GEOTHERMAL WELL COSTS AND THEIR SENSITIVITIES TO CHANGES IN DRILLING AND COMPLETION OPERATIONS

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ABSTRACT

This paper presents a detailed analysis of the costs of drilling and completing geothermal wells. The basis for much of the analysis is a computer-simulation-based model which calculates and accrues operational costs involved in drilling and completing a well.

Geothermal well costs are discussed in general, with special emphasis on variations among different geothermal areas in the United States, effects of escalation and inflation over the past few years, and comparisons of geothermal drilling costs with those for oil and gas wells. Cost differences between wells for direct use of geothermal energy and those for electric generation are also indicated. In addition, a breakdown of total well cost into its components is presented. This provides an understanding of the relative contributions of different operations in drilling and completions. A major portion of the cost in many geothermal wells is from encountered troubles, such as lost circulation, cementing difficulties, and fishing. These trouble costs are considered through both specific examples and statistical treatment of drilling and completions problems.

The sensitivities of well costs to variations in several drilling and completion parameters are presented. The model makes it possible to easily vary parameters such as rates of penetration; bit lifetimes; bit, rental, or rig costs; delay times; number of cement plugs; etc. The effects of these variations on different types of geothermal wells are compared.

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INTRODUCTION

The costs associated with drilling and completing geothermal wells make up a significant portion of the costs of utilizing geothermal energy. Recent studies have shown that well costs account for roughly half of the cost of electricity generated from geothermal sources and, depending on the project, from one-fourth to three-fourths of the cost of space and process heat derived from geothermal resources [1,2].

The US Department of Energy has instituted a program, the Geothermal Drilling and Completion Technology Development Program, with the purpose of significantly reducing well costs in order to enhance the economics of geothermal development [3]. Programmatic goals are to develop and demonstrate technologies sufficient to reduce well cost by 25% by 1983 and by 50% by 1987. The work described in this paper is a portion of the systems analysis being performed to focus the R&D efforts.

Previous studies have surveyed geothermal well costs [4]; analyzed the effects of well costs on energy costs [1,5]; and considered the effects of generic improvements in technology on well costs [6]. This current study is different since well costs are important to the technology development program only for their use in evaluating the cost reduction potentials of new technologies. To enable such evaluations, it is necessary to understand the factors that contribute to geothermal well costs. Sufficiently detailed cost breakdowns are seldom available in records of wells that have been drilled. Instead, it has been necessary to project detailed costs through constructive modeling of geothermal drilling and completion -- modeling supported by the limited historic records.

Extensive previous work has been performed at Sandia in developing a computer code that simulates the drilling of a well and accrues the detailed costs associated with each separate operation [7,8,9]. The emphasis in the current analysis has been the construction of the detailed well models for various US geothermal areas. These models will be shown to be representative of actual wells drilled in the various areas, and include all operations required for drilling and completing wells using current technology. They detail the times and costs required for each operation. These representative well models, or "generic wells," are used with the computer code to provide a well-cost baseline for evaluation of technologies.

This paper presents a compilation of well-cost data and points out interesting trends and comparisons. These data were collected to provide a framework for well cost considerations and a basis for comparison and validation of the representative well models. Following this, the construction technique used for the representative well models is outlined, and a sample model for the East Mesa, California, resource is presented. Comparisons between the historic and the modeled costs are emphasized for several geothermal areas. Finally, the results are summarized. These include sensitivity results showing the contributions of various drilling and completion operations to overall well costs and results that display the impact of drilling and completion problems on well costs. It should be emphasized that the materials presented serve as tools used for technology evaluation and are not intended for projection of geothermal energy costs.

HISTORIC DATA

Well Costs -- Compilation of historic well costs is an essential part of the drilling and completion program. Because of the program goals, evaluation of new technologies must be tied to geothermal well costs. Unfortunately, historic costs themselves cannot provide a sufficient baseline for evaluation of the cost effects of new technologies because:

1. Seldom are the costs of a well collected in sufficient detail to allow analysis of the effects of changing individual operations.

2. Historic well costs are tied to conventional technology. New technology may completely change the way a well is drilled and completed.

3. Historic costs often are inaccurate. Published total cost figures for the same well have been found to differ by as much as 40%. Discrepancies in the details of cost breakdowns can be significantly larger.

4. Often well cost data are proprietary and are unavailable. The data in this study come mostly from wells in which the government has a financial interest.

In spite of these problems, the cost data presented below[a] display important trends. Furthermore they are valuable in establishing the validity of the representative well models which are designed specifically for technology evaluation.

Figure 1 illustrates the escalation of well costs with time. Geothermal well costs have remained roughly three times the national average for oil and gas wells [10], although individually they range from costing the same to costing six times as much. The escalation factor for both oil and gas and geothermal drilling was approximately 17% per year for the seven-year period indicated. (For comparison, the escalation in the wholesale price index for the same period was 10.2% annually.)

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[a]The authors are grateful to Joe Fiori of the Nevada Operations Office of the Department of Energy for providing cost data on several wells from the Industry Coupled Drilling Program and to A. J. Mansure of the BDM Corporation for aiding the collection of other cost data.

In Figure 2 all of the well costs compiled for this analysis are shown. The dependence of well cost on depth is apparent, but the wide variation among costs dominates. Some order is introduced by identifying envelopes for the various geographic regions as shown in Figure 3. The envelopes are meant to indicate only general trends in the cost data; but they show that drilling in Cove Fort, Utah, has historically been expensive, and Imperial Valley, California, drilling is relatively inexpensive. Excluding these two areas, geothermal drilling tends to be two to four times as expensive as oil and gas drilling -- the same conclusion as drawn from Figure 1.

Table 1 presents a breakdown of geothermal well costs. The data presented are averages for fifteen wells that have been drilled at the Baca location in New Mexico [11]. This breakdown is typical of the most detailed level of historic cost information commmonly available. It is sufficient to help identify operations with significant potential for reducing costs. However, it is not adequate for evaluating specific technological improvements. Data such as those in Table 1 have been obtained and analyzed for approximately thirty-five geothermal wells.

Drilling Time -- Drilling time information that reflects the total number of days to drill and complete a well shares many of the drawbacks -- as far as technology evaluation is concerned -- of total cost data. However, it does have the advantage that it is much easier to obtain, and it is just as useful as cost data in validating the representative well models. The number of days required for a well does not escalate with drilling costs, and so comparisons of the times required to drill and complete different wells in a resource area would more truly reflect changes in technology or experience than would comparisons of well costs.

Figures 4 and 5 present historic drilling time data for the Imperial Valley and for The Geysers area in California [12]. Similar data have been compiled for other geothermal resource areas. The spread among the data points in these figures is perhaps their most impressive feature. There could be several factors contributing to this spread, but unplanned drilling troubles, or contingencies, comprise one of the most important. An interesting point that is not evident in the figures, is that the spread of data changed little over time. For example, in The Geysers area there was no discernable drilling-days difference between the drilling in the early 1970s and that five to ten years later. That is, there was no "learning curve" effect in the 1970s. It is possible that the drilling and completion methods in The Geysers were mature by 1970 and there were no subsequent improvements, or that improvements based on experience were offset by expansion into areas in which drilling was more difficult.

REPRESENTATIVE WELL MODELS

In order to have sufficiently detailed cost data to evaluate new technologies it was necessary to construct representative well models for the major US geothermal areas[b]. These well plans represent the operation by operation sequences involved in drilling and completing wells in particular resource areas. The wells modeled are trouble-free wells with representative depths and casing programs. In addition to the construction of these trouble-free models, probability estimates have been made for the frequency and severity of trouble. Together, the trouble-free generic well models and the trouble statistics describe the drilling in each resource area adequately enough to allow evaluation of new technologies.

Several steps are involved in the construction of a generic well plan. A survey of the drilling and completion history for an area provides data for designing an initial casing program. A schedule of drilling and completion operations is then compiled from well records and conversations with producers, operators, and service companies active in the region. This schedule is then filled out with specific times and costs for each portion of each operation. These are compiled from several sources, including manufacturers price lists, actual quotes and bills, bit records, drilling records, conversations with operators, etc. Finally when this process is complete, the entire well plan with detailed, subtotaled, and totaled costs and times is discussed with producers and operators. The result of this effort is a (trouble free) generic well.

