Proceedings Seventh Workshop Geothermal Reservoir Engineering
Stanford, December 1981. SGP-TR-55.

GEOTHERMAL RESERVOIR ENGINEERING DEVELOPMENT THROUGH INTERNATIONAL COOPERATION

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Introduction About twenty years ago when the Geysers Geothermal Steam Field in California first started producing steam in significant quantities for the generation of electricity there were probably no more than five or six people in the U.S.A. who could qualify as geothermal reservoir engineers. Then as now, the Geysers field was the only field in the U.S.A. producing steam in significant quantities on a commercial basis. We are now entering a new era, however, and can expect steam production in this country to rise markedly in the next few years.

In 1960 there were at least a few thousand persons in the U.S.A. who were practicing reservoir engineering in the petroleum industry and in groundwater management organizations. Thus the U.S.A. had at its disposal a great deal of talent and expertise but very little experience in either the operation of natural underground steam reservoirs or in the development of needed geothermal reservoir engineering technology. In contrast, various other countries had been producing natural underground steam reservoirs for many years and had developed from practical experience a considerable fund of knowledge about reservoir behavior. However, these countries had no reservoir engineers in the sense we now conceive this profession, and there was no common awareness of the need for new technology.

What we conceive as reservoir engineering is of importance in the preparation and understanding of international cooperative agreements in geothermal energy. Reservoir engineering is related to other branches of engineering involved in the development and operation of geothermal-fluid reservoirs. As examples, it is related to drilling, production, and process engineering. It is also related to management functions pertaining to development and production.

The conventional concept limits its scope mainly to: (1) Analyses of well logs, (2) Analyses of reservoir pressure, temperature, production and well-effluent composition histories, (3) The design implementation, and analysis of field tests, (4) theoretical studies of reservoir behavior, reservoir modeling, and studies of physical models in the laboratory. All this is for the purpose of developing and applying techniques to forecast well and reservoir deliverabilities and ultimate economic recoveries under different operating conditions.

In some instances the concept of reservoir engineering is much broader, encompassing additional functions which may include land management, drilling, engineering, production geology, production engineering, pipeline transportation of products to local storage facilities or power plants, and managerial decision-making regarding such things as redrills, selection of sites for new wells, processing facilities, or power plants. This broad concept places the reservoir engineer in the role of reservoir manager and in this capacity he would also initiate feasibility studies and arrange for research along lines that appear best to him.

In the geothermal community the conventional concept of reservoir engineering has been adopted generally although it has been subject to change, and often to additions as more is learned about new factors affecting reservoir behavior.

Binational cooperative geothermal research programs were developed as a logical means to benefit both the U.S.A. and the countries participating with it. Some binational programs covered a number of areas of research on geothermal energy, but from the outset, reservoir engineering became widely recognized as an important subject of general concern.

Efforts were made early in binational studies to develop new geothermal reservoir engineering technology through applications and modifications of existing petroleum and groundwater technology. These studies led to a better understanding of the physical nature of geothermal reservoirs, a deeper appreciation of the physical differences between steam, petroleum, and groundwater reservoirs; and they helped researchers avoid duplication of effort.

Laboratory studies of physical models were made, computer models were developed, and reservoir engineering field studies were made. Generally accepted methods of approach were followed in making field studies. Field performance data were used to formulate hypotheses regarding the nature of reservoirs. These hypotheses were then tested using physical or mathematical models, or both. The physical laws involved in the performance of the reservoirs could then be recognized so that pertinent engineering equations could be derived and solved. If results from such equations appear valid based on comparisons to field performance data, then it is possible to study various methods of field development and production, and to forecast performance.

Bilateral programs active during recent years have been the source of a substantial fund of knowledge, useful new technology, and transfers of technology to the U.S.A.

These technical gains for participating countries would not be possible without well understood written agreements carefully prepared in advance of joint research activities. Some comments on these agreements follow.

Comments on The Execution of International Cooperative Agreements International cooperative research has been government-sponsored, an outgrowth of private consulting, or a necessity for industrial development. Regardless of how they came about or how they were implemented, binational programs in which the U.S.A. has been a participant have been of benefit to this country.It is important that participants sign international agreements with a spirit of good will. Both sides should be well aware of the non-technical problems which can confront them. There are many such problems. Joint determination of the specific research to be undertaken is one of them. Another is the manner in which joint research proposals are to be submitted to government sponsors. Another is naming in the proposals the researchers from the participating countries and delineating the distribution of work among them. Less significant but also important are the plans that must be made for working together in each others home offices and laboratories. This involves the need for travel plans. It has become clear that binational cooperative research, if it is to be successful, demands that participants work together at fairly frequent intervals and write their reports together. Doing so is unmistakable evidence of cooperation. If each side works mainly alone and a mere exchange of reports takes place at the end of a contract period, the research cannot be judged as truly cooperative.

