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ENERGY POLICY ACT OF 1992
OPENS DOORS FOR INDEPENDENT GEOTHERMAL POWER PRODUCERS

John E. Mock, Director
Geothermal Division, U.S. Department of Energy

Gene V. Beeland
Meridian Corporation

ABSTRACT

The Energy Policy Act of 1992 embraces and implements many of the actions recommended by the President in the National Energy Strategy. Independent geothermal power producers may be direct beneficiaries of 1) further deregulation of IPPs through their exemption from the provisions of the Public Utility Holding Company Act and 2) potentially freer access to utility-owned transmission facilities. However, these doors will not be fully opened to geothermal energy until this resource can compete with other fuels in cost considerations. While changes in public policy, such as inclusion of externalities in the price of power or financial penalties on carbon dioxide emissions, will level the playing field somewhat, reductions in cost will be the ultimate marketing tool. This is particularly critical in the economics of power derived from "new," as yet undiscovered reservoirs which will reflect the high costs of today's exploration methods. The Department of Energy's geothermal R&D program, in cooperation with industry, is undertaking, as described in this paper, to achieve the technology cost reductions needed to permit this resource to enjoy a status equal to or better than that of competing fuels at the utility least-cost bargaining table.

INTRODUCTION

The Energy Policy Act of 1992 is described by Energy Secretary James D. Watkins as "the most comprehensive and balanced energy legislation ever enacted (which) will bring new jobs, greater energy security, and a cleaner environment." The Act, he continued, will stimulate domestic energy production, promote energy efficiency, increase competition in the electricity sector reducing consumer costs, and develop alternatives to imported oil.

PROVISIONS OF THE ACT FAVORABLE TO GEOTHERMAL POWER PRODUCERS

A number of the Act's provisions are favorable to geothermal development. Some of them that will directly benefit the geothermal industry and open new doors for growth are not directed specifically toward geothermal power per se, but are broad enough to encompass independent geothermal power producers along with other IPPs. These provisions include further deregulation of their structure and operations and a strong mandate for IPP access to transmission facilities. The first of these is accomplished by creating new entities known as "exempt wholesale generators" (EWG's) that may generate and sell power without the restrictions of the Public Utility Holding Company Act. Structuring project ownership to avoid triggering PUHCA regulation has long been considered a major impediment to IPPs, and the freedom granted by the Act is designed to encourage companies that are not electric utilities to get into the power generating business and *compete* to sell electricity to any utility that will buy it. Significantly, EWGs do not lose their status as qualifying facilities under the Public Utility Regulatory Policies Act (PURPA), and its requirement for utilities to purchase the power of such facilities remains intact. However, the geothermal industry should be alert to the fact that at least one influential senator in the energy field has served notice that this issue will surface again in the Congress recently convened due to his belief that PURPA "creates a huge advantage" for QFs over other IPPs.

Perhaps one of the most important provisions of the Act for the geothermal power industry, as it is currently structured, continues another trend established in PURPA -- i.e., affiliation of an EWG with a utility does not preclude the utility from purchasing power from the EWG if cognizant state regulators determine that such transactions meet certain criteria -- e.g., that they will benefit consumers, are in the public interest, and would not provide the utility affiliate unfair competitive advantage. Certainly, given the benign geothermal characteristics compared to those of other available fuel choices for power generation, unregulated utility subsidiaries should have little difficulty substantiating consumer benefit and public interest in its use.

Transmission access for EWPs is provided through authority granted to the Federal Energy Regulatory Commission (FERC) to order utilities, upon application by a qualified EWG, to provide wholesale transmission services under terms that would 1) permit the utility to recover all of its costs in connection with the transmission services, and 2) would not unreasonably impair the continued reliability of the affected electrical systems. While the legislation as passed omitted earlier language that left FERC no discretion to do otherwise, numerous observers say that regardless of the change in wording, "mandated access will be the order of the day."

According to Electric Power Alert, a leading utility representative described the legislation as "a hell of a bill with a wonderful balance between meaningful access and effective PUHCA reform. The combination is unbeatable. This makes the future a lot less scary for IPPs and utilities alike."

While these portions of the Act will tend to make geothermal development somewhat less onerous and lessen tensions over transmission access in some areas, the geothermal power industry cannot share this unrestrained anticipation of the conventional segments of the industry until it can *compete* with them on cost. Put another way, competitiveness, as we all know, is the key which will open these doors of opportunity.