The gathering of trouble statistics, currently being performed, combines compilation of available historic data with the gathering of subjective opinions (of trouble frequency and severity) from those active in a region. Unfortunately, the paucity of historic data precludes direct statistical modeling of troubles and necessitates the subjective distribution approach, relying on expert opinion. The actual data that are available will be used when possible and will provide verification of the trouble distributions derived from subjective opinions. When completed, the trouble distributions will be used to add trouble times and costs to the trouble-free generic wells.

As an example of the generic wells, Figure 6 shows the casing program for a 7600 ft (2316 m) well in the East Mesa anomaly in the Imperial Valley.[c] This casing program is typical of those that have been or could be used in this part of the Imperial Valley. Table 2 shows the detail included in a typical portion of the East Mesa well model. This portion covers the cementing of the 13-3/8 in. (34.6 cm) surface casing.

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[b]For brevity, the term "generic well" is used for "representative well model" in the figures, and the two are used interchangeably in the text.

[c]For help with this and the other representative well models, the authors are indebted to B. J. Livesay of Livesay Consultants.

Figure 7 illustrates the breakdown of times and costs for the East Mesa generic well. Such breakdowns by drilling and completion operations are especially important for evaluation of technologies. The total cost of the well is estimated to be $730,000 (third quarter 1979 prices). The comparison of this total to historic costs, such as those in Figure 2, is one measure of the validity of the well. A second measure is the consistency of the cost breakdown with historic breakdowns similar to those illustrated in Table 1. Using both of these cost-related validity measures the East Mesa generic well model and the other generic models are indistinguishable from historic experience with actual wells.

A third measure of the well model's validity is its total drilling time. In Figures 4 and 5, which showed total time data for historic wells, the drilling and completion times for generic wells of various depths were indicated by dashed lines. In comparing the generic wells with historic data, it should be recalled that the generic wells represent trouble-free wells. The trouble, or lack of it, encountered in drilling and completing a well accounts for much of the data spread in Figures 4 and 5. Similarly, the trouble distributions will add time and cost to the trouble-free generic wells. The comparisons indicate that the trouble-free generic well models, although nearly lower bounds, are not optimal wells -- that is, they are not minimum cost or minimum time wells. Instead they realistically represent drilling and completion that are average except for being completely free of significant well troubles. They are constructed using average drilling rates and operation times, and so certain specific wells may be drilled faster or more cheaply. This is reflected in the data of Figures 4 and 5.

RESULTS

<u>Sensitivity Results for Trouble-Free Wells</u> -- Once they have been constructed, the representative well models can be used to characterize the effects on well costs of modifying drilling and completion operations. Samples of the resulting well-cost sensitivities are shown in Figures 8 and 9 for different drilling and completion operations, geothermal regions, and well depths. These results display relationships among operations and help identify primary targets to reduce costs in trouble-free wells. However, they are not sufficient for evaluating specific technological improvements. New technologies often impact multiple parameters, and thus their effects on well costs cannot be displayed by simple sensitivity charts.

Cost effects illustrated by the sensitivity results include:

1. Increasing the rate of penetration without affecting other performance parameters can significantly reduce costs in a trouble-free well. Other work has shown that in wells with frequent trouble, increasing the rate of penetration has a much reduced effect.

2. Well costs are highly sensitive to rig rates. Although this is an obvious relationship, it is worth noting. Because of this a technology that increases both rate of penetration and rig costs may not be worth developing.

3. Reducing the costs involved in casing operations can have an impressive impact on well costs.

4. Systems to eliminate or speed tripping will have only limited impact on well costs, unless they change other operations as well.

Sensitivity results can be obtained for any parameter or operation of interest for any of the major geothermal areas.

Trouble Statistics -- The sensitivity results above are for the trouble-free well models; and as discussed, drilling and completion troubles can be included in these models via probability distributions. Current work in the modeling emphasizes statistical characterization of the problems that are encountered and then expansion of the models to realistically account for these troubles. Preliminary results for this work are shown here.

Figure 10 shows distributions for the probability of first encountering significant trouble as a function of depth. This figure was constructed from all available historic drilling records for the three geothermal areas indicated. For a trouble to be included, it had to be noted as a significant problem on the daily drilling record. Even though the figure is based on incomplete information, the differences among geographic areas are evident. Nearly all of the Baca wells, for which records were available, encountered some trouble during drilling and completion, as did roughly two thirds of The Geysers wells and one third of the Imperial Valley wells. This suggests more difficult drilling at The Geysers and especially at the Baca than in the Imperial Valley. The types of troubles encountered were different for the individual areas; but in all, there seemed to be a tendency toward multiple troubles. If a well encountered one problem, others were very likely to follow.

Figure 10 considered only the probability of encountering first troubles. In Figure 11 the time lost to each trouble occurrence is described for the Baca wells [13]. These data also came from the daily drilling reports. The mean of the trouble time distribution, that is the average length of delay for each trouble occurrence, is roughly 4 days and the median trouble delay is a little less than 2 days. In Table 3 the drilling and completion troubles at the Baca are identified as to type, frequency, and mean duration. The table shows that lost circulation and stuck pipe are the most frequent problems at the Baca. Detailed trouble distributions such as this are being constructed from the drilling experience at all areas of interest.

The problems encountered in drilling and completing a specific well are reflected in the total number of days required for that well. Figures 12 and 13 present histograms of the differences in drilling days between actual wells and trouble-free generic wells of the same depth. These figures were derived from Figures 4 and 5, and they define probability distributions for the dispersion around the baselines provided by the generic wells for the Imperial Valley and The Geysers. The generic models were constructed before the drilling time data were collected. Yet for both areas, the generic wells fall at about the 15^{th} to the 20^{th} percentile in terms of drilling days. Once again this illustrates that the generic models represent non-optimal, trouble-free drilling. Encountered trouble will add to both the time and cost of the wells -- just as extreme good fortune could shorten and cheapen drilling and completion. From the figures it is seen that in both areas there is a long tail representing extreme drilling problems. The Imperial Valley distribution is more peaked and seems to have a smaller spread than does the distribution for The Geysers, again indicating more problems at The Geysers than in the Imperial Valley.

SUMMARY

This paper has presented work in three major areas.

1. Extensive effort has gone into compilation of historic data. The well cost and drilling time data, most of which were previously unpublished, illustrate the following points:

    a. Geothermal well costs average 2 to 4 times those for oil and gas wells.

    b. Well costs are strongly dependent on well location and depth.

    c. Even within a single resource and for wells with similar depths, costs can vary widely -- factors of more than 2 to 3 are not uncommon.

    d. Drilling days variability is even greater -- the times required for similar wells can vary by an order of magnitude.

2. The major portion of the current effort has been in the development of representative well models for many geothermal areas. These models provide the detail necessary to evaluate new technologies. They were constructed independently of, but are well supported by, the historic cost and time analyses. Consideration of these models has illustrated the following points:

    a. The models represent non-optimal, trouble-free wells in the various geothermal areas and allow sensitivity analyses of trouble-free well costs.

    b. Rates of penetration, drilling-rig rental rates, and casing costs are parameters to which well costs are quite sensitive.

3. Work is continuing in the analysis of the cost impacts of drilling and completion problems. Results to date have demonstrated:

   a. Drilling and completion problems affect a large portion of geothermal wells -- the portion is as high as 100% for certain drilling regions.

   b. Problems can add significant costs and times to geothermal wells -- they account for much of the historic variability noted above.

   c. Trouble costs and times can be incorporated into the generic well models using probability distributions for frequency and severity of occurrence.

The major conclusions that have been drawn from this work are: the well modeling yields well costs and drilling times that are consistent with historic data, and use of the models in the evaluation of new technologies is one means by which the programmatic goals can be evaluated.