Researchers and research managers on both sides should be tolerant regarding language problems which might arise. They should recognize that social, cultural, and economic differences are ever present but will not cause difficulties if both sides act in good faith and display good will. The ways of doing business in one country are not the same as in another. Researchers and research managers should accept this fact and consider their pursuit of joint objectives as a contest to be won through patience and the best use of their abilities and resources.

International Cooperative Studies In the ensuing paragraphs we discuss some of the international cooperative work that has been done in geothermal energy in recent years. By necessity our treatment of this subject is sketchy because there have been so many cooperative arrangements, formal and informal. Published information on many of these apparently is either scarce or nonexistent. Moreover, we recognize that compiling available data for a more comprehensive treatment could become a virtually impossible task, but would not alter our views if the cooperative arrangements covered in our discussion are representative of the whole. Lastly, we admit that making our selection was naturally influenced by projects we are most familiar with and those are the ones which have involved Stanford either directly or indirectly. We do not mean to imply in any way that Stanford's role in the development of geothermal reservoir engineering has been any more important than those of many other organizations concerned with geothermal energy problems.

Our purpose is to disclose benefits to participating countries, to indicate the practicality of these benefits, technically and economically, and to show that international cooperative work can accelerate the development of the geothermal industry and thereby ease energy shortage problems.

Costa Rica - In 1980 Professor H.J. Ramey, Jr., of Stanford University consulted for the government of Costa Rica on the Miravalles geothermal field. He made pressure transient analyses, designed well tests, and made engineering assessments. He presented a talk on the Miravalles field in the fail of 1980 in one of the weekly seminars of the Stanford Geothermal Program.

One of the geothermal engineers at Miravalles, Eduardo Granados, an employee of the Costa Rican government utility, ICE, was invited to come to Stanford during the winter of 1980-81 as a visiting scholar. After completing his visit Mr. Granados applied for admission to the graduate geothermal study program at Stanford and was admitted. This kind of interaction with practicing engineers throughout the world yields worthwhile benefits not only to graduate students and faculty at Stanford, but also to the U.S.A. as a whole. It provides an important indirect aid to our national geothermal development program.

El Salvador - In 1975 Professor W.E. Brigham of Stanford University did some consulting work for El Salvador on that country's Ahuachapan geothermal field. This work concerned the possibility of increasing the size of the power plant, the longevity of the field, locations for new wells, and possible reinjection of produced water. The questions which arose characterized the type of development planning that uses reservoir evaluations as a basis for decision-making. The Ahuachapan field is the first hot water field in the western hemisphere that produced from volcanic sediments. Since 1975 a number of other similar fields have been found, however, in Central America and the U.S.A.

Consulting assignments of the kind taken by Professor Brigham in El Salvador expand the experience background of reservoir engineers, augment their understanding of geothermal reservoir behavior and improve the skills they need to forecast reservoir performance. The new technology gained is of primary value to the U.S.A. as an aid in the development of the American geothermal industry.

Iceland - Several years ago there was a formal agreement in effect between the Atomic Energy Commission in the U.S.A. and the Iceland Energy Authority. This agreement called for cooperation between the two countries in the field of geothermal energy. It was broad in scope and dealt more with conventional engineering matters at the ground surface than with geosciences. Apparently it was in force for a period of about five years but used in only a few instances. Experience disclosed that formal procedures were not necessary for these.

By means of the agreement the U.S.A. was seeking access to the extensive background knowledge Iceland had accumulated on non-electrical applications such as direct heating with geothermal water. The U.S.A. used no particular method to gain its objectives. Generally the activities of the U.S.A. were limited to visits to plants and to other installations. These visits also could have been arranged informally.

Reservoir engineering was not mentioned in the agreement, probably because this branch of engineering was relatively unknown in the geothermal community at the time and it had been applied to few geothermal systems.At about the end of the 1970's decade the agreement was due for renewal, but neither of the two countries took the initiative to see that this was accomplished. Their passive attitude may have been due to the agreement's shortcomings. It was quite general, outlining no specific programs which should be undertaken or any specific problems which should be attacked. Moreover, no special funding for the work was provided for. Thus, interest waned.

