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A PROGRAM IN GEOTHERMAL WELL TECHNOLOGY DIRECTED TOWARD ACHIEVING DOE/DGE POWER-ON-LINE GOALS

Joseph Polito and Samuel G. Varnado

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ABSTRACT

This document presents the material used in an oral presentation to the DOE/Division of Geothermal Energy, which was designed to illustrate the importance of well technology development in reducing geothermal well costs, and to achieve geothermal power-on-line goals. Examination of recent studies of the economics of geothermal energy leads to the conclusion that the overall sensitivity of geothermal power-on-line to well cost is in the range of one to two. Current data suggest that a vigorous R&D program in rotary drilling technology can reduce geothermal drilling costs by about 20%, but a reduction of 40-50% is needed to achieve DOE/DGE goals. Research in advanced drilling systems is needed to satisfy this more stringent requirement. This report details some critical technological deficiencies that occur when current rotary drilling techniques are used for geothermal drilling. A broadly based development program directed at correcting these deficiencies is defined.

ACKNOWLEDGMENT

The authors gratefully acknowledge the help of Alan L. McFall and Robert C. Reineke in preparing this presentation. In addition, H. M. Stoller and M. M. Newsom reviewed early drafts of the text and viewgraphs and made many suggestions that substantially improved the final form.

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A PROGRAM IN GEOTHERMAL WELL TECHNOLOGY
DIRECTED TOWARD ACHIEVING DOE/DGE
POWER-ON-LINE GOALS

Introduction

This document presents material used in an oral presentation to the DOE/Division of Geothermal Energy in December of 1977. The presentation was designed to illustrate the importance of well technology development in reducing geothermal well costs and to achieving geothermal power-on-line goals. Each major viewgraph is followed by a short text. The written section explains the viewgraph and provides background material.

Recent studies of the economics of geothermal energy were examined. Several conclusions can be drawn from them:

1. DOE/DGE power-on-line goals will probably not be met unless the economics of geothermal energy become more favorable,

2. the sensitivity of power-on-line to busbar cost is high, in the range of one to two,

3. the sensitivity of busbar cost to well cost is also high (in the range one-half to one).

All of this suggests that reductions in geothermal well costs will have a significant impact on increased power-on-line.

Several chronic problems combine to make the costs of geothermal drilling abnormally high. These difficulties fall in the categories of

1. temperature effects

2. formation effects, and

3. erosion and corrosion effects.

Most conventional drilling equipment is not designed to operate at geothermal temperatures or in the erosive and corrosive environment of geothermal wells. Also, the difficult, fractured formations in whcih geothermal wells are often found reduce penetration rate and lead to high replacement costs. All of these effects combine to make geothermal drilling substantially more expensive than conventional drilling.

Examination of current cost and technical data for geothermal drilling indicates that a vigorous development program in rotary drilling technology can reduce drilling costs by approximately 20%. Examination of the economic data previously discussed reveals that well cost reductions of 40-50% are needed to meet DOE/DGE goals.

If power-on-line goals are to be met, research must be directed at developing advanced systems for drilling geothermal wells. A broadly based program is outlined which includes

1. Improved methods and materials for drilling,

2. Laboratory and field testing facilities,

3. Development of advanced geothermal drilling systems,

4. Safety and training programs for geothermal drilling, and

5. Development of data acquisition and automation systems for geothermal drilling.

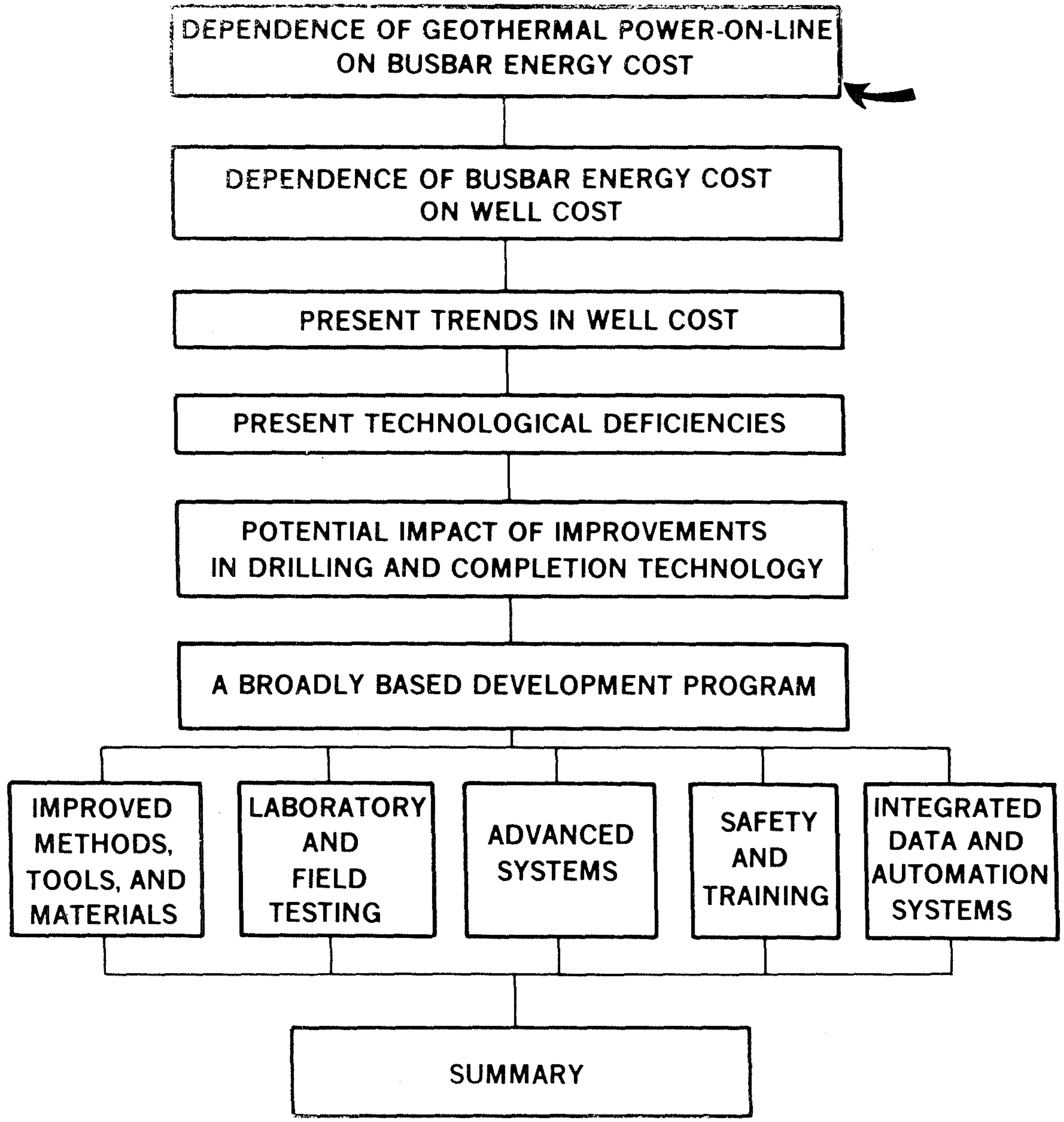
The above program must develop radically new technology in order to meet the goal of a 40-50% reduction in geothermal well costs. Such development is not a certain event, of course, but power-on-line goals will almost surely not be met if no attempt is made to reduce costs beyond 20%.

A PROGRAM IN GEOTHERMAL DRILLING TECHNOLOGY

DIRECTED TOWARD ACHIEVING

DGE POWER-ON-LINE GOALS

VG-1


DEPENDENCE OF GEOTHERMAL POWER-ON-LINE ON BUSBAR ENERGY COST
DEPENDENCE OF BUSBAR ENERGY COST ON WELL COST
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IMPROVED METHODS, TOOLS, AND MATERIALS
LABORATORY AND FIELD TESTING
ADVANCED SYSTEMS
SAFETY AND TRAINING
INTEGRATED DATA AND AUTOMATION SYSTEMS
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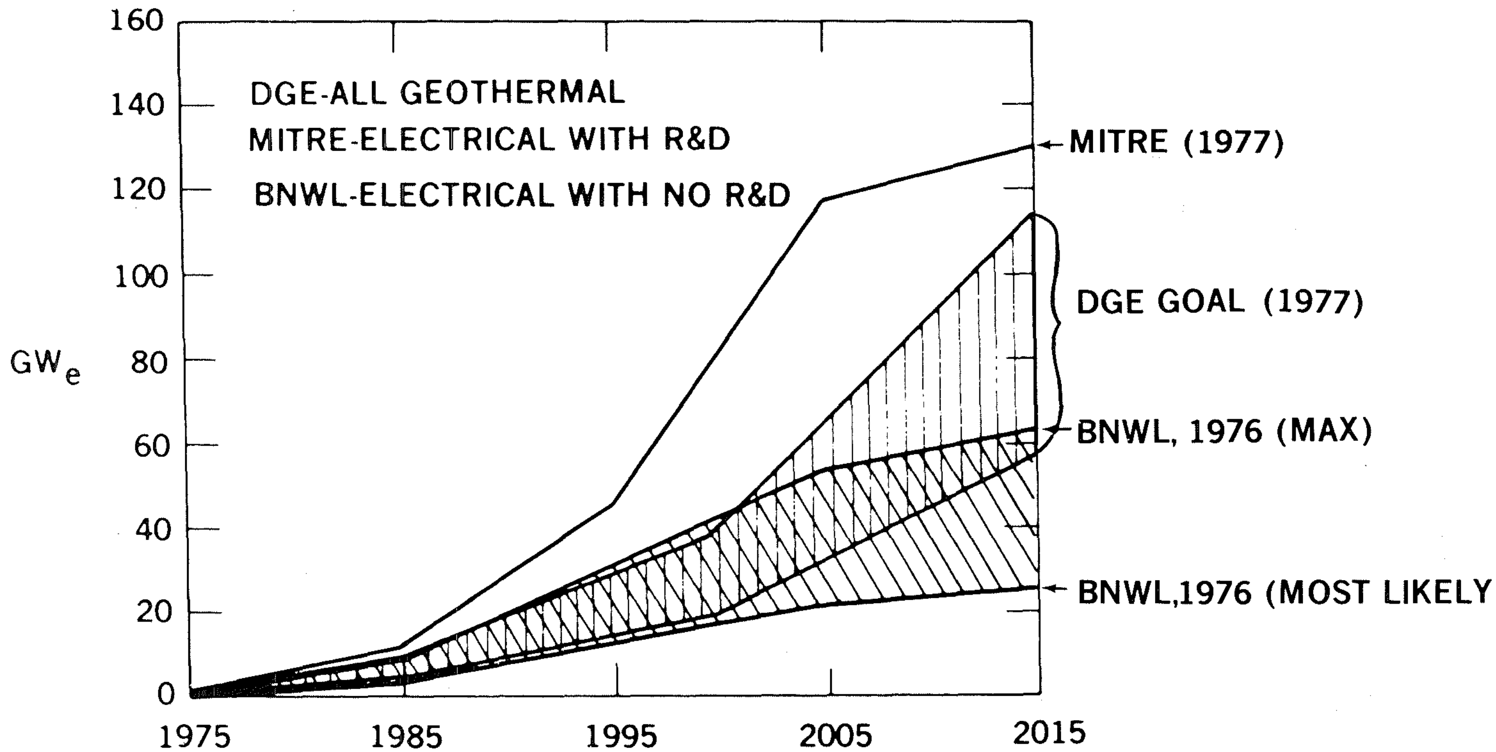
VG-2

VG-2 The purpose of this presentation is to provide justification for a vigorous program in Geothermal Well Technology Development. This program is directed toward achieving DOE/DGE power-on-line goals by reducing the cost of drilling and completing geothermal wells. The justification for such a program is based on the relationship between geothermal power-on-line and the cost of geothermal wells.

This viewgraph presents an outline of the presentation. The first topic is the dependence of geothermal power-on-line to busbar energy cost.

PROJECTED GEOTHERMAL POWER-ON-LINE



VG-4

VG-4 DGE power-on-line goals[1] for all uses of geothermal energy are shown along with Mitre[2] and Battelle Northwest (BNWL)[3] projections for geothermal electric capacity to the year 2015.

The Mitre projections result from an optimistic assumption for growth rate based on an aggressive federal R&D program.

The BNWL projections result from a linear programming model in which geothermal electrical power competes with power produced from fossil and nuclear fuels to satisfy projected demand. Fossil and nuclear fuel supply curves are held constant in 1974 dollars, as are well costs, which are fixed at $300,000. Recent data indicate that current average well costs are $400,000-$450,000 expressed in 1974 terms. The "Max" and "Most Likely" designations result from uncertainty as to the amount of hydrothermal energy that is available at economically competitive temperatures. No federal R&D program is assumed. The area between the BNWL scenarios represents the most probable range for geothermal development if no R&D program is pursued.

Two factors would move the BNWL estimate up to meet DGE goals. The first is a discovery that more hydrothermal energy exists at competitive temperatures than is now believed. In other words, a discovery that the resource base is larger than is now expected.

A second possibility is that technological advances will reduce the busbar cost of geothermal energy. Reduction in busbar cost will have two effects.

EFFECTS OF REDUCTIONS IN GEOTHERMAL BUSBAR COST

REDUCED GEOTHERMAL BUSBAR COST WILL

- LEAD TO SUBSTITUTION TOWARD GEOTHERMAL ENERGY
- INCREASE THE AMOUNT OF ECONOMICALLY RECOVERABLE GEOTHERMAL RESOURCES

VG-5

VG-5 Technological advances will

(a) reduce the busbar cost of producing electricity from currently competitive resources. This will improve the relative position of geothermal electricity in the marketplace and will lead to substitution of geothermal electricity for electricity generated from fossil and nuclear fuels, and

(b) make it possible to economically produce electricity from lower temperature reservoirs (this effectively increases the amount of resource available).

Reductions in geothermal busbar cost ($\overline{BBEC}$) which are independent (or nearly so) of temperature would accomplish both (a) and (b).

BNWL has computed the sensitivity of power-on-line estimates to changes in $\overline{BBEC}$.

SENSITIVITY OF POWER ON LINE TO REDUCTIONS IN GEOTHERMAL BUSBAR COST

BNWL, 1976

CHANGE IN BBEC		RESULT
-6%	→	13% INCREASE IN 'MOST LIKELY' CASE!
-10 TO -35%	→	COULD DOUBLE THE AMOUNT OF COMPETITIVE RESOURCE!