SECTIONS OF THE ACT WHICH MAY POTENTIALLY IMPACT GEOTHERMAL R&D

While other sections of the Energy Policy Act are specifically designed to support increased competitiveness of geothermal energy and other renewable energy resources, their frame of reference in this particular legislation should alert the geothermal community that they do not yet constitute a mandate for action. That is, those portions that would most directly impact and expand federal/industry research and industry development are only *authorized*, and the extent to which they are ultimately implemented is subject to the availability of *appropriated* funding. This is both a challenge to make the industry's voice heard in the new Congress and an opportunity to acquaint newcomers with the nationwide benefits of geothermal energy. The geothermal community should not stand silently by while their R&D support is committed to more vocal competitors.

The provision of the Act that would most immediately impact the R&D program, if funded for geothermal, is the call for support of "demonstration and commercial application" projects that utilize high- and low-temperature geothermal energy and other renewable energy resources. DOE is required to solicit proposals for projects within nine months of enactment of the Act on the basis of advice provided by an Advisory Committee on Demonstration and Commercial Applications of Renewable Energy and Energy Efficiency Technologies. $50 million total is *authorized* for fiscal 1994.

In addition, subject to the availability of appropriations, DOE is directed to establish a "production incentive program for renewable energy" which would provide payments to "qualified renewable energy facilities" for a 10-year period at a cost of 1.5¢/kWh, adjusted for inflation. Power plants using dry geothermal steam would not qualify.

Fortunately, extension of the 10 percent business energy tax credit for qualified geothermal energy property on a *permanent* basis is a "done deal" and requires no further legislation. As before, qualifying geothermal property includes equipment to produce, distribute, or use geothermal energy, but excludes electrical transmission structures.

Other provisions that may provide longer range benefit for the economics of the geothermal industry are embraced in provisions to promote the export of domestic renewable energy products and services and to investigate the feasibility of reducing greenhouse gases. In addition, there are requirements for utility integrated resource planning that is to include evaluation of renewable energy resources and cost recovery mechanisms for demand-side management strategies that may encourage increased use of geothermal heat pumps and other direct uses of the resource.

Considerations such as these, regulatory reform, and the geothermal-specific support if it is funded, combined with movement at the state level toward public policy changes -- such as inclusion of externalities in the price of power and/or financial penalties on carbon dioxide emissions -- will gradually level the playing field for geothermal competitiveness. Yet, reductions in geothermal costs will be the ultimate marketing tool. This, then, is the goal of the DOE geothermal R&D program -- to achieve, in cooperation with industry, the technology cost reductions that will enable this resource to enjoy a status equal to or better than that of competing fuels at the utility least-cost bargaining table.

ELEMENTS AND OBJECTIVES OF THE DOE GEOTHERMAL R&D PROGRAM

At this point, this presentation will to a large extent repeat the program discussion at the workshop a year ago. However, this repetition may have two benefits. First, at this stage of geothermal development, and at current levels of research funding on the part of both government and industry, our efforts are essentially a process of gradually evolving technology improvements, efforts which can only benefit from repeated examination of their merits or need for change. Second, although it is the strong intent of the R&D program to keep industry continually informed of its activities and direction, it is understood that this information is not reaching all interested parties. This is a matter of considerable concern to the Geothermal Division, and it is hoped that repetition here will help funnel the information to all who have a need to know.

Exploration and Reservoir Assessment Tools

A particularly critical element in geothermal economics is the high cost of identifying "new" reservoirs and assessing their commercial potential. The deep production-size wells used for these purposes with today's technology cost from $1.5 to $3.5 million each, representing prohibitive costs for many developers or potential developers. Thus, a major objective of the DOE geothermal drilling R&D is to reduce by 50 percent the costs currently required to obtain financing for power plant development. In support of this objective, and at the request of the Hard Rock Penetration Industry Review Panel, DOE has initiated an effort at Sandia National Laboratory to determine whether slimhole drilling can adequately substitute for the costly wells drilled with conventional rotary rigs. This effort will be carried out in a cooperative DOE/industry program that will also support development of geothermal energy in the Pacific Northwest to meet utility needs.

Sandia will first evaluate the slimhole concept through review and documentation of Japanese slimhole data, and then drill and test, in partnership with industry, slimholes at several locations where reservoir parameters are known from large hole flow tests. By comparing these data with those developed from the same formation by large and small wells, it can be determined whether sufficient data can be obtained with the far less costly wells alone.

