TWO-PHASE FLOW IN GEOTHERMAL ENERGY SOURCES

Annual Report

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DISCLAIMER

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ABSTRACT

The purpose of this research program is to create a Design Manual for the design of geothermal production wells that operate in the two-phase flow regime. The team of the Denver Research Institute (contractor) and subcontractors Coury & Associates and the University of Houston are cooperating to achieve this purpose.

The role of the Denver Research Institute has included overall administration of the contract, acquisition and handling of two-phase flow data, contacts with other organizations, and development of a probe to measure pressure and temperature in geothermal wells with a precision not previously available, and in real time.

For performing the functions involved in placing the measuring probe in a well, the U.S. Geological Survey in Denver has agreed to employ the measuring probe in some of their geothermal test series.

The necessity to develop this measuring probe has delayed other portions of the program, but the probe is now almost ready for use, and a calibrating system has been constructed for the probe.

I. ADMINISTRATIVE REVIEW

A. Objectives of the Research

The objective of the proposed research program is to provide a Design Manual that will aid drillers of geothermal wells and designers of process plants for utilizing geothermal fluids to determine:

The preferred producing zone in which to complete the geothermal well;

The best well design, including the diameter of the producing stringer and allowable changes in diameter up the well;

Production techniques, whether by natural flashing two phase flow, stimulated two phase flow by injection of liquids or gases, or suppressed flashing flow by pumping or artesian methods;

Optimum wellhead temperature and pressure upon which to base the design of the energy conversion system on the surface;

Scaling potential due to CO_2 release and calcium carbonate deposition on the well casing, and the potential effectiveness of scale control by gas injection. The CO_2 injection technique was developed by Dr. Glenn Coury during an Office of Saline Water Program, wherein calcium carbonate scaling of heat exchangers was prevented during the desalination of sea water.

The methods outlined in the users' Design Manual will permit rapid parametric studies to be made of specific geothermal field discoveries as related to specific energy conversion systems. The parametric study is intended to permit the best design to be made in terms of the long range potential of the field and to assist in predicting the need to drill new wells to maintain production levels.

The Design Manual programs will also permit the analysis of the performance of new and existing wells to help determine the cause of problems and to suggest solutions. The manual will provide a means to determine the permeability and effective transmissivity of the entire producing zone attainable by a well as opposed to the limited determinations possible with existing well logging systems.

The Design Manual is to be prepared along the following work plan guidelines and accomplished in three phases:

Phase I: The preparation of a design code based upon best available current information and preliminary well tests, and based upon the determination of long range research and test needs. The preliminary design manual is to be developed at this time, and it will be updated later with the results of Phases II and III.

Phase II: The design and installation of a vertical, two-phase flow test unit for the development of basic data, and the laboratory test program will be accomplished in Phase II. This phase will also include the final field tests. Preliminary dissemination of results to users will take place at this time.

Phase III: Upgrading of design code and final dissemination of results to the users.

The overall proposed program will consist of a design study oriented toward actual needs, supplemented by university research aimed at filling specific gaps in the knowledge base of this system.

The essence of the program proposed here is that the results be usable and that they be used. Therefore, it is planned to bring potential users into the program as soon as is practicable. This will be accomplished by the presentation of papers, and by conducting a workshop and seminars. The workshop is particularly pertinent to the present discussion, for it indicates the approach that will be taken to make this a practical study.