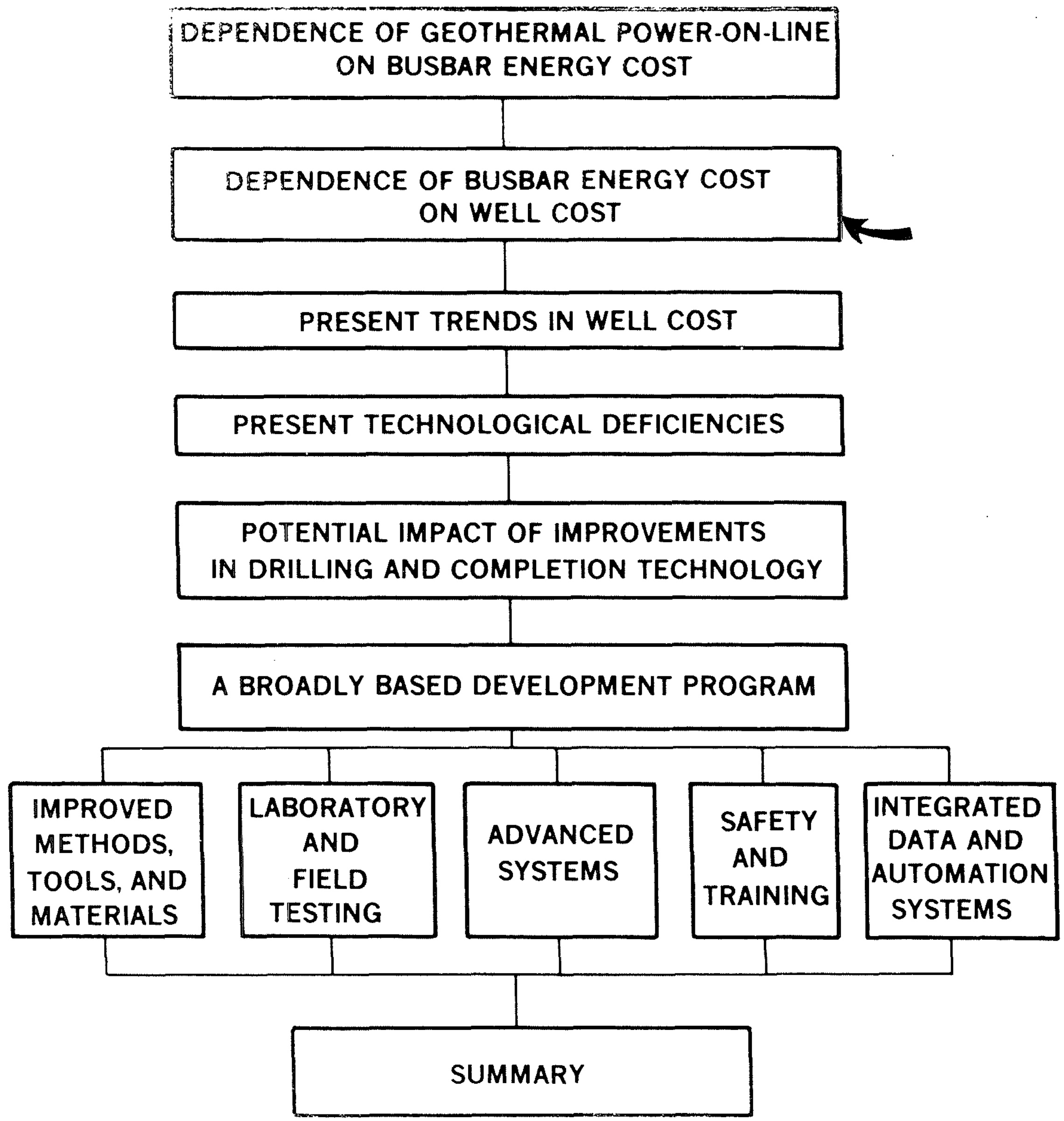
VG-6

VG-6 The BNWL model shows that a reduction of only 6% in the busbar cost of geothermal electricity will lead to a 13% increase in the power-on-line estimates for the "most likely" scenario. Thus, the sensitivity of power-on-line to busbar cost is approximately 2, so small reductions in the cost of geothermal electricity can cause proportionately greater substitution toward geothermal energy.

BNWL also estimates that reductions of 10% to 35% in $\overline{\text{BBEC}}$ may double the amount of geothermal energy that is economically attractive because large, lower temperature reserves become competitive. While they do not estimate the increase in installed capacity, a larger resource base would lead to greater opportunity for exploitation and therefore to greater utilization of geothermal energy.

The critical question concerning geothermal drilling and completions is: "What is the impact of well costs on the busbar energy cost of electricity produced from geothermal reservoirs?" In other words, how effective can improvements in well technology be in producing the desired reductions in geothermal $\overline{\text{BBEC}}$?

This question can be answered by considering recent work by BNWL,[3,4] USGS,[5] and the Mitre Corporation.[6]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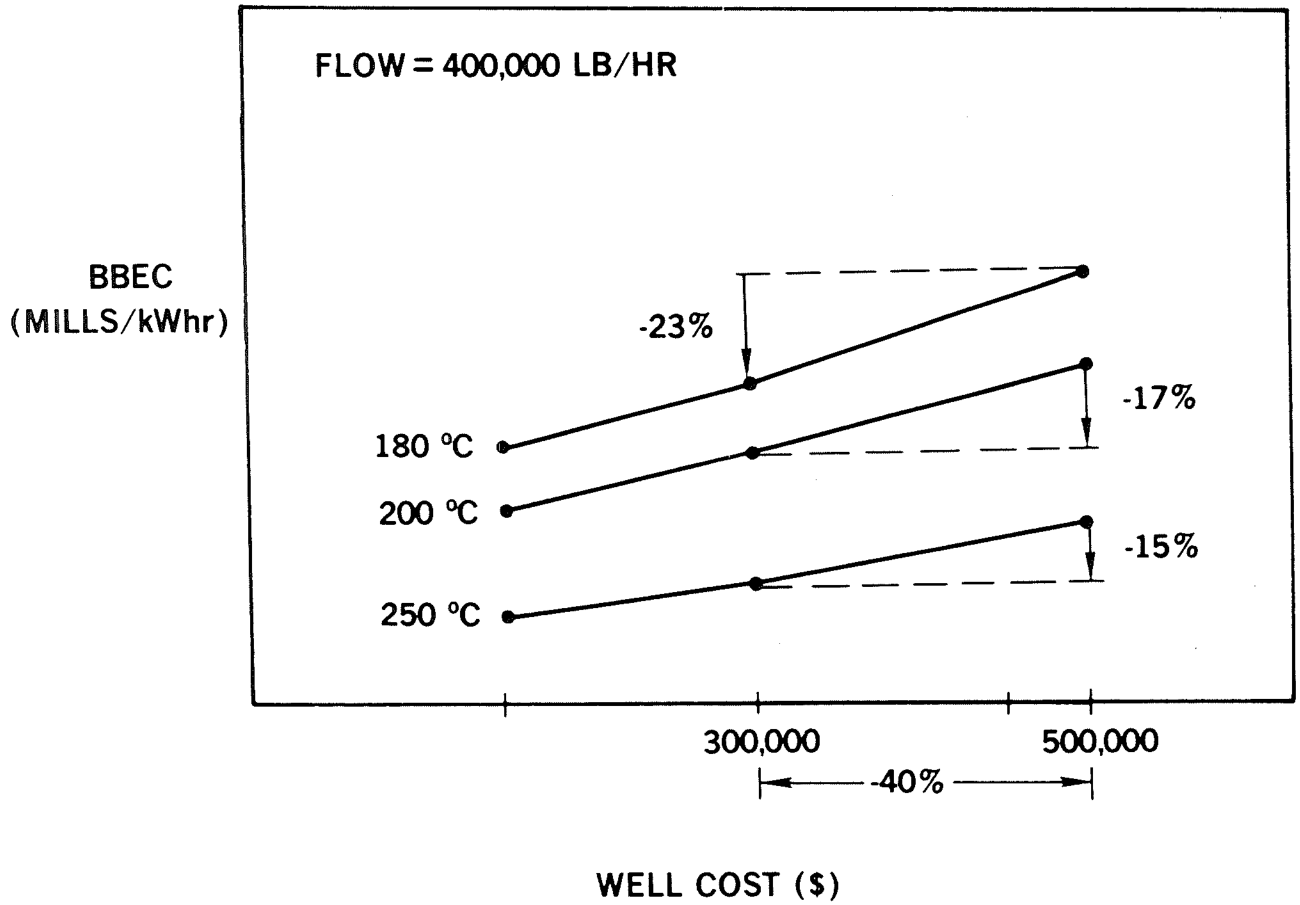
VG-7

RECENT ESTIMATES OF THE IMPACT OF REDUCTIONS IN WELL COST

BATTELLE NORTHWEST, 1976



VG-8 BNWL[3] computed geothermal $\overline{\text{BBEC}}$ costs for several well costs and reservoir temperatures. All other costs were held constant, as was the flow rate from the wells. Using an assumed base cost of $500,000 per well, a 40% reduction in well cost, for example, would result in the following changes in geothermal $\overline{\text{BBEC}}$.

Temperature - C	Change in $\overline{\text{BBEC}}$ - %
180	-23
200	-17
250	-15

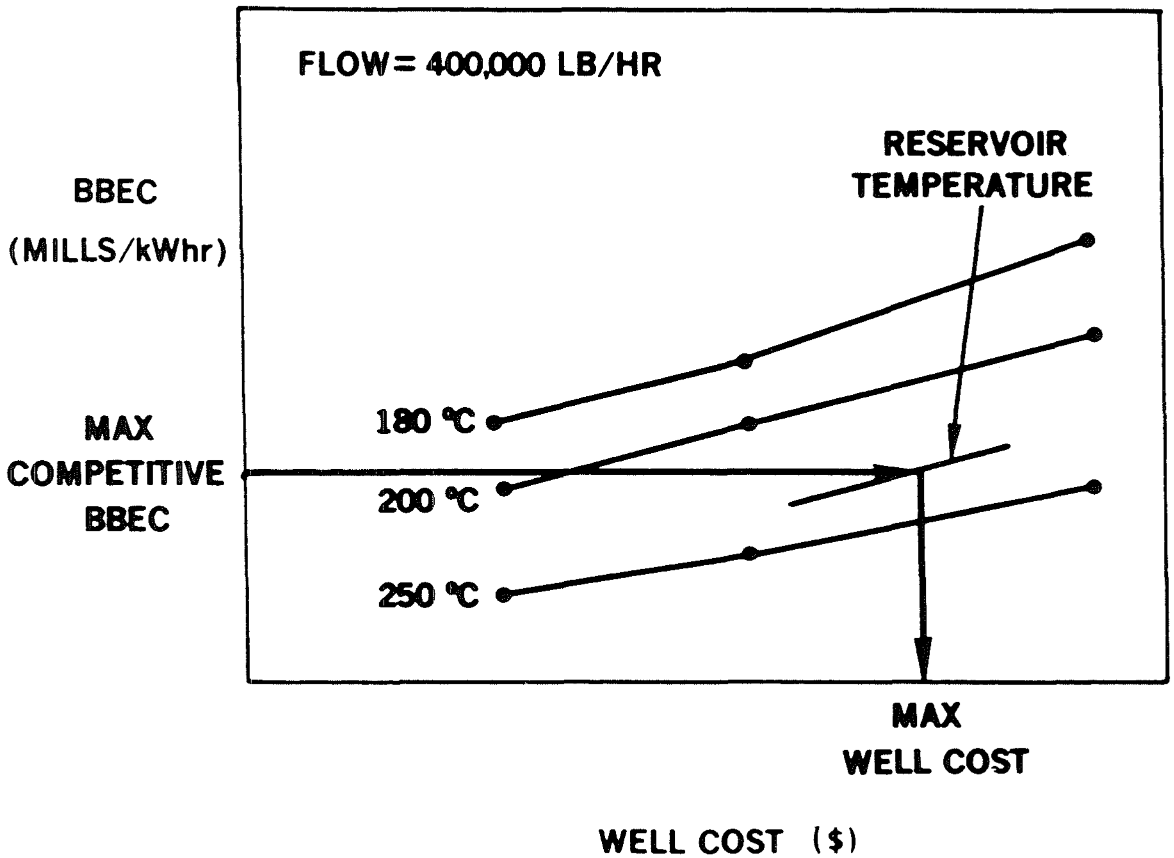
These reductions in busbar costs are large enough to produce the significant increase in geothermal availability suggested on the previous slide.

Also note that the effect of well cost reductions is most significant for lower temperature resources because at a given flow rate more wells are required to provide a specified power output. Therefore, a higher fraction of total costs are well-related.

The approach taken by USGS[5] considers this question from a slightly different perspective.

RECENT ESTIMATES OF THE IMPACT OF REDUCTIONS IN WELL COST

USGS, 1975



VG-9

VG-9 Results from the USGS[5] emphasize the relationships between well costs, reservoir temperature, and geothermal economics. For a given conversion technology and maximum competitive $\overline{\text{BBEC}}$ (which is determined by the prevailing price of fossil or nuclear generated electricity), the maximum price which can be paid for a well is a function of temperature.* Conversely, for a given maximum $\overline{\text{BBEC}}$ and well cost, the minimum competitive reservoir temperature can be determined. As wells become less expensive, lower temperature reservoirs become competitive.

This reiterates the BNWL conclusion that reducing well costs increases the amount of economically competitive geothermal resources.

Mitre/METREK[6] has recently completed a site specific analysis of geothermal development, and they also have projected the impact of reductions in well costs.

*More correctly, the maximum well cost is a function of the power output per well. For illustrative purposes, and to be compatible with the BNWL data, the flow rate is held constant on this graph. The result is that the maximum well cost is a function of temperature only.

RECENT ESTIMATES OF THE IMPACT OF REDUCTION IN WELL COST

MITRE 1977 - - - SITE SPECIFIC ANALYSIS

AREA (BASE WELL COST)	1990 CHANGE IN BBEC FOR 20% REDUCTION IN WELL COSTS (1977 DOLLARS)
ROOSEVELT H.S., UT ($530,000)	-15.3%
COVE FORT-SULPHURDALE, UT ($1,500,000)	-19.3%
SURPRISE VALLEY, CA ($920,000)	-17.9%
LASSEN, CA ($615,000)	-17.4%

VG-10

VG-10 Mitre[6] has computed well cost sensitivities for geothermal power plants projected to come on line in 1990. Comparisons are between wells with no cost reduction, and wells that are reduced in cost by 20%, and have increased lifetimes because of technological improvements. All costs in this study are expressed in 1977 dollars.

Four typical sites are presented; they all produce low salinity brine with medium-hard overlaying rock (Mitre's designation). They were selected to be similar reservoirs, although Roosevelt has much more powerful wells than the other three. Surprise Valley, Lassen, and Cove Fort wells are all similar in output. As seen before, the lower quality resource exhibit is greater sensitivity to well cost, but these sensitivities are not directly comparable because the analysis is site specific, and "other things" are not necessarily equal between locations. In particular, well costs vary substantially, as indicated on the accompanying figure.

As before, substantial reductions in $\overline{\text{BBEC}}$ are possible by reducing well costs. Note that only a 20% reduction in well costs is required in Mitre's study to produce approximately the same change in $\overline{\text{BBEC}}$ as a 40% reduction in BNWL's report.

These differences result from somewhat different methodologies and assumptions concerning base costs of wells, piping, and other items. An estimate of the sensitivity of busbar cost to well cost is about 0.5 from the BNWL report and about 1.0 from the Mitre study.

These results, while they differ numerically, are not contradictory. They all point to substantial reductions in geothermal $\overline{\text{BBEC}}$ resulting from well cost reductions.