One cost-shared project has been initiated at Steamboat Hills, Nevada, with Far West Capital using slimhole flow tests and multiwell tracer tests. Other DOE/industry partnerships are under discussion which would involve three geothermal sites in the Cascades.

Further improvements in exploration and reservoir assessment technology are expected to accrue from other R&D program elements which are also directed to other stages of development.

Reservoir Technology

This program element is dedicated to developing better methodology for analyzing the performance of known reservoirs and predicting and managing the effects of fluid injection, in addition to exploration technologies. Currently, the emphasis in reservoir technology is on measures to remedy the decline in production and deterioration of steam quality at The Geysers. These include:

- development of conceptual geological, geochemical, geophysical, and hydrological models of the steam field and immediate environs
- modeling of injection performance, development of means to predict the effects of water injection into the reservoir, and injection strategies.
- development of means to model the reservoir on a fieldwide and subregional scale
- determine methods for improvements in efficiency of power plants, both in the long-term and short-term.

In addition, a cost-shared program with industry is underway to: 1) design, develop, and test the most innovative exploration methods for an integrated exploration technology, and 2) conduct exploratory drilling to identify new resource areas and expand the available geothermal data base. Also in conjunction with industry, the predictions provided by advanced brine chemistry models developed previously are being correlated with actual site data, and model parameters refined where needed. Improvements on submodels are ongoing on such parameters as aluminosilicates, sulfate/bisulfate, and methane.

Drilling Technology

In addition to the slimhole research described above, drilling R&D includes development of technologies for controlling lost circulation, improving the mechanics of rock penetration, and innovative downhole measurement. Activities associated with lost circulation control include, among others:

- field testing the recently-developed rolling float meter under a variety of conditions. This equipment provides early indications of fluid gain or loss which will reduce blow-out and lost circulation problems.
- continued development of the drillable straddle packer, a packer assembly for isolating and directing the flow of cement into a selected loss-zone interval.
- improvement in data analysis techniques and display software of the borehole televiewer for measuring downhole fracture apertures.
- development of several cementitious drilling mud systems for various applications.

Rock penetration mechanics research includes, in addition to slimhole drilling, development of a new concept for measurement while drilling data transmission. This research will be correlated with an industry-developed system for seismic imaging-while-drilling.

The focus of the downhole instrumentation activity is development of a suite of memory logging tools applicable to geothermal operations. Consultation with operators has resulted in a program to develop three different slim (2 inches in diameter), high-temperature (400°C) tools.

Conversion Technology

The focus of the heat cycle research project is the use of the Rankine binary power cycle with the hydrothermal resource to produce electric power, with emphasis on the utilization of mixed hydrocarbon working fluids. Investigations to define the technology base for allowing binary cycle performance to approach the thermodynamic maximum, and thus reduce costs, are being completed this year. Final tests of the supercritical cycle will provide data for different heat exchanger tube mass and heat flux conditions, allowing a more complete evaluation of the capabilities of the Heat Transfer Research Inc. (HTRI) heat exchange design codes. Field investigations of the condensation behavior of supersaturated turbine expansions are being conducted utilizing a two-dimensional expansion nozzle and laser droplet detection system with the isobutane/hexane working fluid family. These tests are needed to validate the predicted absence of condensate during the supersaturated turbine expansions with hydrocarbon working fluids in order to assure both turbine manufacturers and users that the turbines can be operated in this manner without equipment damage or performance degradation. Operation of the Heat Cycle Research Facility, a small-scale (50kW) binary plant which is the basic tool for conducting these experiments, is being transferred from the Idaho National Engineering Laboratory to the National Renewable Energy Laboratory. It is currently located adjacent to the B. C. McCabe plant in Imperial Valley.

Materials Development

This is a very important research element, the results of which industry is believed to have made considerable use. Its FY 1993 development activities include:

- advanced high-temperature lightweight cements to improve the life expectancy of geothermal well completions

- chemical systems for lost circulation control (in conjunction with drilling research)

- thermally conductive composites for heat exchanger tubing to reduce scaling, corrosion, and other brine handling problems

- corrosion mitigation at The Geysers which involves optimization of previously developed polymer cement formulations and polymer coating systems for use in high acidic environments at high temperatures

- advanced high-temperature coupling systems needed to bond high-temperature elastomers to metal reinforcements.