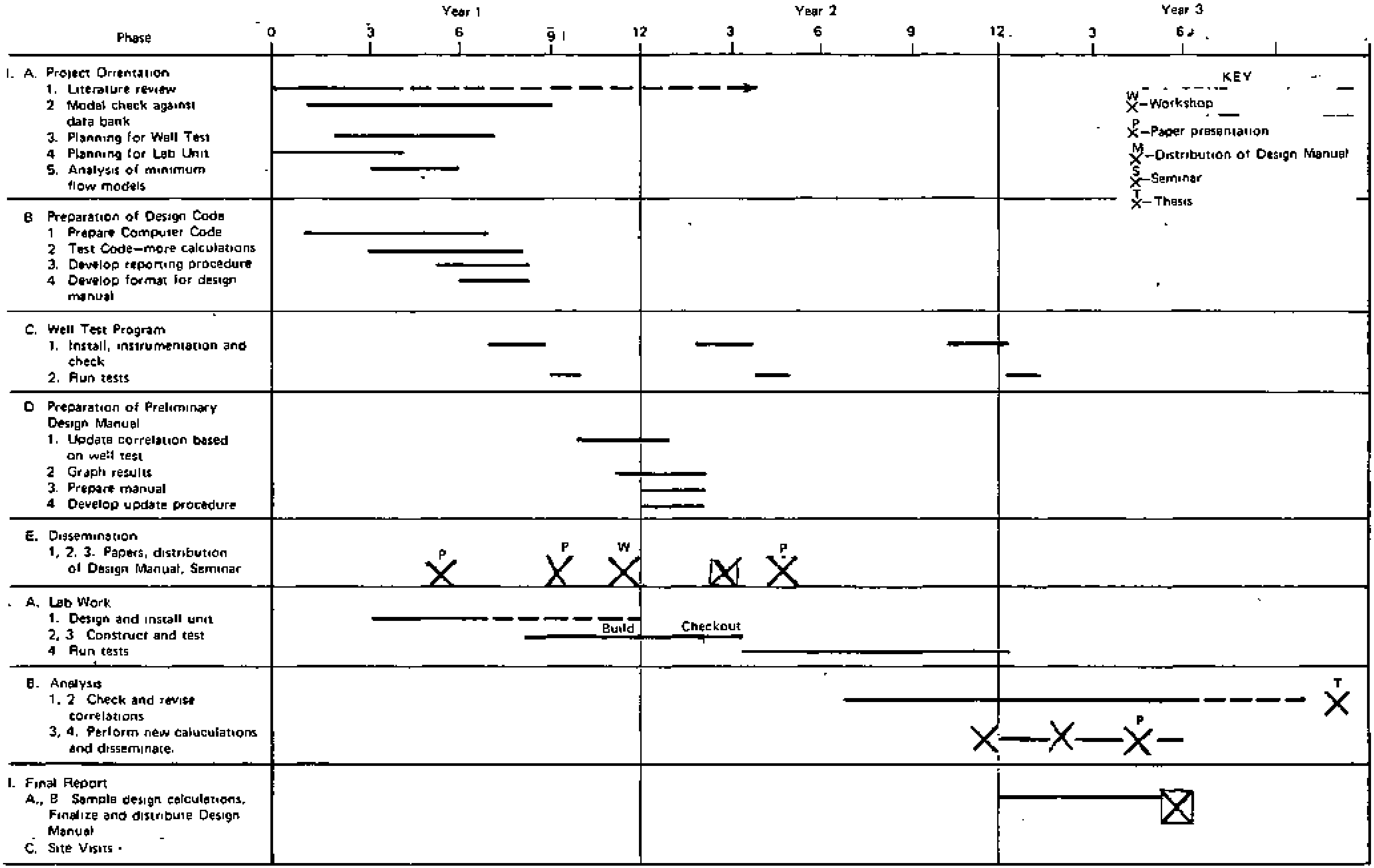
When the Phase I study is well along, and the principal results are in hand, a workshop is planned. It is anticipated that a small group of potential users, representing drillers, developers and plant designers, will be invited. The program will be presented to them and their reactions will be requested, and most likely recorded on tape, with the objective of developing the basic format of the Design Manual at that time. With this input, the Design Manual format will be one that is meaningful and practical to the user.

B. Contractual History of the Program

The proposal to perform the research described here was submitted to the National Science Foundation, Research Applied to National Needs (RANN) in October 1974, and a 3-year period of effort was envisioned. Early in 1975 this was revised to 30 months at the request of NSF, in view of pressing national energy needs. The revised program is enclosed here as Management Chart I. For the convenience of the University of Houston, an additional six months was projected in order to allow completion of a doctoral thesis.

The contract was signed on June 17, 1975, and the starting date was assigned as June 1, 1975. The subcontract with Coury & Associates was signed on August 13, 1975, after extended negotiations with the ERDA administrative offices in Chicago, and the subcontract with the University of Houston was signed on October 29 after even more extended negotiations. The last revisions required by the sponsor were mailed from the Denver Research Institute on November 13. On November 10, 1975, as a result of the considerations discussed in II.A below, a proposal was sent to ERDA from the Denver Research Institute together with a "Request for Supplemental Appropriation" to cover the costs of performing improved measurements, without additional research. Revisions based on the methods to be employed were introduced in the ensuing weeks, and the proposal was rewritten in its final form in January (letter of January 14, 1976, from Laurence W. Ross to Lawrence Ball).

At the end of the reporting period, this appropriation had been approved, but had not been received by the Denver Research Institute.



Management Chart I

II. CONTACTS WITH OTHER ORGANIZATIONS

A. Arrangements for Downhole Geothermal Measurement Capability

When it was realized in the summer of 1975 that conventional measurement techniques would not be adequate for the type of data required to create the design manual (see Section IV below), alternatives were immediately sought.

Technologies were identified which would permit the required measurements, but the capability for lowering the probes into geothermal wells was soon recognized as the limiting factor. The cost of a hoist or winch assembly and an armored cable with internal conducting wires was too expensive for the project's budget, and furthermore, it was believed that such a hoist-cable assembly might duplicate the existing or planned capability of other ERDA-supported agencies.