RECENT ESTIMATES OF THE IMPACT OF REDUCTIONS IN WELL COST

BNWL, 1975

PARAMETER	CHANGE	% CHANGE IN BBEC
WELL COST	-40%	-20%
WELL FLOW RATE	+50%	-17%
WELL LIFE	+100%	-10%
PLANT CAPITAL	-50%	-14%
PLANT LIFE	+33%	-1%
INTERNAL POWER CONSUMPTION	-50%	-11%
OPERATING EXPENSES	-50%	-3%

VG-11

VG-11 In 1975, Bloomster[3] at BNWL computed geothermal $\overline{\text{BBEC}}$ sensitivities for a number of cost factors. The reference case is a 200°C reservoir that produces 500,000 lb/hr flow from wells that cost $500,000 (1974 dollars).

Initial well cost is an important factor, with a reduction to $300,000 per well resulting in a 20% decrease in $\overline{\text{BBEC}}$.

The importance of completion technology is emphasized by the sensitivities to well flow rate and well life. Technology improvements in well stimulation and completion which increase the flow rate 50% and the well life from 10 to 20 years will reduce $\overline{\text{BBEC}}$ by 17% and 10%, respectively. The well-related sensitivities are, of course, not additive; but they do point out that improvements in drilling and completion technology are at least as important as, and perhaps more important than, improvements in energy conversion technology.

The four studies cited vary in their assumptions and methodology, and therefore the numerical results differ. But they all point out the fact that geothermal busbar cost is strongly influenced by well-related factors. Furthermore, Bloomster[3] indicates that well cost is at least as important as conversion costs in determining busbar costs. This effect can be seen clearly by examining the fraction of total capital cost attributable to well cost.

WELL COST FRACTION OF TOTAL CAPITAL COST

MITRE, 1977

RESERVOIR	WELL COST- $	TEMPERATURE –°C	WELL FRACTION
BEOWAWE, NV	984,000	240	55%
PUNA, HA	2,300,000	356	50%
VALE H.S., OR	590,000	160	48.5%
EAST MESA, CA	600,000	180	42.9%
BRADY H.S., NV	656,000	214	48.2%
ALVORD, OR	2,437,000	200	67%
SAFFORD, AZ	2,140,000	210	61%

VG-12

VG-12 The viewgraph shows the fraction of total capital cost attributable to well costs for several reservoirs from Mitre's site specific analysis.[6]

In the first group we see that high well fractions exist when the well costs are high ($1,000,000), even if the reservoirs are relatively hot. For cooler reservoirs (second group), well fractions remain high even though wells are less expensive ($500,000 - $600,000).

Finally, if high cost wells must be drilled into moderate temperature reservoirs, then well fractions over 60% result.

Well fraction, by itself, does not determine whether a field is competitive, but it does indicate the impact that reductions in well cost can have on total busbar cost. Areas with high well fractions will be most affected by reducing well costs.

Taken together, the information presented so far leads to the following conclusions.

SUMMARY

- GEOTHERMAL POWER ON LINE AND RESOURCE AVAILABILITY ARE VERY SENSITIVE TO BUSBAR COST
- SIGNIFICANT REDUCTIONS IN BUSBAR COST ARE POSSIBLE BY REDUCING WELL COSTS
- THE ECONOMICS OF LOWER QUALITY RESOURCES ARE MOST SENSITIVE TO WELL COSTS
- WELL COSTS WILL BE EVEN MORE SIGNIFICANT FOR NON-ELECTRIC APPLICATIONS

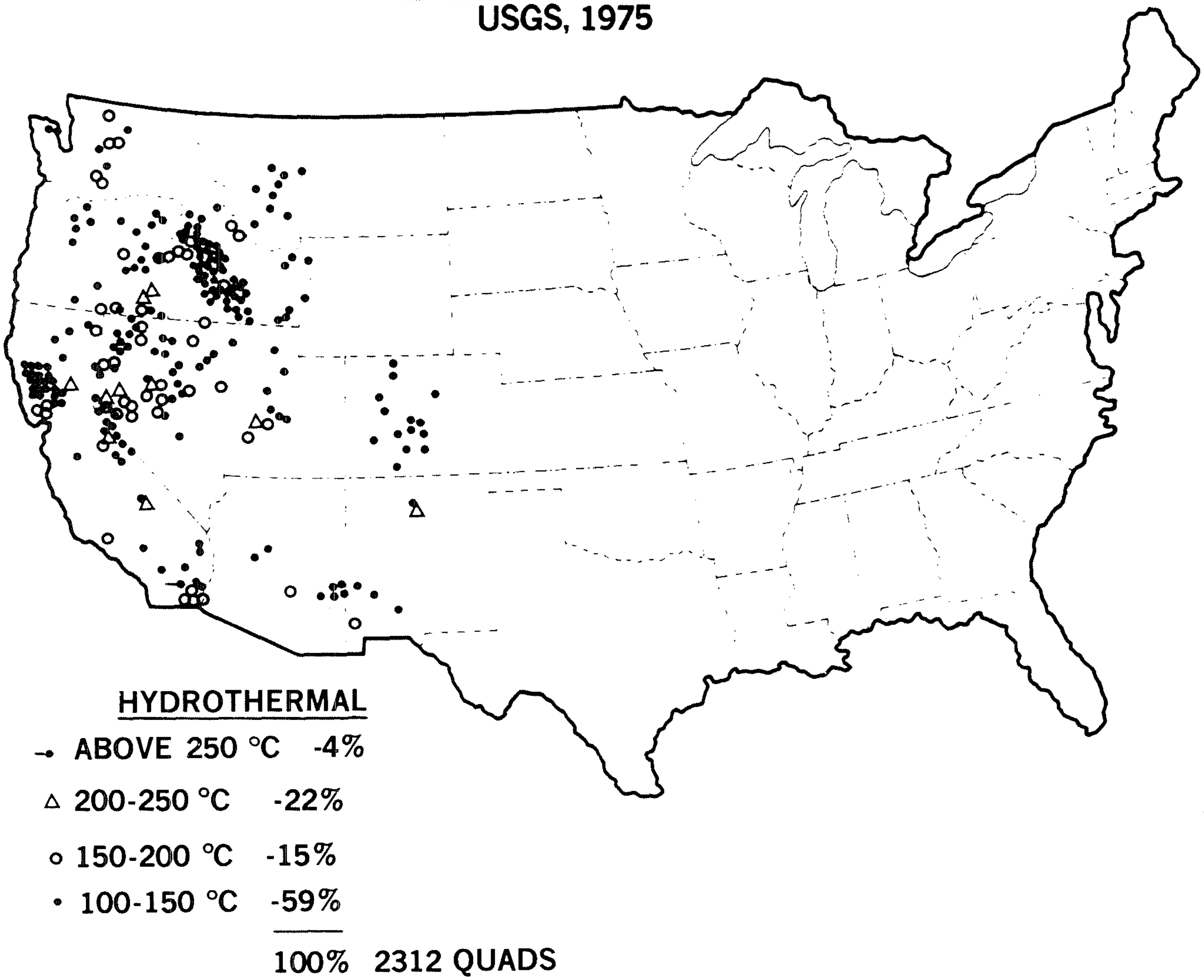
VG-13

VG-13 The amount of substitution of geothermal energy for nuclear and fossil energy is dependent upon the relative busbar costs. If relative reductions in geothermal costs occur, then geothermal power will become a significant alternate energy source. Reductions in geothermal cost have the dual effect of increasing substitution toward geothermal energy and of effectively increasing the amount of resource available by making more reservoirs economically competitive. Reductions in geothermal BBEC can have significant impact on geothermal power-on-line.

Sensitivity analyses show that sizable reductions in geothermal busbar costs will result from reduced well costs. The greatest impact of well cost is on busbar costs for lower quality resources. This fact is important because the USGS[5] estimates that, of the known hydrothermal resources above 150°C, 55% are between 200°-250°C, and 37% exist below 200°C. Thus, well cost reductions can lead to vast increases in the amount of competitive resources.

Finally, although the studies cited earlier concern electrical production, the results should apply to non-electric applications as well. Since well costs are a higher fraction of total cost for non-electric than for electric applications, reductions in well cost should have an even greater impact on reducing the delivery price of geothermal space and process heat.

GEOTHERMAL SITES
USGS, 1975



VG-14 An indication of the temperature distribution of hydrothermal resources can be obtained by examining data from the USGS.[5] The Salton Sea (indicated by a solid circle with a dash) is the single hydrothermal reservoir in the lower 48 states with a temperature over 250°C (one other exists in Hawaii, but Hawaii and Alaska sites are not shown).

4

Triangles. In the range of 200-250°C, only ten more sites are included.

Open Circles. If sites between 150-200°C are included, then 51 reservoirs are added.

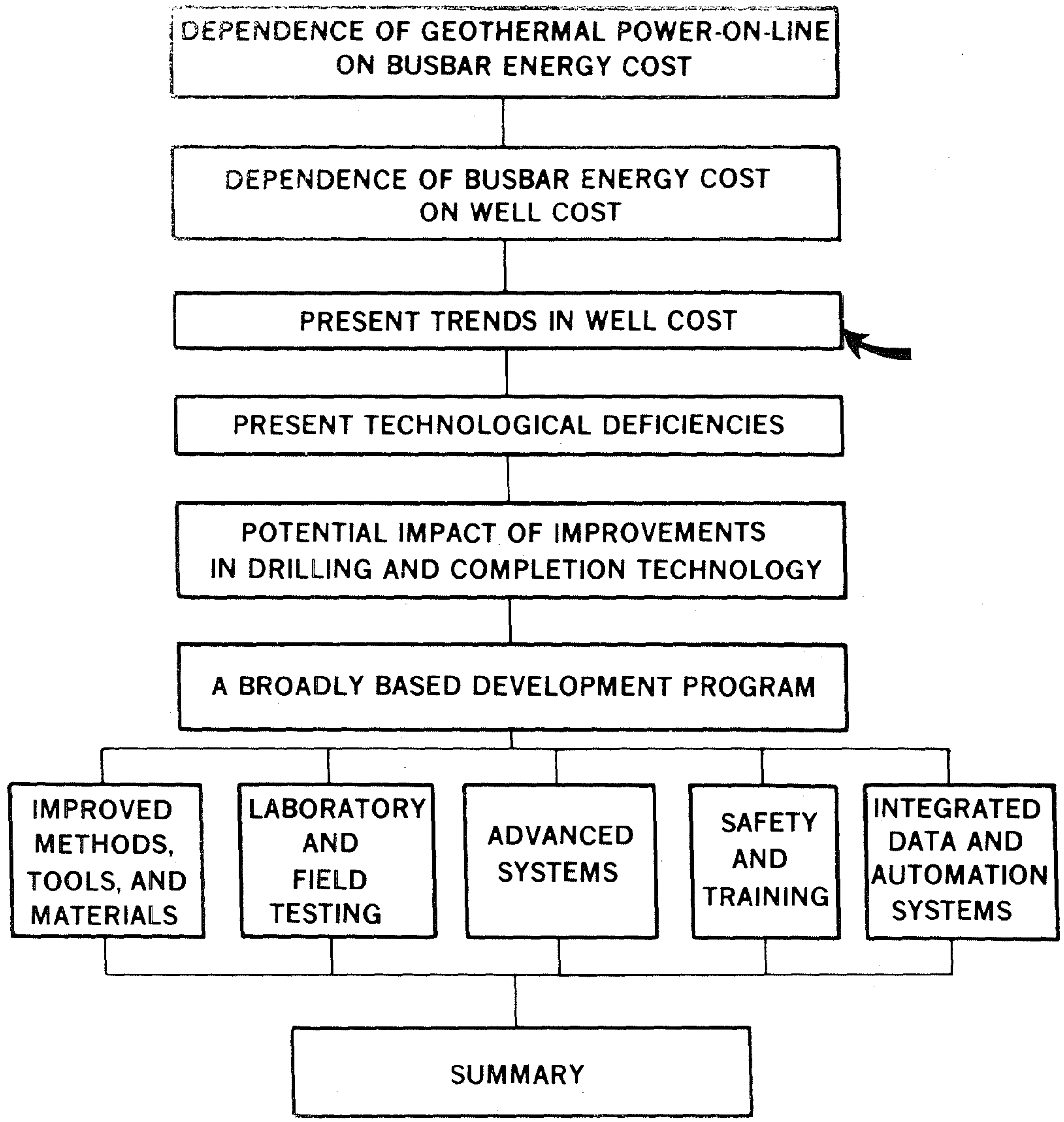
Solid Circles. In the range 100-150°C, 224 sites (including Alaska and Hawaii) are added.

The breakdown of total energy stored in these temperature ranges is

above 250°C	4%
200-250°C	22%
150-200°C	15%
100-150°C	59%
	100% = 2312 Quads

On the previous viewgraph we discussed the breakdown of energy above 150°C for electrical production. Here we see that twice as much energy is available if non-electric applications are included (i.e., reservoirs with temperatures in the range of 100-150°C).

Given the importance of well cost to the economic potential of this resource, it is natural to examine recent trends in the cost of wells.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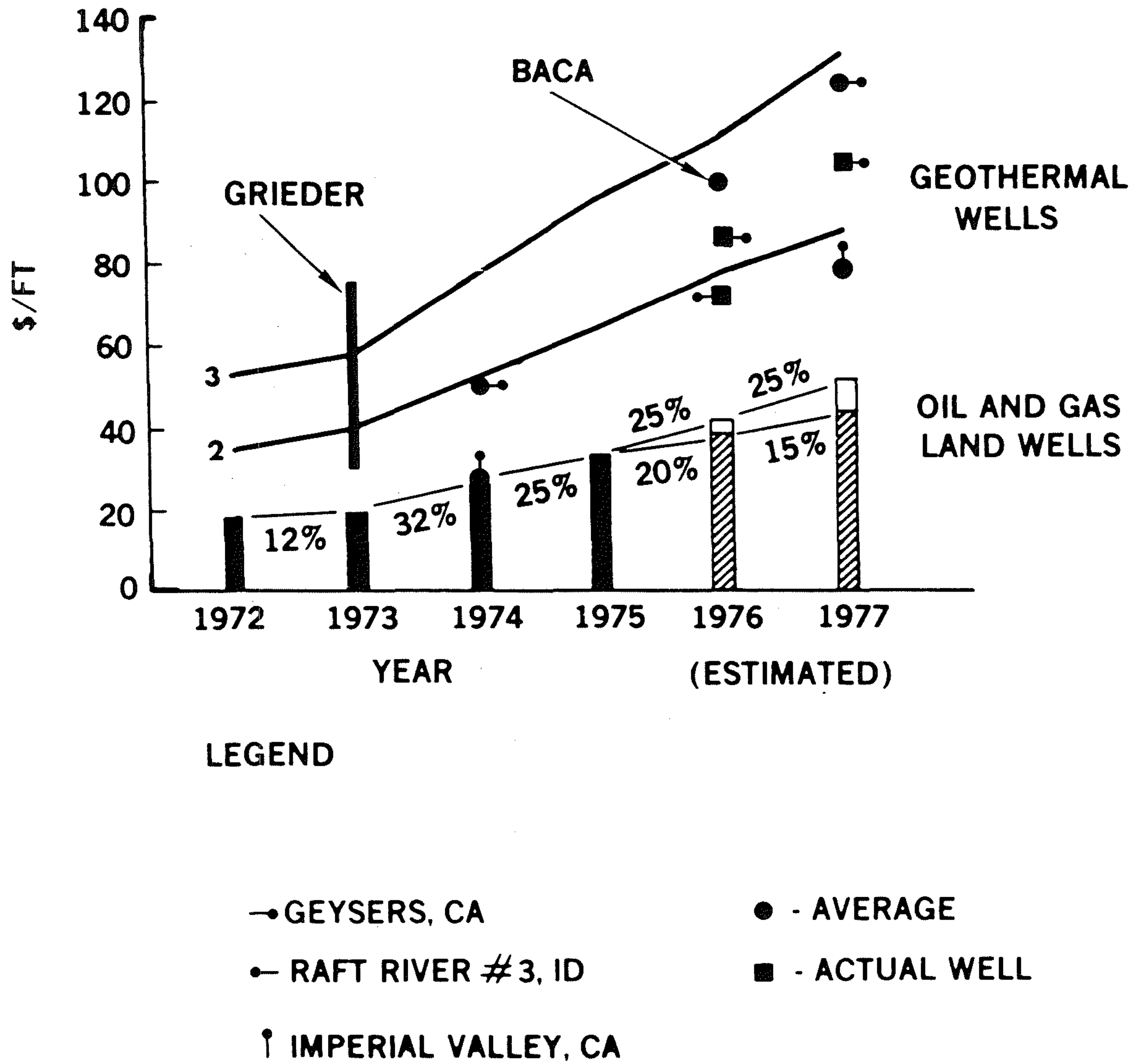
VG-15