Biochemical Processes for Geothermal Brines

This activity is a laboratory effort to develop methods for the utilization and/or low-cost environmentally acceptable disposal of toxic geothermal residues. In this work, microorganisms which can interact with toxic metals and convert them into soluble species for subsequent injection or concentration have been identified that are highly efficient at elevated temperatures (>55°C) and acidic pH (1-2). It is anticipated that the new biotechnology will reduce the cost of surface disposal of sludges derived from geothermal brines by 25 percent or more.

SUMMARY

While many of the Stanford geothermal reservoir workshop attendees are participants in certain aspects of DOE's geothermal R&D program, and others are very knowledgeable on all developments affecting the costs and use of this resource, it is hoped that these thumbnail sketches of the broad range of R&D activities will serve to establish their close interrelationships in technology improvements and cost reductions. It is also hoped that those attendees or their colleagues and associates who are not yet conversant with the details of the program will attend the Geothermal Division's annual program review in San Francisco, April 27-28 of this year. Please convey this invitation to whomever you encounter who may have a need or desire to learn more about the federal program.

It is also hoped that the recitation of the favorable or potentially favorable actions impacting geothermal development will encourage those who might tend to listen to the "naysayers" on geothermal's future. And, finally, it is hoped, and expected, that when and where increased power demand exists in "geothermal" areas, geothermal power will be economically prepared to provide a major share of the required capacity.

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HDR Reservoir Flow Impedance and Potentials for Impedance Reduction

Robert DuTeau and Donald Brown
Los Alamos National Laboratory
Earth and Environmental Sciences Division
Los Alamos, New Mexico 87545

ABSTRACT

The data from flow tests which employed two different production zones in a well at Fenton Hill indicates the flow impedance of a wellbore zone damaged by rapid depressurization was altered, possibly by pressure spallation, which appears to have mechanically propped the joint apertures of outlet flow paths intersecting the altered wellbore. The rapid depressurization and subsequent flow test data derived from the damaged well has led to the hypothesis that pressure spallation and the resultant mechanical propping of outlet flow paths reduced the outlet flow impedance of the damaged wellbore. Furthermore, transient pressure data shows the largest pressure drop between the injection and production wellheads occurs near the production wellbore, so lowering the outlet impedance by increasing the apertures of outlet flow paths will have the greatest effect on reducing the overall reservoir impedance. Fenton Hill data also reveals that increasing the overall reservoir pressure dilates the apertures of flow paths, which likewise serves to reduce the reservoir impedance. Data suggests that either pressure dilating the wellbore connected joints with high production wellhead pressure, or mechanically propping open the outlet flow paths will increase the near-wellbore permeability. Finally, a new method for calculating and comparing near-wellbore outlet impedances has been developed. Further modeling, experimentation, and engineered reservoir modifications, such as pressure dilation and mechanical propping, hold considerable potential for significantly improving the productivity of HDR reservoirs.

INTRODUCTION

The Hot Dry Rock (HDR) geothermal reservoir designed for mining heat at Fenton Hill, New Mexico has shown that thermal energy contained within large bodies of crystalline basement rock can be harvested for use on the earth's surface. The Fenton Hill reservoir demonstrates how a large volume of hot rock at considerable depth can be hydraulically opened with high pressure to circulate water and mine heat with minimal water consumption. Furthermore, many months of reservoir circulation and heat removal have shown no drawdown in the mean temperature of the water produced from the reservoir. Therefore, the major remaining technical challenge is to engineer a reduction in reservoir flow impedance to increase the productivity of an HDR system to a commercial level. The data from Fenton Hill offers valuable information for designing methods for significant reductions in flow impedance.

BACKGROUND

While the creation of an HDR reservoir in deep basement rock is determined by the initial volume of highly pressurized water used to open and extend an originally impermeable joint and fracture system, the working size of a reservoir is determined by the hydraulic pressure maintained on the reservoir. After the initial hydraulic fracturing, the reservoir can be sustained at a stable volume by operating the reservoir below a hydraulic pressure which would induce microseismicity at the reservoir boundaries and cause reservoir growth. Below this seismic threshold, water pressure acts against the in situ stress regime to open joint systems and elastically deform reservoir rock to create flow paths connecting an injection and production wellpair. While the volume of the flow paths within the reservoir is strictly a function of pressure, the rate of fluid flow through a jointed system is both a function of the size of flow path apertures and the driving pressure difference across the system. Two conceptual models used to simulate the fluid flow in the deep Precambrian jointed system at Fenton Hill are the Gangi joint opening law and the cubic law for fluid flow through parallel plates.