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Table 1

Baca Drilling Cost by Category

Category	Average Cost ($x10^3)*	%
Drilling Contract	$ 504.7	39.9
Mud/Chemicals	72.7	5.7
Cement	233.5	18.5
Bits	102.0	8.1
Equipment Rental	53.2	4.2
Casing	117.5	9.3
Miscellaneous	41.7	3.3
Logging	--	--
Transportation	11.8	0.9
Location Preparation	25.2	2.0
Mobilization	13.9	1.1
Fuel	46.3	3.7
Supervision	23.0	1.8
Wellhead	19.9	1.6
Total Well Cost	$1,265.0	100

*1979 dollars

Table 2

Sample of Operation Sequence - East Mesa Well Model

Activity/Equipment/Service	Depth (ft)	Δ Time (h)	Variable Cost ($1x10^3)	Direct Cost ($1x10^3)	Cumulative Time(h)	Cumulative Cost($1x10^3)
Wiper Trip for Casing/ Cementing	1700	3.4	1.346		40.5	100.05
Rig Up to Run 13-3/8 in. Casing	1700	2.0	0.792		42.5	100.84
Run 1700 ft. 13-3/8 in. Casing	1700	8.5	3.365		51.0	104.21
Casing				41.65		145.86
Casing Tool/Service				4.86		150.72
Cement Equipment				3.14		153.86
Rig Down Casing Tools	1700	1.0	0.396		52.0	154.25
Rig Up to Cement	1700	2.0	0.792		54.0	155.05
Cementing	1700	2.8	1.108		56.8	156.15
Cement				12.99		169.14
Services				3.73		172.87
Rig Down Tools	1700	1.0	0.396			173.27
Wait-on-Cement	1700	4.0	1.583		60.8	174.85
Install Wellhead/BOP	1700	12.0	4.75	15.07	72.8	194.67
Test Well Head/BOP	1700	4.0	1.583		76.8	196.26
Trip In (12-1/2 in. Smith Bit)	1700	1.8	0.713	1.17	78.6	198.14
Stabilizers	1700			1.69		199.83
Drill Cement	1700	2.5	0.990		81.1	200.82
Condition Mud	1700	1.0	0.396		82.1	201.21
Test Shoe	1700	3.0	1.188		85.1	202.40

Variable Cost Rate ($/h)	
Rig	235.40
Fuel	41.25
Trans/Misc	62.50
Rental	15.00
Supervision	20.85
Mud	20.85

Table 3

Relative Frequency and Severity of Various Troubles -- Baca Wells

	Type of Trouble	Frequency of Occurrence (%)	Average Lost Time (Days)
1.	Lost Circulation	29	2-1/2
2.	Stuck Pipe	17	8
3.	Twist off	9	1-1/2
4.	Side track	4	16
5.	Rig Problems	13	2
6.	Casing Problems	9	11
7.	Cementing Problems	8	8-1/2
8.	Fishing/Junk	11	2-1/2
		100	