Commercial well-logging companies such as Schlumberger and Gearhart-Owen were willing to assist the project on a contract basis. In particular, Schlumberger would be able to provide logging support to the project at the East Mesa (California) geothermal field from their Bakersfield, California, office. However, the projected cost was quite high, on the order of $10,000 per week, and there was genuine doubt that the cables employed by Schlumberger could withstand geothermal temperatures.

The project personnel then identified two organizations which would be capable of lowering probes into geothermal wells under flowing conditions, i.e.,

U.S. Dept. of Interior
Geological Survey
Water Resources Division
Borehole Geophysics Research
(W. Scott Keys, Research Hydrologist)

Sandia Laboratories
Drilling Research Division
(M. M. Newsom)

Both these organizations are involved in measurements within geothermal wells, and both have expressed interest in cooperating with the Denver Research Institute.

After further discussions, the Denver Research Institute and the U.S. Geological Survey reached agreement on mutual cooperation in research whereby the U.S.G.S. would employ the DRI-developed probe in conjunction with some of their geothermal measurement series. The correspondence pertinent to this agreement includes:

> Letter of December 16, 1975, from Laurence W. Ross of DRI to Lawrence Ball of ERDA.
>
> Memorandum of February 26, 1976, from W. Scott Keys to Program Manager, Exploration Technology, ERDA, Geothermal Division.

Sandia Laboratories may cooperate with the Denver Research Institute in the future, when Sandia's advanced capability for downhole geothermal measurements is fully developed.

B. Contacts with Other Organizations Engaged in Geothermal Research and Exploitation

At the instigation of the sponsor and other organizations who have commented on the present program, project personnel have visited several universities, laboratories and industries who have been active in geothermal investigations, both in the laboratory and the field.

From these organizations, the project has gained valuable insights into questions affecting the immediate and future conduct of the research. For example, since the project is committed to perform three series of downhole measurements in geothermal wells, it is of interest to identify which wells (and which geothermal fields) are likely to be operational and available for measurements during the period of project activity.

The project has obtained useful information on the present status of geothermal production from the University of California; from Geothermal Kinetics, Inc., of Phoenix, Arizona; from Hydro-Search, Inc., of Reno, Nevada; and from Phillips Petroleum Co. of San Diego, California.

The project has obtained useful information on the present state of knowledge on phase equilibria and geochemistry from the Lawrence Berkeley Laboratories, and on the interactions of flowing steam-water mixtures from the University of California.

Looking forward to the necessity of performing downhole geothermal measurements in wells apart from those at the East Mesa field, as specified in the original proposal (pp. 39-40), project personnel have conducted extensive discussions with the parties responsible for development of the facility at Niland, California. This facility, which is owned by Imperial Magma Corp. and operated by the San Diego Gas and Electric Corp., with support from ERDA, consists of a complex plant designed for extraction of electrical power from a relatively hot (~ 500°F) geothermal source, with the geothermal fluid flowing in a two-phase (steam-brine) mode. The Niland facility has begun its announced program of preliminary flow tests, and has met with operational problems, but there is little doubt that the Niland facility will be one of the few wells in the U.S. that will be flowing on a more or less consistent schedule in the next year or two.

Discussions with Mr. Arthur Follett of ERDA, the San Diego Gas and Electric Company, and Imperial Magma Corp., have made clear that all parties at the Niland facility are interested in cooperating with parties such as the Denver Research Institute who desire to perform measurements in the flowing wells at Niland, especially insofar as such tests may benefit the facility by information obtained.

The discussions at Nialnd have revealed a significant and perhaps critical restriction in the application of the DRI-developed probe into a given geothermal well. The restriction is that, although most geothermal wells are six inches in diameter or more, the associated fittings that will accommodate test probes are smaller, usually three inches in diameter or less.

III. DEVELOPMENT OF DOWNHOLE PRESSURE-TEMPERATURE MEASUREMENT PROBE AND CALIBRATION ASSEMBLY

A. Introduction

The originally proposed program of research envisioned that measurements of pressure and temperature would be performed in static wells, and in wells producing at various flow rates, as a routine part of the data-gathering program is support of the subsequent correlations and analysis.

By the fall of 1975 (i.e., 3 months after project initiation) it had become apparent, on the basis of assessment by the contractor and by Coury & Associates, Inc., that the conventional techniques of pressure and temperature measurement in geothermal wells would not be sufficient to provide data of the accuracy required for the analysis anticipated by the proposed research program.

These "conventional techniques" consist of mechanically driven pens that record a trace on a brass foil as a function of the relative expansion of a bourdon tube. The principle is used to record both pressure and temperature. The objections to the use of this type of measurement probe are as follows:

1) Real time measurements cannot be obtained, and therefore the actual hydrodynamic mode of the mixed fluid cannot be evaluated (e.g., slug flow, bubble flow, etc.).