The Gangi opening law describes the size of a flow path aperture as a function of pressure and is given by

$$a(P) = a_0[1 - (P/P_0)^m],$$

where P is the fluid pressure at the aperture, P_0 is the closure stress of the flow path joint, a_0 is the initial joint opening at closure stress, and m is a characteristic of the asperity heights in the joint where ($0 < m < 1$).[1] The cubic flow equation relates the rate of flow through a joint to the cube of the joint aperture by

$$q = a^3 / (12\,u\,f) * (dP / dx),$$

where q is the flow rate, a is the joint aperture size, u is the dynamic viscosity of the fluid, f is the friction factor or joint tortuosity, and dP/dx is the pressure gradient across the joint.[2]

Since the flow rate follows a cubic function of flow path aperture, increasing the joint aperture greatly enhances the flow (and reduces the impedance), while the driving pressure difference across a joint has only a linear influence on flow. These concepts incorporated into an implicitly coupled finite element model have successfully simulated flow test results for experiments conducted at Fenton Hill.

To analyze HDR reservoir impedance, data from the Initial Closed-Loop Flow Test (ICFT), performed in 1986, and data from the Long Term Flow Test (LTFT) and other recent flow tests conducted in 1992 were investigated. A brief history of Fenton Hill follows in order to explain the distinctly different wellbore zones of the ICFT and the LTFT, because the lower portion of the original well used for the ICFT was redrilled and the redrilled wellbore has produced the flows of the LTFT and subsequent flow tests.

The original wellbore, designated EE-2, was used in 1983 to conduct a Massive Hydraulic Fracturing (MHF) reservoir creation test which stimulated intense microseismic activity with the injection of 21000 m^3 of water (5.7 million gallons) at rate of 106 l/s (840 gpm). During this injection, the wellbore was altered and a portion of casing was damaged when a flange at the wellhead failed and a rapid back-flow of water, steam, and about 0.3 m^3 of rock fragments were ejected from the reservoir. In 1986, this damaged EE-2 wellbore served as the production well during the ICFT.

Then in 1987, the original EE-2 wellbore was sidetracked and redrilled through the same fractured reservoir on a trajectory essentially parallel to, but 15 to 30 meters away from the old wellbore. The redrilled well, designated EE-2A, serves as the current production well, and has carried the outlet flow for the LTFT and other recent flow tests. The difference in the flow behavior of the two wellbores suggests that a mechanism, possibly mechanical propping, changed the outlet flow character of the EE-2 well and reduced its outlet impedance.

RAPID DEPRESSURIZATION OF EE-2

During the MHF test when the hydraulic fracturing pressure was accidentally vented, the rapid depressurization of the wellbore flashed water to steam and threw shards of rock from the wellbore. The fragments of rock were apparently broken from the surface of the wellbore by pressure spallation. Pressure spallation is thought to occur when microcracks beneath the surface of a rock fill with water at a pressure higher than the tensile strength of the rock, then when the pressure at the surface is quickly released, the force of the pressure difference between the interior and the surface of a rock causes spallation. Investigation of the outlet impedances of the two wellbores, EE-2 and EE-2A, indicates distinct differences in the outlet flow impedances of the wellbores which may be explained by mechanical propping due to pressure spallation. The pressure spallation seems to have occurred on the surfaces of outlet flow paths as well as on the wellbore surface, which allowed fragments of rock to lodge within and prop open the reservoir connections to the outlet wellbore as flow paths were closing with the release of the pressure. A laboratory experiment designed to verify the principle of pressure spallation has been planned but has not yet been carried out. Therefore, pressure spallation and the resultant mechanical propping of the damaged wellbore zone remains just a hypothesis at this time, however flow test data strongly supports this hypothesis.

The following paragraphs first discuss the overall impedance results from the ICFT, LTFT and more recent flow tests, then go on to analyze the outlet impedances of these flow tests and distinguish the differences in outlet impedances for the two wellbores. The results suggest that two methods of increasing the flow path apertures, pressure propping and mechanical propping, have been demonstrated at Fenton Hill.

ICFT OVERALL IMPEDANCE RESULTS

In May and June of 1986 the ICFT was divided into two 15 day flow segments. Table 1 shows the measured parameters at selected times during each flow segment of the test, along with the calculated impedance. The flow impedances shown in Table 1 were calculated from the pressure drop between the wellheads divided by the produced flow rate.