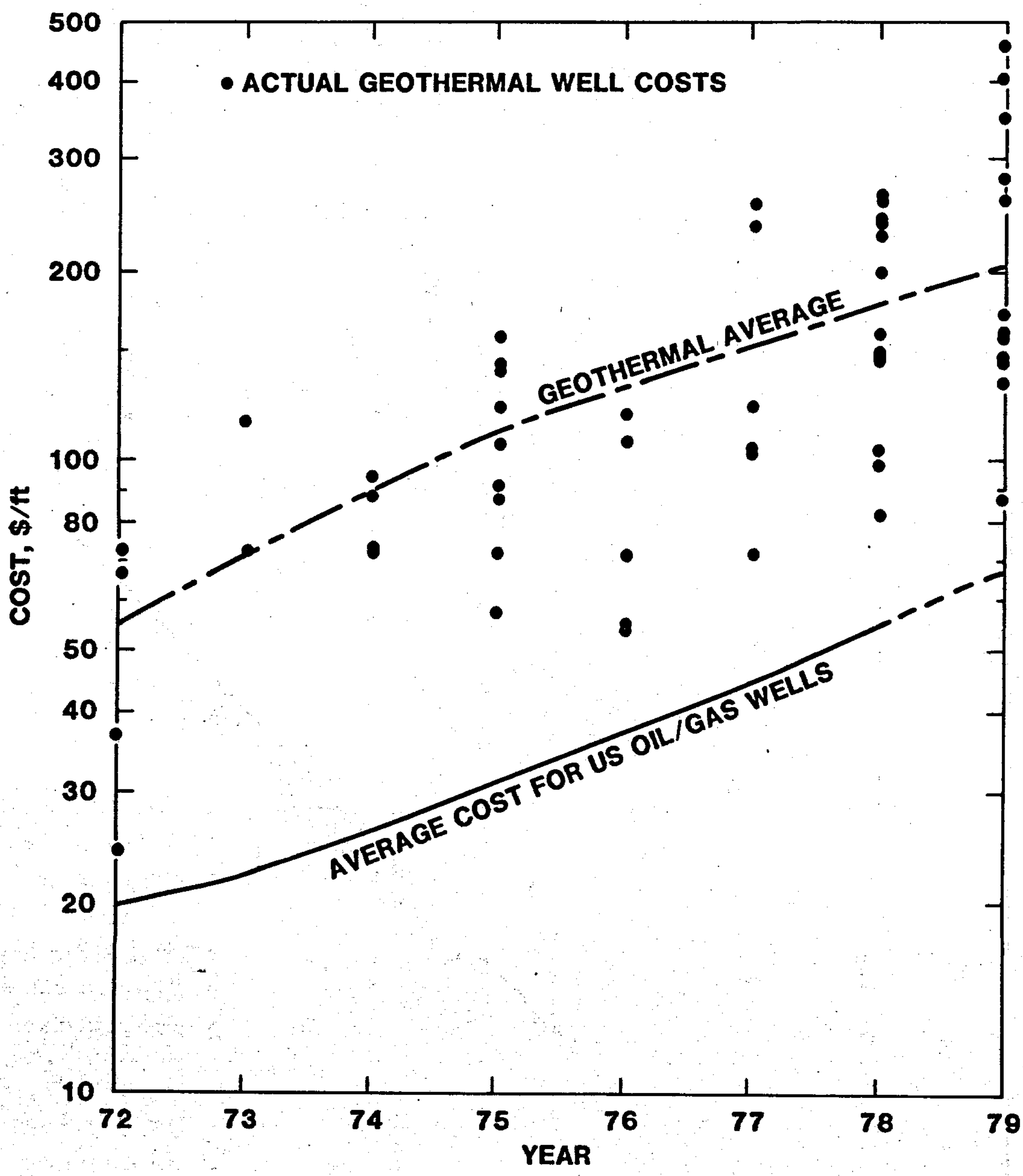

Figure 1. Well Cost Escalation

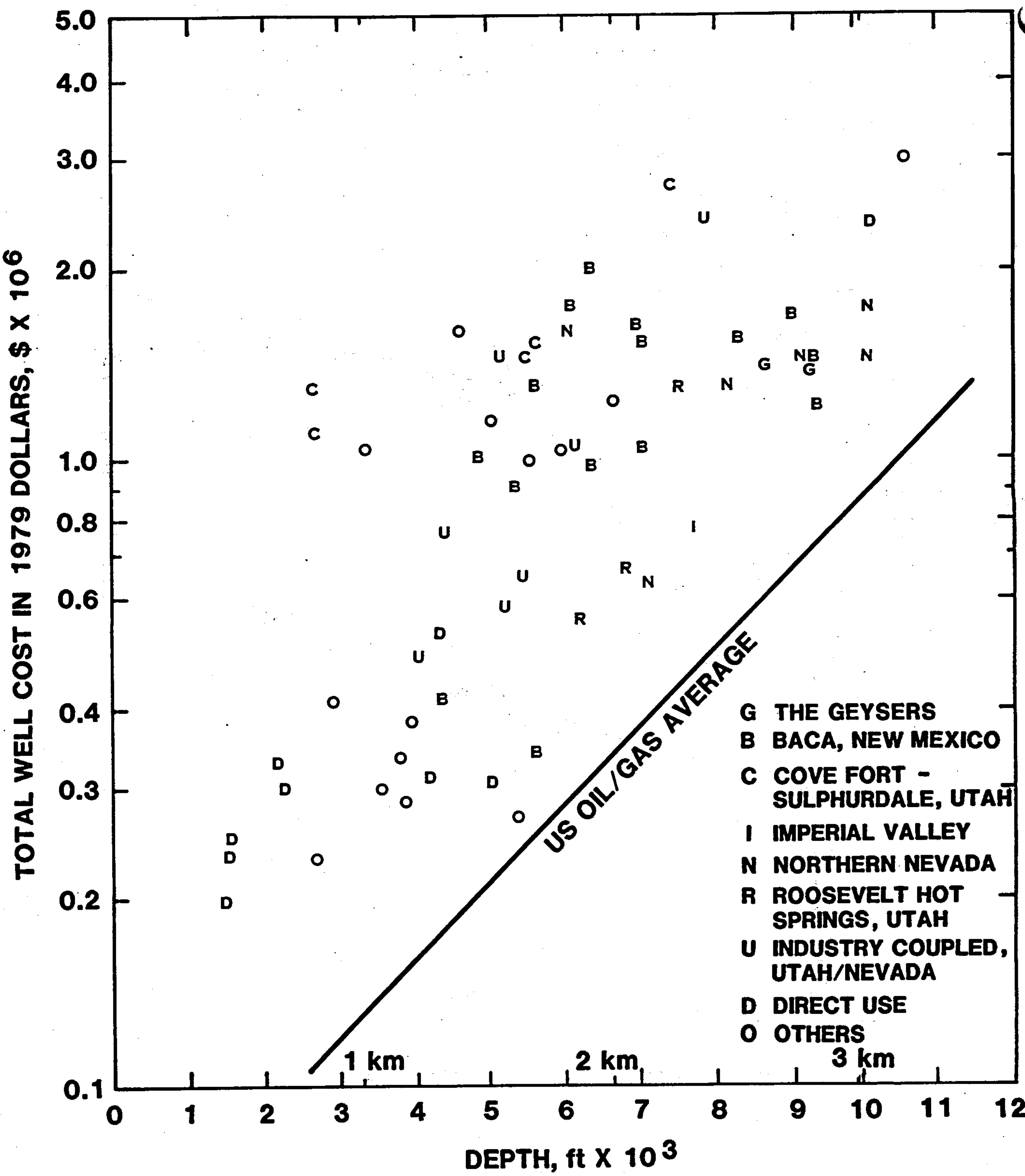

Figure 2. Geothermal Well Cost by Depth

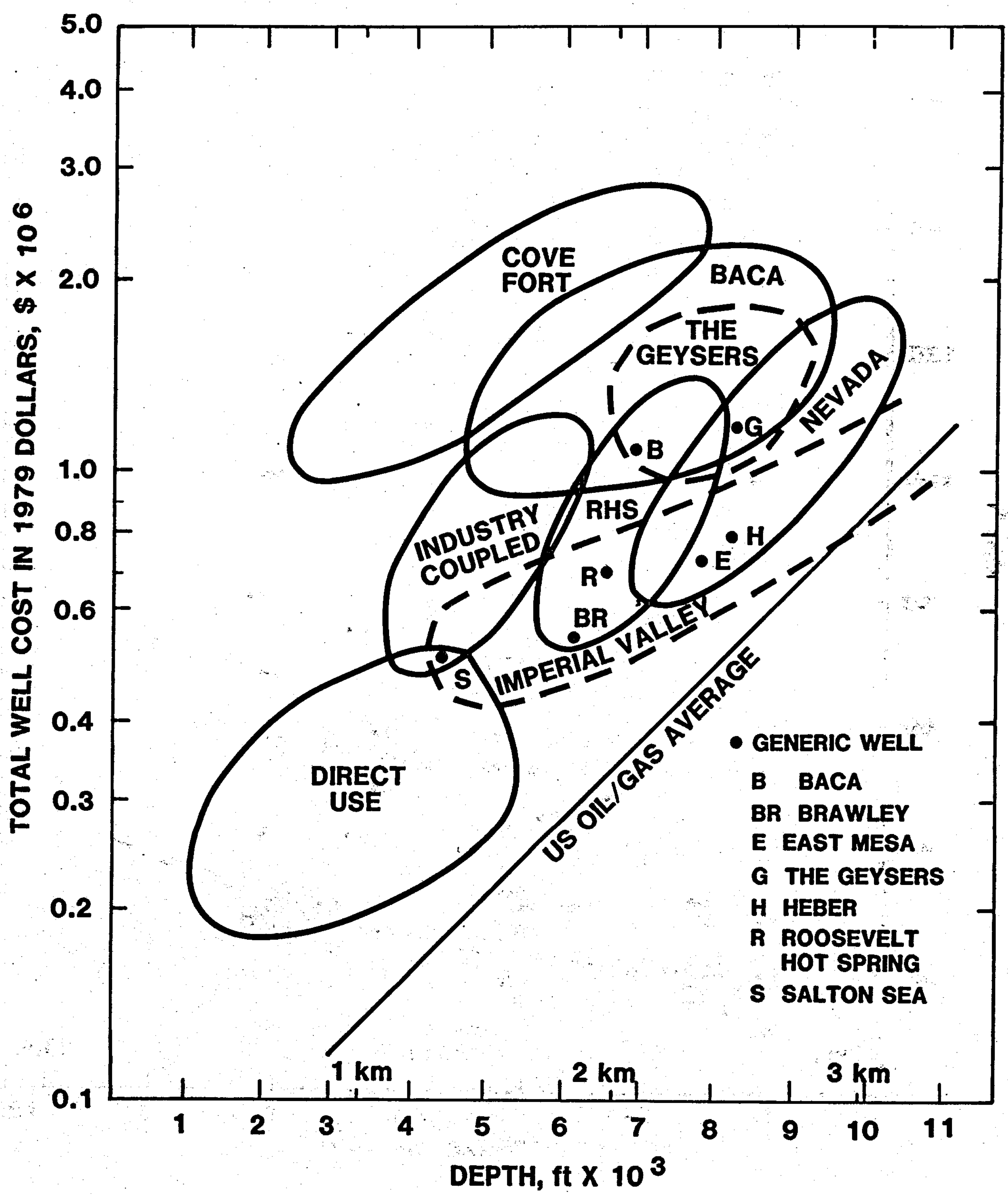

Figure 3. Geothermal Well Cost Pattern by Region

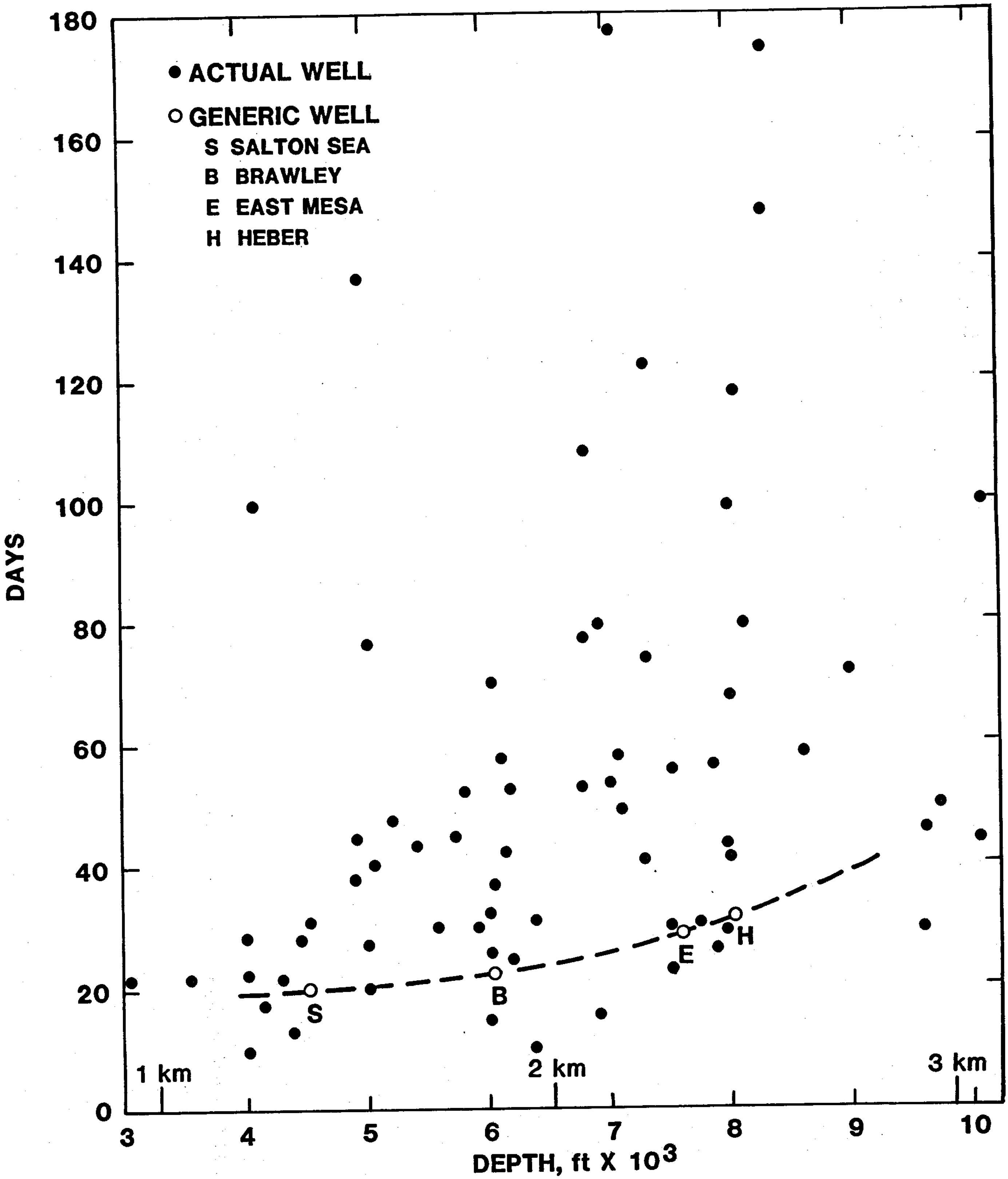

Figure 4. Total Time -- Imperial Valley Wells