2) Reproducibility is questionable, particularly in pressure measurements at the higher temperatures. Some users have found that a temperature of 500°F induces weakening of the drive springs within the mechanism, and performance is altered permanently.

3) A time delay of several minutes is required to warm (or cool) the probe to each new temperature.

These considerations led the investigators to analyze the present-day state of pressure and temperature measurement technology, in search of devices to measure temperatures up to 500°F and pressures up to 3,000 psia. It was soon apparent that the well-logging industry has an upper limit of about 300°F, due to the fact that their instruments, packers, and cables employ insulating and constriction materials that will not withstand higher temperatures. Therefore it was decided to use probes to generate electrical signals downhole, and to transmit these signals to the surface via a cable where they would be conditioned and recorded.

In the use of such probes, it was recognized that calibration would be necessary. Therefore a calibrator assembly was anticipated to be constructed by the Denver Research Institute, with its own temperature and pressure measurement capability.

With these considerations in mind, the Denver Research Institute sent a "Request for Supplementary Appropriation" attached to Proposal No. MC7617, letter of November 10, 1975, from Laurence W. Ross to Mr. Morris Skalka of ERDA, and this request was subsequently approved.

At the end of the reporting period, both the probe and the calibrator were constructed, but the pressure transducers were not completely calibrated.

B. Pressure and Temperature Probe

For measurement of pressure, the bourdon tube principle was believed to offer the best promise of reliability plus accuracy. Therefore a potentiometric type transducer was specified for service at conditions up to 500°F and 3,000 psia in a hydrogen sulfide-containing environment. Gulton Industries, Inc., was the only vendor among those contacted who was responsive. Therefore the order was placed for a Gulton Industries Model 2091 unit, consisting of an Inconel helical bourdon tube, with specifications of ±1% static error band (full range) and a temperature coefficient of 0.012% per degree Fahrenheit of full range. The static error includes effects of nonlinearity, hysteresis, frictional contributions, resolution and repeatability. The temperature effect can be calibrated out, and the pressure transducer accuracy is therefore approximately the static error band ($\pm$1% of full range).

Four transducers were ordered: two for service up to 500°F and 3,000 psia, and two stock transducers for service up to 350°F and 500 psia. The order was placed on December 29, 1975; delivery was taken on May 23, 1976.

For measurement of temperature, the platinum resistance principle was judged to offer the best combination of accuracy and simplicity. Four probes were ordered from the YSI Sostman Company, with specifications as follows: accuracy $\pm$1/3%, self heating coefficient approximately 20 milliwatts/°C in H_2O at 3 ft/sec, response speed about 5 sec in water at 3 ft/sec.

The body of the containing probe is an alloy steel tube 2 inches in external diameter. Figure 1 shows a scale drawing of the probe with all elements in place. The shape of the nose was suggested by the U.S. Geological Survey for minimum chance of hanging upon protrusions down the well bore. The cage was designed such that the outlet slot area exceeded the nose inlet port area, thus assuring flow-through under even low flows. In this drawing, the pressure transducer is shown at left, just ahead of the retaining wall. The cable head connector was purchased from Gearheart-Owen Industries. The probe is designed for use with a seven-conductor armored cable.

C. Calibrator Assembly

The calibrator body is shown in Fig. 2. The assembly is designed to hold the DRI probe in position such that its temperature probe is a fraction of an inch from a similar probe inserted through the flange at right. Pressure is fixed by an Ametek model T-30 dead weight tester, designed for use to a pressure of 3,000 psia in increments of 20 psia, with an accuracy of $\pm$0.1%