TREND IN FOOTAGE COSTS



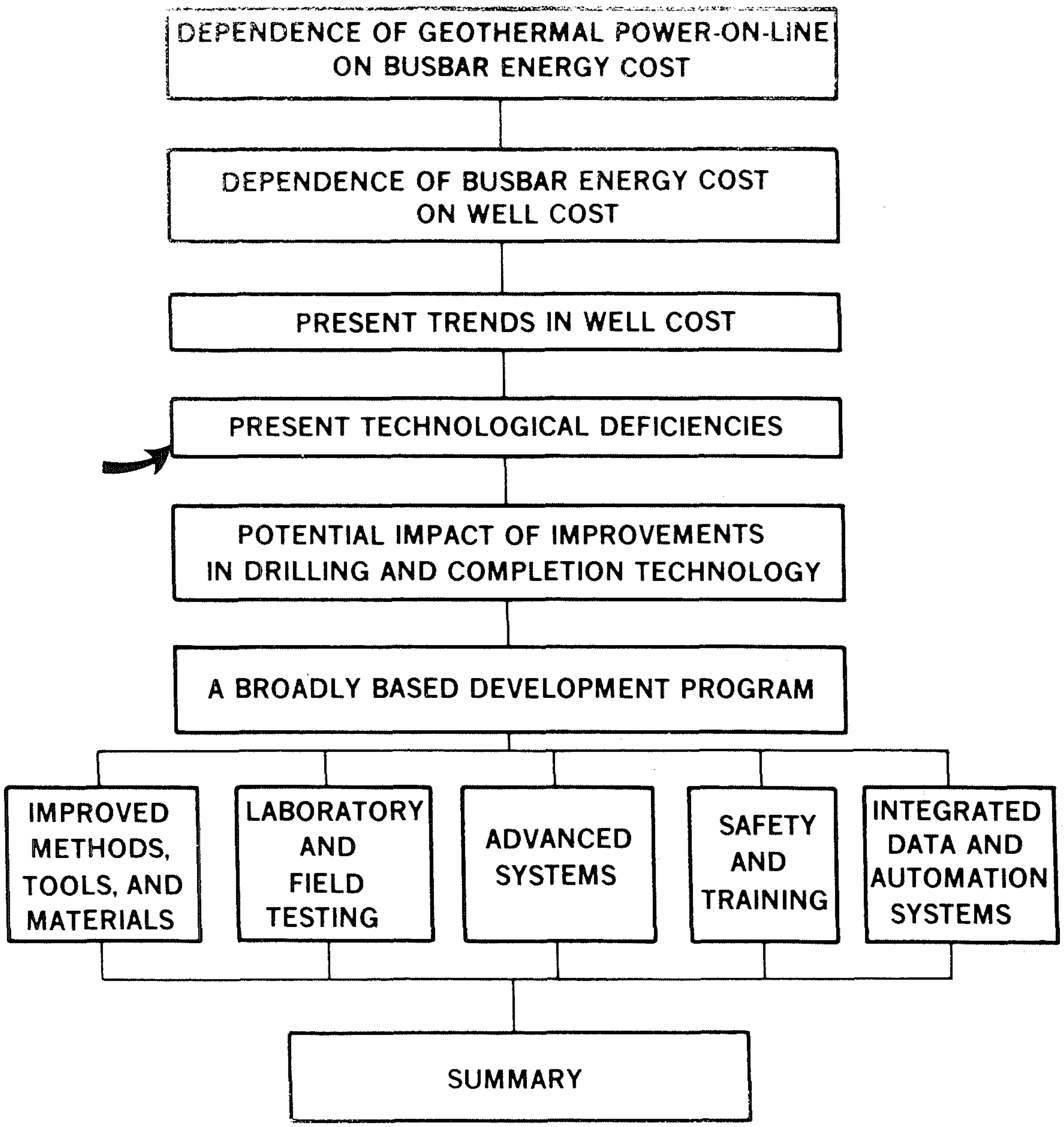
VG-16 Average footage costs for all land wells are shown by year with bars.[7,8] The trend is clearly one of rapid escalation, at a rate exceeding the general inflation rate.

In general, the cost of geothermal wells has escalated at a rate comparable to that for all land wells. Furthermore, geothermal footage costs have remained substantially above the industry-wide average cost for all land wells. Greider's[9] 1973 estimates of $30-$75/ft yield the often cited fact[10,11] that geothermal footage costs are about two to four times the average for land drilling. Recent data and estimates for average geothermal footage costs do not contradict this multiplier range. Average costs at Baca, NM[43] and the Geysers, CA[12,13] are about three times the average land rate. This suggests that the spread of costs at these different drilling areas would easily fall within a range of two to four times that of average land well costs.

In primarily sedimentary regions such as the Imperial Valley, CA, average geothermal well costs are about twice the land average.

Finally, it should be noted that the costs cited here are for production type wells. Exploratory wells may cost substantially more than four times the average for land wells.

The high costs associated with geothermal wells are due in part to a number of chronic deficiencies in geothermal drilling technology.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VG-17

DEFICIENCIES IN CURRENT GEOTHERMAL DRILLING TECHNOLOGY

- TEMPERATURE EFFECTS
- FORMATION EFFECTS
- EROSION, CORROSION

VG-18

VG-18 The chronic difficulties in geothermal drilling are attributable to three effects which are found uniquely or primarily in geothermal environments.

Geothermal reservoirs, by definition, involve high temperatures. Difficulties resulting from drilling into high temperature formations are significant, well documented, and pervasive.

Formation effects refer to the increased cost of drilling through hard, fractured or otherwise difficult rocks.

To a lesser extent, corrosion and erosion also impose higher drilling costs. These problems tend to be site dependent but they can be very significant when present.

Each of the above problem areas requires special materials and special procedures. The results are that expensive tools and equipment are needed and that drilling crews must be trained in the special procedures required in the geothermal field. Crew training is significant because an otherwise competent drilling crew will not be prepared to deal with the unfamiliar problems encountered in drilling hot wells.[14]

An expanded discussion of each of these effects will be given in the following viewgraphs.

TEMPERATURE EFFECTS

- ON DRILLING FLUIDS

  LOSS OF EFFECTIVENESS AT HIGH TEMPERATURE

  PROBLEMS INDUCED BY INADEQUATE FLUID PROPERTIES

  NEED FOR EXPENSIVE MUD TREATMENT

- ON CASING AND CEMENTING

  PROBLEMS INDUCED BY INTERACTIONS WITH DRILLING FLUID

  PROBLEMS INDUCED BY IMPROPER RETARDATION

VG-19 Drilling and Completion Fluids. Drilling-fluid-related difficulties form the single most frequently cited category of geothermal drilling problems.[10,15,16,17,18,19,20,21] Lost circulation is a pervasive difficulty in the geothermal field because of the highly fractured formations in which geothermal resources are found. Fluids which remain stable at high temperature often do not have adequate filtration characteristics for control of lost circulation.

Furthermore, conventional muds tend to gel when circulation is stopped for tripping, logging, and running casing. This can lead to induced problems such as stuck tools and failures of the drill string from differential sticking. Expensive procedures are required to correct these fluid-related failures. Improved fluids and automated fault detection systems would substantially reduce fluid-induced contingency costs and non-rotating rig costs.

High direct costs are associated with geothermal drilling fluid systems, too, because expensive treatment and complete replacement of the circulating fluid is often needed to prevent or minimize the above problems. In addition, extra training must be provided so that crews can properly prepare and condition the unusual fluids used in geothermal drilling.

Casing and Cementing. High temperature cements are being developed by Brookhaven National Laboratory.[22] But the problems of cementing geothermal wells are not caused entirely by the quality of the cement. Difficulties arise in assuring its correct placement,[10,15,16,21,23] and in determining the proper chemical formulation for the temperatures encountered.

Drilling fluids tend to contaminate the cement, and muds that have gelled and thickened leave excessive filter cake on the casing and formation. This filter cake inhibits good cement bonding. Also, a thickened mud can cause the cement to channel behind the casing and can result in large uncemented regions. These regions can fill with water which can vaporize at geothermal temperatures. The pressures which build up have the potential for causing collapse of the casing.

A further problem results from uncertainty in determining the temperature profile of the well. Geothermal cements must be formulated with the proper amount of retardants. Incorrect mixtures will fail to set up properly and lead to expensive remedial cementing ("perf and squeeze"). Such operations are expensive in themselves and also increase non-rotating rig costs. Downhole monitoring of temperature and improved thermal well models will improve the probability of good cementing.

Special training requirements for casing and cementing include procedures for handling large diameter casing,[14] determination of proper casing programs to account for thermal expansion, estimation of the thermal environment which will be encountered by the cement, and determination of the proper retardant mixture by the service company.

TEMPERATURE EFFECTS (Continued)

- ON BITS
  - EXCESSIVE BEARING WEAR
  - SOFTENING OF STEEL AT HIGH TEMPERATURE
  - REDUCED BIT LIFE
- ON ELASTOMERS
  - DETERIORATION OF
    - BIT SEALS
    - BOP'S
    - PACKERS
    - DOWNHOLE MOTORS
    - LOGGING TOOLS, ETC.

VG-20 Bits. The predominant mode of bit failure in geothermal wells is through bearing failure. Unsealed bearings are normally used because elastomeric seals will not survive the high temperatures encountered. The bearings and races are lubricated only by the drilling fluid. High downhole temperature and increased friction cause these critical parts to experience much higher temperatures than the main bit body. Research at the Geysers,[24] where formation temperatures are about 240°C, has shown that temperatures up to 540°C are experienced at the friction pin, and that significant softening of the steel occurs at 260-316°C. The high temperature and resultant softening of the bearing surfaces reduces bit life at the Geysers to 1/4-1/5 normal.* Costs are increased by the need for more bits, the greater number of round trips required, and reduced penetration rates while drilling.

Real time knowledge of downhole bit conditions would permit measurement or prediction of bearing, tooth, and gauge wear. Optimal adjustments of weight-on-bit, rpm, circulation rate, and fluid composition could be made to reduce costs. Also, warning of impending bit failure would prevent leaving cones and other "junk" in the hole and eliminate many expensive, time-consuming fishing operations.

Elastomers. Currently the best elastomers fail at temperatures of 175-225°C depending upon use and environment. These materials cease to be elastomeric when subjected to high temperatures and pressures, and thus their value in geothermal applications is limited. Unfortunately, elastomers are important to virtually every aspect of drilling. The best current designs of rock bits, downhole motors, blowout preventers, packers, and logging tools all contain elastomers. Most of the equipment either cannot be used or can be used only with frequent, costly inspection, repair, and special procedures.

The result is that, in geothermal wells, bits with unsealed bearings are used, existing downhole motors have only limited utility, blowout preventers must be cooled and frequently repaired, logging is an uncertain operation requiring specially designed tools, and many operations requiring long term use of removable packers are not possible.

References: 10, 11, 21, 24, 25.

* Measured lifetimes are about 1/3 normal, but the bits are loaded to only 1/2 normal weight-on-bit. This leads to an equivalent life of 1/4 to 1/5 normal.[24]

FORMATION EFFECTS

- ON DRILLING EQUIPMENT

  EXCESSIVE WEAR AND TEAR DUE TO HIGHLY FRACTURED FORMATIONS

  SLOW PENETRATION IN DIFFICULT FORMATIONS

VG-21 In addition to the extra costs due to high temperature, additional costs are often incurred in geothermal drilling because of the type and condition of the formations which must be penetrated.

The fractured formations that predominate in most geothermal reservoirs (except the geopressured Gulf Coast) cause severe stresses on drilling equipment. Furthermore, many reservoirs exist in hard or medium-hard formations where penetration is slow and equipment wear is high.

MOST GEOTHERMAL RESERVOIRS EXIST IN DIFFICULT FRACTURED ROCK

AREA	RESERVOIR ROCK TYPE	HARDNESS
GEYSERS, CA	GRAYWACKE	HARD
ROOSEVELT HOT SPRINGS, UT	GRANITE & VOLCANICS	MEDIUM HARD
STEAMBOAT SPRINGS, NV	GRANITE & METAMORPHIC	MEDIUM HARD
BEOWAWE, NV	BASALT	HARD
VALLES CALDERA, NM	VOLCANICS, IGNEOUS	HARD
RAFT RIVER, ID	QUARTZ MONZONITE	HARD
HEBER, CA	SANDY DELTAIC SEDIMENT	SOFT
GULF COAST	SEDIMENTARY	SOFT

VG-22 Most geothermal reservoirs are located in hard or medium-hard, fractured rock. The best known exceptions are the Imperial Valley, California, and the geopressured Gulf Coast area. In other regions, the reservoir is usually located in hard, difficult formations even though these may be overlain with sedimentary rocks.

The difficulty and expense of drilling hard, fractured rock is well documented.[10,13,14,15,21,25,26,27] Costs for drilling these formations are high because of low penetration rates and heavy wear and tear on equipment. Also, the hard, fractured rocks are usually encountered in the deepest, hottest part of the well as the reservoir is penetrated. Temperature effects are at their maximum, directional drilling is frequently required, lost circulation problems may be severe, and the selection of drilling fluid characteristics is constrained by the necessity to leave the reservoir undamaged.

These problems highlight the need for improved methods and fluids for drilling hard, fractured rock in deep, hot wells.