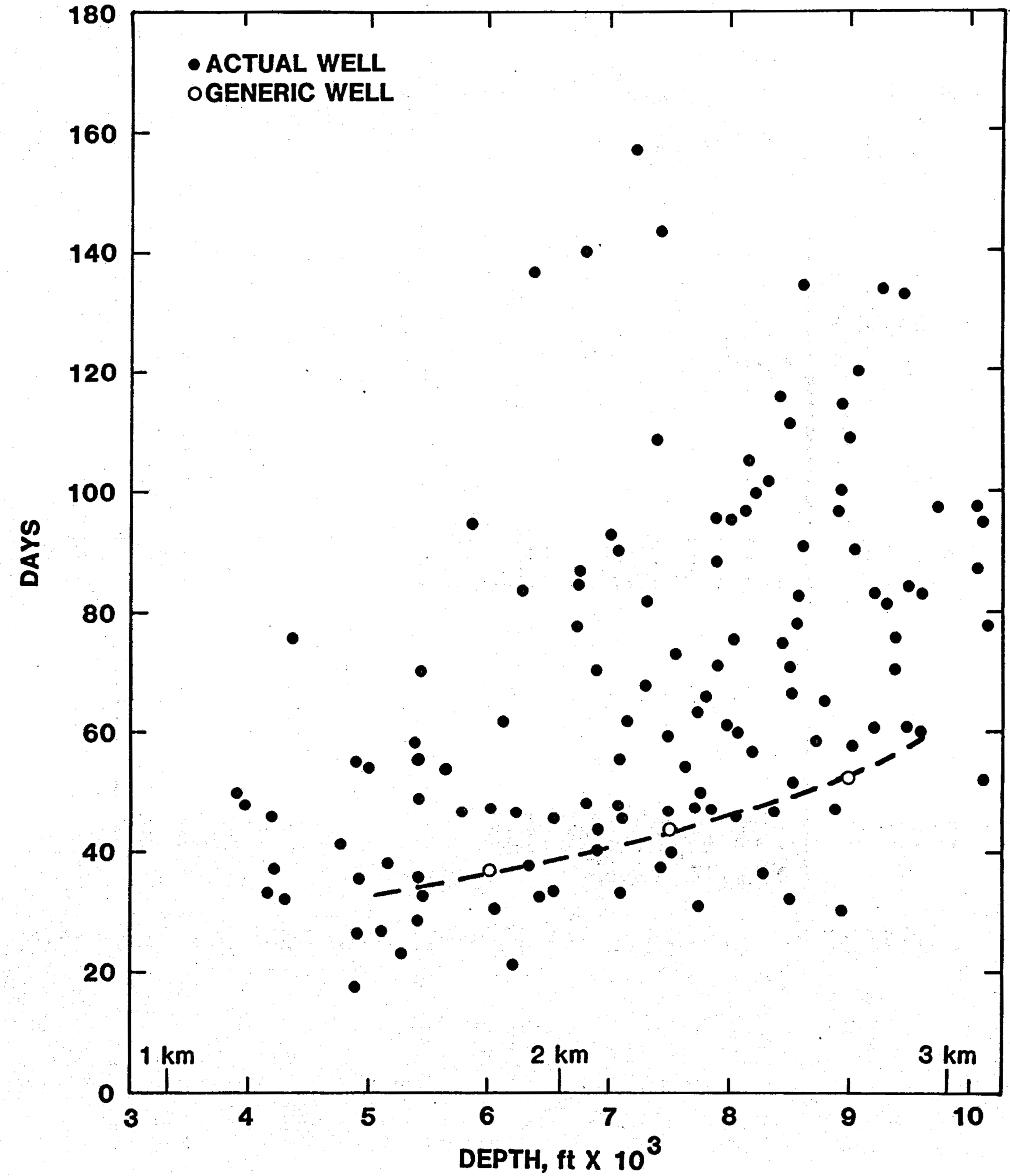

Figure 5. Total Time -- The Geysers Wells

HOLE SIZE	PIPE SPECIFICATIONS		
26 in.	20 in. 94 lb/ft H40 CONDUCTOR	100 ft	
17-1/2 in.	13-3/8 in. 48 lb/ft H40 BUTT SURFACE CASING	1700 ft	200 ft
12-1/4 in.	9-5/8 in. 36 lb/ft K55 BUTT INTERMEDIATE CASING/LINER	5500 ft	200 ft
8-3/4 in.	7 in. 29 lb/ft N80 LT&C SLOTTED LINER	7600 ft	

