy conversion methods for:
  - Increased efficiencies
  - Utilization of HT/HS brines
  - Application to other resources
- Materials development for:
  - Erosion/corrosion resistant turbine
  - Low cost plant components
- Brine disposal strategy – injection
- Commercial applications
  - Economic feasibility
  - Transfer of technology

FIG. 6

STRATEGY FOR TOTAL FLOW SYSTEM DEVELOPMENT PROGRAM


Concept definition

Conversion engineering

Evaluate scale control methods and materials in field and lab

Eval. expanders dev. analytical design tools component tests

Scale control established component tests

Select materials

Design and test optimized system

Industrial participation
- Turbine design
- Balance of plant

Design/test 2 MW brine tolerant system

Com'l scale pilot

FIG. 7

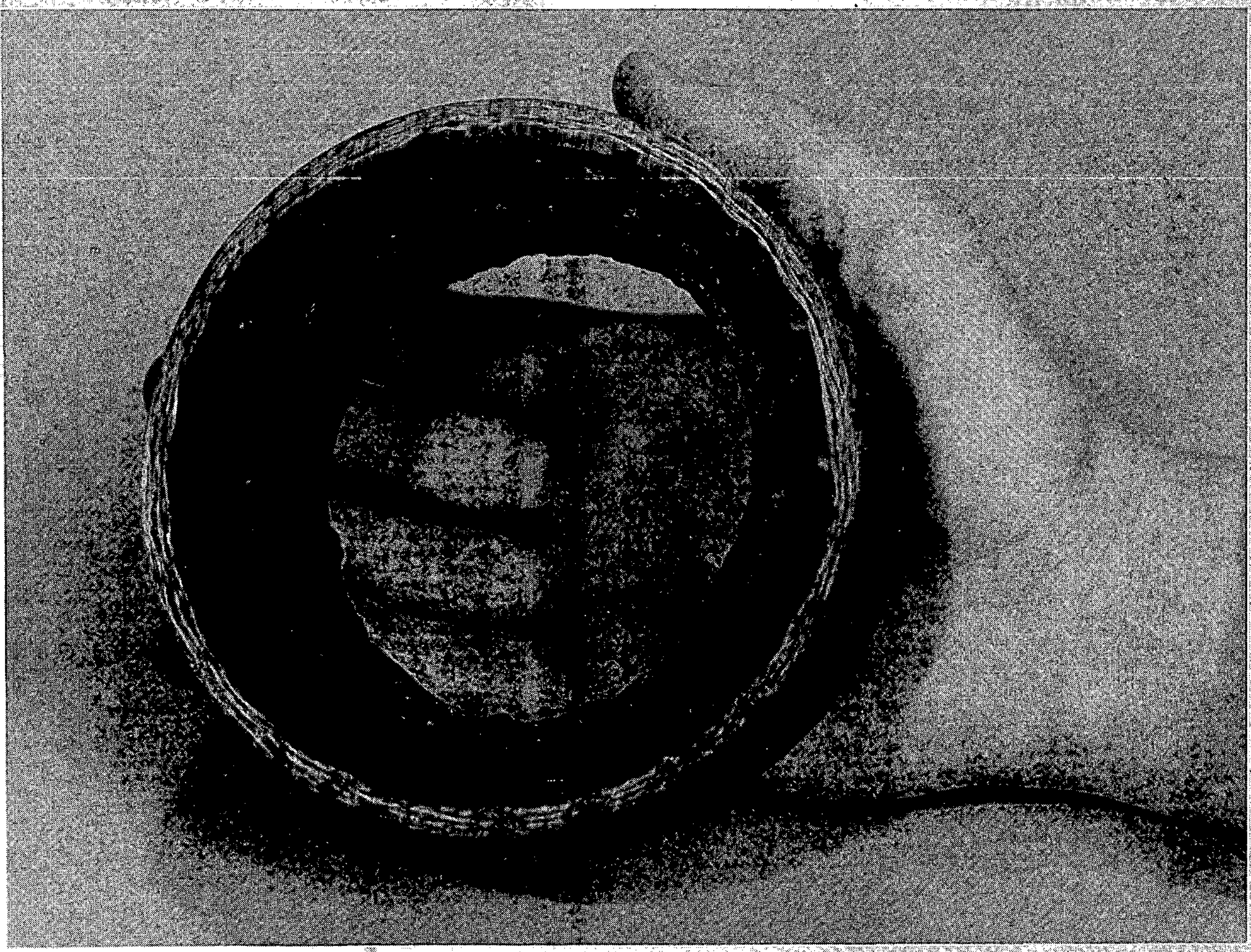


Fig. 8 - Typical Scale Formation

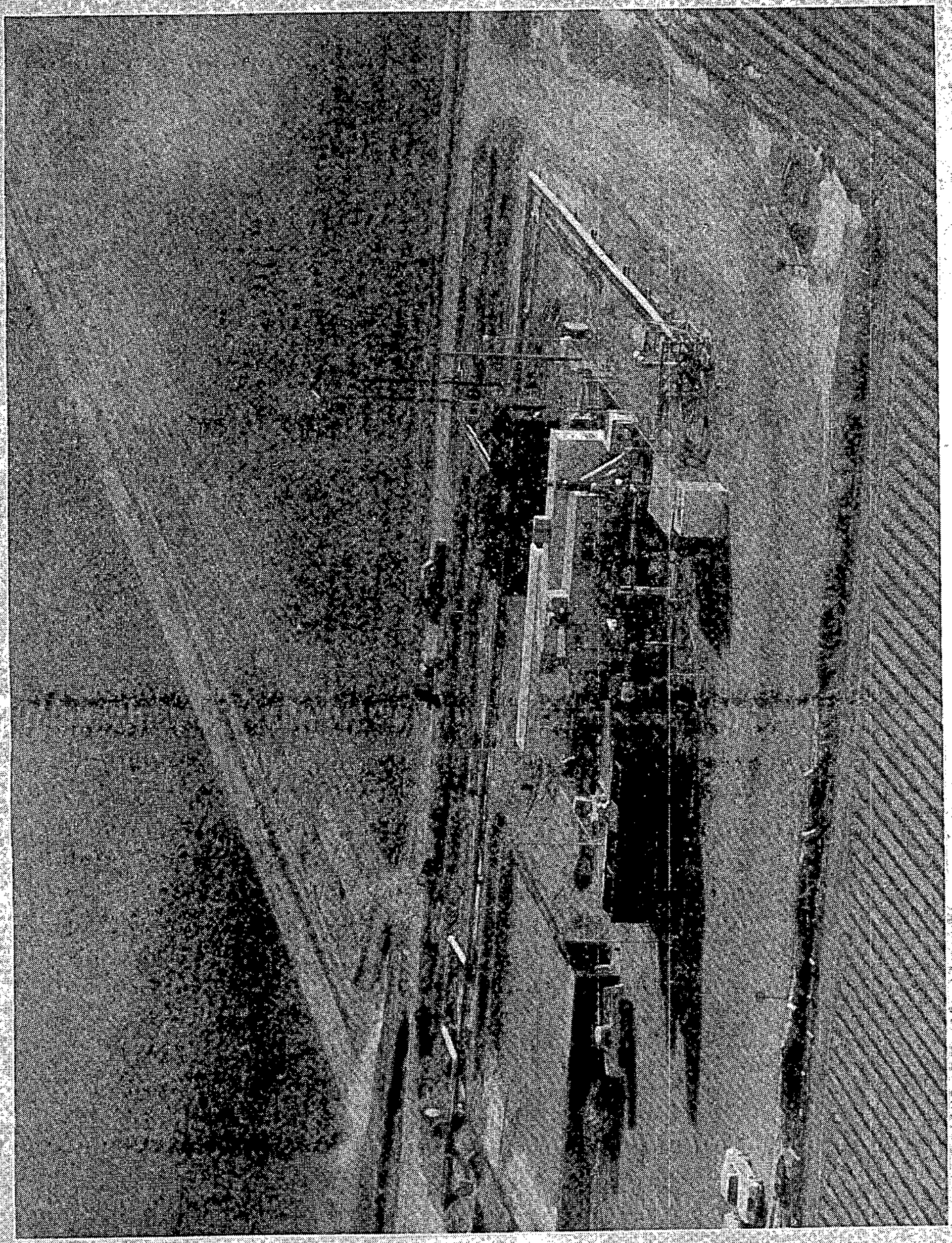


Fig. 9 - The LLL Geothermal Test Station

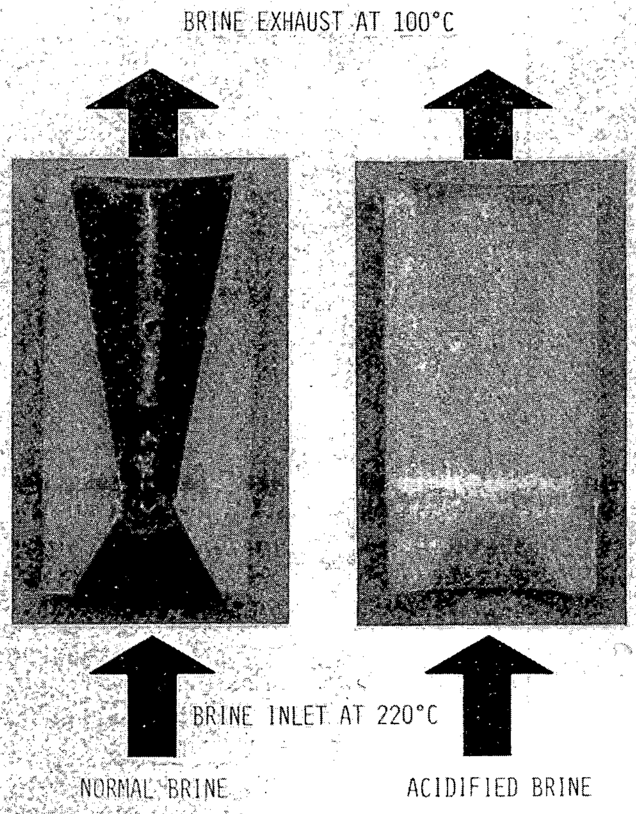


