Geothermal Reservoir Definition

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ABSTRACT

The study of geothermal reservoir behavior is presently in a state of change brought about by the discovery that reservoir heterogeneity--fractures in particular--is responsible for large scale effects during production. On the other hand, some parts of a reservoir, or some portions of its behavior, may be unaffected by fractures and behave, instead, as if the reservoir were a homogeneous porous medium. Drilling has for many years been guided by geologists prospecting for fractures (which have been recognized as the source of production), but until recently reservoir engineers have not studied the behavior of fractured systems under production. In the last three years research efforts, funded by the Department of Energy and others, have made significant progress in the study of fractures. The investigations into simulation of fracture flow, tracer analysis of fractured systems, and well test analysis of double porosity reservoirs are all advancing. However, presently we are at something of a conceptual impasse in defining a reservoir as fractured or porous. It seems likely that future directions will not continue to attempt to distinguish two separate reservoir types, but will focus instead on defining behavior types. That is, certain aspects of reservoir behavior may be considered to be generally of the porous medium type (for example, field wide decline), while others may be more frequently fracture type (for example, breakthrough of reinjected water). In short, our overall view of geothermal reservoir definition is becoming a little more complex, thereby better accommodating the complexities of the reservoirs themselves. Recent research results already enable us to understand some previously contradictory results, and recognition of the difficulties is encouraging for future progress in the correct direction.

INTRODUCTION

The Stanford Geothermal Program has had as its prime objective the development of procedures to aid in reservoir definition. This has been an area of focus also for several other groups, both in the geothermal industry and under U.S. Government support. This paper summarizes the state of geothermal reservoir definition research and postulates the future of research in this area.

The purpose of reservoir definition is to discover, delineate and quantify a geothermal reservoir, and thus to identify an optimum way of producing the resource to best advantage. Reservoir definition, therefore, encompasses geological and geophysical exploration, exploratory drilling and reservoir engineering. Since the reservoir engineering aspect is that of most interest to the Department of Energy, this presentation will focus in that direction. Reservoir engineering covers several subtopics including well test analysis, simulation and modelling, tracer testing and discharge test analysis.

Rather than examine each of these topics in detail, this paper will consider them in reference to a broader concept, namely the importance of fractures in geothermal reservoirs. Fractures are prominent features in many geothermal reservoirs, and their influence dominates several reservoir engineering procedures. However, some standard analysis methods appear to be unaffected by the presence of fractures, and can be used as if the reservoir were a homogeneous porous medium. It is important to recognize which engineering methods are so affected, otherwise time and understanding can be lost.

Finally, the value of any applied research can be estimated by examining its successful adoption by the industry. This paper will, therefore, also give examples of field applications of reservoir engineering procedures.

FRACTURES

It has long been known that in many geothermal reservoirs the principal permeability lies in fractures. this is particularly true in volcanic formations. Geologists and drillers have targeted production wells to intersect faults from which the most successful production has been achieved. Experience while drilling has also indicated that reservoir fluid enters the well suddenly over a narrow depth range - probably through a single fracture each time. However, despite the known prominence of fractures, it was not widely realized until quite recently how widely they may affect some aspects of field behavior. In the late 1970's, after the accumulation of some experience in reinjection, it was discovered in tracer tests that fluid may be mobile through fractures over distances exceeding 500 meters, sometimes within a period of a few hours. Figure 1 shows an example of such a flow at Wairakei geothermal field (from McCabe, Barry and Manning, 1981). Figure 2 (from Nakamura, 1981) shows the effects of a similar cross-field flow at Kakkonda, where several production wells suffered significant losses in output after the breakthrough of cooler injection water. This production was recovered after the offending injection wells were shut in.

These large scale phenomena clearly affect the results of tracer tests and injection tests, yet appear not to be as significant in well test analysis or field-wide modelling and simulation. Fractures also govern the interpretation of smaller-scale measurements, for example, wellbore pressure and temperature logs. The variety of these influences will be discussed in more detail in the following sections.