Some benefits to both countries did accrue, however, as a result of informal cooperative arrangements. Lawrence Berkeley Laboratory (LBL) in the U.S.A. and various institutions in Iceland worked together on the Krafla high-temperature area of northeast Iceland. Iceland was interested in having work &ne at LBL on the troublesome Krafla reservoir. It was the first high-temperature reservoir in the country to produce less than what was expected originally.

Iceland has not yet developed the experience to deal with complex reservoirs except for low-temperature reservoirs where classical groundwater hydrology can be applied. Icelanders working in geothermal energy have broad experience, but only a limited part is specifically in reservoir engineering.

Although the problems at Krafla have not yet been solved the cooperative effort with LBL has provided some insight into the processes underlying these problems. The U.S.A. gains technologically from its involvement with these problems.

Italy - In the early part of the 1970's, Professor H.J. Ramey, Jr. of Stanford University discussed possible cooperative research between the U.S.A. and Ente Nazionale per l'Energia Elettrica (ENEL) in Italy. He delivered lectures in Italy on reservoir engineering and geothermal reservoir behavior. In the spring of 1975 Dr. Graziano Manetti and Engineer Antonio Barelli, both with ENEL came to the Petroleum Engineering Department of Stanford University as visiting scholars, for a period of about two months. Cooperative work between the U.S.A., through Stanford, and ENEL was discussed at length. Tentative plans were made after many discussions and seminars.

Later the proposed program was reviewed and discussed on a more formal basis with Dr. Raffael Cataldi of ENEL and some of his associates. Dr. Cataldi had already discussed with Professor Ramey in Italy the prospective Stanford-ENEL cooperative effort, before the visit of Dr. Manetti and Engineer Barelli. During the period of Dr. Cataldi's visit joint meetings were held. Those present included Professors F.G. Miller and H.J. Ramey, Jr. from Stanford, Professor P.A. Witherspoon and Drs. R. Schroeder and J.H Howard from LBL, Dr. L.J.P. Muffler from the USGS, and Dr. Cataldi and his associates from ENEL.

These activities led to a five-year agreement on cooperative research in geothermal energy which was signed in 1975 by both countries and extended in 1980 for a second five years. The agreement was between Ente Nazionale per l'Energia Elettrica (ENEL), Italy, and the Energy Research and Development Administration (ERDA), now the U.S. Dept. of Energy (DOE), U.S.A. Six major areas for joint research were involved. One of these, Project 3, was on "reservoir physics and engineering and resource assessment", and is the one of interest here.

Through this agreement and resultant DOE contracts, Stanford and LBL with ENEL, have used the Larderello region of geothermal steam fields in Italy as an experimental laboratory to develop new reservoir engineering technology. Field data are available back to **1945.** Under the cooperative research program field tests have been designed and implemented and the results analyzed. Important results have been published, attention being invited particularly to Project **3** papers presented at two ENEL-DOE Workshops for Cooperative Research in Geothermal Energy. The first was held at **ENEL** facilities in Larderello, Italy, Sept. **12-16, 1977.** The papers presented were published in the Workshop Proceedings and iater in a special issue of thermics.

The second Workshop was held at Lawrence Berkeley Laboratory, Berkeley, California, October **20-23,** 1980. Presented papers are published in the Workshop Proceedings.

An example of an important transfer of technology to the U.S.A. is a successful new method developed to forecast steam production. It was developed from studies made in the Gabbro field in Italy, and can be applied to similar fields in the U.S.A. The results are published in the 1980 Workshop Proceedings.

Another example of a transfer of technology to the U.S.A. is a method of engineering analysis developed to estimate flow patterns and fracture trends in certain geothermal steam reservoirs in which a principal producing well penetrates a vertical fracture extending part way to the bottom of a reservoir, hypothesized as a boiling water interface. The method was developed from well interference studies made on the Travale steam field in Italy. Results are published in the foregoing special issue of Geothermics.

Japan - Contacts between Stanford University and the Japanese geothermal industry were initiated as a result of participation in that industry by postgraduates. An informal cooperation has been in effect for the last two years. Professor Roland N. Horne of Stanford has spent two months in Japan during that time. His activities included consulting arrangements for reservoir evaluations and the teaching of a geothermal reservoir engineering short course with 63 attendees, done in cooperation with the Japan Geothermal Energy Center which is now a part of the New Energy Development Organization (NEDO). This organization in Japan **is** approximately equivalent to the Department of Energy in the U.S.A. Professor Horne also delivered various lectures and made a number of site visits. This interaction proved invaluable from the U.S.A. geothermal standpoint because a wide range of Japanese geothermal experience hitherto buried in Japanese language publications came to light. The subsequent presentation of the impact of reinjection experience in Japan has evoked controversy in U.S.A. geothermal reservoir engineering circles and has stimulated new research as the apparent implications are confirmed or **dis**proved.

