COURY and ASSOCIATES
6600 W. 13th Avenue
Denver, Colorado 80214

CONSULTANT, CHEMICAL ENGINEERING
GEOTHERMAL ENERGY
WATER: REUSE, DESALTING, DISPOSAL
ENVIRONMENTAL STUDIES

(303) 232-3623

PRODUCTION OF GEOTHERMAL
FLUIDS BY THE NATURAL FLASHING PROCESS

DESIGN AND ANALYSIS OF GEOTHERMAL WELLS IN
TWO-PHASE FLOW

FIRST ANNUAL REPORT UNDER ERDA
CONTRACT

MASTER

Prepared By:

Coury and Associates, Inc.

June 18, 1976

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

REA

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Contents

	Page
I. Summary-----	1
II. Introduction-----	3
A. Program Objectives-----	3
B. The Two-Phase Flow Problem-----	5
III. Laboratory Test Program-----	14
IV. Instrumentation and Well Testing-----	16
V. Well Design and Analyses-----	20
VI. Status of Computer Program-----	23
A. Pressure Drop and Holdup Correlations-----	23
B. Physical Property Data-----	27
C. Data Base-----	28
VII. Future Work-----	30
VIII. Related References-----	31
I. Analyses of Two-Phase Vertical Flow-----	31
A. Correlations for Holdup, Frictional Loss, and Minimum Flow-----	31
B. Flow Regimes-----	34
C. Flow Fluctuations and Instabilities-----	34
D. Data and Evaluations of Correlations-----	35
II. Sonic Velocity in Two-Phase Flow-----	36
III. Heat Transfer in Two-Phase Flow and in Wells-----	37
IV. Physical Properties and Thermodynamics of Solutions-----	38
A. Steam-Water and Brines-----	38
B. Solubilities of Gases and Dissolved Solids-----	39
C. Properties of Hydrocarbon Mixtures-----	41
V. Geothermal References--Flow, Sampling, Data, Etc.-----	42

<u>Figures</u>	Page
Figure 1. Flow Regimes in Vertical Flow-----	7
Figure 2. Regime Transitions During Vaporization-----	9

<u>Tables</u>	
Table 1. Casing and Completion Record of Geothermal Well Mesa 6-1--	17
Table 2. Correlations Already Programmed, and Optional Computational Groupings-----	25

I. SUMMARY

The well design project sponsored by ERDA calls for the design and analysis of geothermal wells operating in the flashing mode to produce a steam and brine mixture. The hot, overpressured geothermal brine enters the well at the bottom of the hole as an all liquid phase. As the brine flows up the well, the pressure is constantly reduced, mainly because of the reduced hydrostatic load imposed by the fluid column above. Finally, a point in the well is reached at which the local pressure is the boiling pressure for the brine temperature. At this point, flashing begins and some steam is formed. As more steam is formed, the flow velocity increases and the rate of pressure drop increases because of increased frictional forces and reduced density of the overlying mixture. Enough steam is formed so that the vapor is the continuous phase, while the brine is present as droplets or as a liquid film on the well casing. At this point, the steam must drag the liquid upwards by the friction forces exerted on the liquid surface.

The objective of this program is to analyze the two-phase flow system as it develops and changes in the well. The product of the study will be a calculational technique to allow the design of geothermal wells in two-phase flow. The study program involves three groups--the Denver Research Institute (DRI), the University of Houston (UH), and Coury and Associates, Inc. Each group has its own primary functions and objectives; however, the scope of work envisions a close coordination among them and some overlap in their responsibilities.

Coury and Associates, Inc.

This report summarizes the status of the program effort being undertaken by Coury and Associates, Inc., after the first eleven months on the study (July 1, 1975 to June 1, 1976). In the next section of the report, the overall approach to the project is summarized, and the nature of the two-phase flow problem is discussed. In subsequent sections, the various elements of the program and the interaction between Coury and Associates and the other groups are presented in more detail.

Reports and publications that are specifically referred to in the text of this report are specified in footnotes. A preliminary general bibliography of materials related to this study is given in Chapter VIII. Although reasonably complete, this bibliography has not been finalized; it consists, rather, of publications that we have been able to collect in a straightforward manner. A systematic literature search has not yet been made.

II. INTRODUCTION

A. Program Objectives

The objective of this study is to develop a calculational procedure for both the analysis and the design of geothermal wells that are producing a two-phase mixture of steam and brine. Because of the complexity of the calculations, the procedure is being formulated as a Fortran IV code for use with electronic computers. There is only a meager amount of good data available for two-phase flow at high rates in large diameter vertical lines. To compensate for this lack, a multifaceted approach is being taken to the resolution of the problem. These aspects are summarized briefly below, and covered in more detail later.

Several correlations are available in the literature for calculating the pressure drop in two-phase flow. These have been developed by both empirical and semi-theoretical means. Most of them contain arbitrary constants that have been evaluated by curve-fitting a limited set of data. None has been specifically evaluated for geothermal wells. Accordingly, it is not known which, if any, of these correlations is suitable for geothermal service. Thus, the first step has been to review the correlations that are available, and to program those that appear best suited to geothermal applications.

Secondly, these correlations will be tested against the data that is available for two-phase flow in vertical lines. This has already been done by some authors for some correlations, but the previous efforts have not been sufficiently consistent or systematic for our purposes. Thus, our data-checking phase has two sub-objectives: to systematically evaluate the preferred correlations that exist, and to provide a verification of our

procedures by overlapping to some extent the data versus correlation checks previously reported in the literature.

The data available for checking the correlations are only partially suitable to our needs. The existing steam-water data, which comes closest to simulating geothermal wells, has been taken only in small diameter systems. The large diameter data that does exist is for oil wells. These data fulfill some of our requirements for checking correlations, but are inadequate in other respects. For example, the physical properties of the hydrocarbon fluids and the gas-liquid flow ratios are not completely consistent with the geothermal case. Finally, the data available for oil well tests is limited with respect to actual fluid compositions and physical properties.

Because of these limitations in the available data base, the third phase of the program calls for actual field measurements of the two-phase flow parameters in producing geothermal wells. Three sets of flow tests will be made, the first one being scheduled for September 1976 at the East Mesa Field, California, in the Bureau of Reclamation Well 6-1.

As part of the well-testing program, it was determined that existing instrumentation for down hole measurements were not suitable for our purposes. New instrumentations that could provide real-time readout at the surface of the downhole temperatures and pressures is required. The concept for the new instruments was developed by Coury and Associates. The instruments are being designed and fabricated by DRI, and will be tested by Coury and Associates as part of Phase 3.

In recognition of the lack of fundamental understanding of vertical two-phase flow, a research program has been initiated at the University of Houston, and will run in parallel with the other work. A fourth phase

of the Coury and Associates program consists of working with UH to help maintain a solid connection between the research program and the real geothermal problems, and to interpret the research results for industrial utilization.

Finally, the fifth phase of the program will be to correlate the results obtained in all previous phases, and develop an analysis and design procedure usable by industry. The literature, field, and laboratory data will be analyzed and meshed into improved correlations that are specifically adaptable to the geothermal situation.