Fig. 10 - Effect of Acidification on Scale Formation

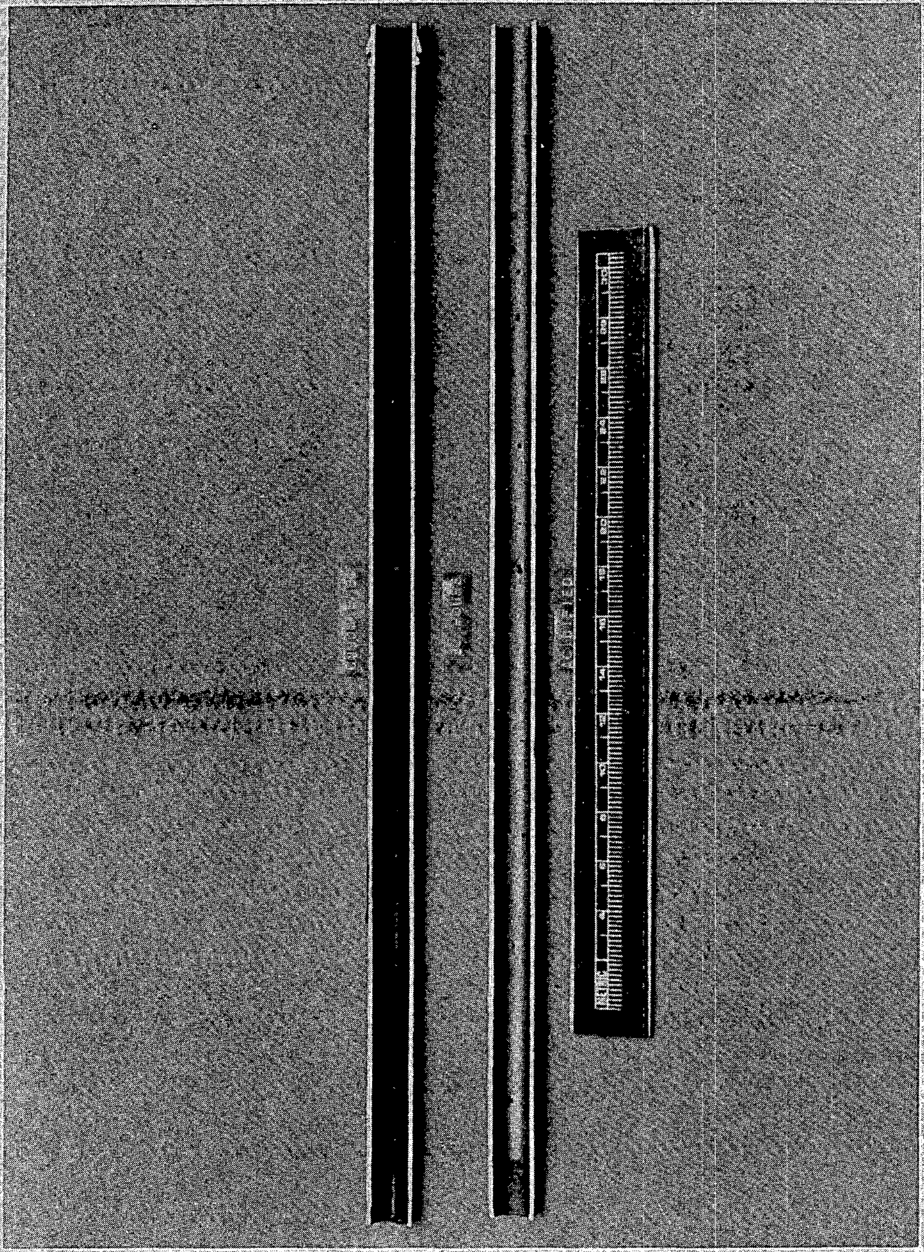


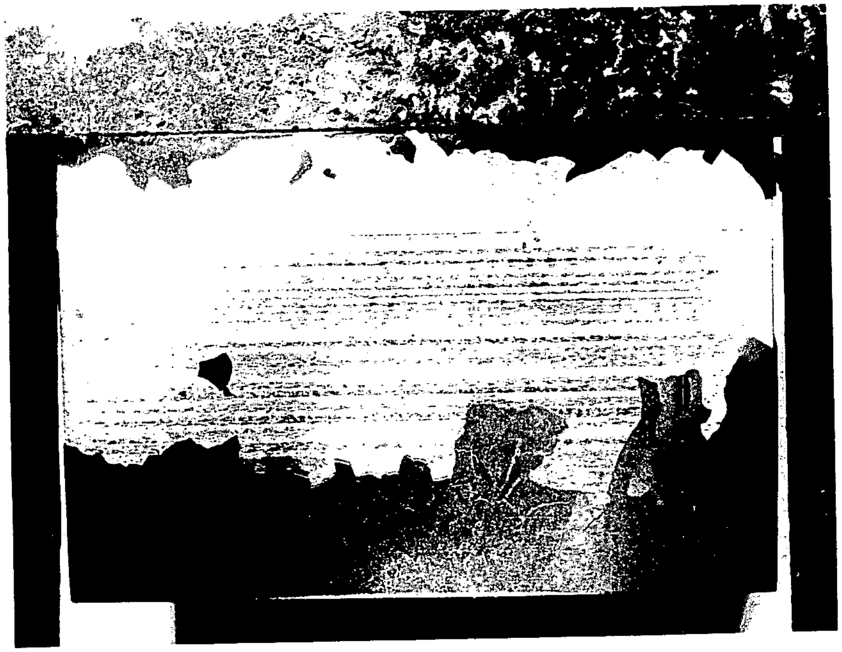
Fig. 11

NORMAL ACIDIFIED BEFORE COOLING

APPEARANCE OF BRINE AFTER COOLING

Fig. 12 - Effect of Acidification on Stabilization of Colloidal Silica

LM-w6-3



pH = 5.4

Fig. 13 - Simulated Turbine Blade Subjected to Flow of Unmodified Brine. Note Scale Formation.

LM-w6-2

pH = 3.1

Fig. 14 - Simulated Turbine Blade Subjected to Flow of Acidified Brine. No Scale Formation.