TRACER ANALYSIS

As was shown in Figure 1, tracer is transported in fractures across large distances through the reservoir. It should then be possible to interpret the results of such a test as if the tracer were transported through only a single dominant path (this may not be the case, however, appears likely). Fossum and Horne (1982) demonstrated some success at fitting Wairakei tracer test data from McCabe, Barry and Manning (1981), however, it was never possible to obtain very satisfactory matches to the data without resorting to a two-path model. Furthermore, the most prominent tracer return (WK121 - this one responding at 500m distance) could not successfully be matched with less than 3 assumed paths - a rather unsatisfactory result considering the single major peak in the return. Horne, Breitenbach and Fossum (1982) suggested that the poor match could be attributed to a tracer "holdup-and-release" mechanism caused by tracer retention. Before abandoning the single path approach, research was, therefore, focused on the retention mechanism and how it could be incorporated into the tracer flow model. This work is still continuing under the Stanford Geothermal Program, and results appear promising - Figure 3 and Figure 4 compare matches to field data with and without the retention function model (from Jensen and Horne, 1983).

Recognition of the reinjection problem under Department of Energy sponsorship under the GREMP program has directed considerable attention towards tracer testing, and the current emphasis on fracture identification and analysis is perhaps one of the most widely supported by the geothermal industry.

PRESSURE AND TEMPERATURE LOGS

Since many geothermal wells intersect more than one fracture or feed zone, it is not uncommon to see internal flows of fluid from one feed zone to another. Such intra-well flows are due to pressure differences at different depths in the reservoir, and may occur even though the well is shut in at the surface. It is, therefore, very difficult to interpret temperature logs, since the temperature measured by a tool is only that of the fluid flowing past and not that of the formation. These intra-well flows have been recognized for many years, but were brought to wide attention by Grant, Donaldson and Bixley (1982) who proposed ways of analyzing such logs despite the disguises imposed on the data.

WELL TEST ANALYSIS

As a result of the intra-well flows described above, the only place where the pressure in the well is the same as that in the reservoir is at a primary feed point. However, provided the location of the feed point is correctly identified and the pressure tool is lowered to that depth, then standard well test analysis methods may often be applied. This is in spite of the fact that these methods were derived under the assumption that the reservoir is homogeneous and isotropic. It appears that transmission of pressure pulses through a reservoir is more strongly governed by bulk properties of the medium rather than the severe heterogeneities caused by the individual fractures.

Notwithstanding this observation, there are still many cases where the effects fractures are apparent in well test data. Some of these appear in early time data (the characteristic 1/2 slope 1/2 slope log-log straight line) and have been shown in field data by Ramey and Gringarten (1975) among others. Later time data may also shown fracture effects, in the form of "double porosity" behavior. Such behavior has been clearly identified in Klamath Falls data by Deruyck et al (1982).

SUMMARY

Fractures play a dominant role in the performance of a geothermal reservoir, and the science of reservoir definition requires that specific attention be addressed to the analysis of fractures. Location of fractures or faults within a reservoir is important in defining a drilling program, location of the fractures or feed zones within a specific well is important in correctly interpreting pressure logs, temperature logs and discharge tests. Location of fractures between injection and production wells is important in proposing the design of a reinjection scheme.

However, some broad features of reservoir behavior are relatively unaffected by reservoir heterogeneities. Field wide decline analysis, for example, treats the reservoir as a few large "tanks", and can sometimes reasonably match field data. Classic well test analysis also treats the reservoir as a homogeneous system, and often can adequately represent actual observations.

Thus, in the overall field of reservoir definition, there is no longer a question of defining a geothermal field as "fractured" or "not fractured". Rather, it is now recognized that a reservoir may be expected to act as "fractured" in some respects but "not fractured" in others. Geothermal reservoir engineers have reached a similar impasse to that of physicists who decided that light behaves sometimes like a particle and sometimes like a wave. Geothermal engineers must now treat reservoirs sometimes as fracture Gringarten and sometimes as porous media.