Contact between Stanford University and Japanese geothermal agencies is now extensive. These agencies include NEDO, New Energy Foundation, University of Tokyo, Kyushu University Geological Survey of Japan, Electric Power Development Company, Kyushu Electric Power Company, Japan Metals and Chemical Company, Mitsubishi Metals Corporation, Mitsubishi Heavy Industries, Toshiba International, Nippon Steel Corporation, Japan Oil Engineering Company and West Geothermal Energy Company. In January **1982** Stanford University will welcome its first Japanese geothermal exchange visitor. He is from the Electric Power Development Company and will join two Japanese students currently in residence.

Cooperation between the geothermal communities of the U.S.A. and Japan is formalized also through Japanese financial and technical participation in the Los Alamos Hot Dry Rock Program. The enthusiasm and technical expertise which Japan is applying to geothermal utilization is certain to be of benefit to the U.S.A. if joint relations continue at their present **or** an increased level.

Mexico - Two cooperative agreements have been in effect in recent years. One of these, signed in **1977,** was between the U.S. Energy Research and Development Administration (now DOE), represented by Lawrence Berkeley Laboratory, and the Comision Federal de Electricidad (CFE), Mexico. The other agreement, signed in 1980, and supported by the DOE, is between the Petroleum Engineering Department of Stanford University and the Instituto de Investigaciones Electricas, Mexico. Together these agreements involve field tests, reservoir modeling and laboratory research.

The cooperative research of LBL and CFE is based on a formal bi-national agreement. Stanford-IIE cooperative research is based on a memorandum of understanding, akin to a letter of intent or gentlemen's agreement. For the joint purposes of Stanford and IIE this more informal arrangement, which was recommended by DGE, seems more practical.

Objectives of the Stanford-IIE proposed program were discussed with the U.S. Division of Geothermal Energy in early 1980 by Professors Miller and Ramey, of Stanford University, and Dr. Pablo Mulas del Pozo of IIE. In the early part of 1980 three engineers from IIE, Dr. Francisco Cordoba, Ing. Vicor Arellano, and Alberto Yanez, spent about three months at Stanford as visiting scholars participating in many seminars relating to the prospective cooperative research effort. This led to the DOE-Stanford Contract for joint research with IIE. Prior to this, however, Stanford professors F.G. Miller and Heber Cinco-Ley, in 1979, performed consulting services for the United Nations, assisting IIE with its plans for research facilities and a research program.

Long term reservoir performance data needed by the U.S.A. to develop new technology are being made available from the Cerro Prieto Geothermal Steam Field and from other Mexican fields.

During fiscal year 1981, Stanford-IIE work included investigations of: (a) the use of pressure gradients and profiles in well analysis, (b) Tracer analysis for fractured systems, (c) Interference tests in flashing reservoirs, and, (d) Lumped parameter modeling of the Cerro Prieto reservoir.

New Zealand - Most of the scientific interchange between the U.S.A. and New Zealand is probably at the personal level. New Zealand government laboratories frequently provide office space for short term appointments of the fellowship type to scientists of the U.S.A. wishing to work closely with New Zealand colleagues. Similarly, the U.S. Geological Survey (USGS) and U.S. universities frequently provide opportunities for New Zealand scientists to spend time in the U.S.A. pursuing their research and exchanging ideas with American colleagues.

A major contribution of New Zealand to the U.S.A. geothermal program is an open supply of data from developed geothermal fields in New Zealand. Data from Wairakei, for example, are available in the U.S.A. through an exchange arrangement in which the USGS is the U.S. coordinator.

Professor Michael O'Sullivan of the Theoretical and Applied Mechanics Department of the University of Auckland spent a year recently at the Lawrence Berkeley Laboratory doing research on reservoir simulations. Earlier he did similar work on New Zealand's Wairakei and Broadlands fields. Conversely, Dr. Michael Sorey who is an American scientist with the USGS recently spent two years with the Department of Scientific and Industrial Research (DSIR) in New Zealand. Dr. Sorey had earlier gained experience with reservoir simulation work on the Long Valley geothermal area of California. While he was in New Zealand he did similar work on the Wairakei field.

What is believed to be the first reservoir engineering study of a New Zealand geothermal reservoir was made by Professors R.E. Whiting and H.J. Ramey, Jr., in the early 1960's. Both men were faculty members of Texas A&M at the time. A report on their work, published by the Society of Petroleum Engineers of AIME, dealt with the development of material-and-energy balance equations for the Wairakei field.