B. The Two-Phase Flow Problem

The initiation of the two-phase flow regime in a geothermal well has already been described in Chapter I. To design a geothermal well, it is necessary to be able to predict the total pressure drop as a function of fluid flow rates, physical properties, and line diameter. The total pressure drop is the sum of three terms: the frictional pressure loss, the loss due to gravity, and the loss due to acceleration, as shown below:

$$\Delta P = \Delta P_f + \Delta P_g + \Delta P_a \quad (1)$$

The magnitudes of these three terms cannot be predicted on the basis of experience with single phase flow systems. They depend strongly on the flow pattern or flow regime actually present in two-phase flow, the liquid holdup, and the interaction between the two phases at the gas liquid interface.

These factors were analyzed in great detail in the proposal, and reference is made thereto. They will be summarized here briefly. As the geothermal fluids flow up the well, the continually decreasing pressure

causes more and more steam to form. As the fraction of steam increases, the flow regime will change progressively, as shown schematically on Figure 1.

When the steam constitutes only a small fraction of the total fluid, the bubble flow regime will exist, in which the steam is distributed as small discrete bubbles. When the bubbles are very small, they will rise at approximately the liquid velocity and the flow pattern will be almost homogeneous. As the bubbles become larger when increased vaporization occurs at lower pressures, they will rise faster, agglomerate, and eventually form large bubbles. This finally results in a transition to the slug flow regime, in which large plugs of vapor separate slugs of liquid, and the liquid is propelled upwards at the high velocities characteristic of the gas phase. This is potentially a mechanically destructive flow situation.

As the amount of steam and the velocity of the steam phase increase, some of the gas will break through the liquid slugs, and the annular flow regime is formed. All the liquid will now be on the wall in a thin film, and will be dragged upwards, in opposition to the force of gravity, by the shear forces at the interface caused by the fast moving steam. The interfacial shear force increases when additional steam is formed by flashing of the liquid; the increased force causes waves to form at the interface. Some of the liquid in the waves will be sheared off to form droplets carried upwards by the steam, giving the spray annular regime. At high enough steam velocities, essentially all of the liquid can be carried as droplets in the fog or dispersed regime. Even here, however, there will be continuous collisions of drops with the wall to reform a liquid film, from which droplets will be torn away again. That is, a dynamic equilibrium will exist.

BUBBLE

SLUG

ANNULAR

FOG OR DISPERSED

SPRAY ANNULAR

FIGURE 1. Flow Regimes in Vertical Flow

The actual flow rates at which the various flow regimes will exist depend strongly on the system parameters such as well diameter and fluid properties. In the pressurized geothermal well, for instance, the slug flow regime can be expected over a much broader range of quality (gas to liquid ratio) than in an air-water system at atmospheric pressure. It should also be noted that different investigators have described the flow regimes differently, and have sometimes subdivided the flow system into even more regimes. The system described here, however, is adequate to clearly identify the hydrodynamic mechanisms that are at work.

In a single geothermal well, several or all of the flow regimes may exist at various well depths. As the steam fraction increases up the well while the pressure is decreasing, the flow regime will evolve continuously as indicated on Figure 2. In most high flow rate geothermal wells it can be expected that all the flow regimes will be encountered, and that the dispersed regime will exist at the wellhead. For lower temperature, lower flow rate wells, it is possible that slug flow will exist almost throughout.

It can be seen that the frictional pressure loss due to two-phase flow will be a strong function of the flow regime and the liquid holdup, the latter being defined as the volume fraction of liquid within the line. (Because the gas will be moving much faster than the liquid, the liquid holdup in any section of the line will be greater than the volumetric fraction of liquid in the feed stream entering that section.) The holdup affects the average fluid density, and the average mixture velocity, both of which are significant factors in the frictional pressure loss. The flow regime, for its part, is a measure of the relative area of the

FIGURE 2 . Regime Transitions During Vaporization

gas-liquid interface within a section of the line, and therefore is a measure of the frictional pressure loss due to interfacial shear forces.

The pressure loss due to gravity is a major contributor to the overall loss in geothermal wells. Since this term is a direct function of the average fluid density, the liquid holdup is, here also, the determining factor.

Finally, the contribution of acceleration to the total pressure drop must be considered. This term is practically always negligible in single phase flow and in most two-phase flow systems. In the geothermal well, however, much of the liquid will change phase and attain the velocity of the gas phase. Depending upon the flow regime, the remaining liquid may also attain a very high velocity, even reaching the gas velocity in some cases. Thus, the acceleration term of equation 1 must be closely considered in the analysis of geothermal wells.

Several investigators have proposed correlations for calculating holdup and frictional pressure drop in vertical two-phase flow. In many cases, these correlating equations have been developed empirically, or on the basis of similitude analogies, without consideration given to the flow regime that exists at given flow conditions. In other cases, correlations have been developed on the basis of a model for one flow regime, but have then been applied, sometimes successfully, to other flow regimes. Even when the correlation is specifically intended for a single flow regime, it is difficult to verify the correlation because there does not now exist any reliable method of predicting what the flow regime will be in any given situation.

For the case of horizontal two-phase flow, Dukler*et al., have made a thorough evaluation of five correlations for frictional pressure drop that were widely used in 1963. The correlations were tested against the "best" 2,620 data points available from the literature. These data were grouped into several data sets according to line size and fluid properties. When the calculated pressure drop was compared to the measured pressure drop, the best correlation of the five had standard deviations that ranged from 10 to 50% for the various data sets. The least accurate correlation had values of the standard deviation that ranged from 200 to 5000%. These values are presented here to give an idea of the difficulties with accuracy that one could encounter when "pulling correlations out of the literature" to serve as a basis of design for industrial applications. A similar evaluation procedure has not been systematically applied to vertical two-phase flow data and correlations, in a manner that is applicable to the design of geothermal wells.

The design problem described so far has involved only the hydrodynamic aspects of two-phase flow. The design of an actual geothermal well may be complicated by several other factors. The first involves heat transfer from the fluids within the well to the formations outside. In some instances of high heat removal rates from the outside of the casing, the rate of formation of steam by flashing could be significantly reduced as compared to an adiabatic well. The evolution of flow regimes and the pressure drop and temperature profiles within the well would be changed accordingly.

* A. E. Dukler, M. Wicks III, and R. G. Cleveland, "Frictional Pressure Drop in Two-Phase Flow--A Comparison of Existing Correlations for Pressure Loss and Holdup," AICHE J, 10, 38-43 (1964).

Other factors affecting well design are the result of gases and mineral salts dissolved in the geothermal liquids. The gases will be liberated at pressures above the saturation point of a brine containing no dissolved gases; that is, the bubble point of the brine is reduced. As a result of the release of gases, the two-phase flow region could be initiated in the well significantly before it would have been otherwise expected.

In addition, the liberation of some gases, especially CO_2 and H_2S , trigger certain chemical reactions within the liquid. For example, the pH increase in the liquid that accompanies the release of acid gases will result in the formation of carbonate ions in solution. The latter is very insoluble in the presence of calcium. Precipitates of calcium carbonate (CaCO_3) can then form, which may stick to the well casing and eventually plug the well.