Figure 6. Casing Plan for Representative East Mesa Well Model

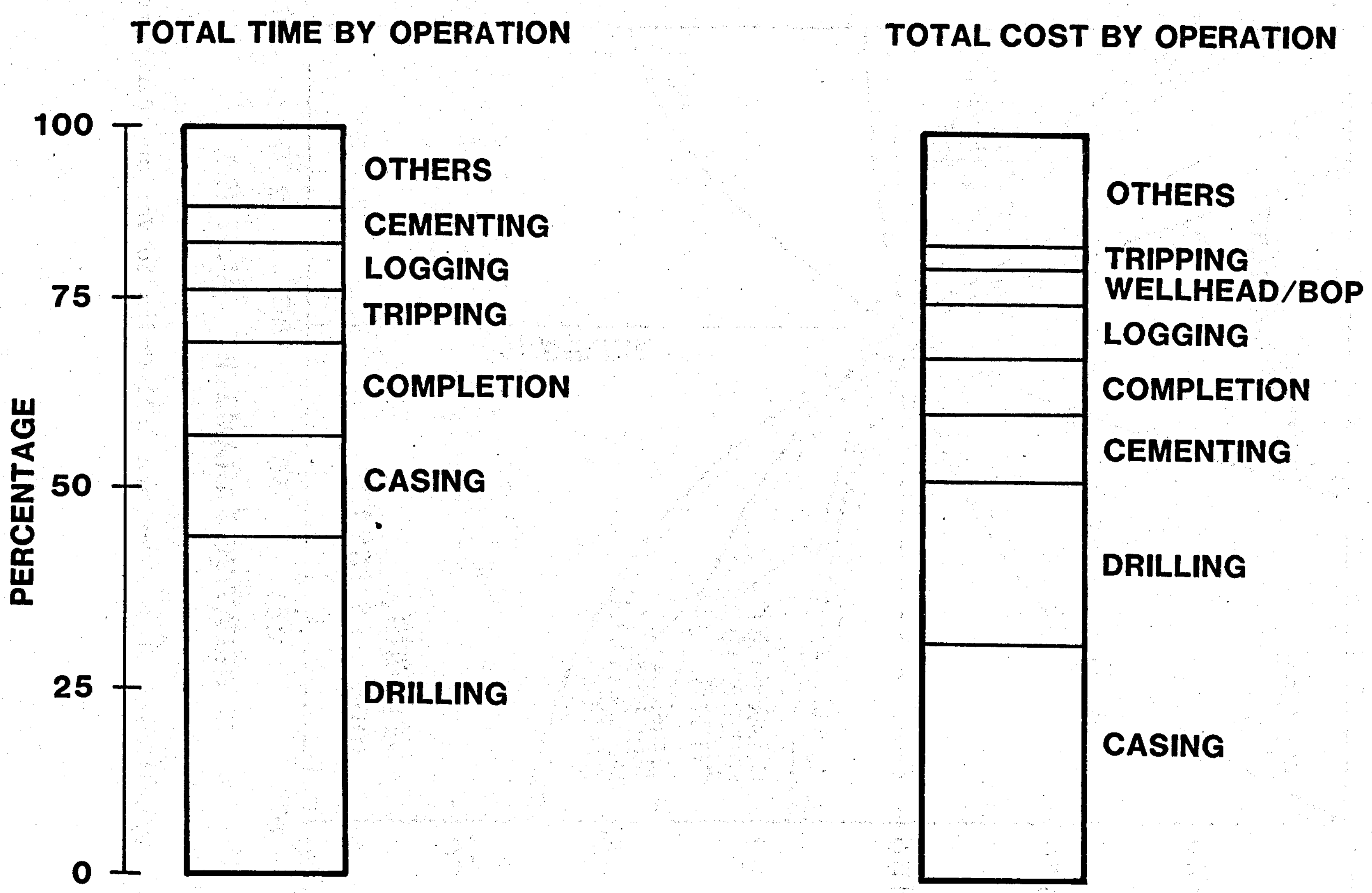

Figure 7. Drilling Time and Cost by Operation -- East Mesa Well Model

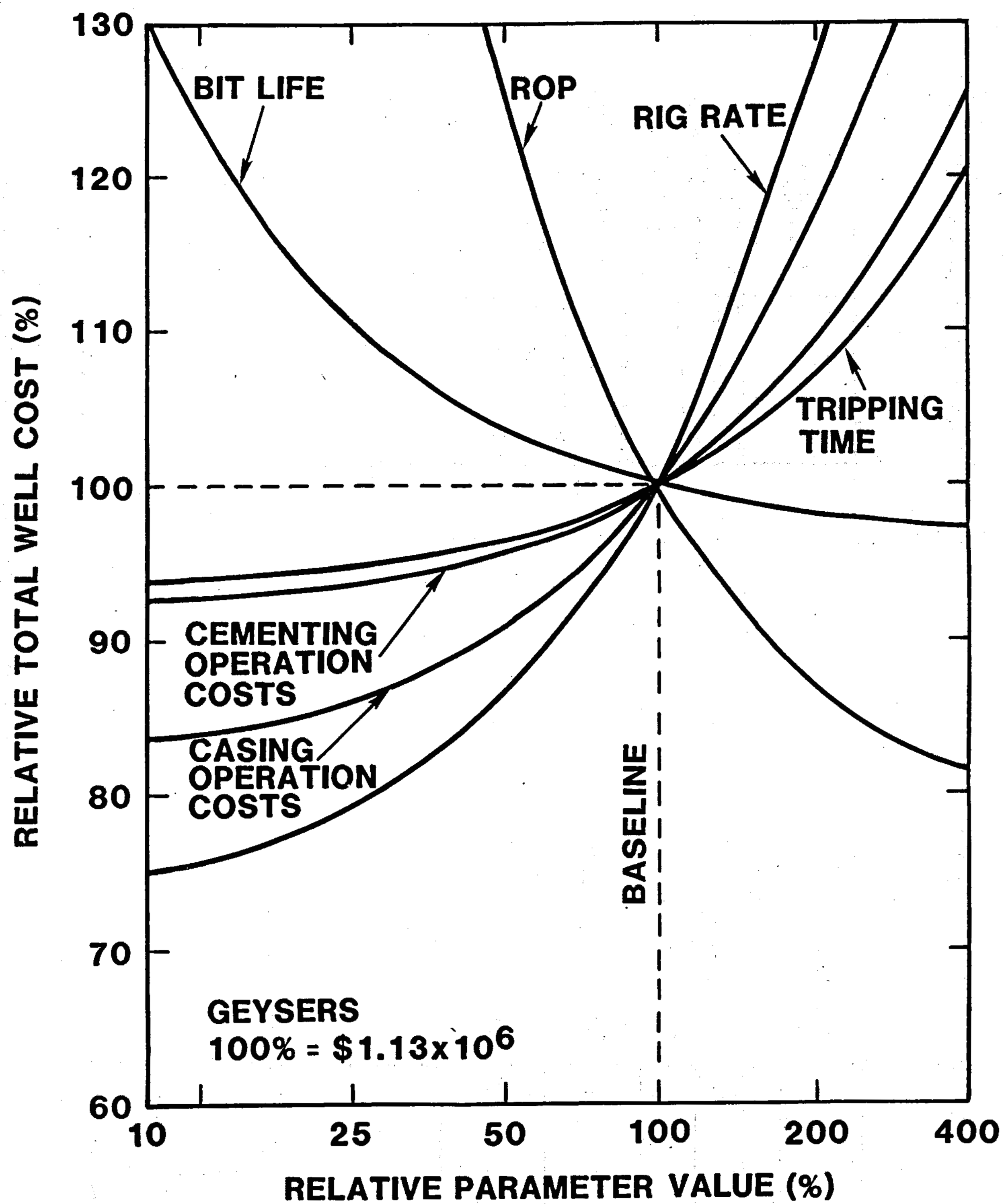

Figure 8. Sensitivity of The Geysers Well Costs to Various Parameters