	ICFT 1st Segment	ICFT 2nd Segment
	6/2/86	6/18/86
Injection Pressure, MPa (psi)	26.8 (3890)	31.5 (4570)
Production Pressure, MPa (psi)	2.4 (351)	3.4 (495)
Production Flow Rate, l/s (gpm)	8.5 (135)	13.5 (214)
Production Temperature, °C (°F)	173 (343)	190 (374)
Impedance, MPa/l/s (psi/gpm)	2.87 (26.2)	2.08 (19.0)

Table 1. ICFT Performance Results

A comparison of overall impedances derived from the first and second segments of the ICFT illustrates the result of impedance reduction by pressure propping. During the second segment of the ICFT, the higher mean reservoir pressure reduced the overall reservoir impedance by pressure dilating the flow paths connecting the injection and production wells. Similar results are also seen in the data of more recent flow tests.

RECENT FLOW TESTS AND OVERALL IMPEDANCE RESULTS

During 1992, the LTFT operated for 16 weeks with a steady injection pressure controlled below a seismic threshold of 27.3 MPa (3960 psi) while the production pressure was held constant at 9.67 MPa (1400 psi). After a pump breakdown which interrupted the test, a series of interim flow tests (IFT's) were conducted to continue gathering data until the pressure and flow conditions of the LTFT could be resumed. Table 2 displays the flow conditions attained with various injection and production pressures and the resulting overall flow impedances.

	LTFT	IFT	IFT2	IFT3
	7/28/92	9/29/92	12/10/92	12/27/92
Injection Pressure, MPa (psi)	27.29 (3958)	22.36 (3243)	27.32 (3963)	27.32 (3962)
Production Pressure, MPa (psi)	9.66 (1401)	9.65 (1399)	15.18 (2201)	12.40 (1798)
Production Flow Rate, l/s (gpm)	5.66 (89.7)	3.85 (61.1)	5.34 (84.6)	5.71 (90.5)
Production Temperature, °C (°F)	183 (361)	165 (329)	177 (351)	183 (361)
*Impedance, MPa/l/s (psi/gpm)	3.11 (28.5)	3.30 (30.2)	2.27 (20.8)	2.61 (23.9)

Table 2. Recent Flow Tests and Overall Impedance Results

* As the production rates vary with different pressure conditions, production temperatures also vary because more heat loss per unit of fluid is conducted away from the production wellbore at reduced flow rates. Density differences in the produced flow rates have been normalized.

Again, the empirical parameters of the LTFT and IFT3, which show similar flow rates and production temperatures, reveal a reduction in overall impedance due to the pressure dilation of flow paths. Even with a reduction in the pressure difference across the reservoir, the flow rate measured at a backpressure of 1798 psi was not less than the flow rate produced at 1401 psi with nearly the same injection pressure. That is, because the apertures of flow paths were dilated with a higher mean reservoir pressure, the overall flow impedance declined enough to maintain the level of production flow in spite of a smaller driving pressure difference across the reservoir. An even higher backpressure of 2200 psi, shown in column IFT2, further reduced the overall impedance of the system at LTFT conditions by about 27% with only a 5% reduction in flow. These data suggest that within a certain range of wellhead pressures the reservoir productivity is a much stronger function of absolute pressure level than the driving pressure difference between wellheads, and that experimentation, modeling, and system modifications may be employed to optimize the system.

IMPEDANCE ANALYSIS FROM SHUT-IN PRESSURE RESPONSE

When the injection and production wellhead valves are rapidly closed, the pressure response at the wellheads displays valuable information about the magnitude and location of reservoir impedance. Figure 1 shows the time response of pressure at both wellheads when the wellheads were quickly closed during steady state flow conditions on July 31, 1992. The injection pressure showed a step decrease of about 100 psi followed by a slow pressure decline toward the mean reservoir pressure. At the same time the production wellhead pressure rose rapidly almost 1700 psi when the well was shut in and then slowly increased toward the mean reservoir pressure. These responses illustrate how the pressure gradient between the injection and production wells levels out rapidly where the gradient is steep but slowly across the body of the reservoir where the gradient is moderate. The small steep pressure drop at the injection well quantifies the small reservoir inlet impedance due to the pipe friction of the injection wellbore casing, since the reservoir inlet flow paths are dilated by cooling as well as propped open by high injection pressure. The magnitude of the pressure rise at the production well, however, illustrates the location of a steep gradient which defines a large pressure drop over a small distance near the production well. This sizable gradient identifies the largest pressure drop between the wells and therefore the greatest portion of the overall impedance. Finally, the residual pressure difference between the injection and production wells, after the initial rapid changes, represents the moderate pressure drop across the body of the reservoir.