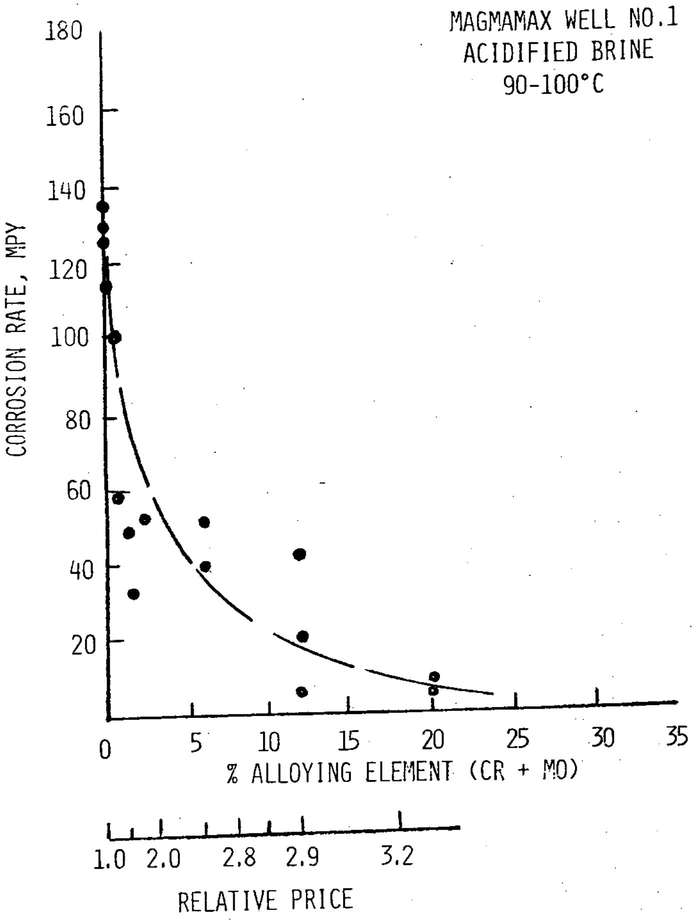


FIG. 15 EFFECT OF ALLOYING ON CORROSION RATE REDUCTION IN MILD STEEL

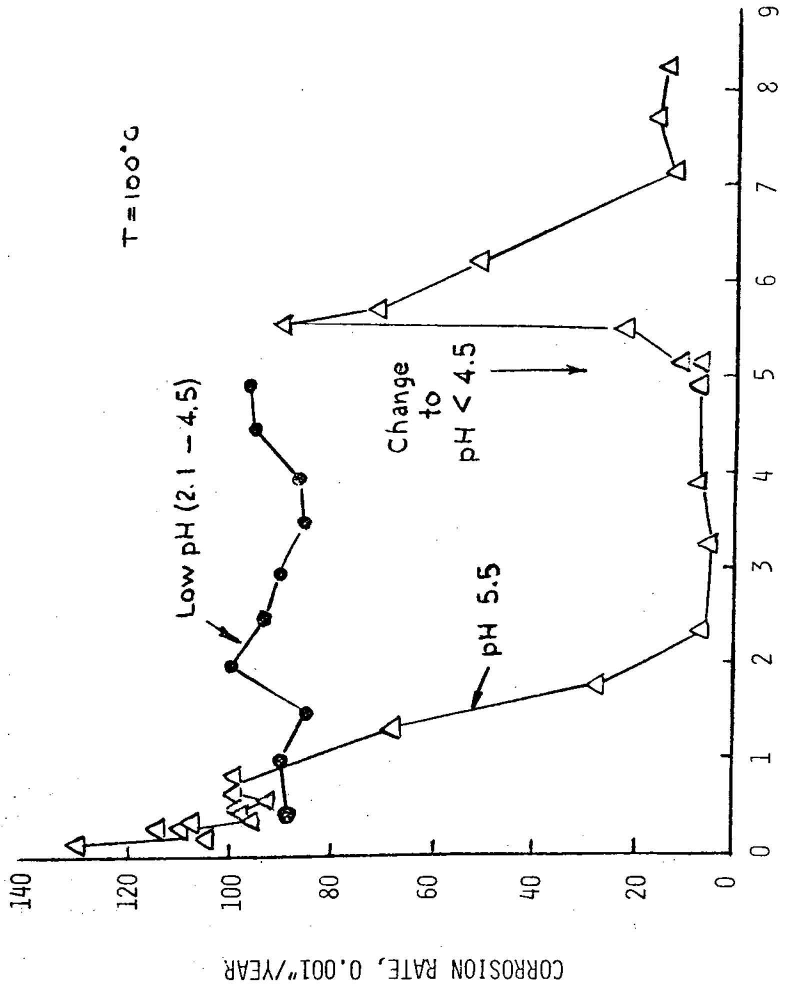


FIG. 16 EFFECT OF pH OF EFFLUENT BRINE ON CORROSION RATES OF MILD STEEL

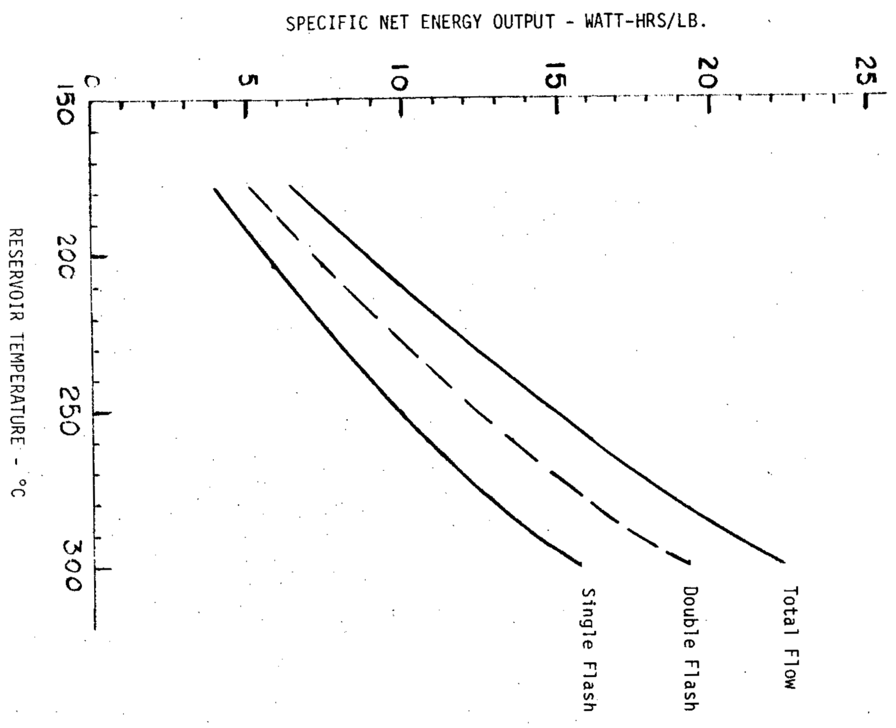


Figure 17 - Calculated Performance Comparison of Total Flow Concept With the Flashed Steam System

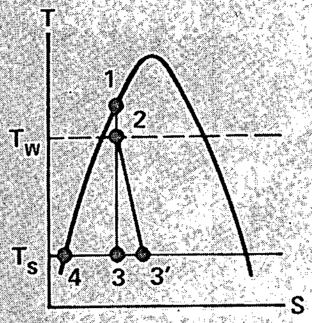
Single Flash - 75% Engine Efficiency
Double Flash - 75% Engine Efficiency, Both Stages
Total Flow - 70% Expander Efficiency
All Systems Assumed to have 10% Parasitic Losses
Non-Condensibles - 0%
Condensing Temp. = 49°C (120°F)
Calculations Based on Properties of Pure Water

CLASSES OF EXPANDERS FOR TOTAL FLOW APPLICATIONS

1. Impulse/reaction machines
   - Axial flow — Curtis/Rateau steam turbine
   - Radial inflow — Francis turbine and multiple disc drag turbine
   - Radial outflow — rotating nozzle (pure reaction). Hero's turbine multiple disc turbine — bladeless impulse or reaction drag turbine.
2. Positive displacement machines
   - Helical screw expander
   - Rotating oscillating vane machine
3. Impulse machines
   - Tangential flow — Pelton wheel, Re-entry turbine
   - Axial flow — DeLaval, Curtis turbine

Fig. 18

THE AXIAL FLOW IMPULSE TURBINE



$$\Delta h_s = h_2 - h_3$$
$$V_{3'} = \eta V_3 = \eta \sqrt{2g\,(h_2 - h_3)}$$
$$P_{OUT} = \dot{w}\,(h_2 - h_3)\,\eta^2 e_w$$
$$\therefore \eta^2 e_w = e_t$$