EROSION EFFECTS

- ON DRILLING EQUIPMENT

  RAPID WEAR WHILE AIR DRILLING

- ON COMPLETION EQUIPMENT

CORROSION EFFECTS

- ON DRILLING AND COMPLETION EQUIPMENT

  H_2S PROBLEMS

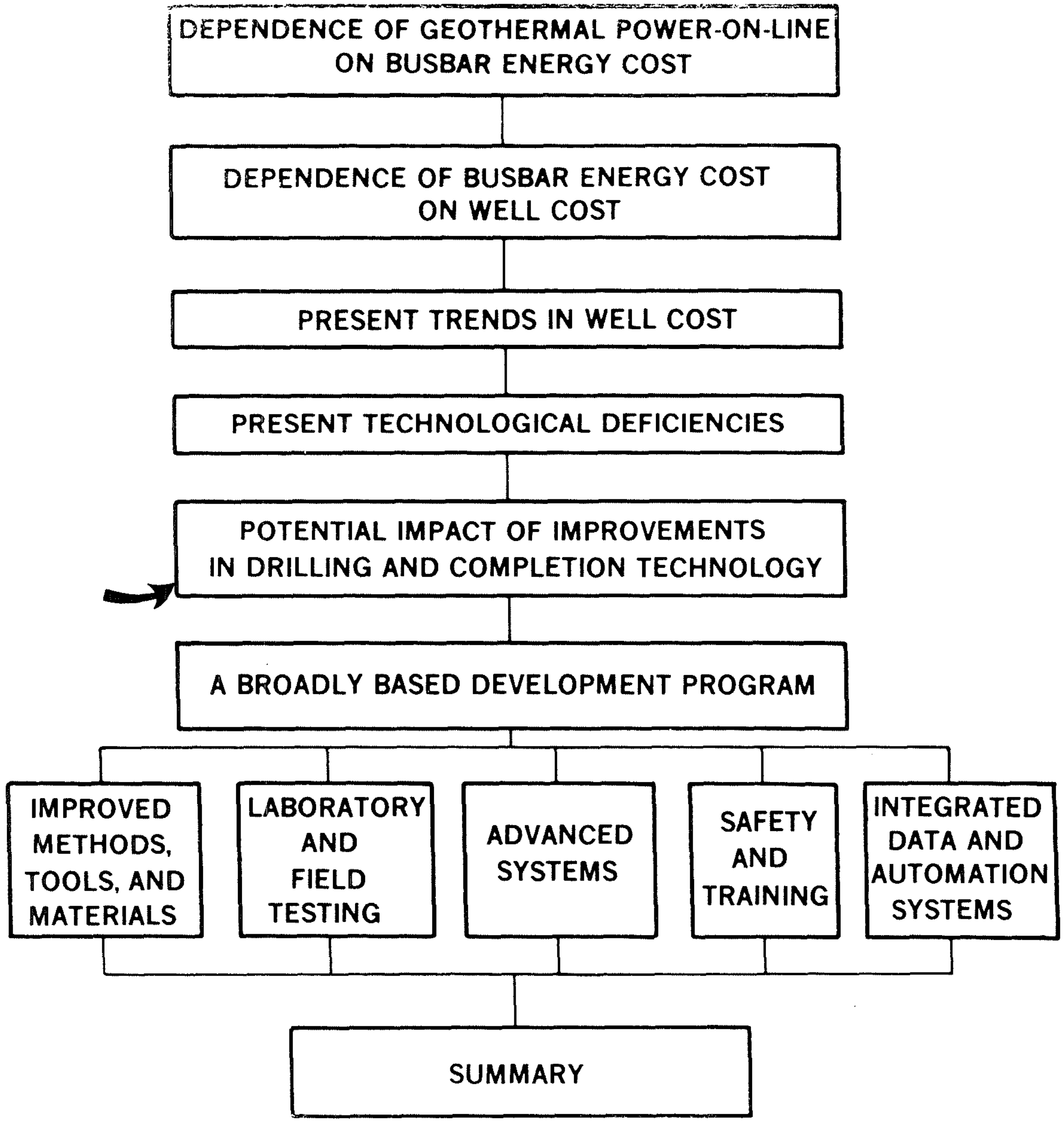
  CORROSION FROM HOT, ACIDIC BRINES

VG-23 At those sites where erosion and/or corrosion occur, severe difficulties and high costs can result. Air is an attractive fluid for drilling into competent reservoirs because it will not damage the formations and generally improves rate of penetration. However, air drilling causes rapid erosion of downhole equipment.[10,13,15,19,20,21,24,28] At the Geysers, where the drill string is frequently inspected and hardbanded and where a special anti-erosion additive is used in the air stream, it is still necessary to junk one foot of drill pipe for each seven feet of hole.[28] These procedures require extra services and additional training for the rig crew, and the high discard rate for pipe requires advance planning to insure adequate supplies of replacements.[29]

Completion problems can arise for those wells which produce wet steam which erodes casing as the high speed fluid strips water film from the casing surface.[20,25] Higher quality casing must be used with flush joints to reduce the problem.

When hot, acidic brines or H_2S are present, downhole equipment is subject to embrittlement and corrosion.[19,21,24,25,30,31] These conditions also require special procedures and training for the crews. Also, more expensive, corrosion resistant materials are used, and additives may be required in the drilling fluid to help control corrosion.

Hydrogen sulfide poses a special problem if it escapes into the air. Crews must wear respirators and rig efficiency drops by 2/3.[32] Also, state regulations may require special safety procedures for wells likely to produce H_2S.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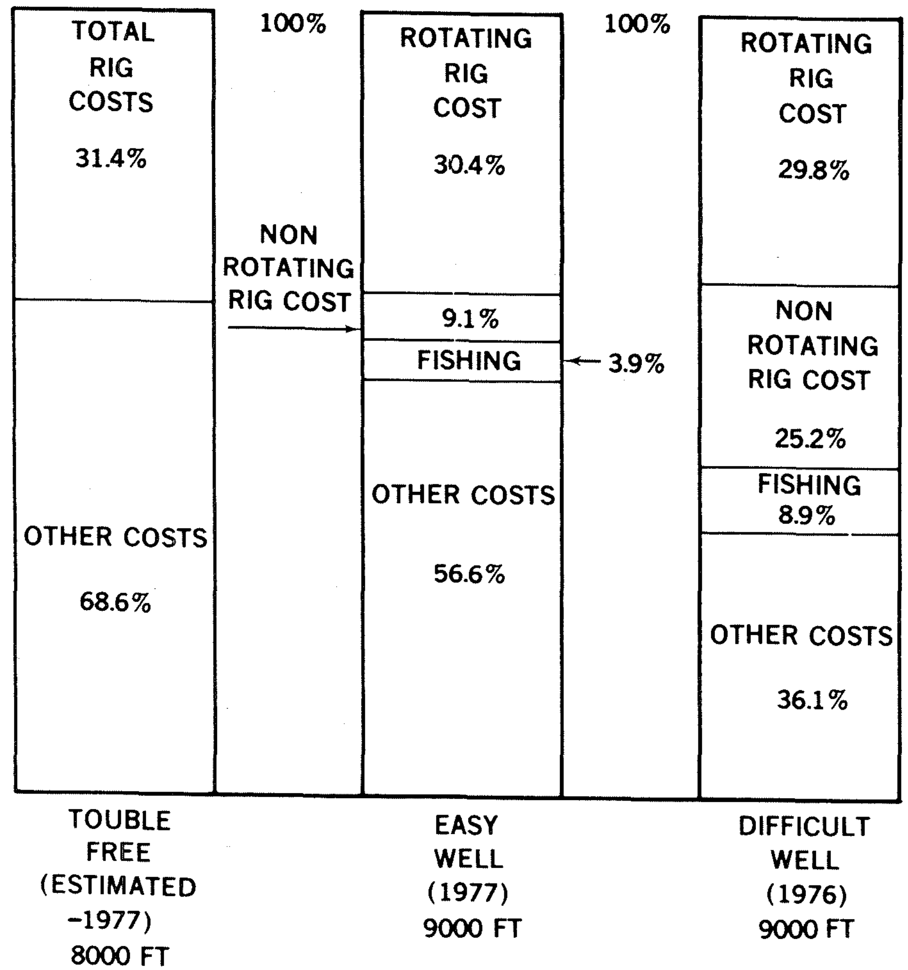
VG-24

ASSESSMENT OF THE POTENTIAL IMPACT OF IMPROVEMENTS IN GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY



GEYSERS WELLS

VG-25 In order to assess the potential impact of improvements in drilling and completions technology on well costs, it is necessary to examine the effect of technological deficiencies. Costs (as percentages of the total well cost) for three wells at the Geysers are shown below and on the the previous page.

	1977 Trouble Free 8000 ft (Estimated)	1977 Easy Well 9000 ft (Actual)	1976 Difficult Well 9000 ft (Actual)
Rig Cost	31.4%	39.5%	55%
Rotating	--	30.4%	29.8%
Non-rotating	--	9.1%	25.2%*
Direct Fishing Cost	0%	3.9%	8.9%
Other Costs	68.6%	56.6%	36.1%
	100.0%	100.0%	100.0%

Data for the idealized trouble free well are taken from estimates by Glass, 1977.[13] The data for the easy and difficult wells are taken from actual well costs for two wells drilled at the Geysers in 1977 and 1976, respectively.[33]

Several conclusions can be drawn by studying the trends revealed in these figures:

1. The percentage of cost attributable to rotating rig time is about 30% of total cost.** A development program aimed solely at improved penetration rate cannot reasonably expect to achieve more than about 15% savings in total well cost. A savings of this size would require a major improvement that doubles the overall average rate of penetration.

2. As difficulties in drilling the well increase, non-rotating rig costs increase substantially. This suggests that one of the main effects of problems is to increase the time required to complete the well. Since many drilling failures are due to deficiencies in present technology, improved materials and equipment for geothermal applications might save 10-15% <u>on difficult wells</u> (by reducing non-rotating costs to approximately the same percentage as on easy wells). Note that this does not mean 10-15% savings on <u>average</u> well costs. Rather,

*Note: This well was plugged back and kicked off. All rig time from twist off until depth again reached the level at twist off is counted as non-rotating time, i.e., the fishing, plug back and re-drill time is taken as non-rotating.

**Note: In areas of easier drilling, this fraction can be expected to be even less than 30%.

it means that fewer wells will be classified as expensive, "difficult" wells. The cost of an "average" well might be reduced by five or perhaps ten percent.

Neither the easy nor the difficult well was characterized as atypical by the contractor who drilled them. If we assume that the "average" well is somewhere between these, and that percent improvements are additive, then an aggressive program to increase rate of penetration and develop better geothermal drilling fluids, cements, and equipment can reasonably be expected to reduce average well cost by about 20%.

3. Cost reductions substantially in excess of 20% can be achieved only by attacking the basic cost structure of rotary drilling. At the Geysers, this is represented by the idealized, trouble-free estimate. An improved drilling system would be required which could reduce the fraction of "other costs" and at least equal the average rate of penetration of rotary drilling. In summary, it is reasonable to expect that a 20% reduction in average well cost is possible through a vigorous program to improve present rotary drilling technology. Cost reductions that are substantially greater than this will require advanced technological development.

SUMMARY

EVEN IF A RADICAL IMPROVEMENT INCREASES AVERAGE PENETRATION RATE BY A FACTOR OF TWO, AND

EVEN IF IMPROVED MATERIALS ELIMINATE MOST CONTINGENCY COSTS,

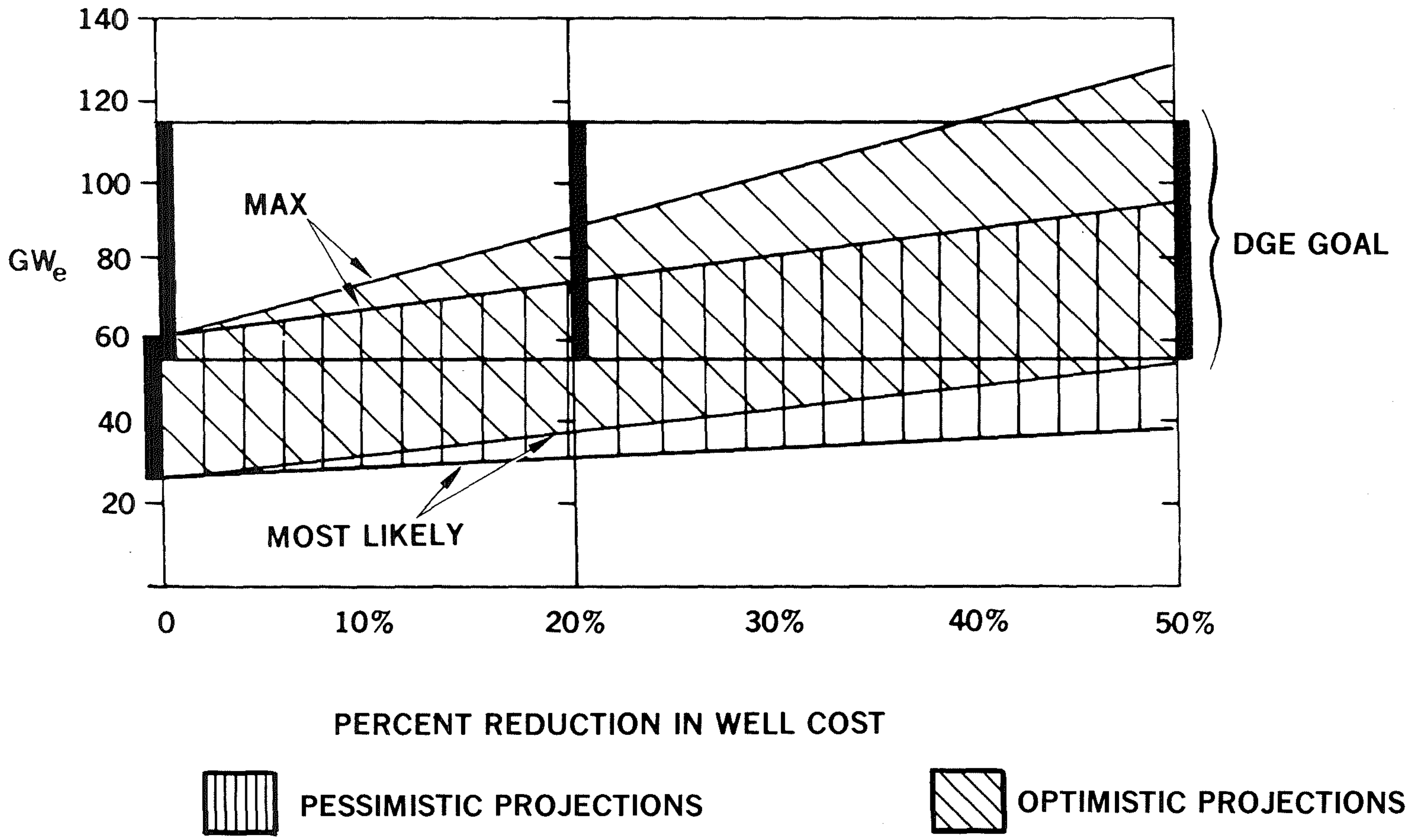
THE POTENTIAL REDUCTION IN AVERAGE GEOTHERMAL WELL COST WITH CONVENTIONAL ROTARY DRILLING IS APPROXIMATELY 20%

IS 20% ENOUGH?