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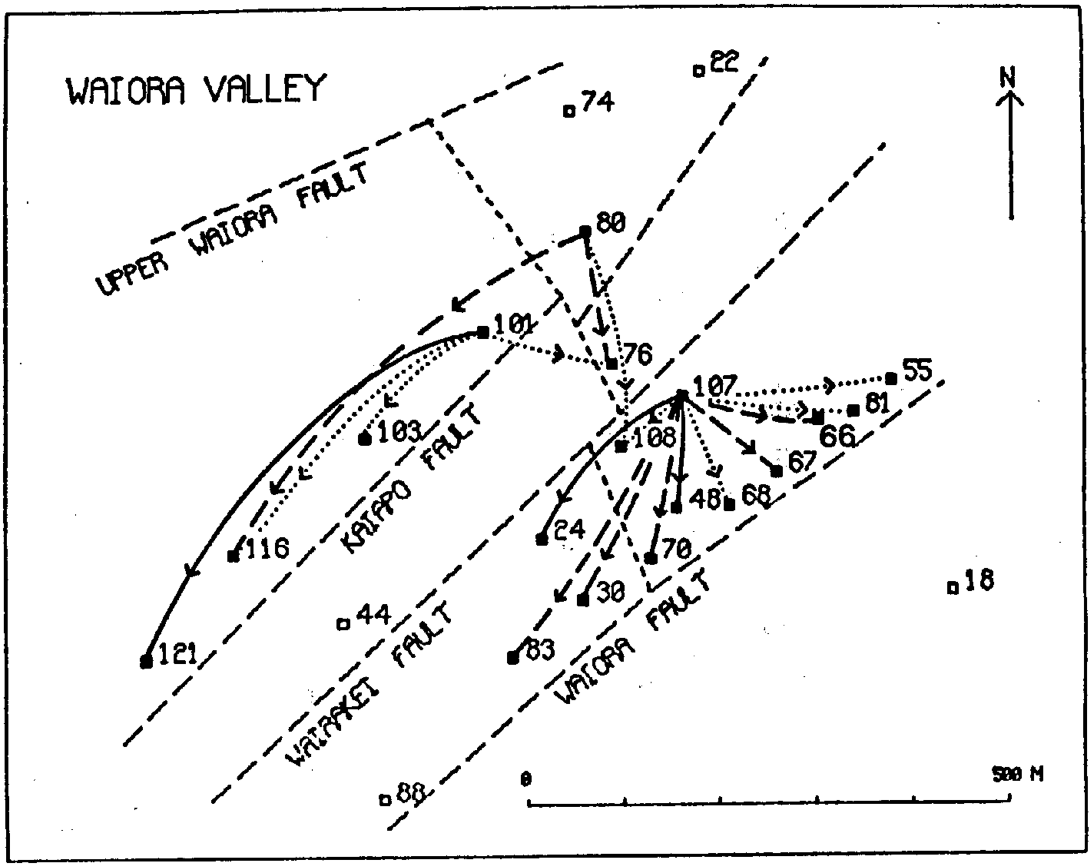

Figure 1: Tracer returns at Wairekei (from McCabe, Barry, and Manning, 1981).