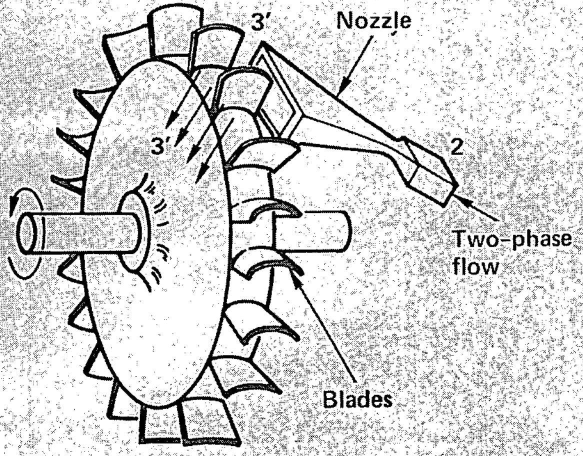


Fig. 19

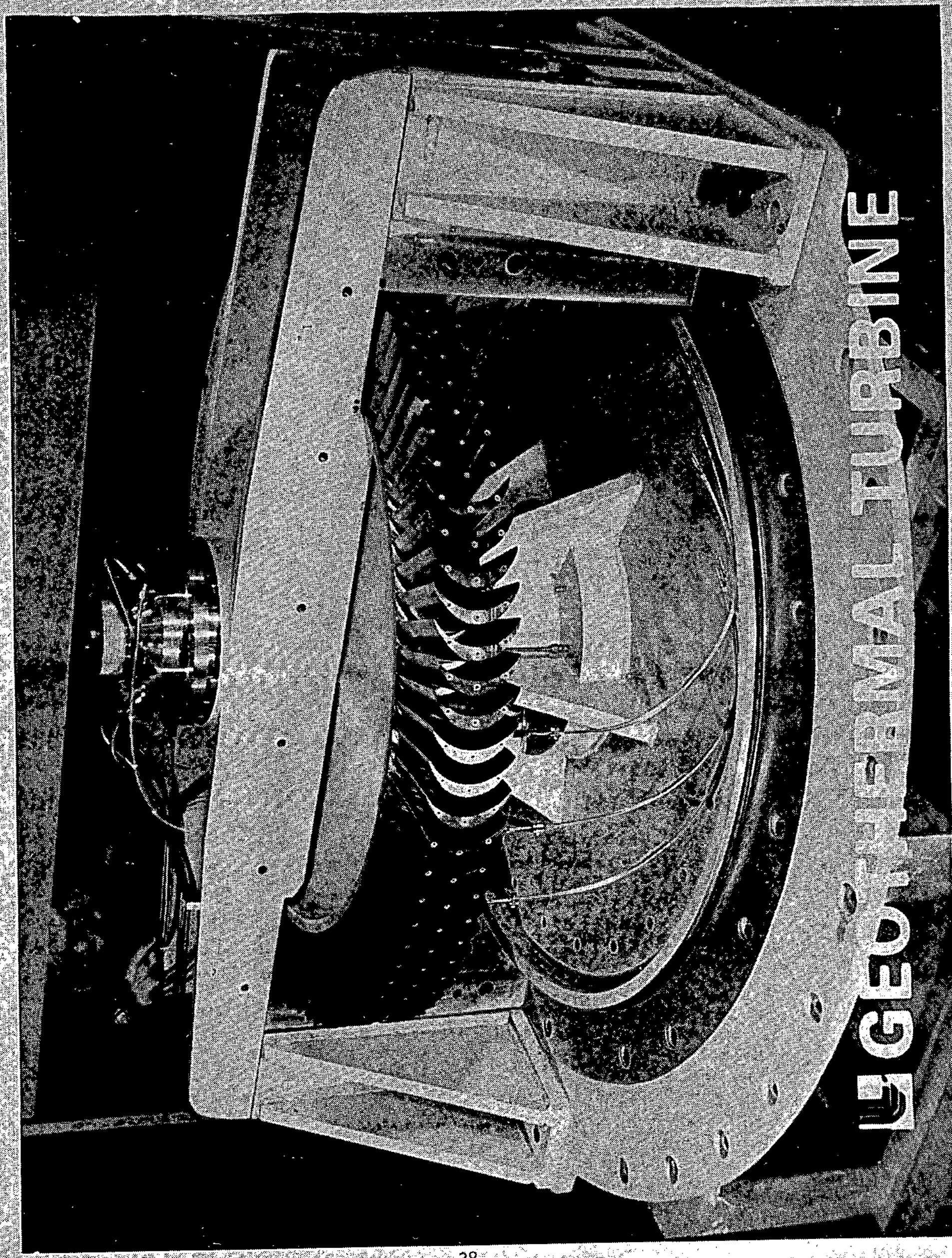


Fig. 21 Test conditions

Fluid state at nozzle entrance

P_o = 2.53 MPa (367 psia)

X_o = quality = 14%

T_o = 224°C (434° F)

h_o = 1.2 MJ/kg (526 BTU/1bm)

$\dot{m}$ = 0.59 kg/s (1.31 lbm/s)

Exhaust pressure and temperature

P_e = 0.0137 MPa (2 psia)