VG-26

VG-26 Technological developments directed toward improvement of geothermal rotary drilling have the potential to reduce drilling costs by approximately 20%. The important question is whether 20% is sufficient to give reasonable certainty of achieving DGE goals.

PROJECTED GEOTHERMAL POWER-ON-LINE IN THE YEAR 2015



VG-27

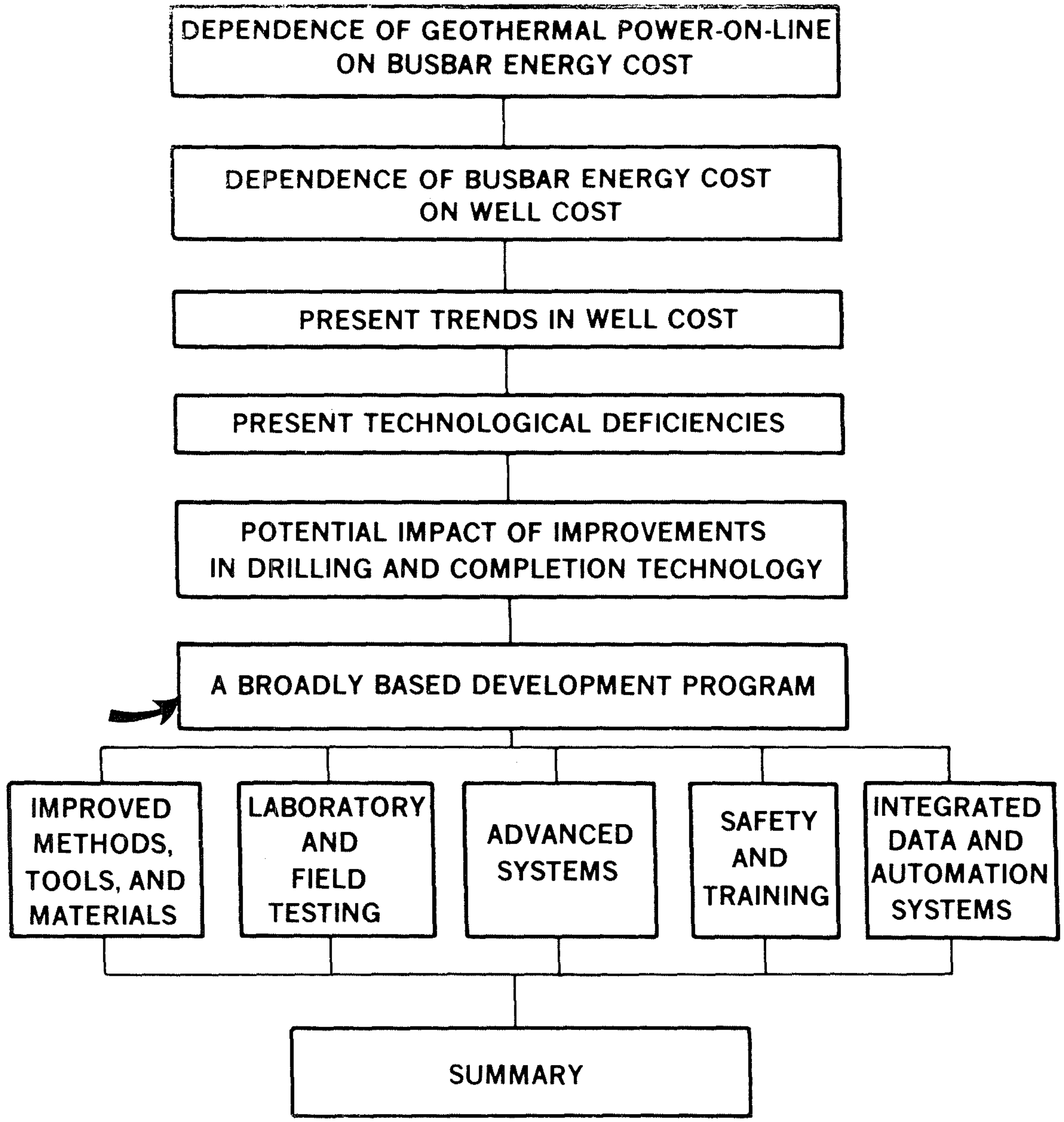
VG-27 This viewgraph is obtained by assuming that the 2015 elasticity of power-on-line to busbar cost is constant at two, and by using pessimistic (0.5) and optimistic (1.0) values for the elasticity of $\overline{BBEC}$ to well cost (the BNWL studies yield the approximate value of 0.5 and Mitre's site-specific analysis[14] yields the higher value of 1.0).

The two elasticities have been applied to the "Max" and "Most Likely" BNWL cases to obtain the optimistic and pessimistic fans for a range of well cost reductions from zero to 50%.

The range of uncertainty for 20% well cost reduction does not offer substantial assurance that DGE goals will be met. This is especially clear, since the "most likely" values for both the optimistic and pessimistic cases are well below DGE goals.

At 40% to 50% well cost reduction, however, the range of uncertainty begins to bracket DGE goals. And at 50%, the optimistic, "most likely" case essentially meets DGE goals.

There is much uncertainty in this graph, but it does indicate that cost reductions in excess of 20% are needed to yield reasonable assurance of meeting DGE goals. In order to accomplish this, a broadly based development program is needed.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A BROADLY BASED DEVELOPMENT PROGRAM FOR GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY

- DEVELOP IMPROVED TOOLS, DRILLING FLUIDS, AND MATERIALS FOR USE IN GEOTHERMAL DRILLING.
- ACQUIRE NECESSARY LABORATORY AND FIELD TESTING FACILITIES.
- DEVELOP ADVANCED SYSTEMS FOR DRILLING GEOTHERMAL WELLS
- DETERMINE THE NEED FOR AND DEVELOP TRAINING AND SAFETY PROGRAMS FOR GEOTHERMAL DRILLING
- DEVELOP INTEGRATED BOREHOLE AND SURFACE DATA ACQUISITION AND AUTOMATION SYSTEMS

VG-29

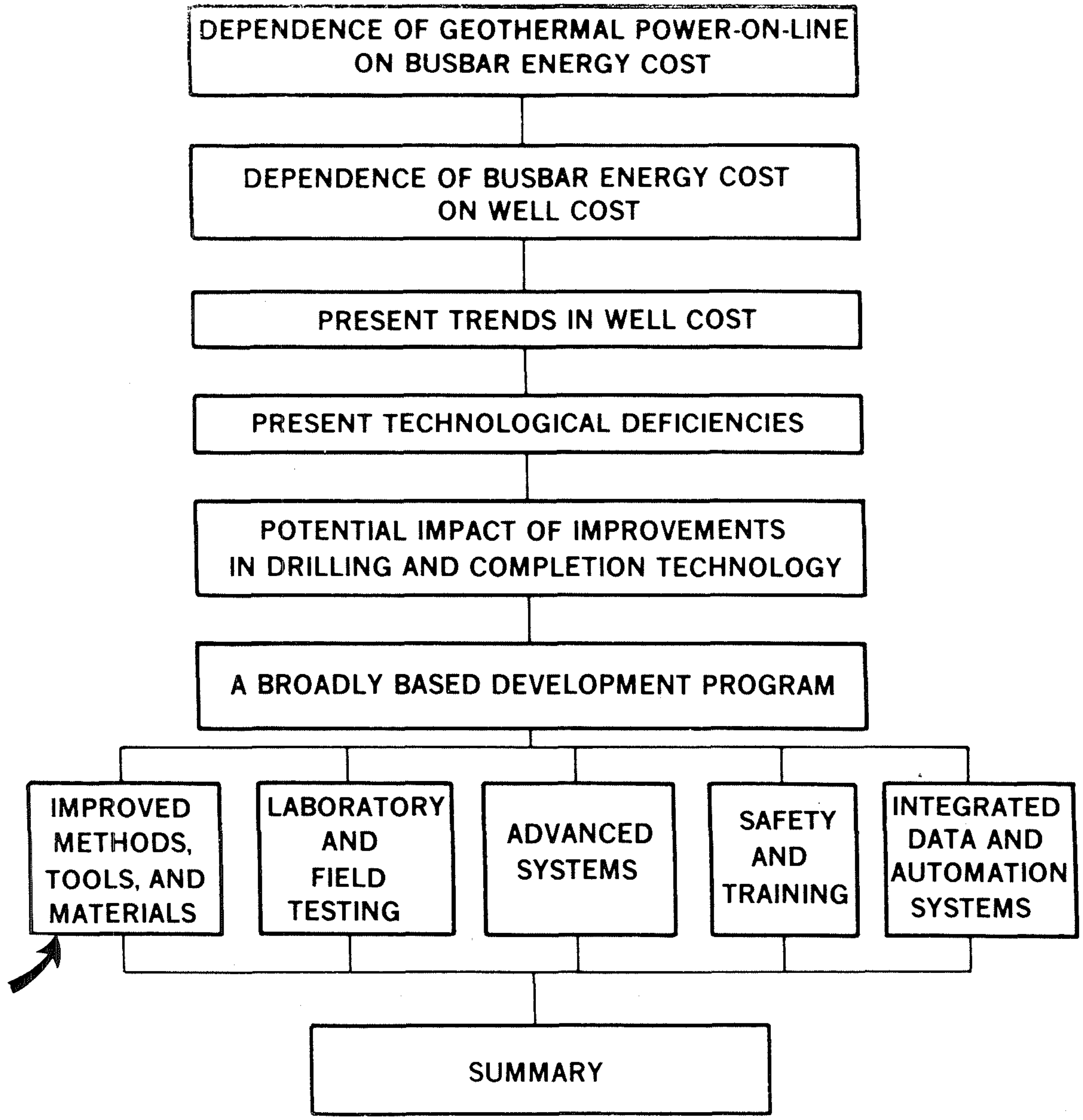
VG-29 The current development activities in geothermal drilling are directed primarily at the first area. Improvements in this category will reduce contingency costs and produce near term, tangible results. As discussed previously, however, the ultimate potential of projects in this category is a cost reduction of about 20% in average well cost.

Development of new geothermal drilling hardware will be accelerated if adequate facilities are available for laboratory and field testing under realistic geothermal conditions. Furthermore, no new concepts or equipment will be accepted by the drilling industry until they are thoroughly and credibly demonstrated in laboratory and field tests.

In order to achieve a 50% reduction in average cost, activities aimed at revolutionary improvements in drilling are needed. Novel rock breaking methods and advanced drilling systems must be developed. New geothermal training and safety programs are needed to insure that crews are well prepared to function efficiently in the geothermal field, and rig automation and instrumentation systems which make optimum use of real time drilling parameters must be developed.

The research areas proposed here are consistent with the topics outlined by the Ad Hoc Committee on Technology of Drilling for Energy Resources of the National Academy of Sciences[34] and with the needs for geothermal and geoscientific exploration.[35]

VG-30



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IMPROVED METHODS, TOOLS, AND MATERIALS FOR USE IN GEOTHERMAL DRILLING

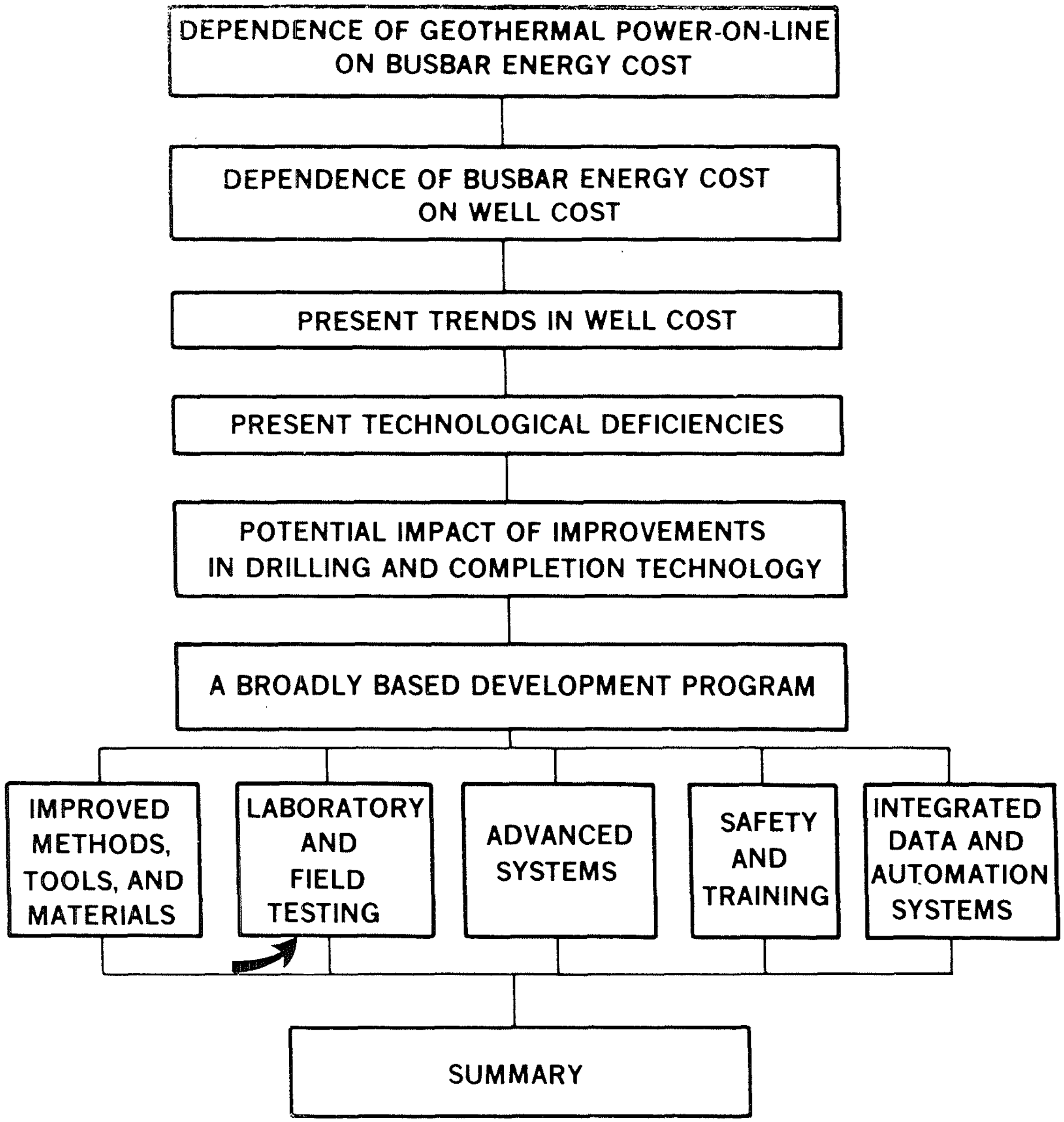
CURRENT DEVELOPMENT ACTIVITIES INCLUDE PROGRAM ELEMENTS IN THE FOLLOWING AREAS

- GEOTHERMAL ROCK BITS
  - STRATAPAX
  - CHAIN
  - JET ASSISTED ROLLER CONE
  - ROLLER CONE
- GEOTHERMAL DRILLING MOTORS
- GEOTHERMAL DRILLING FLUIDS
  - 'MUD'
  - FOAM, MIST
- GEOTHERMAL COMPLETION TECHNOLOGY

VG-31 Current activities are concentrated in the areas shown. The Rock Bit and Drilling Motor programs are intended to develop tools that are rated for use in geothermal drilling. Programs in these areas have the potential to relieve current materials problems and also to increase the rate of penetration in hard, fractured geothermal formations.