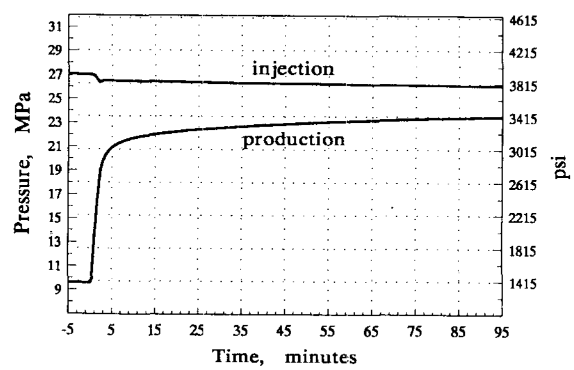

Figure 1. Wellhead Shut-in Pressure Responses

The nature of this pressure response allows the overall reservoir impedance to be divided into three impedances, an inlet impedance, a body impedance, and an outlet impedance. Thus, the pressure measurements in Figure 1 show the LTFT reservoir conditions where a small percentage of the pressure drop between the wellheads occurs on the injection side while the majority of the pressure drop occurs near the production well, leaving a moderate amount of the pressure drop to occur within the body of the reservoir. This asserts that a reduction in the production well impedance will have the greatest impact on reducing the overall reservoir impedance. Therefore, further analysis of the outlet impedance follows.

PRODUCTION WELL SHUT-IN PRESSURE ANALYSIS

In order to more precisely quantify the pressure drop near the production well, the method illustrated in Figure 2 is being developed. Further work in modelling the buoyancy, compressibility, and heat transfer of the water in the wellbore and near wellbore region will be presented in a subsequent paper. Figure 2 plots the pressure rise at the production wellhead when the production valve is quickly closed.

During the initial transient pressure rise, the slope of the curve reflects wellbore and near-wellbore phenomena such as the compressibility of water and heat transfer from the wellbore, but after the short steep rise the pressure at the wellhead shows the gradual relaxation of the pressure gradient across the body of the reservoir. At the same time, flow paths connecting the production wellbore to the body of the reservoir are dilating and storing water due to the increasing pressure. The combination of all these phenomena yields the pressure response measured at the wellhead. Accordingly, the contributions of these influences allow the curve to be divided into two regions, one which follows the steep transient behavior, and a second which follows the gradual long term pressure rise. For the purpose of analysis these two regions of the pressure rise have been modeled with curve fits. The initial slope, which is highly influenced by compressibility and wellbore heat transfer, is nearly linear for a brief few minutes. Therefore, the initial transient is modelled with a linear curve fit whose slope depends upon the initial temperature, pressure, and flow conditions. The subsequent slow pressure rise, which is determined by the relaxation of the pressure gradient across the reservoir and the increasing storage of water in dilating joints near the production wellbore, correlates well with a geometric equation of the form $P = C1\ (t)^{C2}$, where the pressure P is a function of time, C1 is a large constant with the magnitude of the steep transient pressure rise, t is time, and C2 is a very small constant which delineates the long term gradual pressure rise.

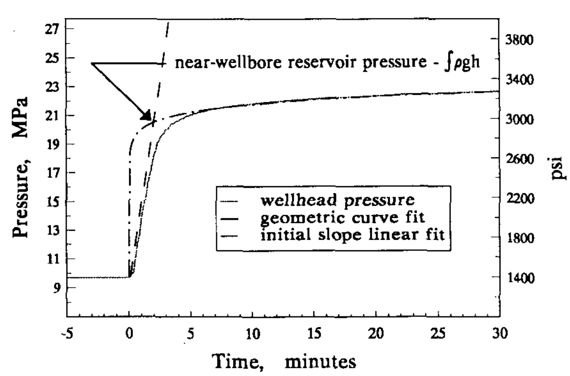

Figure 2. Production Wellhead Shut-in Pressure Analysis

Figure 2 shows the intersection of a linear curve fit following the initial slope of the pressure rise and a geometric curve which models the long term pressure response. The intersection of these curves determines a pressure which represents the reservoir pressure a small distance from the production wellbore. This small distance defines the production zone of steep pressure gradient in a consistent manner for different shut-in curves. Thus, when added to the pressure of the fluid column in the production well, this determined pressure represents the near-wellbore reservoir pressure, which can be used to quantify the pressure drop from the reservoir to the production wellbore in a way that allows comparison of outlet impedances at different production wellhead backpressures.