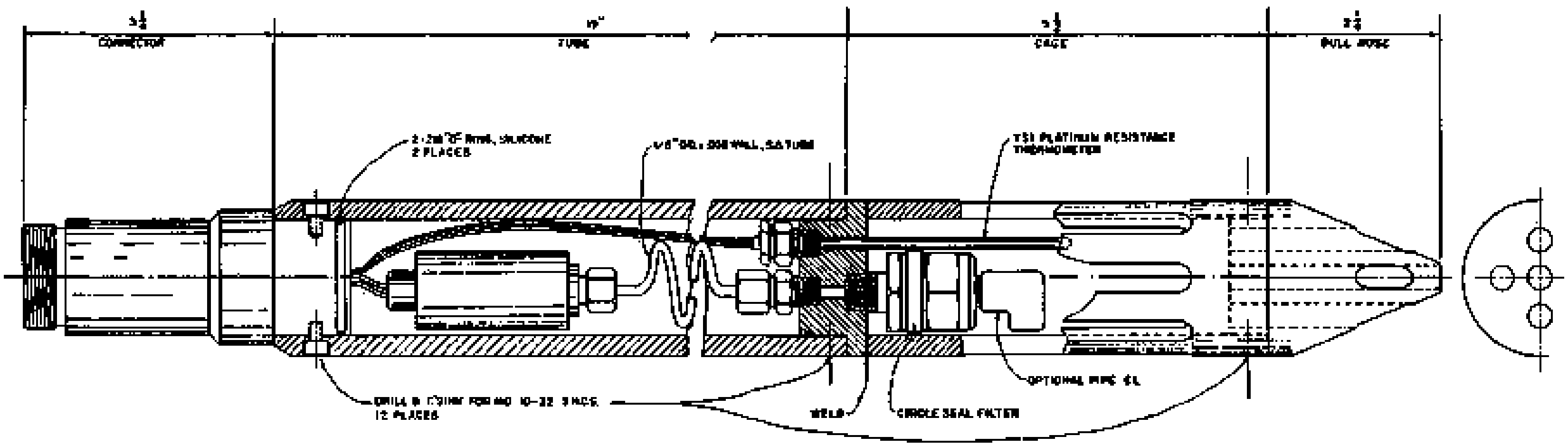

CONNECTOR
TUBE
CAGE
BULL NOSE
2 PLACES
YSI PLATINUM RESISTANCE
THERMOMETER
OPTIONAL PIPE ℄
12 PLACES
WELD
CIRCLE SEAL FILTER