The drilling fluid program will develop fluids that retain desired properties at high temperature, and the Completion Technology Program is addressing the difficulties associated with conventional completion of geothermal wells.

Developments in these areas could potentially reduce well costs by 20%. To achieve further reductions, a more broadly based development program is needed.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VG-32

LABORATORY AND FIELD TESTING FACILITIES

CURRENT LABORATORY FACILITIES CANNOT SIMULATE GEOTHERMAL DRILLING CONDITIONS.

NO ADEQUATE FIELD TEST CAPABILITY EXISTS

POTENTIAL DEVELOPMENT AREAS INCLUDE

- LABORATORY TEST FACILITIES

  SIMULATE IN SITU GEOTHERMAL CONDITIONS (PORE PRESSURE, ETC.)

  TEST NOVEL FLUIDS, DRILLING TOOLS, AND METHODS

  TEST DOWNHOLE MOTORS

- FIELD TEST CAPABILITY

  DEVELOP REQUIRED INSTRUMENTATION

  DEVELOP A DATA ACQUISITION SYSTEM FOR USE IN THE FIELD

VG-33 Present facilities for laboratory testing of geothermal drilling equipment cannot adequately simulate downhole conditions. The only available geothermal drilling test stand is limited to an 8 inch diameter with a two foot working length.[36] The vessel can be pressurized to 5000 psi at about 315°C, but no capability to circulate drilling fluid is available. Furthermore, available facilities are intended almost solely to obtain data on performance of the rock bit only.

A comprehensive laboratory test capability is needed because it quickly differentiates between competing designs, reduces development cycle time, permits design optimization before field testing, and ultimately reduces the time to place new technology in the field. The drilling industry has demonstrated its reluctance to accept untested technology. Risks in drilling are very high, and only proven methods can be financially justified in the field.

A laboratory testing facility should have the capability to perform controlled, full scale tests that simulate geothermal borehole conditions. It must be capable of simulating in situ geothermal conditions for temperature, confining pressure, pore pressure, etc. It is essential that the facilities be able to:

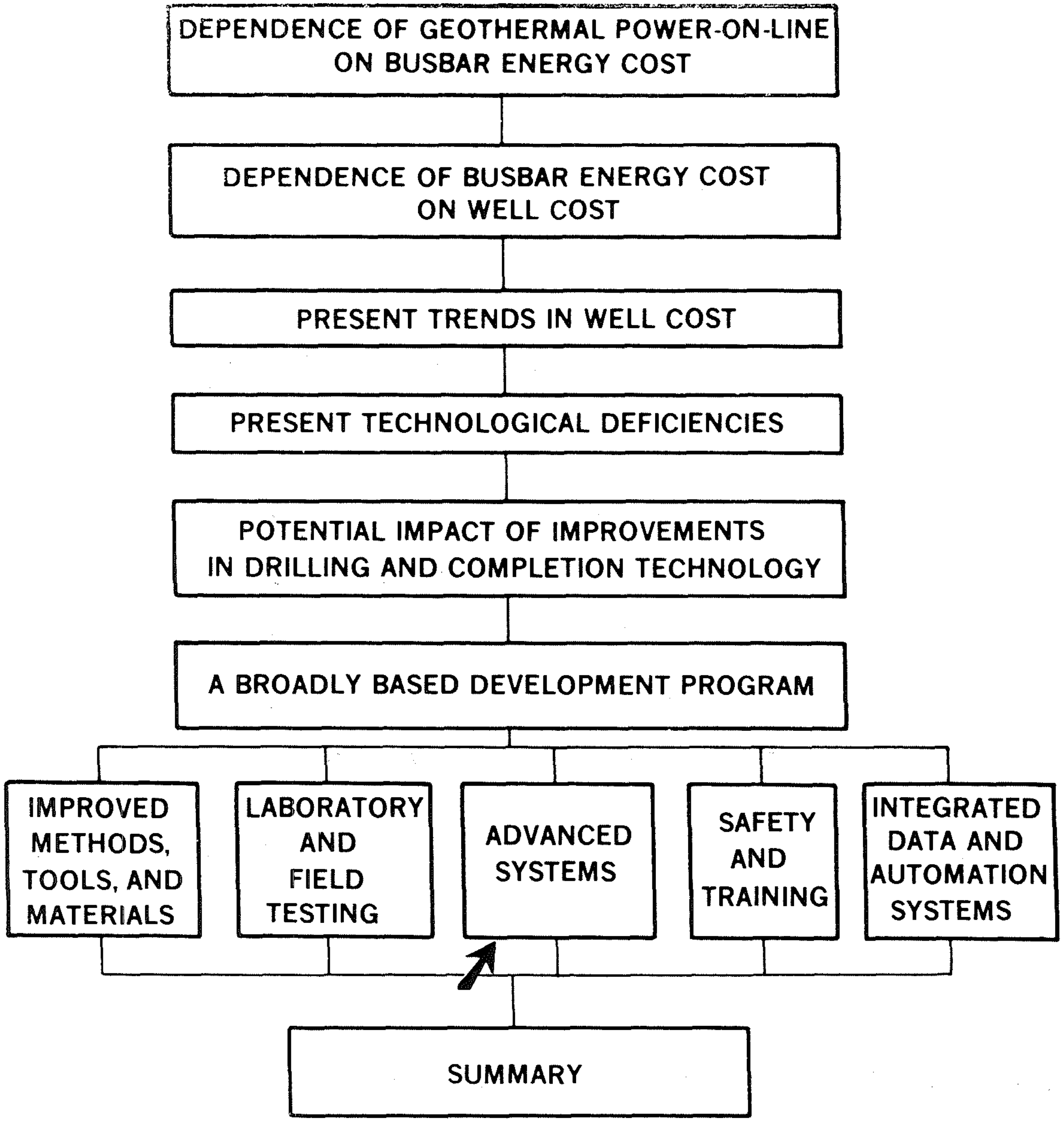
a. Circulate drilling fluids under geothermal conditions,

b. Test unconventional drilling fluids such as air and foam,

c. Accommodate novel drilling methods such as jet drilling, and

d. Test prototypes of geothermal drilling motors and completion tools.

Field testing is an important part of the development cycle of any new tool. It is doubly important in drilling because no new method or tool will be used commercially until it has been credibly demonstrated in the field. The route to rapid commercialization of new geothermal drilling hardware is through thorough field demonstration.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VG-34

ADVANCED SYSTEMS FOR DRILLING GEOTHERMAL WELLS

POTENTIAL DEVELOPMENT AREAS INCLUDE

- ADVANCED METHODS FOR ROCK DRILLING
  - ROCK MECHANICS AND ENERGETICS OF IN SITU FORMATIONS
  - MECHANICAL AND PERCUSSION METHODS
  - JET AND CAVITATION METHODS
  - THERMAL SPALLING, ETC.

- ADVANCED DRILLING SYSTEMS
  - FLEX PIPE
  - NOVEL COMPLETIONS AND NEW MATERIALS
  - NOVEL AND/OR SPECIALIZED RIG DESIGNS

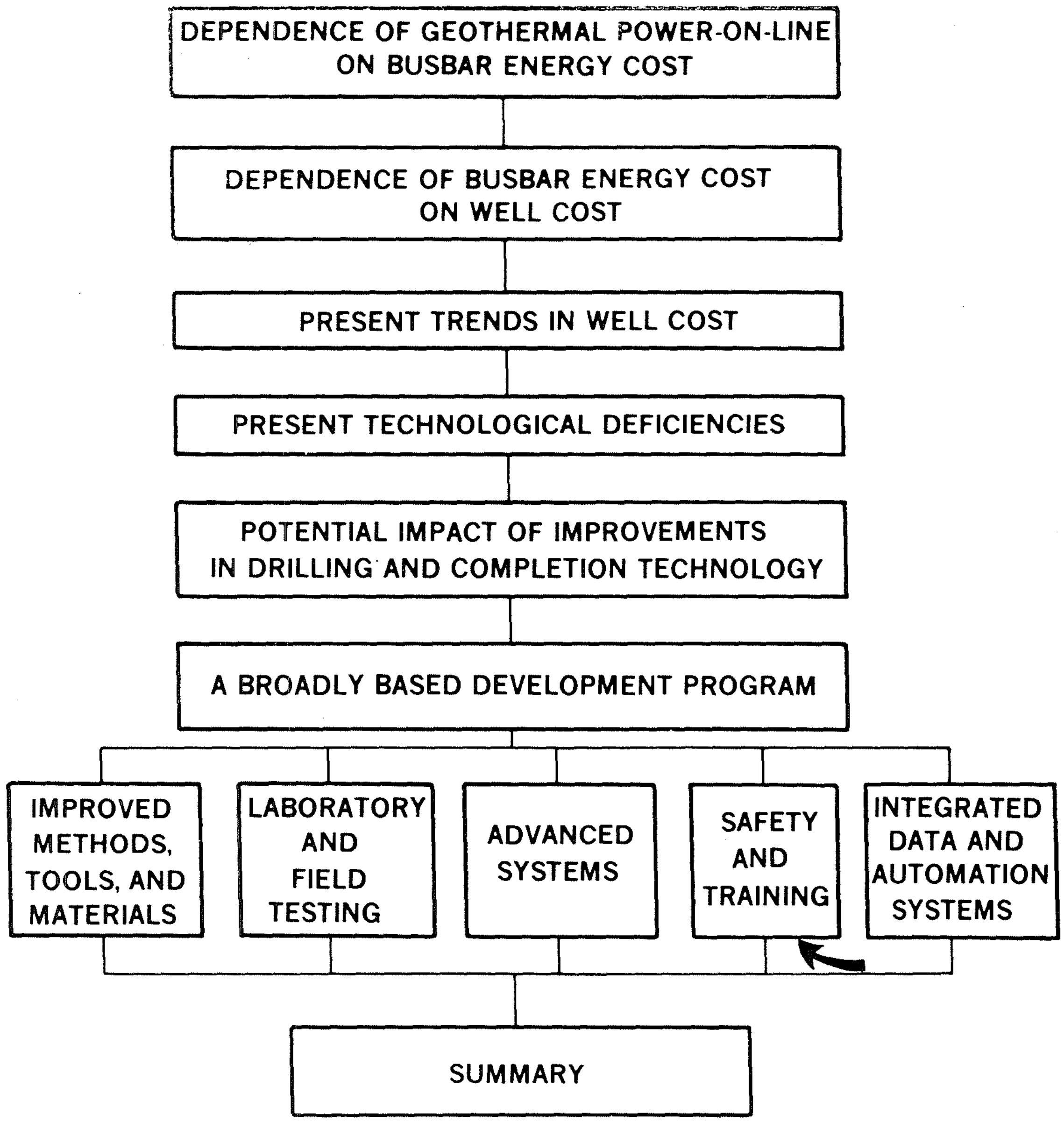
VG-35 Additional effort is required to define and develop the next generation of rock drilling methods. Central to this issue is the need to better understand the basic mechanics and energetics of *in situ* rock. Additional geophysical measurements in the field are needed to improve the knowledge of rock characteristics as they vary with depth. A complement to these endeavors is the development of improved models of rocks which bridge the gap between microscopic and macroscopic theories of fracture and which include the effects of porosity, contained fluids and ductility. An essential feature of such activities is the establishment or utilization of high pressure geophysical laboratory facilities that can contain large samples. This will allow grain size distribution effects to be evaluated and transport properties to be measured at conditions simulating those *in situ*. These laboratory data are needed to validate model predictions which can then be used in the interpretation of field measurements.

Many novel methods for geothermal drilling have been proposed.[11] Some of the more promising suggestions are listed. Jet, or jet with cavitation, has shown promise, especially when combined with percussion or mechanical methods. Thermal spalling with electron beam or other methods also efficiently drills rock. Difficulties with these exotic methods involve their application at depth in the well bore. Advanced theoretical and engineering development is needed to fully explore these and other methods in order to develop a method or methods which provide a revolutionary improvement over present technology.

Novel completion methods which substitute lightweight materials for steel casing would complement flexible tube designs by eliminating the need for expensive, heavy duty rigs.

A number of innovative changes are occurring in rig designs that need accelerated upgrading for heavy duty drilling.[38,39] Among these are highly mobile, quick set-up rigs that can be broken down into standard size-weight packages for easy transportation.[40] Also split level rigs with hydraulic hoists replacing conventional draw works can substantially reduce trip times and cost.[41] Push-down rigs[42] have been used to rapidly drill the initial portion of the well when normal bit loads are small. Improvements of 10 to 1 in penetration rate over conventional rigs have been reported. Incorporation of this feature on heavy duty rigs would reduce costs for geothermal wells.

These and other as yet unknown improvements must be investigated to increase the likelihood of achieving the technological breakthrough needed for a 50% reduction in geothermal drilling cost.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VG-36

DEVELOP SAFETY AND TRAINING PROGRAMS FOR GEOTHERMAL DRILLING

SAFETY AND TECHNICAL TRAINING ARE ITEMS OF GREAT CONCERN TO DRILLING CONTRACTORS

ACCIDENT RATES IN THE DRILLING INDUSTRY ARE THREE TIMES THE NATIONAL INDUSTRY AVERAGE

POTENTIAL DEVELOPMENT AREAS INCLUDE

- DESIGNING SAFETY INTO NEW RIGS
- WORKING WITH INDUSTRY TO DEVELOP PROGRAMS TO IMPROVE THE LEVEL OF PROFICIENCY IN GEOTHERMAL DRILLING
- MINIMIZING POTENTIAL FOR HUMAN ERROR THROUGH INSTRUMENTATION AND AUTOMATION

VG-37

VG-37 Rig safety and crew training were recently identified by drilling contractors[43] as very important areas that need improvement.

Engineering development can make improvements in rig safety. Accident rates in the drilling industry are three times the national average for industry.[44] In 1976, 74% of the accidents on land rigs were in the four categories of "falls," "caught between objects," "struck by objects," and "over-exertion."[45] Many hazards related to these problems can be eliminated or reduced by design changes in rigs and drilling tools.

Crew training was identified in a survey[19] as a top priority need. There is a need to assess the adequacy of current training programs and to work with the drilling industry to develop programs which will increase crew proficiency.