The reaction sequence can be illustrated by the following set of equations.

Release of acid gases as the pressure is reduced:

Consumption of acid (H^+) ions as reestablishment of liquid phase equilibrium begins:

The reduced acidity shifts the equilibrium ratio between the bicarbonate and carbonate ions, so that more carbonate is formed:

The highly insoluble carbonate precipitates with calcium:

The above reaction sequence can be summarized by the following overall reaction:

Another factor in the design of a geothermal well for flashing two-phase flow is the concept of the maximum well diameter. In a single phase flow system, the flow rate can be increased for a given pressure drop by increasing the line diameter. This is not always true in a two-phase line. Refer to Figure 1, page 7, to the sketches of the annular and the dispersed flow regime. In these systems, the liquid is dragged up the well by the shear force of the steam flowing past either the film or the droplets. If the steam velocity were too slow (that is, if the well diameter were too large), this shear force would decrease and the liquid would fall under the influence of gravity, rather than continuing to rise. The liquid would then flood the well and production would cease.

The following sections describe the status of the various project phases. These are presented in the context of the project team member (DRI, UH, or Coury and Associates) that has primary responsibility for a particular phase.

III. LABORATORY TEST PROGRAM

The University of Houston has undertaken fundamental laboratory studies of vertical two-phase flow under the direction of Dr. A. E. Dukler. The responsibility of Coury and Associates with respect to this effort is twofold. The first is to provide continued liaison with and consultation to the Houston group to ensure that the fundamental studies provide data directly applicable to the practical geothermal problem. Secondly, the final results of the laboratory study will be interpreted and correlated in a form usable for geothermal well design.

It was determined early in the program that the critical factor for well design is the liquid holdup. This determination was made on the basis of hand calculations by Coury and Associates, and later, from more thorough computer calculations by UH, using existing correlations from the literature. Existing correlations predict significantly different values for the holdup. This is critical because of the effect of holdup on the gravitational pressure drop, the latter being the largest contributor to the overall pressure drop when in the bubble and slug flow regimes, and during the transition from slug to annular flow. On the other hand, when the flow regime is dispersed, or even annular, the direct effect of holdup is reduced. Furthermore, when the flow regime is annular or dispersed, the frictional loss should be less strongly influenced by the flow direction (vertical or horizontal) than in the case of slug or bubble flow. Thus, the correlations for frictional pressure drop that have worked so well in horizontal two-phase flow, such as the Dukler Case 2 correlation, should do as well in this situation. This consideration also indicates that knowledge of the holdup is more important than the need for new knowledge on frictional pressure loss.

On the basis of the preliminary analyses discussed above, recommendations for the laboratory studies have been developed in a straightforward manner. The first priority should be given to the determination of liquid holdup as a function of the principal system parameters. These include gas and liquid density, gas and liquid flow rates, and pipe diameter. The second priority should be given to the determination of the flow regime as a function of these same variables.

It would be too costly to duplicate geothermal conditions in a laboratory unit. Thus, the fundamental studies should be conducted on the basis of similitude, to permit extrapolation with reasonable accuracy from laboratory conditions to geothermal conditions. The basic tests could be made in a relatively small (2-inch diameter) pipe with air-water. Consideration should be given to conducting some supplementary tests with a higher density gas so as to approach the density of geothermal steam, and with a larger diameter pipe.

IV. INSTRUMENTATION AND WELL TESTING

It was determined early in the program that existing equipment for downhole measurements were not adequate to obtain the needed data. They were considered to be too costly and to have too long a delivery time and too low a reliability for measurements in wells at high flow rates. Even more important, however, were certain technical requirements. It was determined that real time measurements should be made, and that the time fluctuations in the measurements should be known. To meet these requirements, we developed a conceptual design for an improved downhole probe. DRI and Coury and Associates then submitted a supplementary joint proposal to ERDA for the additional funds required for the new probe. These funds were subsequently granted.

The new probe is under construction by DRI. Coury and Associates is responsible for reviewing the design drawings and the specifications of the sensors, and later for testing the overall assembly. The drawings and specifications are still under preparation and have not yet been received. When ready for testing, the entire assembly will be first run down a cold, non-geothermal well to test the overall system, including cable connector, cable, slip connectors on the cable winch, and recording equipment. This part of the test, as well as the subsequent geothermal runs, will be conducted in cooperation with the U.S. Geological Survey, who is supplying the cable, winch, recorders, and the truck and personnel that go with them.

The first series of geothermal well tests will be run on East Mesa Well 6-1 at the Bureau of Reclamation Test Site in the Imperial Valley, California. This well is about 8000 feet deep and is perforated over an interval of about 2000 feet, as shown on Table 1. The bottom hole

Table 1

CASING AND COMPLETION RECORD OF GEOTHERMAL WELL MESA 6-1
Geothermal Resource Investigations
Imperial Valley, California

Bit Size (inches)	Casing 1/ (O.D. Inches)	Depth 2/ Interval (feet)	Slotted Interval (feet)	Slot Size 3/ (length & width inches)	Perforated 4/ Interval (feet)	Perforation Size (dia. inches)	Open Area Per Lineal Foot 5/ (square inches)
26	20	0-380					
17-1/2	13-3/8	0-2503					
12-1/4	9-5/8	0-7292			*6809-6822	1/2	1.57
					6830-6846	1/2	1.57
					6888-6933	1/2	1.57
					6947-6968	1/2	1.57
					7020-7052	1/2	1.57
					7092-7150	1/2	1.57
					Total 185		
					**6131-6140	1/2	1.57
					6149-6164	1/2	1.57
					6168-6196	1/2	1.57
					6210-6248	1/2	1.57
					6251-6285	1/2	1.57
					6306-6327	1/2	1.57
					6340-6369	1/2	1.57
					6513-6520	1/2	1.57
					6556-6572	1/2	1.57
					6587-6593	1/2	1.57
					6614-6628	1/2	1.57
					6645-6661	1/2	1.57
					6699-6722	1/2	1.57
					6733-6746	1/2	1.57
					6755-6783	1/2	1.57
					6790-6808	1/2	1.57
					Total 331		
8-1/2	7	7262-8015					
			7341-7423	.25x2			16.0
			7465-7594	.25x2			16.0
			7635-7677	.25x2			16.0
			7723-7804	.25x2			16.0
			7890-7982	.25x2			16.0
			Total 426				

1/ All casings were cemented above the slotted section.

2/ Mesa 6-1 was drilled to a total depth of 8,030 feet. All depths measured from Kelly bushing which was 22 feet above ground surface.

3/ Slots are in an offset pattern 16 rows around the casing, 32 slots per foot.

4/ Perforations were made on January 16, 1974, 1/2-inch diameter holes at 8 holes per foot.

* Perforations were made on May 7-9, 1975, 1/2-inch diameter holes at 8 holes per foot.

5/ Total open area perforations 810.1 square inches, total open area slots 6,816.0 square inches.

temperature is just under 400°F. The well has not been produced for more than short periods at a time since it was last perforated, but it is believed that it will be able to produce somewhere between 300 and 500 gallons per minute of equivalent brine.