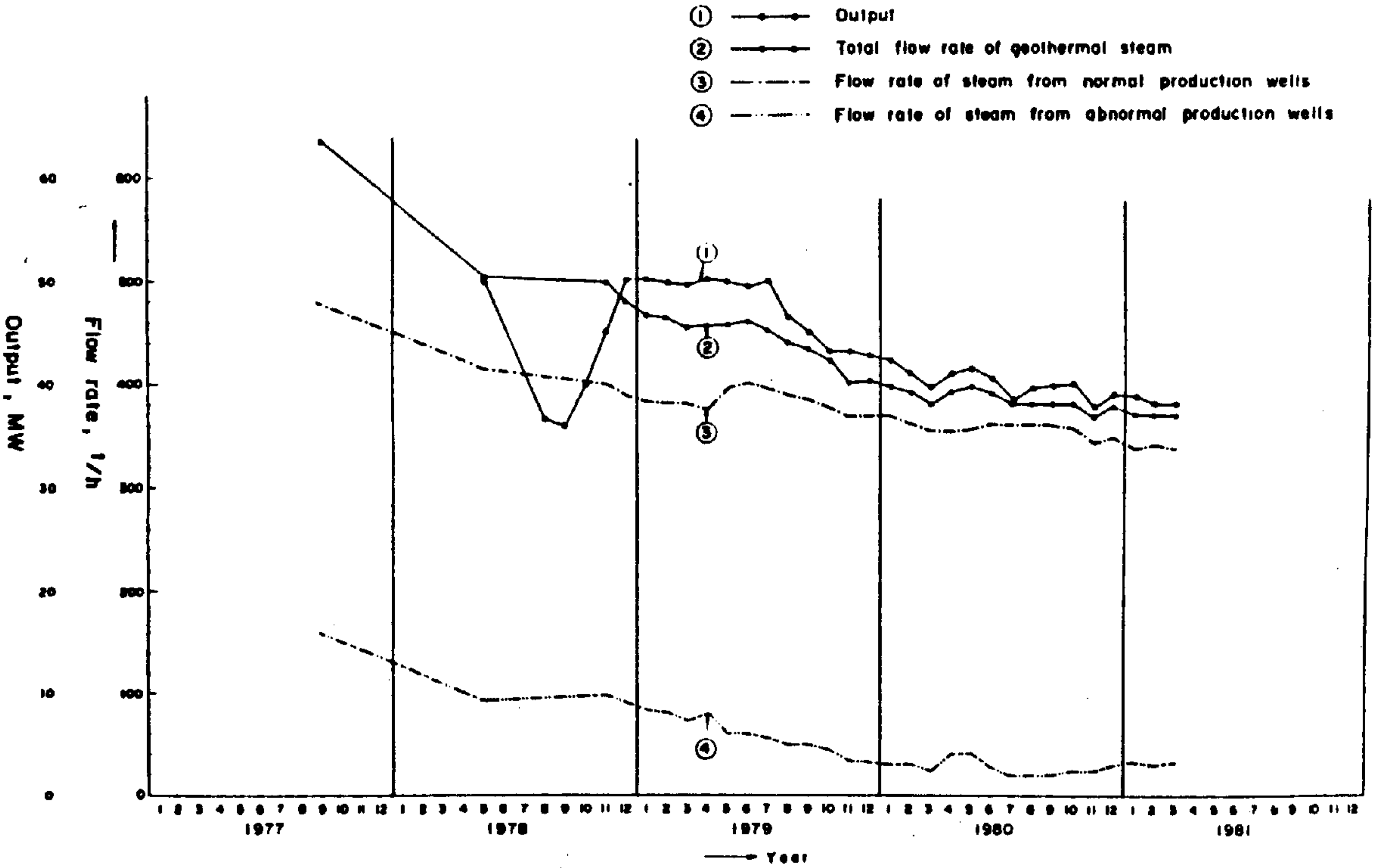

Figure 2: Changes in total output and steam production rate at Kakkonda (from Nakamura, 1981, by permission of Geothermal Resources Council).