Figure 3 shows a shut-in pressure rise at the production wellhead from an initial backpressure of 2200 psi, considerably higher than the initial backpressure of 1400 psi shown in figure 2. The effect of the higher backpressure, which dilates the flow paths connecting the production wellbore to the reservoir, is to decrease the near-wellbore outlet pressure gradient. Since the difference between the reservoir body pressure and the wellbore pressure is reduced, the near-wellbore impedance is also reduced. This is evidenced by the smaller pressure rise recorded at the production wellhead when the production well is shut in.

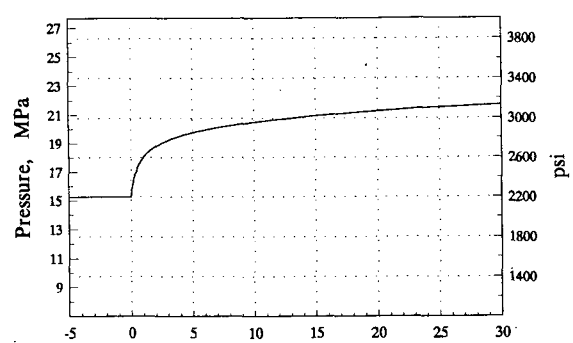

Figure 3. High Backpressure Shut-in Response

Table 3 records the calculated near-wellbore outlet impedances from the earlier ICFT test, with the mechanically propped production outlet, and recent flow tests with the redrilled production well where the outlet impedance is highly dependent upon backpressure. Once again, ongoing work which models compressibility, buoyancy, and heat transfer will refine these numbers, but the qualitative differences in outlet impedances of the two wellbores is evident.

Date	Injection Pressure MPa (psi)	Production Back-pressure MPa (psi)	Near-Wellbore Outlet Pressure Drop MPa (psi)	Production Flow l/s (gpm)	Outlet Impedance MPa/l/s (psi/gpm)
6/2/86	26.82 (3890)	2.42 (351)	6.33 (918)	8.52 (135)	0.743 (6.8)
6/18/86	31.51 (4570)	3.41 (495)	10.13 (1469)	13.63 (216)	0.743 (6.8)
7/31/92	26.96 (3910)	9.64 (1398)	10.73 (1557)	5.85 (92.7)	1.83 (16.8)
12/15/92	27.27 (3955)	15.19 (2203)	4.12 (598)	5.25 (83.2)	0.785 (7.18)

Table 3. Comparison of Near-Wellbore Outlet Impedances

The impedances shown in Table 3 attest to the dependence of outlet impedance upon backpressure for the redrilled wellbore EE-2A, while the ICFT production zone, which connects the reservoir to the EE-2 wellbore, exhibits a considerably reduced and constant outlet impedance. In fact, the constant outlet impedance supports the hypothesis that outlet flow paths of EE-2 were mechanically propped at a fixed aperture when the fluid pressure was below the in situ closure stress of the joints. The composite of all the preceding information allows a number of conclusions to be drawn.

CONCLUSIONS

1. The fluid flow character of the two wellbores, EE-2 and EE-2A, is distinctly different and the reason for the difference is hypothesized to have been caused by pressure spallation and the resultant mechanical propping of EE-2 outlet flow paths by rock fragments.

2. A laboratory experimental verification of pressure spallation should be carried out. (LANL has planned an experiment for summer '93)

3. Two of the potential methods for increasing the size of production flow path apertures are mechanical propping (possibly by pressure spallation) and pressure propping (by holding an elevated backpressure on the production wellhead).

4. Because the largest portion of the pressure drop across the reservoir occurs near the production well, reducing the near-wellbore outlet impedance will have the greatest impact on reducing the overall reservoir impedance.

5. HDR reservoir productivity is a stronger function of the mean reservoir pressure level than the driving pressure difference across the reservoir within a range of the operating pressures employed at Fenton Hill. This is due to the dependence of the flow rate upon the size of the apertures of flow paths, which are a function of pressure.

6. Maintaining a high backpressure reduces both the body impedance and the outlet impedance by pressure dilating flow path apertures throughout the reservoir. In fact, a low backpressure at the production well allows the in situ stresses to pinch off production flow, unless the outlet flow paths are mechanically propped open.

7. The optimization of HDR productivity may be accomplished through modeling, experimentation, and system modifications such as mechanical and pressure propping.

8. Finally, a new method for calculating and comparing near-wellbore outlet impedances at different production wellhead backpressures has been developed.

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