Two recent managers of the Stanford Geothermal Program came from New Zealand, Professor Roland N. Horne who is now a faculty member of the Stanford Petroleum Engineering Department, and Dr. Ian G. Donaldson, who is a scientist with the DSIR in New Zealand. Both men have made important contributions to the development of geothermal reservoir engineering technology applicable in the U.S.A.

Nicaragua - In 1977 H. Dykstra and R.H. Adams, both formerly with the Standard Oil Company of California were engaged by the Nicaraguan government to make a reservoir engineering study and conduct field tests in the Momotombo geothermal reservoir. Both of these men are experienced and highly qualified.

Dykstra reported the principal results of their studies at Stanford's Third Workshop on Geothermal Reservoir Engineering held in December 1977. Flow tests and pressure measurements were made on a group of five wells in the Momotombo reservoir. The purpose was to evaluate this hot water reservoir, to determine well interference effects, to determine reservoir boundary conditions and to obtain mass flow rates and enthalpy.

Bottom hole pressures were measured in four wells, static pressures in three of these and both flowing and shut-in buildup pressure in the fourth. Flow tests were made on all five wells.

Although Dykstra and Adams could not accomplish all their objectives throuqh analysis of their carefully planned and executed tests, they were able to shed light on the performance behavior of the Momotombo reservoir and to explain in logical fashion why the reservoir behaves as it does.

Most important they brought back to the U.S.A. some valuable experience on a hot water reservoir in a volcanic environment which adds to our meager fund of knowledge on the subject.

Taiwan - Professor H.J. Ramey, Jr. of Stanford University visited Taiwan on a consulting assignment in 1979. He made studies on the Chingshui geothermal steam field, near the northeastern coast of Taiwan. This field produces hot water with some carbon dioxide from six wells.

Carl Chang of the Chinese Petroleum Corporation and Professor Ramey performed pressure transient tests jointly and analyzed the results. Their work led to four publications at the Fifth Workshop on Geothermal Reservoir Engineering at Stanford in December 1979. These publications all related to the Chingshui field. They dealt with a preliminary study of the Chingshui geothermal area, a well interference test, pressure buildup tests, and an application of the Horner method to the estimation of static reservoir temperature during drilling operations. These publications present pressure and temperature transient data from field testing, and data interpretation. Field information of this kind is valuable to engineers and scientists in this area of research.

Following the 1979 Workshop, Carl Chang spent a quarter in residence at Stanford as a visiting scholar.

Concluding Remarks It is clearly evident from this brief review of international cooperation in geothermal energy development that the countries involved have made important additions to their fund of knowledge on geothermal energy. Efforts made are easing energy shortages, revealing this source as a viable alternative to oil and gas throughout many parts of the world.

Technically, much has been gained from new engineering methods and scientific techniques which shed light on the physical and chemical nature of geothermal-fluid reservoirs. These methods and techniques help explain why reservoirs behave as they do and they thereby facilitate forecasts of performance- Geothermal energy development appears to be on the threshhold of a new expansion. Much has been learned and there is still much to be learned.

Looking ahead, we must consider problems now surfacing. A few questions which arise are how can we make better use of geochemical data to explain past reservoir behavior and explain future behavior? To what extent can these data be best applied to determine underground flow patterns? How can we best advance reservoir analysis by applying to steam zones the knowledge we now have on vapor pressure lowering and liquid adsorption? How can we best design tracer studies so that they will yield needed information on reservoir size and configuration and on fracture size, orientation, and distribution? What compaction and fracture effects can be expected from the reinjection of cool water? Can land subsidence become a major problem in residential, industrial or farm areas? What are the economic implications? What should be done to further develop well testing theory so that the results of field tests can be interpreted more easily and with more confidence? How can we extract heat economically from reservoir rocks after rates of fluid production have become uneconomic? We have, of course, developed partial answers but more complete answers are needed.

International cooperation generally offers economic incentives which should not be minimized. At least as an approximation, the work force on a binational research investigation is twice what it would be for either of the two participating countries considered alone. Easy access to each other's experience background promotes rapid growth of new ideas. The growth that we can anticipate can be similar to the explosion in technology which occurred in the 1930's and 1940's in the petroleum industry. We can foresee that the prospects for continuing an expanded geothermal energy development should remain very good if enough encouragement and support are forthcoming from the governments and private companies involved. International cooperation can be an important factor in this growth.