Flow tests will be made at each of several well flow rates, up to the maximum attainable. In addition, the wellhead pressure will be built up, and the flow rate reduced, until production ceases so as to determine the minimum stable flow. This latter test series will provide the data required to evaluate models and correlations for the minimum gas velocity at which liquid can be transported up a vertical line.

For each flow rate, the temperature and pressure profiles along the well will be measured as the instrument probe is lowered and raised again. The measurements will start well below the flashing zone in the all-liquid section of the well, and will extend to near the well surface. Time fluctuations of the pressure signal will be analyzed in an effort to determine the local flow regime.

During data analysis, temperature and pressure measurements will be correlated to help determine whether equilibrium exists between the gas and liquid phases. In making this correlation, care must be taken to account for the effects of dissolved salts and gases on the thermodynamic properties of water, and the accuracy of the sensors. In addition, the slope of the pressure curve can help determine the average fluid density as a function of the steam-liquid ratio, and thus, indirectly, the holdup. This cannot be done exactly, of course, because the pressure losses due to friction and acceleration must first be backed out of the measured pressure gradient, and these can be determined only on the basis of the correlations used.

It is expected that some modifications in the probe package will be suggested as a result of the first series of tests in the geothermal well. This would not be surprising, since the attempted measurements are quite complex and demanding, and the first of a kind. In particular, it is anticipated that two pressure sensors, spaced two to three feet apart in the probe assembly, might be shown to be desirable as a means of determining when slug flow exists.

In addition to the measured temperature and pressure profiles, several other measurements will be made for each run. These include the gas and liquid flow rates that will be measured with already existing surface equipment, and chemical analyses of liquid and gas samples taken at the surface. On the basis of these, an attempt will be made to reconstitute the composition of the bottom-hole liquid prior to flashing. To provide a double check on the surface samples, some all liquid samples will be taken out of the well from below the flashing zone. The liquid trapped within the sample bomb will tend to change composition as it is brought to the surface, because of chemical reactions that take place due to changes in temperature and pressure. To stabilize the solution, the bomb will be partially preloaded before each sample run with solutions of acid, base or other chemicals. The finalized sampling procedure has not yet been established, nor has the model of the sampler to be used been specified at this time.

The choice of the second and third wells for field testing has not yet been finalized. DRI has initiated conversations with San Diego Gas and Electric Co. about using one of their wells, and the response appears to be favorable. Some Colorado companies with near term drilling plans have been contacted about potential cooperation and, again, the response has been tentatively affirmative.

V. WELL DESIGN AND ANALYSES

This phase of the program is the primary responsibility of Coury and Associates. As has been previously indicated, a computer program is under development for two-phase flow calculations in geothermal wells. The current status of the program is discussed in Chapter VI.

The computer program is designed to have three reasonably distinct functions. Its first function will be to evaluate various correlations for holdup and frictional pressure loss that appear to be widely accepted in the two-phase flow literature. The correlations will be evaluated first on the basis of data taken from the literature. The evaluations will be repeated later, using data from the field tests of geothermal wells, and from the UH laboratory tests. The program is being prepared in modular form so that future revisions may be made with a minimum of effort. This feature will permit the rapid evaluation of other correlations that may be developed following the field and laboratory tests.

A second function of the program is to analyze well performance as a function of the correlation used. The analysis will show how the predicted performance of a well could change when the correlating equations for two-phase flow are changed. This analysis will thus focus on the critical aspects of the correlating equations by showing where small changes in input would lead to large changes in predicted results.

It is hoped that a best or, at the most, a few best correlations can be identified early in the program to reduce the number of parameters to be studied in later work. When the number of correlations to be studied has been reduced to the minimum realistic number, the well analysis will be continued to determine the effect of the various physical parameters on well performance. Among the parameters to be considered are

well depth, well diameter, bottom hole temperature, bottom hole pressure at flow conditions, and the concentration of dissolved solids and gases in the brine. The performance of a given well will be defined by the output curve of wellhead pressure as a function of total flow rate. These analyses will be made for each candidate correlation. The results of this analysis will demonstrate the sensitivity of well output to each of the significant variables for each set of correlations.

The third program function will be to provide a tool for the design of geothermal wells. To accomplish this, a set of parametric calculations will be prepared using the preferred correlations, and the results presented as easy to use curves or nomographs depicting well performance. It is expected that this family of curves will be done first on the basis of the best correlation taken from the literature. The curves would be refined later to incorporate any improvements to the correlations that are developed on the basis of the UH laboratory studies. If it becomes impossible to select a single "best" correlation, it may be necessary to indicate a range of values for the parametric curves.

The calculations described will be based on a specified value for the bottomhole pressure. The bottomhole pressure is not a constant for a given well, however. It will change as the flow rate changes, because of changes in pressure loss as the brine flows through the formation. It will also change with time as the formation is gradually depleted. Thus, in order to use the parametric curves to be developed here, it will be necessary to make an independent estimate of the bottomhole pressure based on reservoir data. It would be worthwhile at a later date to combine the two-phase flow program with a reservoir simulation program. This would provide a

general fluid simulator for the geothermal field, and would allow complete modeling of the reservoir and the production system in a single pass.

Its most valuable feature would probably be for predicting the long-range production from the reservoir, to determine in advance what its performance would be when it were partially depleted.

VI. STATUS OF COMPUTER PROGRAM

An integrated program that is complete in an operational sense has been prepared, but several branch subroutines are to be added to test other correlations and to refine the calculating procedures. This approach has been taken so as to have an operating program relatively early, while refinements and other two-phase flow correlations could be added later.

The program is almost operational. Most of the subroutines have been successfully compiled. Some additional debugging is required, but this appears to be minor. Several combinations of correlations for frictional pressure drop and holdup can be used. Physical property data are available for steam-water systems, hydrocarbon systems, and for other systems taken from the data bank, as is discussed in the following sections.

The computer program is being written in the Fortran IV, generation 21 language, and is being run on an IBM Model 370/145 computer. It should be usable with minor modifications with most other computers set up for the Fortran IV language. If it is necessary in the future to adapt the program for earlier generation versions of the language, any minor modifications that are required will be made.

A. Pressure Drop and Holdup Correlations

A large part of the pertinent literature has been reviewed and catalogued. A systematic analysis of the two-phase flow literature has not yet been made, however, because of the very large number of publications. Since most of the project members have long experience and a strong familiarity with two-phase studies, it was decided to proceed quickly on the basis of literature sources known to be pertinent and easily available. Additional

inputs of value, if any, will be added later, after the comprehensive literature search is made. The references currently being used for all phases of the work are listed in Chapter VIII.

Several correlations have been listed as candidates for evaluation as part of this study. Some of them have been programmed, while others are being added as the overall program becomes operational. Already programmed are the holdup correlations of Hughmark and Orkiszewski, the frictional pressure loss correlations of Orkiszewski, Dukler, and Martinelli, the flow regime correlations of Orkiszewski, and the minimum flow correlation of Dukler. These correlations are programmed to be used in various combinations, as shown on Table 2, where the reference citations are also given.