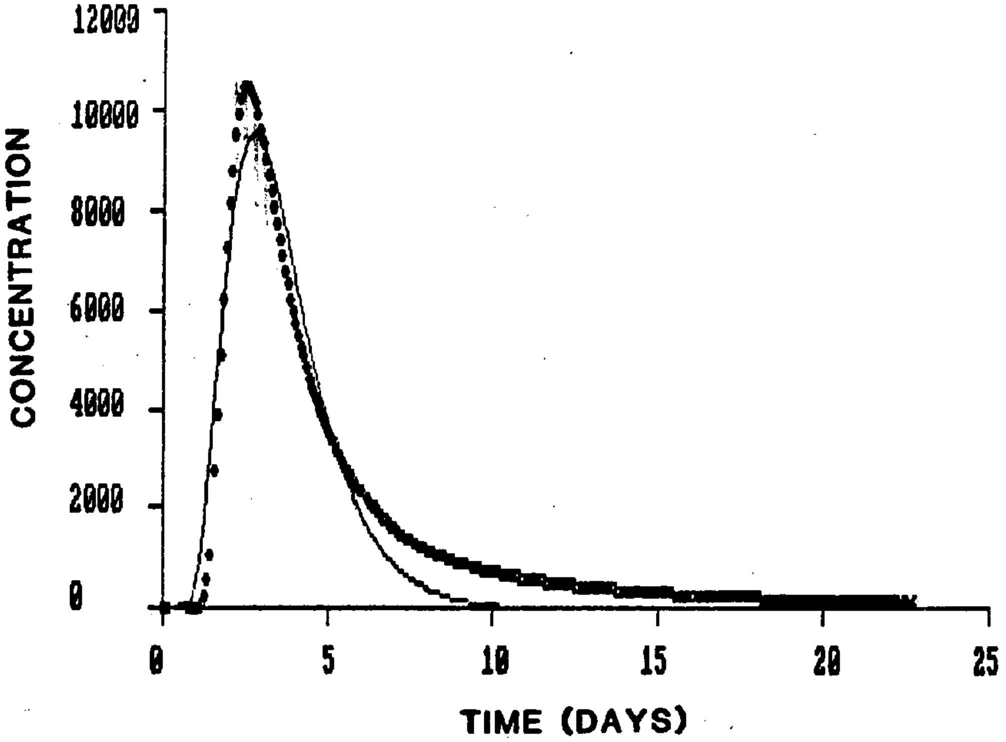

Figure 3: WK 121 Tracer breakthrough profile interpreted without retention model (from Horne, Breitenbach and Fossum, 1982). Dotted line is data, solid line is model.

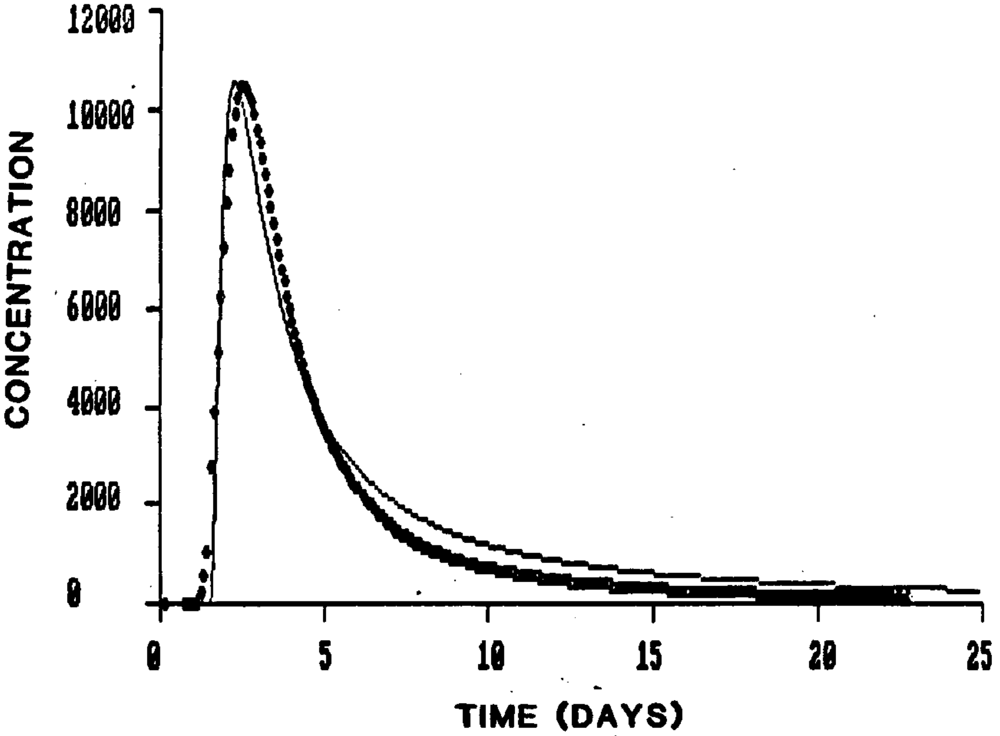

Figure 4: WK 121 Tracer breakthrough profile interpreted with retention model (from Jensen and Horne, 1983). Dotted line is data, solid is model.