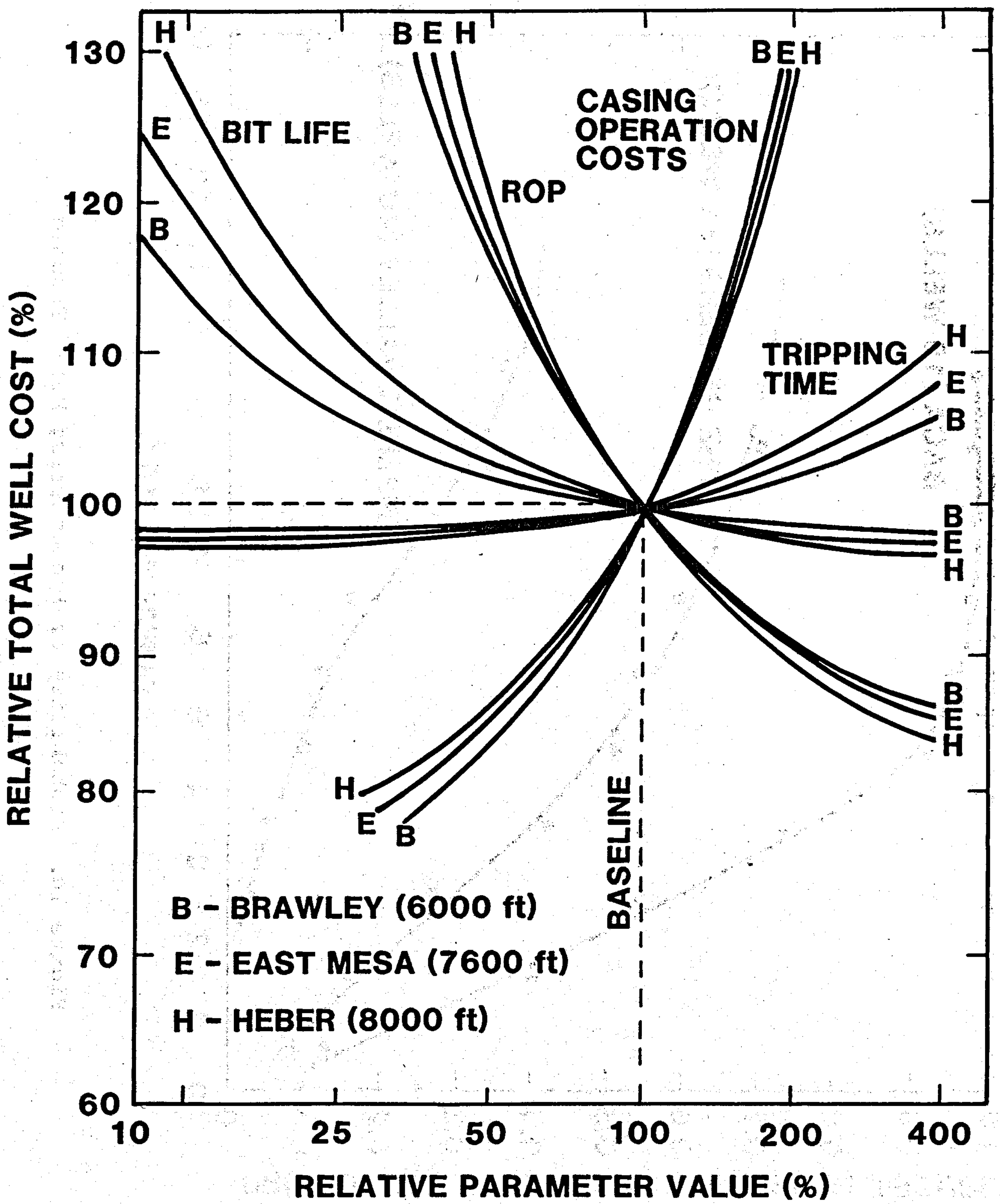

Figure 9. Sensitivity of Well Costs for Imperial Valley Wells

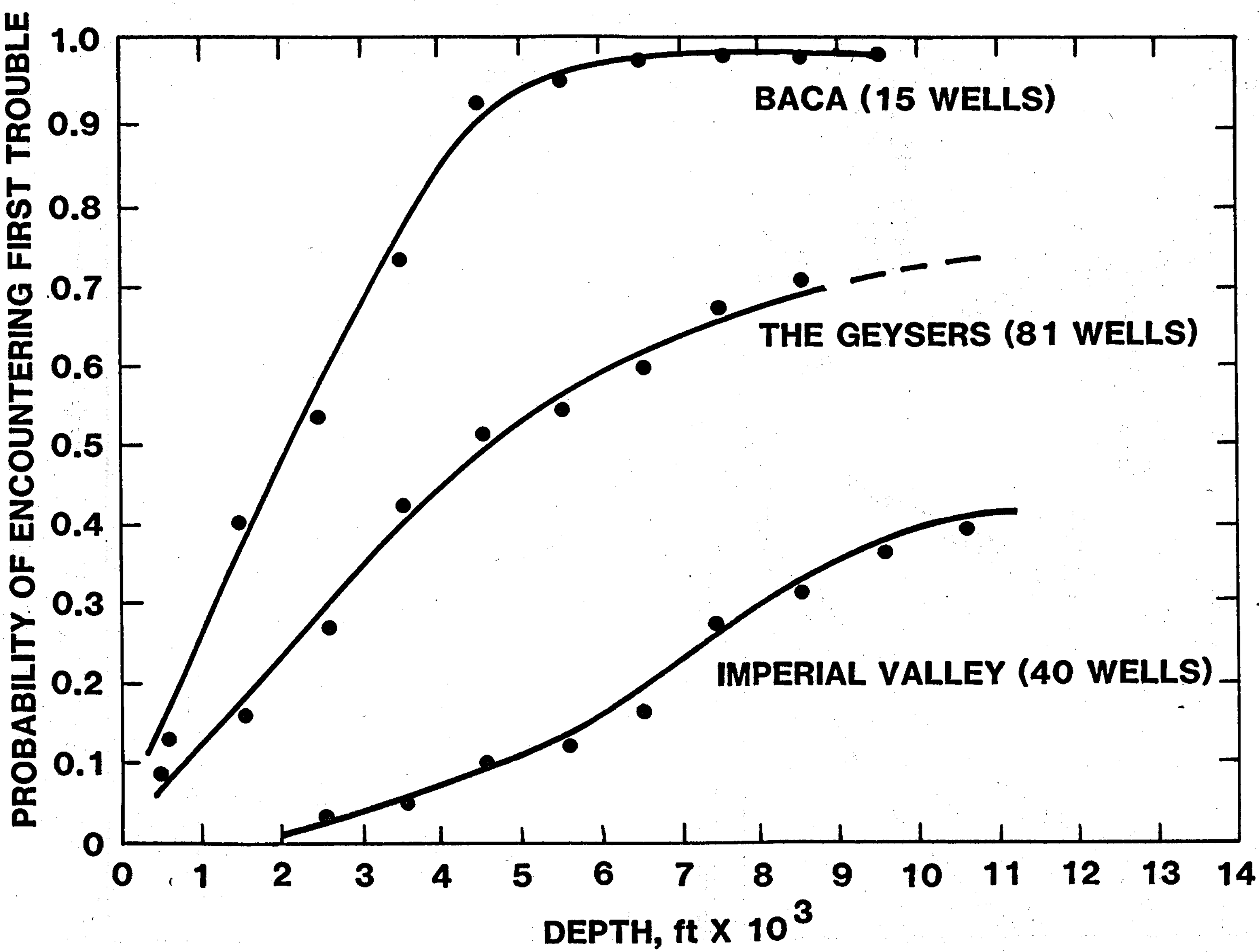

Figure 10. Probability of Encountering First Trouble

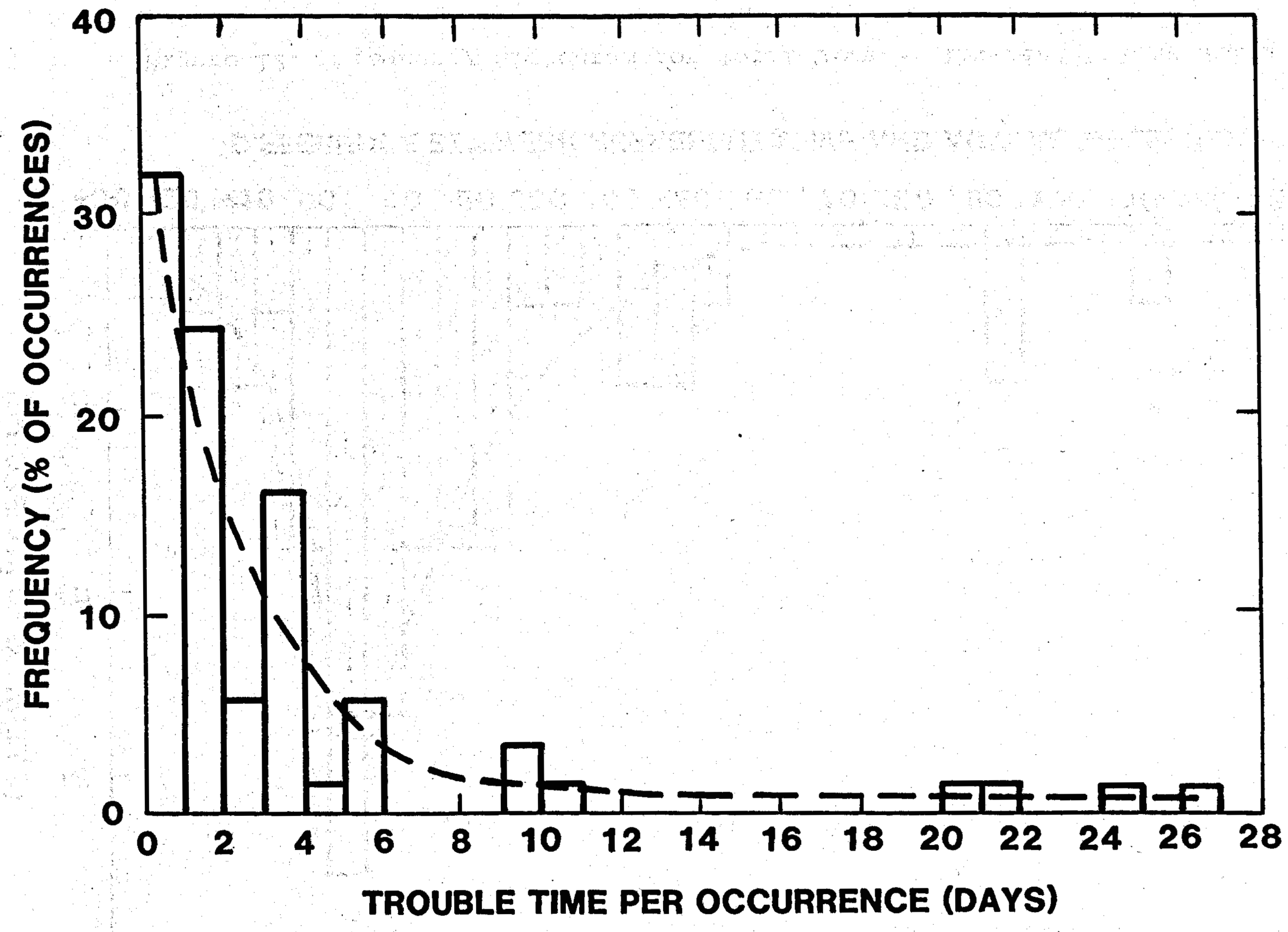