The Hughmark correlation was chosen because of its proven usefulness in several situations, even though it does not appear to have been used in other reviews of vertical two-phase correlations. It was shown to be the best correlation for horizontal two-phase flow by the extensive evaluation of Dukler et al. already cited (see footnote, page 11). However, it was originally developed for vertical two-phase flow. In addition, Hughmark reported in his original work that his correlation had a high accuracy for vertical steam-water systems over a wide pressure range of 15 to 2000 psi.

The Dukler Case 2 correlation was shown to provide the best measure of frictional pressure loss in horizontal two-phase flow in his review study already cited. In addition, a recent work by Wisman* has found the Dukler correlation to be suitable for vertical systems when checked against three

*R. Wisman, Appl. Sci. Res., 30, 367 (1975).

Table 2

Correlations Already Programmed, and Optional Calculational Groupings

<u>Holdup Correlation</u>	<u>Frictional Pressure Drop Correlation</u>
Hughmark ⁽¹⁾	Dukler Case 2 ⁽²⁾
Hughmark	Martinelli ⁽³⁾
Orkiszewski ⁽⁴⁾	Orkiszewski ⁽⁴⁾
Orkiszewski	Dukler Case 2 for Dispersed Flow Regime
Orkiszewski	Dukler Case 2 for All Flow Regimes

(1) G. A. Hughmark, CEP, 58, 62, (1962).

(2) A. E. Dukler et al., AICHE J., 10, 44, (1964).

(3) R. W. Lockhart and R. C. Martinelli, CEP, 45, 39, (1949).

(4) J. Orkiszewski, J. Pet. Tech., p. 821 (June 1967).

data sets. (These data sets are not easily available in the literature and have been requested from the author; it appears that at least one of them is for steam-water.) From another point of view, the high shear stress flow regimes of annular flow and dispersed flow should not differ much from the horizontal to vertical configuration. Thus, Dukler Case 2 should be suitable for these flow regimes in geothermal wells (where the annular and mist flow regimes should dominate) as well as in horizontal lines.

The Orkiszewski correlations have been shown to be reliable with oil well data. It has the advantage of tying together the work of several other investigators to provide a unified vertical flow model that covers all flow regimes. The Orkiszewski equations also are useful in that they provide a means for calculating the expected flow regime, as well as the holdup for that flow regime, within the same calculational framework. However, the data against which the Orkiszewski equations were checked included few tests in the dispersed and annular flow regimes. It was for this reason that it was decided to test a combination of the Orkiszewski and Dukler correlations as shown on Table 2.

Martinelli's correlation for frictional pressure loss is included because it is widely used, even though it was one of the first proposed. It was developed on the basis of an annular flow model, but is used for all flow regimes. Dukler's evaluation report for horizontal lines, previously cited, has shown the Martinelli correlation to be almost as accurate as his Case 2 model.

Other correlations are being programmed or under study for possible future programming. These include the correlations of Wisman, Beggs and

Brill, Duns and Ross, Hagedorn and Brown, Chierici et al., Poettmann and Carpenter, Baxendall and Thomas, Tek, Aziz et al., Fancher and Brown, and Hughmark and Pressburg. It is not expected that all these correlations will be programmed. Rather, the original works as well as other review works will be studied, and a selection will be made of those most likely to be suitable for geothermal applications.

B. Physical Property Data

The physical properties needed for the various correlations, and for analysis of geothermal wells, are the density of the gas and liquid phases, the viscosity of each phase, and the liquid surface tension. When heat transfer is also considered, the thermal conductivity and specific heat of each phase must be known. In addition, the thermodynamic properties must be known to calculate the mass ratio of gas to liquid for given values of pressure and total enthalpy.

The basis for the physical properties of the steam-water system are the ASTM Steam Tables of 1967, which were developed on the basis of correlating equations. These equations have been obtained in punched card form, and have been adapted to utilization with the IBM 370/145 computer being used in this study. The output of the adapted program has been carefully checked against values in the steam tables. The reproduction of values is highly accurate for all properties except the gas and liquid viscosities. Work is underway to determine the reason for these discrepancies.

The properties of pure water will be corrected for the dissolved salt content. Several references are being examined to determine the

best method for making these corrections. Some of these references were derived from the extensive research work on saline solutions by the Office of Saline Water. Others are the result of brine studies conducted by the U.S. Geological Survey.

The solubility of various gases and solids in the water must be known to determine gas release on the one hand, and precipitation of insoluble salts on the other. The data required to make these calculations have been pulled together mainly from the chemical processing and the geochemical literature. The programming now underway will be accurate for dilute solutions. It is not yet certain that accurate data for activity coefficients at high temperatures and high salt concentrations are available. It appears that it would be beyond the present scope of this project to refine the calculations for these conditions.

Much of the available data that most closely simulates geothermal conditions is for gas-lift oil wells. The exact composition of the hydrocarbons being produced is usually not available. Accordingly, empirical correlations taken from the literature have been used to calculate the physical and thermodynamic properties of hydrocarbon mixtures.

All of the reference sources alluded to in this section of the report are listed in the bibliography of Chapter VIII.

C. Data Base

The primary source of existing data is the two-phase data bank of Dukler et al., that was compiled in about 1963. An exhaustive search of the literature at that time yielded about 15,000 points for the

data bank, from several investigators. The data bank was recently updated by a group at the University of Calgary* and has been stored on a tape file for computer usage. The bank contains 28 sets of data for upwards flow in vertical lines. The range of data includes line diameters from 0.2 to 2.5 inches, and consists of air-water, steam-water, and air-organic liquid systems.

Several hundred data points for oil wells have been reported in the literature. Many of these points have been pulled together by Brill et al., at the University of Tulsa**, and will be used in our study, while others will be taken directly from the literature. The data set used by Wisman (previously cited) has been requested. Finally, data from the field tests with geothermal wells, and from the University of Houston laboratory tests, will be added to the data set.

* J. M. Mandhane et al., "Multi-Phase Flow Data Bank," University of Calgary June 1975).

** Personal communications

VII. FUTURE WORK

The work effort to be undertaken in the near term follows directly from the preceding discussion. Some of the tasks are summarized here. The computer program as it is now will be debugged and the correlations now programmed will be checked against data in the data bank. Other two-phase flow correlations will be added to the program. The data base will be extended to include other data from the literature and, later, from the well tests. The physical properties subroutines that calculate the effects of gases and salts dissolved in the liquid will be completed. The new instrumentation probe being fabricated at DRI will be checked out, and the well tests will be run. Liaison with the University of Houston program will continue.