Figure 1

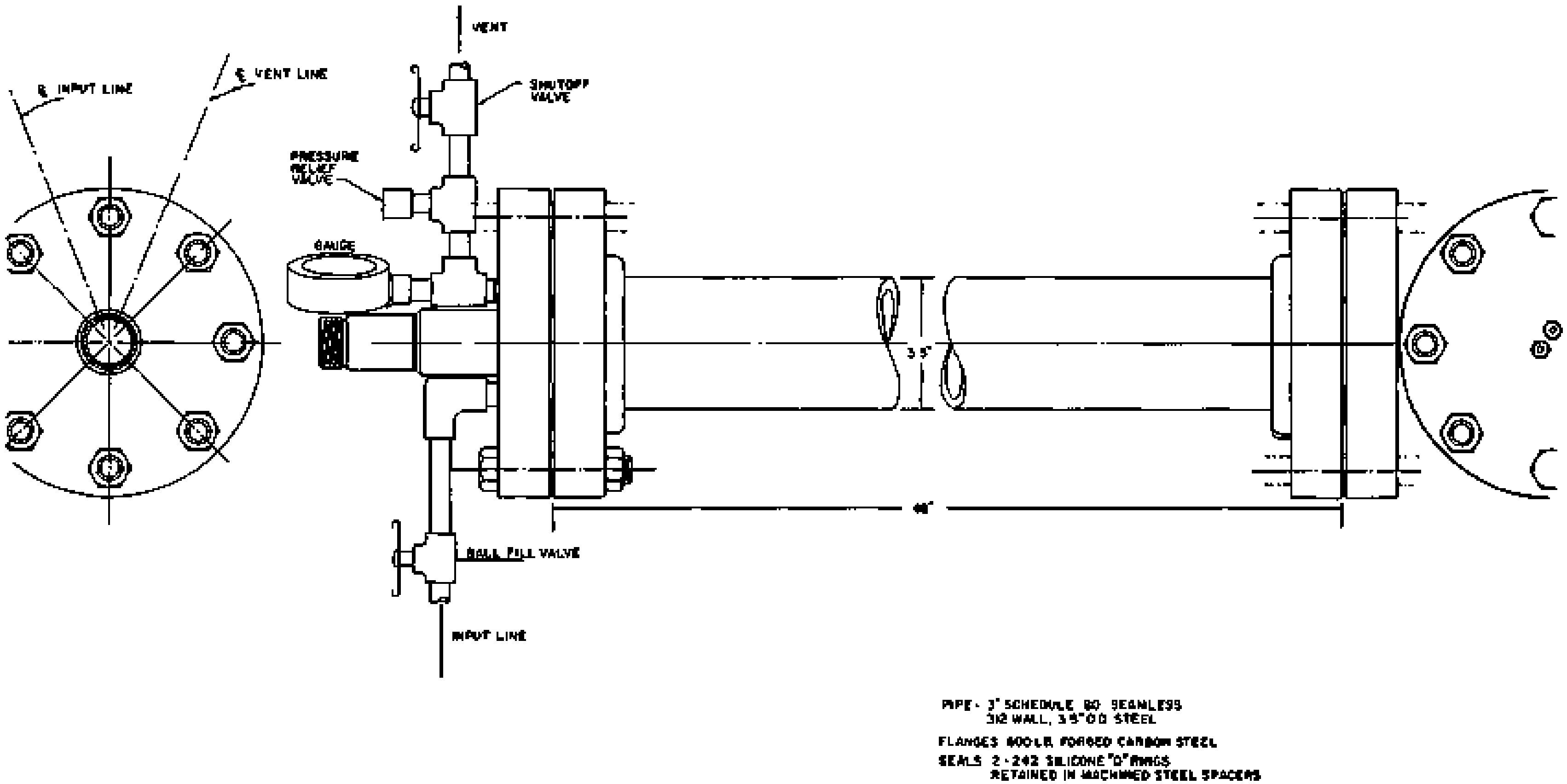

VENT
℄ INPUT LINE
℄ VENT LINE
SHUTOFF VALVE
PRESSURE RELIEF VALVE
GAUGE
3.5"
BALL FILL VALVE
INPUT LINE
PIPE - 3" SCHEDULE 80 SEAMLESS
.312 WALL, 3.5" O.D. STEEL
FLANGES 600 LB. FORGED CARBON STEEL
SEALS 2-242 SILICONE "O" RINGS
RETAINED IN MACHINED STEEL SPACERS

Figure 2

of output pressure. The dead weight tester is filled with distilled water. The calibrator is heated by a wrap-around Iso Tape heater rated at 2200 watts; it employs 110-volt power for convenience in field use. Temperature is controlled by a West Controller, model 405-R with a range of 100°F to 800°F. The design temperature of the calibrator is 600°F. Temperature is read with a Doric Scientific digital temperature readout, model 410A-PT-4-F. The calibrator assembly is fully insulated and has a heat-up time of about 1 hour to achieve 500°F.

D. Riser Assembly

When the probe is mounted on the cable, and any necessary sinker bars have been attached, the assembly is housed in a vertical section of pipe that is mounted on a tee that permits the probe to be inserted down the well. A valve is always required to isolate this vertical pipe, which is termed the "riser".

In the present program, since the Denver Research Institute is cooperating with the U.S. Geological Survey, it is anticipated that such a riser should be adequate to hold their probes, the largest of which is 4½ inches in diameter. In consulation with Dr. J. K. Sullivan of the U.S.G.S., a riser assembly was designed and purchased. It consists of the following parts:

3	10 ft sections of steel pipe, 6 inches in diameter, threaded at both ends
3	hammer unions to join the pipe sections
1	swage nipple to reduce the diameter at top
1	adapter
1	wire line pressure control device ("lubricator") to permit entry of cable into well

In the field, since each well features its own particular size of tee, an adapter will have to be used to mate the rise assembly with the flange of the tee.

IV. DATA ACQUISITION AND MANAGEMENT

The data bank of two-phase flow, which was created by Prof. A. E. Dukler at the University of Houston, is a key part of the investigation because it is an almost exhaustive repository of data on two-phase flow, including pressure drop, flow rates, holdup, and the associated physical properties and pipeline properties. Furthermore, the collection of literature associated with the data bank makes possible the acquisition of the original papers if these have been published in the open literature. A large quantity of the data in the data bank was obtained by unidentified private firms and is available nowhere else.

These data were believed to be valuable to the project as a means of checking the various two-phase flow models in the literature. Accordingly, the project personnel were to receive a copy of the computer tape upon which the data were recorded. However, this tape was available only from the University of Calgary, and an extended Canadian postal strike delayed its receipt until the final week of January 1976.

With the tape now available to the project, the data were transferred to a 9-track tape that was consistent with the operations of the Computing Center of the University of Denver. Then the vertical-flow data were extracted and transferred to another tape which became the master tape.

The raw data are considered unsuitable for direct use in evaluation of two-phase flow correlations, because the measured data from two-phase flow investigations are extraordinarily prone to fluctuations arising from the difficulties associated with blending the two fluids accurately and free of disturbances. This has led investigators to consider that such data must be culled in order to eliminate unreasonable data points. Dukler, et al, (1964) pioneered this culling technique, for the case of two-phase flow in horizontal lines.

Dukler identified several types of errors that occur in two-phase flow, and eliminated them systematically. His procedures cannot be applied directly to the present investigation because (1) he used graphical plots of all data sets to identify "blunder" errors, a very laborious task that was conducted by graduate students; (2) he rejected data where flow rates were determined by phase calculations rather than by direct measurement; (3) he analyzed the surviving data for the influence of bends and fittings; (4) he compared data of any two or more investigators who covered roughly the same range of conditions, and rejected the one with most scatter. This degree of sophistication is not available to the present program, because the detailed information is not included in the data tape.