T_e = 126°F

h_e = 421.8 Btu/1bm

x_e = 32%

Power Input

$\dot{m}(h_0 - h_e)$ = 144 kW_t

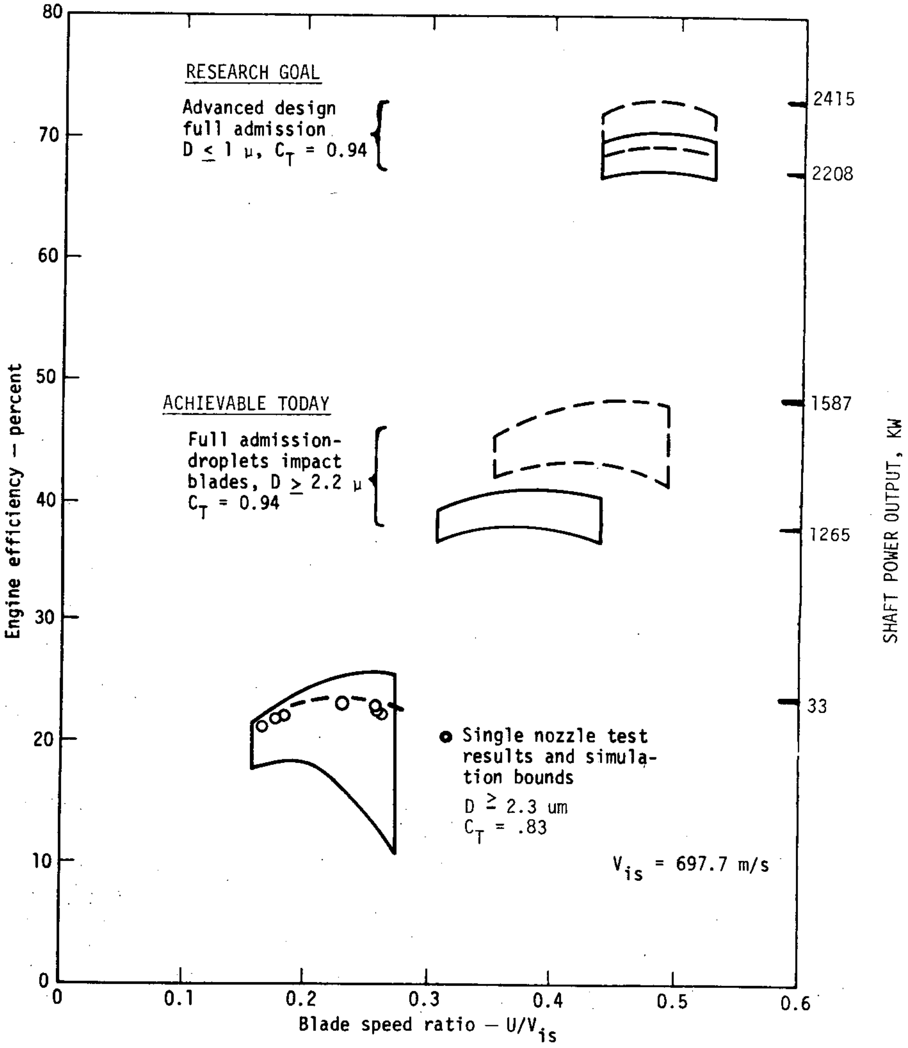


FIG. 22 Total Flow Impulse Turbine Test Results and Performance Evaluation

FIGURE 23

ESTIMATED PERFORMANCE COMPARISONS FOR GROSS ELECTRICAL OUTPUT

	WATER RATE LB/KW-HR	SPECIFIC OUTPUT WATT-HR/LB
I. TOTAL FLOW IMPULSE TURBINE SYSTEM		
• EXISTING DESIGN - FULL ADMISSION (38%-48% ENGINE EFFICIENCY)	86-68	12-25
• ADVANCED DESIGN - FULL ADMISSION (70% ENGINE EFFICIENCY)	47	21
II. FLASHED STEAM SYSTEM		
• SINGLE FLASH (75% ENGINE EFFICIENCY)	70	14
• DOUBLE FLASH (75% ENGINE EFFICIENCY BOTH STAGES)	56	18

NOTES:

1. CALCULATIONS BASED ON THERMODYNAMIC PROPERTIES OF PURE WATER.
2. FOR PRESENCE OF DISSOLVED SOLIDS: REDUCE ENERGY OUTPUT BY 0.85% FOR EVERY 1% TDS.
3. CALCULATIONS BASED ON TEST CONDITIONS: INLET 367 PSIA, 14% QUALITY, EXIT 2 PSIA, (126°F)