VIII. RELATED REFERENCES

I. Analyses of Two-Phase Vertical Flow

A. Correlations for Holdup, Frictional Loss, and Minimum Flow

1. G. H. Anderson and B. G. Mantzouranis, "Two-Phase (Gas-Liquid) Flow Phenomena": "I--Pressure Drop and Holdup for Two-Phase Flow in Vertical Tubes," Ch. Eng. Sci., 12, 109-126 (1960).
2. _____, "II--Liquid Entrainment," Ch. Eng. Sci., 12, 233-243 (1960).
3. K. Aziz, G. W. Govier, and M. Fogarasi, "Pressure Drop in Wells Producing Oil and Gas," J. of Can. Pet. Tech., 38-48 (July, Sept. 1972).
4. C. J. Baroczy, "A Systematic Correlation for Two-Phase Pressure Drop," CEP Sym. Ser., 62, No. 64, 232-249 (1965).
5. P. B. Baxendell and R. Thomas, "The Calculation of Pressure Gradients in High-Rate Flowing Wells," J. Pet. Tech., 1023-1028 (October 1961).
6. H. D. Beggs and J. P. Brill, "A Study of Two-Phase Flow in Inclined Pipes," J. Pet. Tech., 607-617 (May 1973).
7. R. W. Brown, A. Gomezplata, and J. D. Price, "A Model to Predict Void Fraction in Two-Phase Flow," Ch. Eng. Sci., 24, 1483-1489 (1969).
8. G. L. Chierici, G. M. Ciucci, and G. Schlochhi, "Two-Phase Vertical Flow in Oil Wells--Prediction of Pressure Drop," J. Pet. Tech., 927-938 (August 1974).
9. A. E. DeGance and R. W. Atherton, "Chemical Engineering Aspects of Two-Phase Flow: Part 6--Vertical and Inclined Flow Correlations," Ch. Eng., 87-94 (October 5, 1970).

10. A. E. Dukler, M. Wicks III, and R. G. Cleveland, "Frictional Pressure Drop in Two-Phase Flow: B--An Approach Through Similarity Analysis," AICHE J., 10, 44-51 (1964).
11. A. E. Dukler, "Gas-Liquid Flow in Pipelines--Research Results," AGA-API, New York (1969).
12. G. H. Fancher, Jr., and K. E. Brown, "Prediction of Pressure Gradients for Multi-Phase Flow in Tubing," Soc. Pet. Eng. J., 59-69 (March 1963).
13. T. L. Gould, M. R. Tek, and D. L. Katz, "Two-Phase Flow Through Vertical, Inclined or Curved Pipe," J. Pet. Tech., 915-926 (August 1974).
14. G. W. Govier, B. A. Radford and J. S. C. Dunn, "The Upwards Vertical Flow of Air-Water Mixtures: I--Effect on Air and Water Rates on Flow Pattern, Holdup and Pressure Drop," Can. J. Ch. Eng., 35, 58-70 (August 1957).
15. G. W. Govier and W. L. Short, "...II--Effect of Tubing Diameter on Flow Pattern, Holdup and Pressure Drop," Can. J. Ch. Eng., 36, 195-202 (1958).
16. R. A. S. Brown, G. A. Sullivan, and G. W. Govier, "...III--Effect of Gas Phase Density on Flow Pattern, Holdup and Pressure Drop," Can. J. of Ch. Eng., 38, 62-66 (1960).
17. P. Griffith and G. B. Wallis, "Two-Phase Slug Flow," J. Heat Tran.-Trans. ASME, 307-320 (August 1961).
18. A. R. Hagedorn and K. E. Brown, "The Effect of Liquid Viscosity on Two-Phase Flow," J. Pet. Tech., 203-210 (February 1964).

19. G. F. Hewitt, I. King, and P. C. Lovegrove, "Holdup and Pressure Drop Measurements in the Two-Phase Annular Flow of Air-Water Mixtures," Brit. Ch. Eng., 8, 311-318 (1963).
20. G. A. Hughmark, "Holdup in Gas-Liquid Flow," CEP, 58, 62-65 (1962).
21. G. A. Hughmark and B. S. Pressburg, "Holdup and Pressure Drop with Gas-Liquid Flow in a Vertical Pipe," AIChE J., 7, 677-682 (1961).
22. R. W. Lockhart and R. C. Martinelli, "Proposed Correlation of Data Flow in Pipe Lines," CEP, 45, 39-48 (1949).
23. P. A. Lottes, "Expansion Losses in Two-Phase Flow," Nuc. Sci. and Eng., 9, 26-31 (1961).
24. R. C. Martinelli and D. B. Nelson, J. Heat Tran., Tr. of ASME, 70, 695-704 (1948).
25. U. J. Nicklin, J. W. Wilkes, and J. F. Davidson, "Two-Phase Flow in Vertical Tubes," Tr. Ins. Ch. Eng., 40, 61-68 (1962).
26. J. Orkiszewski, "Predicting Two-Phase Pressure Drops in Vertical Pipe," J. Pet. Tech., 829-838 (June 1967).
27. T. Oshinowo and M. E. Charles, "Vertical Two-Phase Flow: Part I--Flow Pattern Correlations," Can. J. Ch. Eng., 52, 25-35 (1974).
28. T. Oshinowo and M. E. Charles, "...Part II--Holdup and Pressure Drop," Can. J. Ch. Eng., 52, 438-447 (1974).
29. F. H. Poettmann and P. G. Carpenter, "The Multiphase Flow of Gas, Oil and Water Through Vertical Flow String," Drill. and Prod. Prac. API, 257-266 (1952).

30. N. C. J. Ros, "Simultaneous Flow of Gas and Liquid as Encountered in Well Tubing," J. Pet. Tech., 1037-1049 (October 1961).
31. M. R. Tek, "Multiphase Flow of Water, Oil and Natural Gas Through Vertical Flow Strings," J. Pet. Tech., 1029-1036 (October 1961).
32. R. G. Turner, M. G. Hubbard, and A. E. Dukler, "Analysis and Prediction of Minimum Flow Rate for Continuous Removal of Liquids from Gas Wells," J. Pet. Tech., 1475-1482 (November 1969).
33. R. Wisman, "Analytical Pressure Drop Correlation for Adiabatic Vertical Two-Phase Flow," Appl. Sci. Res., 30, 367-380 (1975).

B. Flow Regimes

(Many of the references of Section I-A are also applicable to this section.)

1. A. E. Dukler and Y. Taifel, "Flow Regime Transitions for Vertical Upward Gas-Liquid Flow," U. of Houston, Dept. Ch. Eng. (1976).
2. E. R. Hosler, "Flow Patterns in High Pressure Two-Phase (Steam-Water) Flow with Heat Addition," CEP Sym. Ser., 64, no. 82, 54-66 (1965).
3. M. Ishii and M. A. Grolmes, "Inception Criteria for Droplet Entrainment in Two-Phase Concurrent Film Flow," AIChE J., 308-318 (1975).

C. Flow Fluctuations and Instabilities

1. K. Akagawa, "Fluctuation of Void Ratio in Two-Phase Flow-- Report 1: The Properties in Vertical Upward Flow," Bull. of JSME, 7, 122-128 (1964).