After this culling procedure, Dukler and his coworkers analyzed the internal scatter of the surviving data, using a regression technique to generate the best fit of the function

$$\Delta P/\Delta L = f(W_L,\ Q_G)$$

where $\Delta P/\Delta L$ is the pressure drop per unit length of line, W_L is the liquid mass flow rate and Q_G is the gas volumetric flow rate. A sixth-power correlating function was generated, with a total of 28 empirical coefficients, since the number of terms in such a function (including cross-products) is

$$\sum_{n=0}^{6} (n + 1) = 28.$$

Unfortunately, the computer routine for achieving this task has been lost, and the Denver Research Institute is now attempting to find a correlating program that will achieve the correlation and generate an analysis of variance.

The problem is complicated by several factors, including the numerical magnitudes of the flow data (i.e., all below 1.0, as given by the tape). It may be necessary to employ assistance outside the campus of the University of Denver, in order to resolve the computational procedure.

Reference: A. E. Dukler, M. Wicks III and R. G. Cleveland, AIChE J. 10, 38-42 (1964).

V. PROBLEM AREAS AND PROPOSED SOLUTIONS

1. The principal problem of the project is to accomplish all its objectives within the time frame of 30 months. The specific objectives of the Denver Research Institute within the overall effort are largely those associated with organization of the complex intermeshing of technical programs, but the responsibility for development of the DRI probe while simultaneously organizing the combined effort has led to delays.

For example, a workshop or seminar cannot be organized until field tests have been conducted, whereas the field tests must wait upon the development of the probe.

Summarizing the management chart (Section I) and quoting from the original proposal (October 1974),

> The first year will be the most intensive, involving effort by all three participating institutions in the Phase I tasks of (1) project orientation and (2) preparation of the design code, i.e., the model...
>
> By the end of the first year, it is planned to have the well test program devised and some test results in hand.

It is clear that these objectives have not been met, and that the pause for the development of the DRI probe is a principal cause.

The solution of this problem clearly lies in accelerating those portions of the research that have been delayed by development of the DRI probe. A plan for progress in these directions will be implemented in June and July 1976.

2. An emerging problem is the shortage of suitable geothermal wells that can be used for measurements. A "suitable" well is one which has the following characteristics:

a) It is a flowing well that can be opened after a brief series of measurements have been conducted under non-flowing conditions, and which can be maintained in a flowing condition for several days.

b) It is representative of wells that are expected to contribute geothermal power in the foreseeable future of the industry.

c) It can be programmed into the schedule of the agency that performs the physical operations of measurement (e.g., the U.S. Geological Survey), within the constraints of (a) above.

A brief discussion of this emerging problem seems warranted. The proposed program envisioned that the first downhole measurements would be performed in East Mesa well no. 6-1. This well features a downhole temperature of up to 385°F, and a potential flow rate (100,000 lb/hr) that is somewhat low in comparison to what the geothermal power-producing industry anticipates as the economical minimum. At the end of the report period, the project had scheduled a series of measurements in well no. 6-1, beginning June 21, 1976, but several factors caused this date to be shifted. (At present, no firm date has been established). Meanwhile the severe environmental strictures that apply to the operation of geothermal wells in California pose some definite doubts that the East Mesa field will ever provide a "suitable" well. Meanwhile the geothermal facility at Niland, California, is of increasing interest because it is the first such facility in the U.S.A. to address some of the truly demanding problems of continuous power production from two-phase flowing wells, within the context of environmental protection.

Within the context of "suitable" wells, a minor but possibly limiting problem is the fact that most wells are designed to admit probes of 2 to 3 inches in diameter. Although the DRI probe is only 2 inches in diameter, the agency that performs the physical operations may desire to employ certain probes of its own that are much larger in diameter (e.g., 4½ inches), and such an agency may be uninterested in examining wells that do not permit admission of its complete series of probes.

The solution to this problem resides in awareness of the evolving situation in the geothermal industry, and readiness to respond rapidly when favorable situations develop.

VI. FUTURE WORK

Future work by the Denver Research Institute largely revolves around field application of the probe and coordination of the results produced by the subcontractors, eventually leading to production of the Design Manual.

In the field studies, DRI personnel will assist the project by interfacing the probe with the instrumentation of the organization which physically performs the field test (e.g., the U.S.G.S.). DRI will also assist the project by helping to ascertain the current state of availability of geothermal wells for testing.

DRI will assist Coury & Associates and the University of Houston with computations and preparation of correlations as required.

Dissemination of results will be an important activity in the next report period. A seminar is planned for late fall, and two papers will probably be prepared this year. The extent to which the project will interact with the newly formed Denver section of the Geothermal Resources Council is not yet clear, but the GRC will certainly be a major avenue for reaching the industry with the results of the project.

VII. BUDGETARY SUMMARY

The overall financial standing of the project at the end of the first year is summaraized in the attached graph.