Additional training requirements exist to inform contractors and service companies of the special procedures (special muds, special cements, high temperatures, anti-corrosion/erosion measures, etc.) that are needed in geothermal drilling. The difficulties of using an otherwise competent contractor who is inexperienced in geothermal drilling have been noted in the literature.[14]

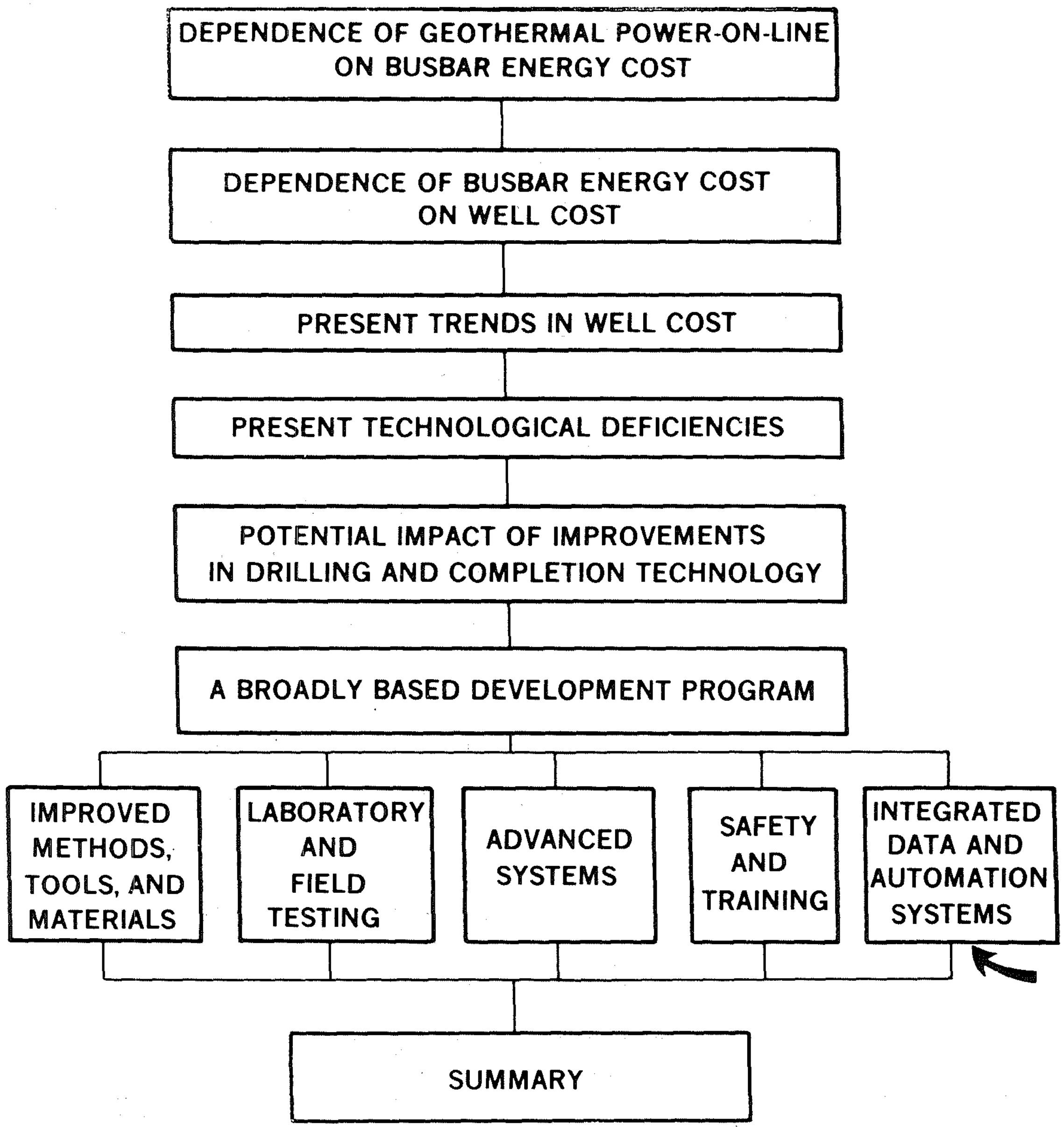
Engineering improvements on the rig will help to alleviate problems with training and safety, too. For example, data acquisition, telemetry, and on site data processing can reduce the potential for human error. Examples of this have been mentioned earlier, and include:

a. automatic fault detection and alarms

b. appropriate automation of contingency actions, and

c. computers to eliminate the need for rig personnel to do calculations and make graphs.

9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VG-38

INTEGRATED BOREHOLE AND SURFACE DATA ACQUISITION AND AUTOMATION SYSTEMS

POTENTIAL DEVELOPMENT AREAS INCLUDE

- UPHOLE MEASUREMENTS
  - INSPECT PIPE
  - DETECT LOST CIRCULATION AND WELL KICKS
  - INFER DOWNHOLE CONDITIONS
- DOWNHOLE MEASUREMENTS
  - MAKE DIRECT MEASUREMENTS OF DOWNHOLE CONDITIONS
  - DETECT LOST CIRCULATION AND WELL KICKS AT EARLIEST OPPORTUNITY
  - MONITOR BIT CONDITION
  - CONTINUOUSLY MONITOR HOLE DEVIATION
- INTEGRATED DATA ACQUISITION AND AUTOMATION
  - PROCESS DATA IN REAL TIME AND OPTIMIZE CONTROLLABLE VARIABLES

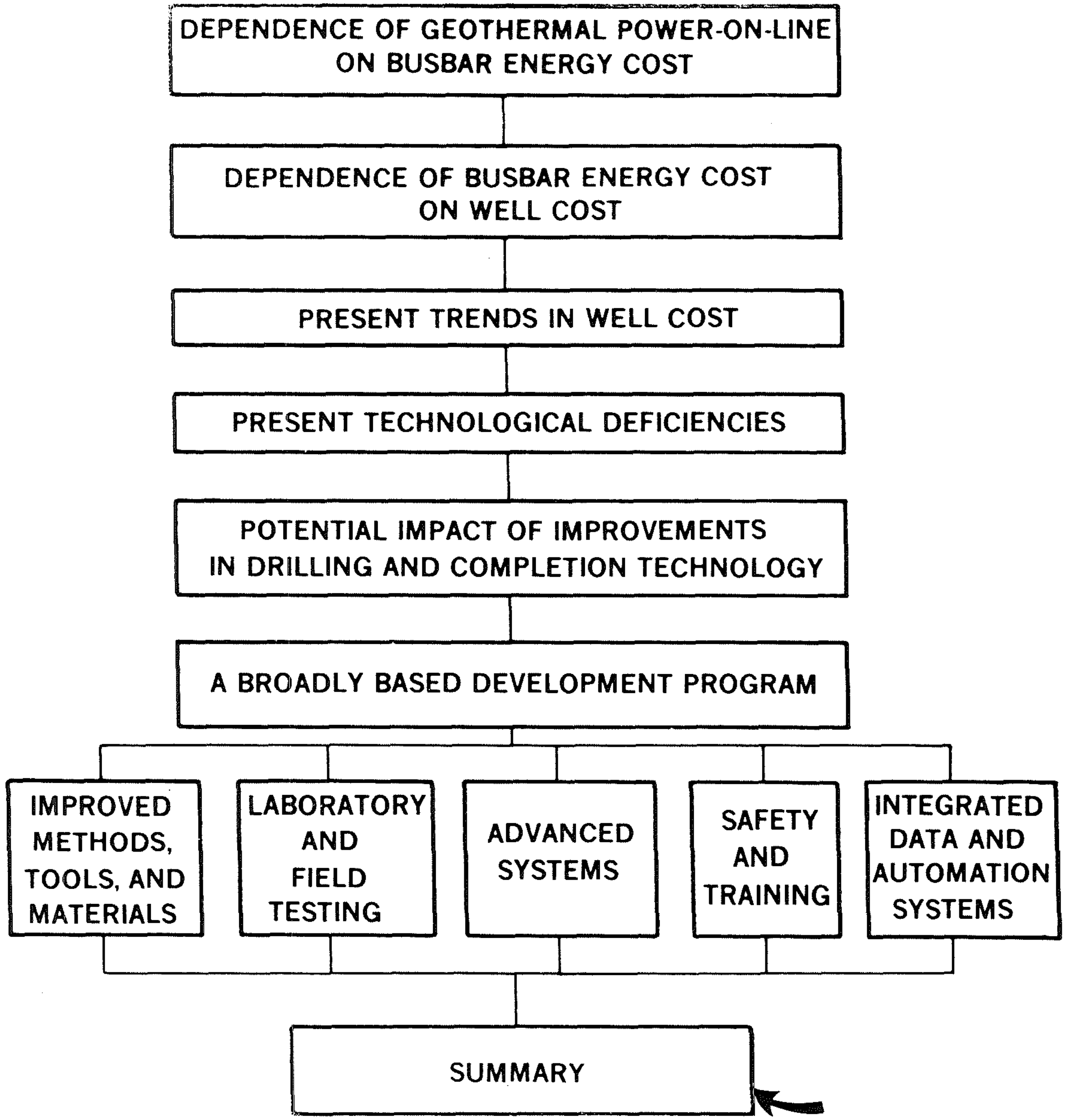
VG-39 A complement to Advanced Systems Development is an integrated approach collecting and using information available at the drill site. Data can be acquired uphole and downhole. Information from each location has value in itself and can provide near term payoff. Integrating the data from both sources into a unified system to make optimum use of all information will maximize the benefit of the total data acquisition system.

Surface measurements are easier to obtain than downhole measurements and can provide valuable, cost saving information. For example, surface measurements can be used to inspect downhole equipment. Suggested projects include development of reliable high resolution means to inspect drill pipe and casing as it is run into or out of the well. Similarly, methods need to be devised to reliably inspect drill string joints for microfractures as the pipe is stacked during tripping. Also, development of reliable flow meters to compare inflow and outflow of drilling fluid may permit more timely detection of well kicks than is possible with mud pit measurements.

In addition, the extent and precision to which downhole conditions can be inferred from uphole measurements need to be determined. Detection of impending equipment failures will be considered a major breakthrough by the drilling industry.[46] Partial realization of this capability from surface data would provide a near term improvement in safety and cost reduction.

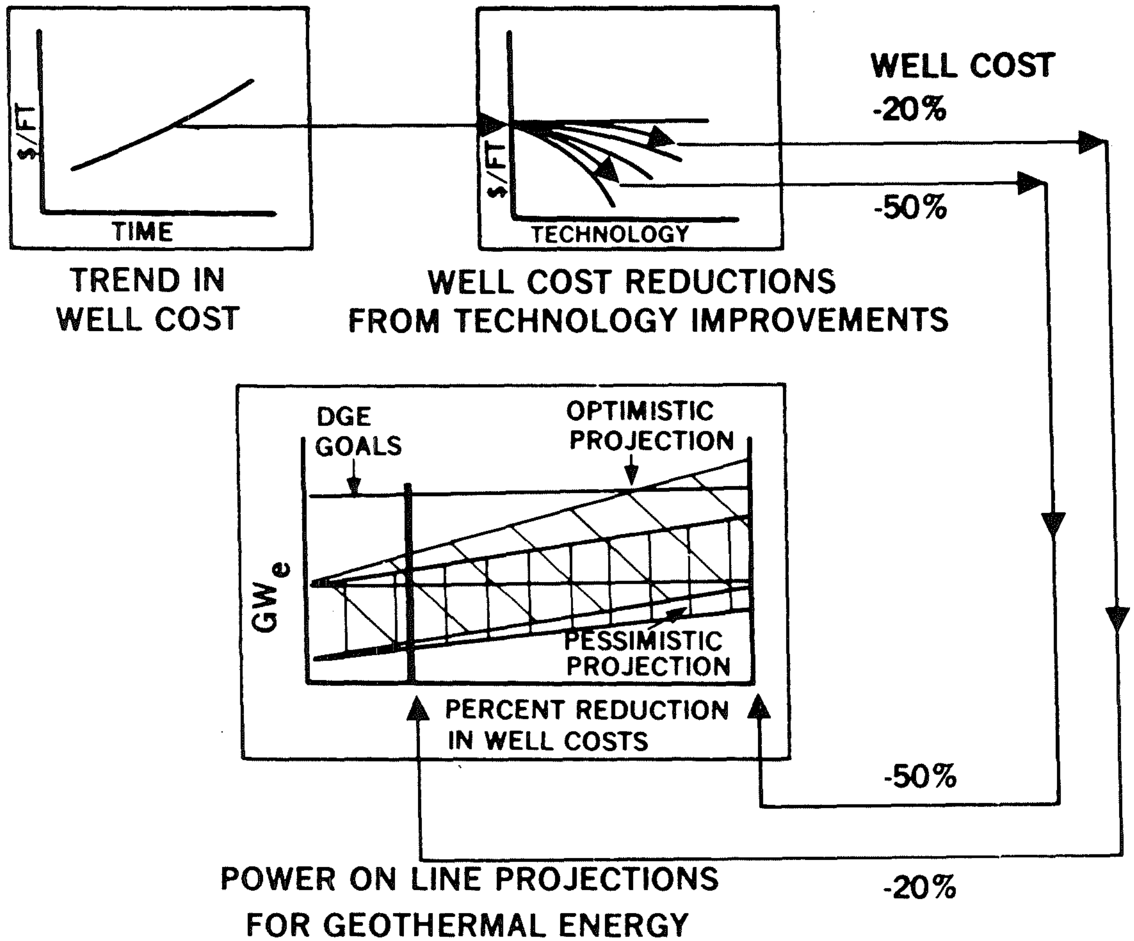
To fully optimize controllable drilling parameters, however, downhole measurements will be required. Borehole measurements offer the capability to make direct observation of important well conditions. For example, in geothermal wells, knowledge of downhole temperature can be a critical factor in assuring good cement jobs. In addition, the potential exists for immediate detection of well kicks, possible warning of impending kicks, and real time monitoring of bit wear and condition. Continuous directional monitoring is especially valuable in geothermal wells which are frequently directionally drilled. Such capability used in concert with a downhole motor will substantially enhance precision drilling.

Ultimately, an integrated, automated data acquisition system will utilize information from both surface and downhole measurements. On site computers will compare direct and inferred parameters in real time and provide information to aid in drilling optimization, warn of impending failures, and trigger alarms when failures do occur.


DEPENDENCE OF GEOTHERMAL POWER-ON-LINE ON BUSBAR ENERGY COST
DEPENDENCE OF BUSBAR ENERGY COST ON WELL COST
PRESENT TRENDS IN WELL COST
PRESENT TECHNOLOGICAL DEFICIENCIES
POTENTIAL IMPACT OF IMPROVEMENTS IN DRILLING AND COMPLETION TECHNOLOGY
A BROADLY BASED DEVELOPMENT PROGRAM
IMPROVED METHODS, TOOLS, AND MATERIALS
LABORATORY AND FIELD TESTING
ADVANCED SYSTEMS
SAFETY AND TRAINING
INTEGRATED DATA AND AUTOMATION SYSTEMS
SUMMARY

VG-40

INFLUENCE OF GEOTHERMAL WELL COSTS ON POWER-ON-LINE GOALS



VG-41

VG-41 This viewgraph is a schematic of the dependence of geothermal power-on-line to well cost. The control variable which is available for this process is the amount of well cost reduction achieved through technological improvements.

Careful selection of technology development tasks by cost/benefit systems analysis and consultation with industry can probably achieve a 20% reduction in well cost through technology improvements for rotary drilling. This reduction does not yield high expectations of meeting DGE power-on-line goals for 2015, however. A 50% reduction in well cost offers high probability of meeting DGE goals; but, of course, the probability of achieving the breakthroughs needed to obtain this reduction is not known.

It is true, however, that DGE power-on-line goals will probably <u>not</u> be reached unless an effort is made to achieve a 50% reduction in geothermal well cost. The broadly based development program just described is directed toward this goal.

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