2. K. Akagawa and T. Sakaguchi, "...Report 2: Existence of Small Bubbles in Liquid Slugs," Bull. of JSME, 9, 104-110 (1966).
3. K. Akagawa and T. Sakaguchi, "...Report 3: Distribution of Small Bubbles in Liquid Slugs," Bull. of JSME, 9, 111-120 (1966).
4. K. Akagawa, H. Hamaguchi, T. Sakaguchi, and T. Ikari, "Studies on the Fluctuation of Pressure Drop in Two-Phase Slug Flow": "Report 1--Experimental Study," Bull. of JSME, 14, 447-454 (1971).
5. _____, "Report 2--Theoretical Analysis," Bull. of JSME, 14, 455-461 (1971).
6. _____, "Report 3--Pressure Recovery Behind a Bubble and Lengths of Bubble and Liquid Slug," Bull. of JSME, 14, 462-469 (1971).
7. S. Jarvis, Jr., "Stability of Two-Phase Annular Flow in a Vertical Pipe," NBS Tech. Note No. 314 (1965).
8. P. M. C. Lacey, G. F. Hewitt, and J. G. Collier, "Climbing Film Flow," AERE Report R-3962 (January 1962).

D. Data and Evaluations of Correlations

(Many of the references of Section I-A are also applicable to this section.)

1. J. A. R. Bennett and J. D. Thornton, "Data on the Vertical Flow of Air-Water Mixtures in the Annular and Dispersed Flow Regions: Part 1--Preliminary Study," Tr. Ins. Ch. Eng., 39, 101-112 (1961).
2. J. G. Collier and G. F. Hewitt, "...Part II--Film Thickness and Entrainment Data and Analysis of Pressure Drop Measurements," Tr. Ins. Ch. Eng., 128-144 (1961).

3. A. E. Dukler, M. Wicks III, and R. G. Cleveland, "Frictional Pressure Drop in Two-Phase Flow: A--A comparison of Existing Correlations for Pressure Loss and Holdup," AIChE J., 10, 38-43 (1964).
4. J. D. Lawson and J. P. Brill, "A Statistical Evaluation of Methods Used to Predict Pressure Losses for Multiphase Flow in Vertical Oilwell Tubing," J. Pet. Tech., 903-914 (August 1974).
5. E. J. P. Browne, "Practical Aspects of Predicting Errors in Two-Phase Pressure-Loss Calculations," J. Pet. Tech., 515-522 (April 1975).
6. J. M. Mandhane, G. A. Gregory, and K. Aziz, "Multiphase Flow Data Bank," U. of Calgary (June 1975).
7. I. R. Vohra, J. R. Robinson, and J. P. Brill, "Evaluation of Three New Methods for Predicting Pressure Losses in Vertical Oilwell Tubing," J. Pet. Tech., 829-832 (August 1974).

II. Sonic Velocity in Two-Phase Flow

1. D. C. Card, G. E. Sims, and R. E. Chant, "Ultrasonic Velocity of Sound and Void Fraction in a Bubbly Mixture," J. Basic Eng., 93, 619 (1971).
2. R. E. Collingham and J. C. Firey, "Velocity of Sound Measurements in Wet Steam," Proc. Des. and Dev.-IEC, 2, 197 (1963).
3. D. F. D'Arcy, "On the Acoustic Propagation and Critical Mass Flux in Two-Phase Flow," J. Heat Tran., 93, 143 (1971).
4. V. J. DeJong and J. C. Firey, "Effect of Slip and Phase-Change on Sound Velocity in Steam-Water Mixtures and the Relation to Critical Flow," Proc. Des. and Eng.-IEC, 7, 454 (1968).

5. R. Eddington, "Investigation of Shock Phenomena in a Supersonic Two-Phase Tunnel," AIAA J., 66 (1966).
6. M. A. Grolmes and H. K. Fauske, "Propagation Characteristics of Compression and Rarefaction Pressure Pulses in One-Component Vapor-Liquid Mixtures," Nuc. Eng. Des., 11, 137 (1969).
7. Y. Katto, "Dynamics of Compressible Saturated Two-Phase Flow," Bull. JSME, 11, 1135 (1968).
8. F. J. Moody, "A Pressure-Pulse Model for Two-Phase Critical Flow and Sonic Velocity," J. Heat Tran., 91, 371 (1969).
9. G. Wallis, "One-Dimensional Two-Phase Flow," McGraw Hill (1969).
10. A. Wood, "A Textbook of Sound," McMillan (1930).

III. Heat Transfer in Two-Phase Flow and in Wells

(Some of the references of Section I-A are also applicable to this section.)

1. J. C. Bell, R. C. Crooks, et al., "Availability of Geothermal Energy for the Demineralization of Saline-Water," OSW Report R and D 27 (1959).
2. J. A. R. Bennett, J. G. Collier, H. R. C. Pratt, and J. D. Thornton, "Heat Transfer to Two-Phase Gas-Liquid Systems; Part 1--Steam-Water Mixtures in the Liquid-Dispersed Region in an Annulus," Tr. Ins. Ch. Eng., 39, 8 (1961).
3. C. E. Dengler and J. N. Addams, CEP Sym. Ser., 52, no. 18, 95 (1953).
4. S. A. Gaerrieri and R. D. Talty, CEP Sym. Ser., 52, no. 18, 69 (1953).

5. R. C. Hendricks, R. J. Simoreau, and R. V. Smith, "Survey of Heat Transfer to Near-Critical Fluids," NASA Technical Note TN D-5886 (November 1970).
6. J. G. Lavin and E. H. Young, "Heat Transfer to Evaporating Refrigerants in Two-Phase Flow," Preprint 21e, 52nd Nat. Meeting, AIChE (Feb. 2-5, 1964).
7. J. R. MacDonald, E. R. Stensaas, P. M. Stafford, and J. H. Cope, "Investigation of the Availability of Geothermal Energy for the Demineralization of Saline Water," OSW Report R and D 28 (1959).
8. H. J. Ramey, Jr., "Wellbore Heat Transmission," J. Pet. Tech., 427 (April 1962).
9. G. P. Willhote, "Overall Heat Transfer Coefficients in Steam and Hot Water Injection Wells," J. Pet. Tech., 607 (May 1967).

IV. Physical Properties and Thermodynamics of Solutions

A. Steam-Water and Brines

1. C. W. Burnham, J. R. Holloway, and N. F. Davis, "Thermodynamic Properties of Water to 1000°C and 10000 Bars," OSW Report R and D 414 (1969).
2. C. W. Burnham and H. L. Barnes, "Properties of Water and Aqueous Solutions at High Pressures and Temperatures," OSW Report R and D 383 (1969).
3. W. Drost-Hansen and L. Korson, "Viscosity and Conductivity Studies," OSW Report R and D 349 (1968).
4. A. E. Dukler, L. C. Elliot, and A. L. Farber, "Distillation Plant Data Book," OSW Special Report (January 1971).

5. B. T. Fairchild and C. S. Rhee, "Simulation of a Multistage Flash Test Module," OSW Special Report (February 1971).
6. W. R. Gambill, "Surface Tension for Pure Liquids," Chem. Eng., 169 (Feb. 10, 1958).
7. M. W. Kellog Co., "Saline Water Conversion Technical Data Book -- Issue No. 2," OSW Special Report (March 1965).
8. C. T. Liu and W. T. Lindsay, Jr., "Thermodynamics of Sodium Chloride Solutions at High Temperatures," J. Solut. Chem., 1, 45 (1972).
9. R. B. McClintock and G. J. Silvestri, "Some Improved Steam Property Calculation Procedures," ASME Paper No. 69-WA/Pwr-2, Annual ASME Meeting (Nov. 16-20, 1969).
10. C. A. Meyer, R. B. McClintock, G. J. Silvestri, and R. C. Spencer, Jr., "Thermodynamic and Transport Properties of Steam--(ASME Steam Tables), ASME, New York (1967).
11. R. J. Rariden, "Properties of Solutions," OSW Report R and D 685 (1971).