A. Salaries and Wages

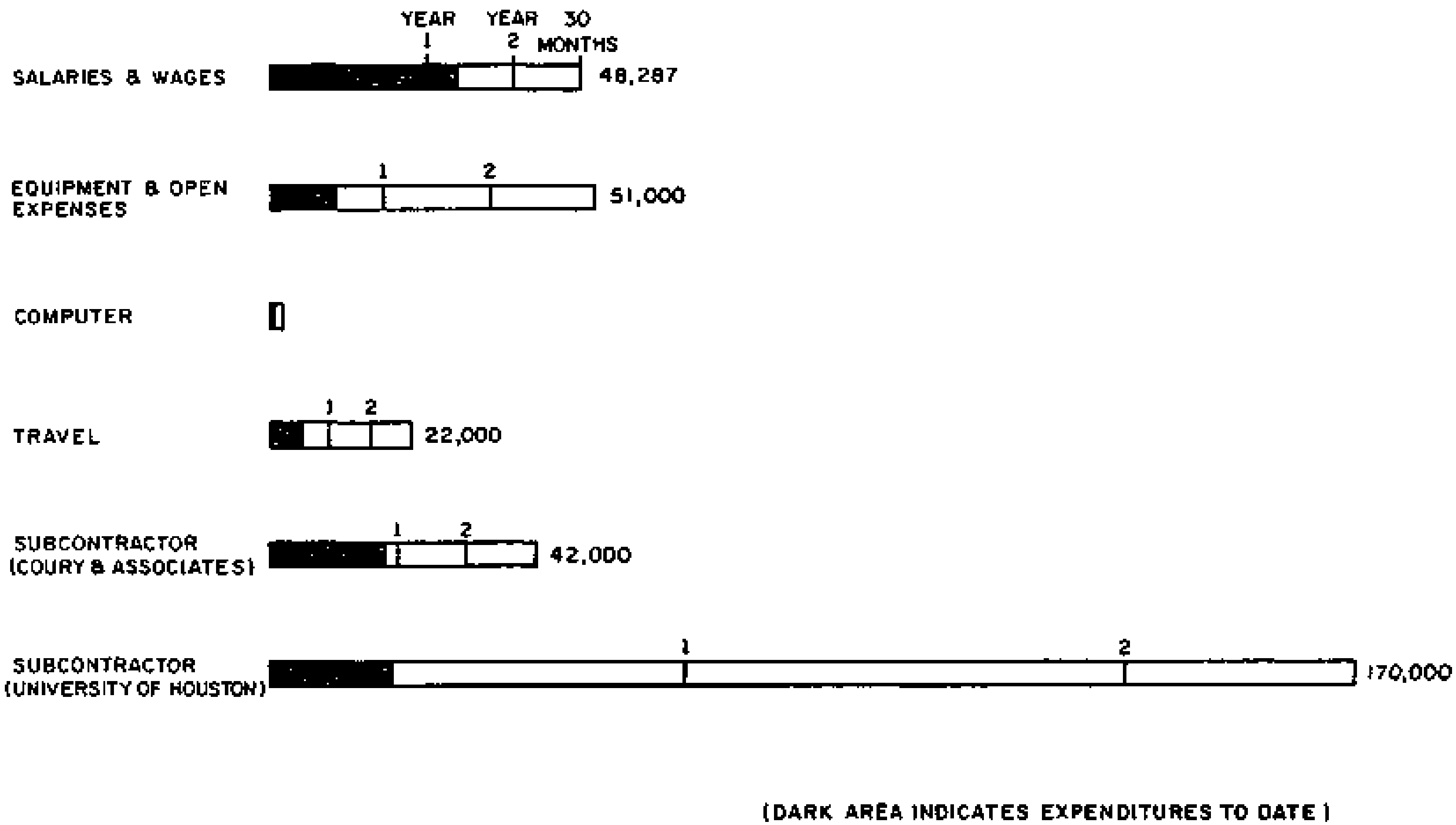
The project expended about $4,000 in excess of the allotment for the first year, or 18% above the budget amount of $24,270. This reflects the intensified effort that was expended to design and build the probe and calibrator assemblies. Although the supplemental appropriation for this purpose had not been received at the end of the reporting period, it was assured in late March, 1976.

B. Equipment and Expense

At the time of reporting the project had spent about $10,000 on equipment and open items of expense (as distinct from labeled items such as computer and travel expense). This leaves about $41,000, about half of which is intended for seminars. However, when the supplemental appropriation is added to the budget, $25,000 of this amount will be subtracted from the equipment budget as "credit", leaving about $16,000 to achieve the desired goals. This should be adequate, since a seminar held on the campus of the University of Denver will save a substantial amount. Computer expense seems adequate to achieve the project goals, and travel seems more than adequate.

C. Subcontractors

Coury & Associates had spent $17,910 at the end of the reporting period (43% of budget) and the University of Houston had spent $28,140 (17%).



SUMMARY OF FIRST YEAR EXPENDITURES CONTRACT NO. E(11-1)-2729