Figure 11. Frequency Histogram for Trouble Time -- Baca Wells

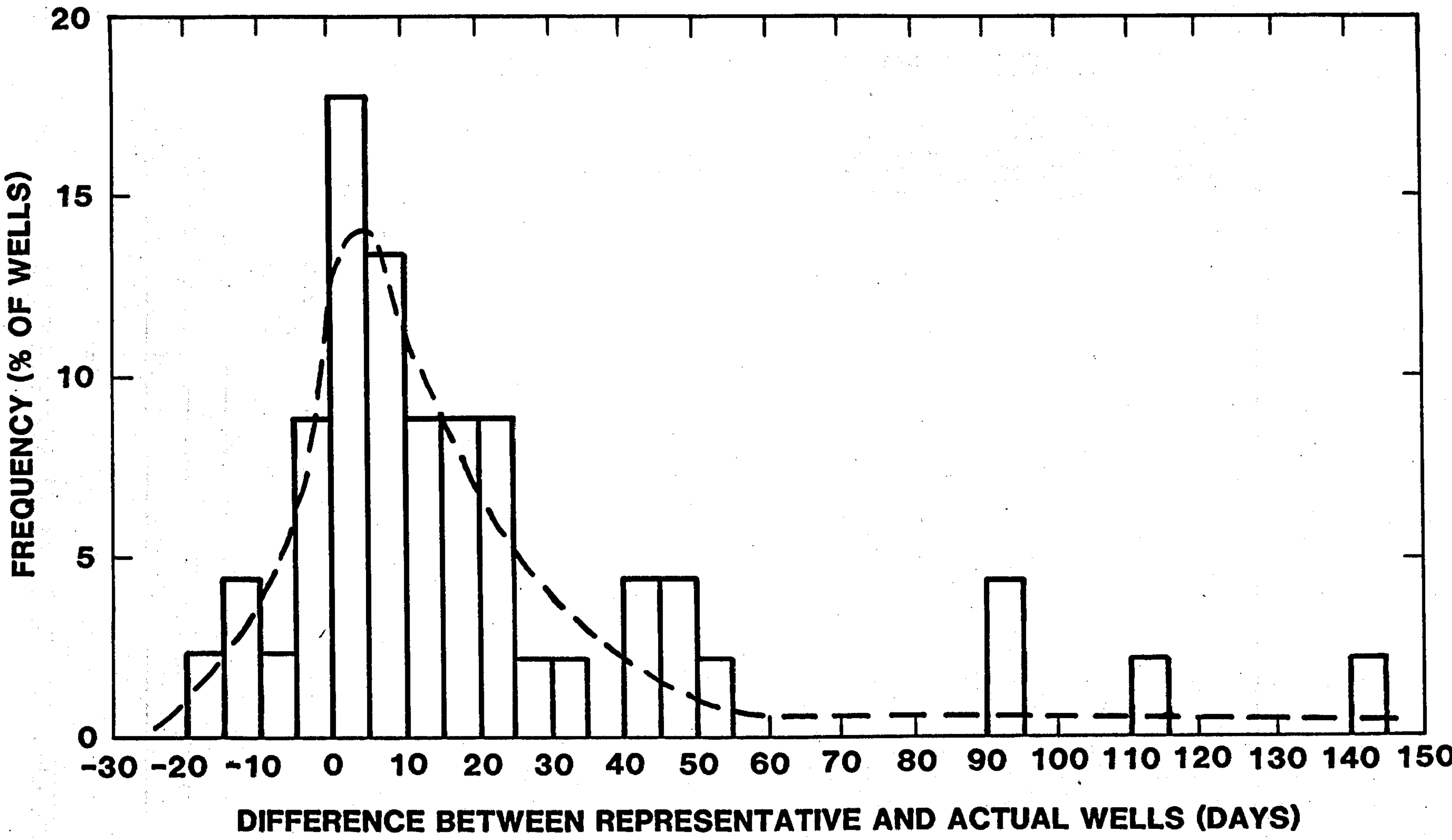

Figure 12. Frequency Histogram for Total Time -- Imperial Valley Wells

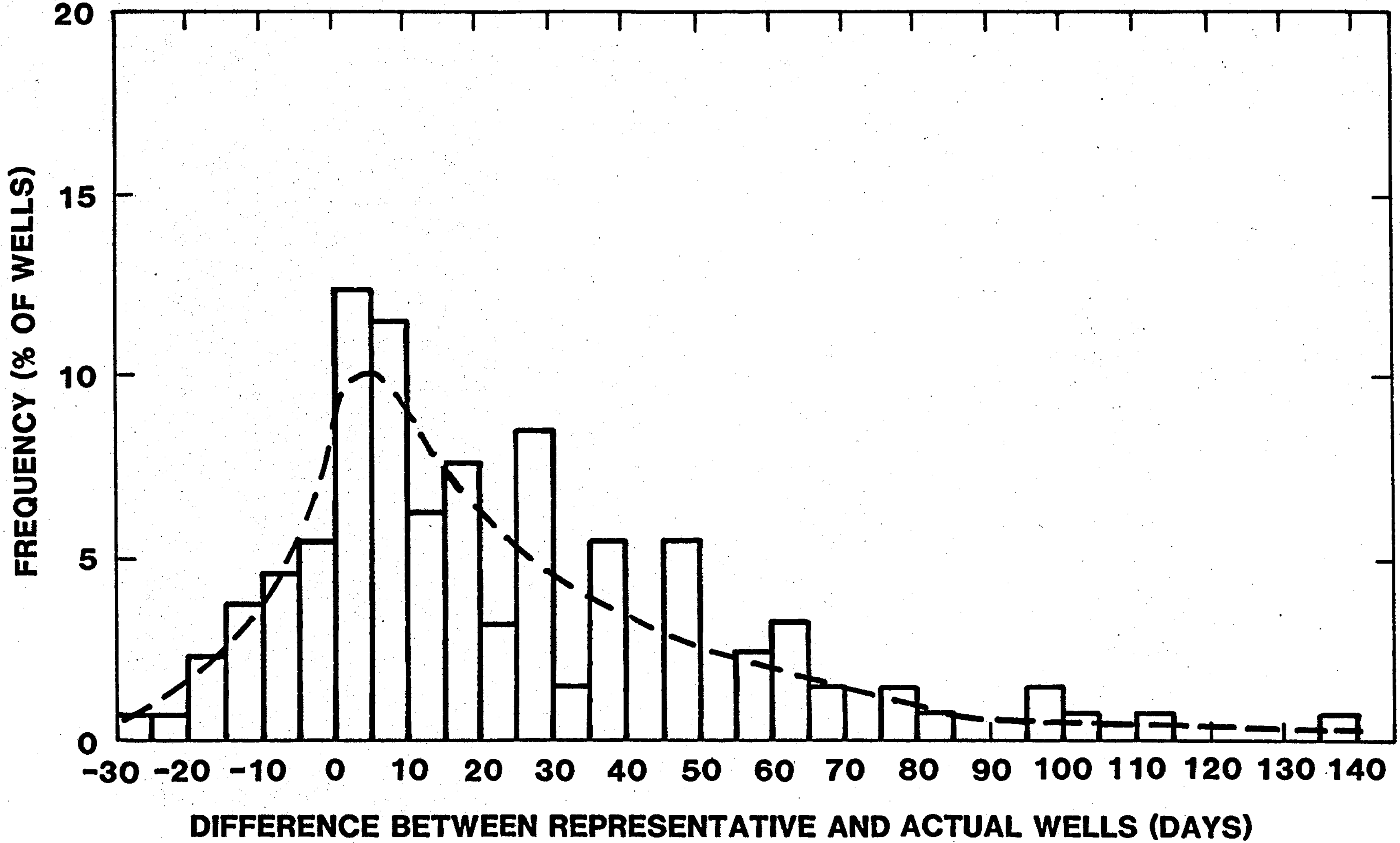

Figure 13. Frequency Histogram for Total Time -- The Geysers Wells