B. Solubilities of Gases and Dissolved Solids

1. S. Arnorsson, "Underground Temperatures in Iceland as Deduced from Silica Content of the Thermal Waters," Geothermics-Spec. Issue No. 2, 536 (1970).
2. I. L. Clifford and E. Hunter, "The System Ammonia-Water at Temperatures to 150°C and Pressures to 20 Atmospheres," J. Phy. Chem., 37, 101 (1933).
3. P. Cohen, "Water Coolant Technology of Power Reactors," (AEC Monograph), Chap. 6, p. 225: "Volatility of Boric Acid from its Solutions," (1969).

4. S. D. Cramer, "The Solubility of Oxygen in Geothermal Brines," Reprinted from Corrosion Problems in Energy Conversion and Generation--Bureau of Mines, 251.
5. D. D. Eley, "On the Solubility of Gases, Part 1--The Inert Gases in Water," Far. Soc. Tran., 35, 1281 (1939).
6. A. J. Ellis, "The Solubility of Calcite in Sodium Chloride Solutions at High Temperatures," A. J. Sci., 261, 259 (1963).
7. A. J. Ellis and R. M. Golding, "The Solubility of Carbon Dioxide above 100°C in Water and in Sodium Chloride Solutions," A. J. Sci., 261, 47 (1963).
8. J. L. Haas, Jr., U.S. Geological Survey Open-File Reports 75-674 and 75-675 (1975).
9. T. F. Hatch and R. L. Pigford, "Simultaneous Absorption of Carbon Dioxide and Ammonia in Water," IEC Fund., 1, 209 (1962).
10. H. G. Helgeson, "Thermodynamics of Hydrothermal Systems at Elevated Temperatures and Pressures," A. J. Sci., 267, 729 (1969).
11. G. C. Kennedy, "A Portion of the System Silica-Water," Econ. Geol., 45, 629 (1950).
12. D. W. Van Krevelen, P. J. Hoftijzer, and F. J. Huntjens, "Composition and Vapor Pressure of Aqueous Solutions of Ammonia, Carbon Dioxide, and Hydrogen Sulphide," Rec. Trav. Chim., Pays Bas, 68, 191 (1949).
13. J. Leyko, "Equilibrium Studies on the $H_2S-NH_3-H_2O$ System"; Part 1 (p. 275); Part 2 (p. 445): Bull. Acad. Pol. Sci., 12, (1964).
14. H. P. Meisner and C. L. Kusik, "Activity Coefficients of Strong Electrolytes in Multicomponent Aqueous Solutions," AIChE J., 18, 294 (1972).

15. L. B. Owen, "Precipitation of Amorphous Silica from High-Temperature Hypersaline Geothermal Brines," UCRL-51860, Law. Liv. Lab. (June 1975).
16. T. Ozawa and Y. Fujii, "A Phenomena of Sealing in Production Wells," Presented at U. N. Sym. on Geo. Resources, Pisa, Italy (1970).
17. T. T. C. Shih, B. F. Hrutfiord, K. V. Sarkanen and L. N. Johanson, "Hydrogen Sulfide Vapor-Liquid Equilibrium in Aqueous Systems as a Function of Temperature and pH," Tappi, 50, 630 (1967).
18. L. F. Silvester and K. S. Pitzer, "Thermodynamics of Geothermal Brines--I , LBL-4456, Law. Liv. Lab. (January 1976).
19. S. Sourirajan and G. C. Kennedy, "The System H_2O -NaCl at Elevated Temperatures and Pressures," A.J. Sci., 260, 115 (1962).
20. W. A. Stuart and A. R. Lister, "The Determination of Carbonate-Bicarbonate Ratios and Total Alkalinity in Treated Sea Water," Desalination, 8, 69 (1970).

C. Properties of Hydrocarbon Mixtures

1. J. N. Chew and C. A. Connally, Jr., "A Viscosity Correlation for Gas Saturated Crude Oils," J. Pet. Tech., 23 (1959).
2. J. A. Lasater, "Bubble Point Pressure Correlation," J. Pet. Tech., 65 (May 1958).
3. D. L. Katz, "Prediction of the Shrinkage of Crude Oils," API Drill. and Prod. Prac. (1942).

4. M. B. Standing, "A General Pressure-Volume-Temperature Correlation for Mixtures of California Oils and Gases," API Paper No. 801-23C, API Meeting (May 16-17, 1947).
5. "NGSMA Engineering Data Book," 2nd Edition, Tulsa, Oklahoma (1957).

V. Geothermal References--Flow, Sampling, Data, Etc.

1. Bureau of Reclamation, "Test Well Mesa 6-1," Special Report, Dept. of Int. (February 1973).
2. Bureau of Reclamation, "East Mesa Test Site--Status Report," Dept. of Int. (November 1974).
3. R. O. Fournier and A. H. Truesdell, "A Device for Measuring Down-Hole Pressures and for Sampling Fluids in Geothermal Wells," U.S.G.S. Prof. Paper 750-C, pages C146-C150 (1971).
4. T. L. Gould, "Vertical Two-Phase Steam-Water Flow in Geothermal Wells," J. Pet. Tech., 833 (August 1974).
5. J. L. Haas, Jr., "The Effect of Salinity on the Maximum Thermal Gradient of a Hydrothermal System at Hydrostatic Pressure," Econ. Geo., 66, 940 (1971).
6. J. H. Hill and C. J. Morris, "Sampling a Two-Phase Geothermal Brine Flow for Chemical Analysis," Preprint UCRL-77544, EPA Workshop on Sampling Geothermal Effluents (October 20-21, 1975).
7. L. E. Klyen, "A Vessel for Collecting Subsurface Water Samples from Geothermal Drillholes," Geothermics, 2, 57 (1973).

8. "The Klyen Subsurface Sampler," Advertising Brochure C1/SFB, Prodelco Eng. Ltd., New Zealand (September 1975).
9. P. A. Kryukov and E. G. Larionov, "Physico-Chemical Sampling of High Temperature Wells in Connection with Their Encrustation by Calcium Carbonate," U.N. Sym.-Dev. of Geo. Resources, Pisa, Italy (1970).
10. "Kuster Subsurface Instruments," Advertising Brochure 2M, Kuster Co., Long Beach, Calif. (August 1973).
11. M. Nathanson, "Flashing Flow in Hot-Water Geothermal Wells," J. U.S. Geo. Survey, 2, 743 (1974).
12. A. H. Truesdell and K. L. Perring, "Geothermal Gas Sampling Methods," U.S. Geo. Survey, Open-File Report 74-361 (1974).
13. D. E. White, L. J. P. Muffler, and A. H. Truesdell, "Vapor-Dominated Hydrothermal Systems Compared with Hot-Water Systems," Econ. Geo., 66, 75 (1971).