THE REACTION TURBINE EXPANDS LIQUID FROM THE HIGH PRESSURE SEPARATOR AND EXHAUSTS INTO THE LOW PRESSURE SEPARATOR

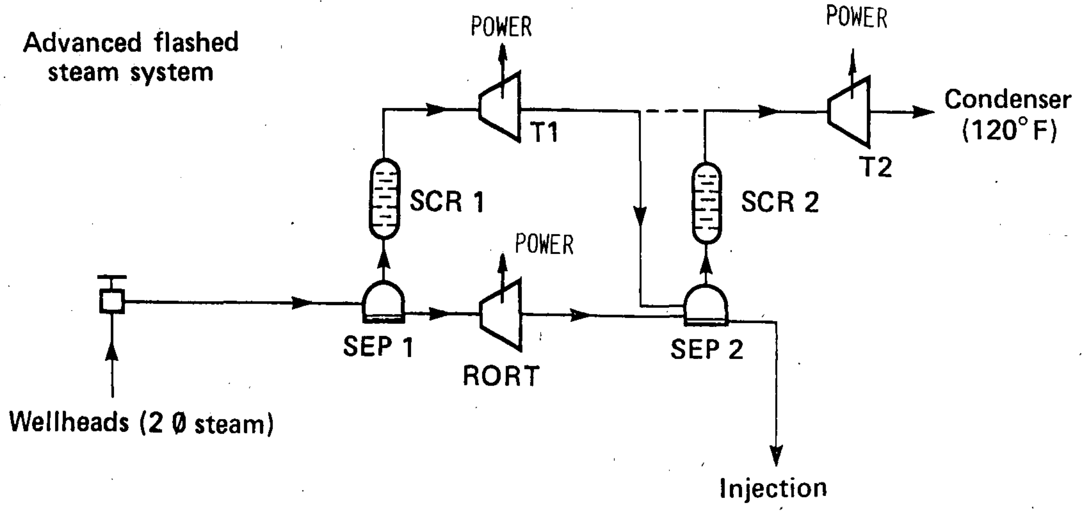


FIGURE 24

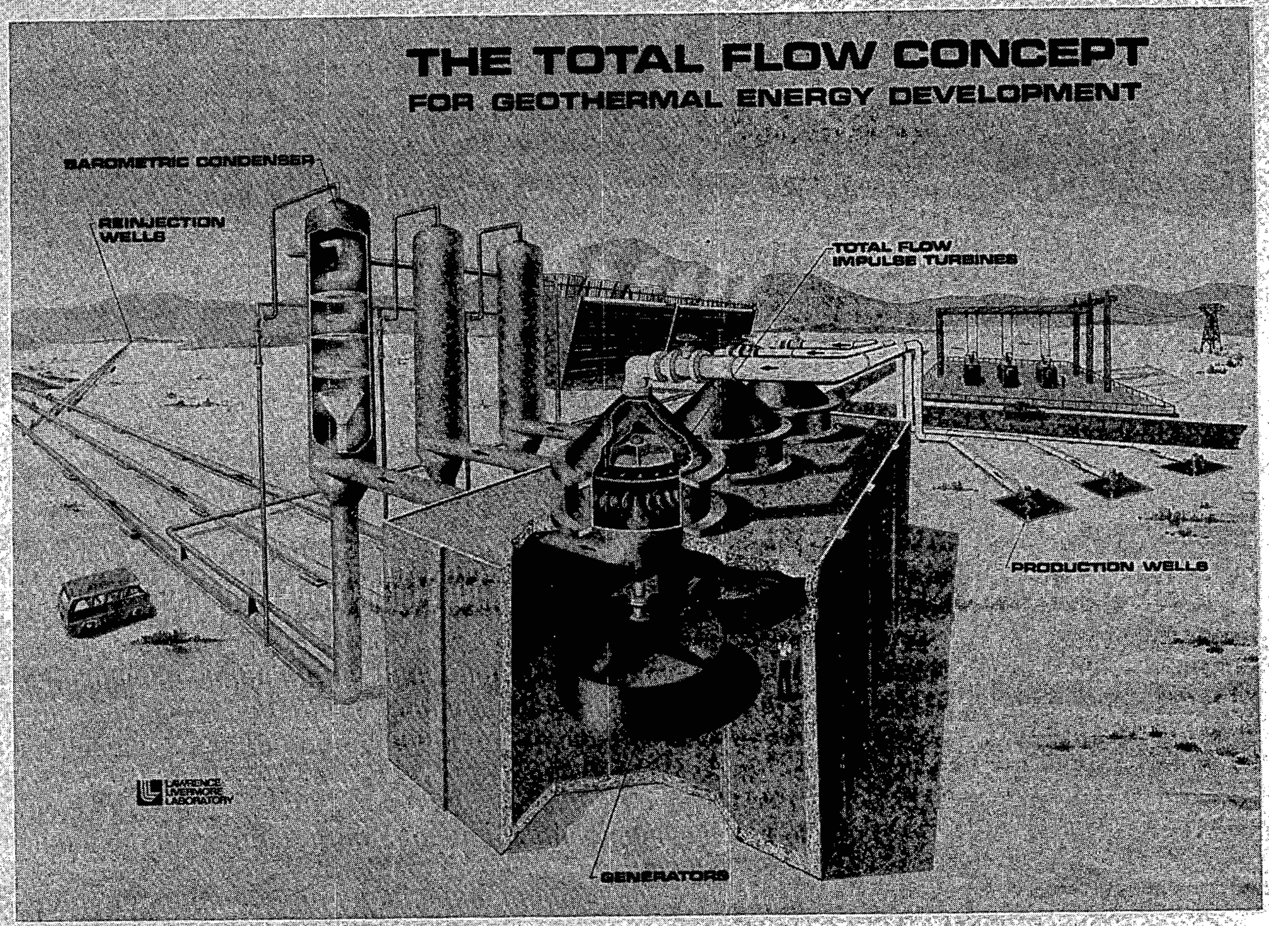

THE TOTAL FLOW CONCEPT
FOR GEOTHERMAL ENERGY DEVELOPMENT
BAROMETRIC CONDENSER
REINJECTION WELLS
TOTAL FLOW IMPULSE TURBINES
PRODUCTION WELLS
GENERATORS
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Fig. 25

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