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IN SITU INSTRUMENTATION: FINAL REPORT OF A JOINT EE/ME GROUP STUDY

D. E. Lord

J. D. Salisbury

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Preface

The Joint Study Group benefitted from a wide sampling of persons participating, each interested in the measurements problem for in situ energy process development but from diverse viewpoints. Persons connected with the energy programs provided much-needed background information as well as specific measurement needs. Some of these persons, together with members of the engineering departments, also suggested instrumentation ideas that may meet these needs.

Because this study involved to varying degrees the efforts of over 50 people, no attempt was made to acknowledge them individually. Detailed technical reports supplied by some of the group members are referenced in this report, however.

Contents

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Abstract

Greater utilization of our fossil fuel and geothermal resources is vital to our future national economic well-being. However, the economic utilization of oil shale, some coal deposits and geothermal resources may depend on *in situ* processing. In turn, the optimal development of *in situ* coal gasification, oil shale retorting and geothermal energy conversion may depend on measurement and control of parameters critical to these processes.

This report summarizes a study to determine the measurements needed for each energy process and the kinds of instrumentation which, if successfully developed, could provide these measurements. Recommended instrumentation development, together with estimated development costs, are presented.

Introduction

The energy crisis has emphasized the need to use our fossil fuels more efficiently, develop all possible fossil fuel resources, and find new ways or improve old ways to harness nonfossil energy resources.

The development of *in situ* processes for utilizing otherwise uneconomical or unusable fossil fuel resources or to increase the utility of geothermal resources could improve our energy resource outlook considerably. However, the development of effective *in situ* processes will challenge our ability to determine, control, and optimize the critical process parameters. We will need suitable measurements to do this. The most critical measurements will be those in or near the reaction zone, and this need calls for *in situ* instrumentation capable of surviving the hostile environment and monitoring the essential process parameters.

It should be remembered that these in-place processes are several steps in complexity more difficult than those required for simply mining or surface removal of combustible substances. An underground process plant presents problems in measurement and control that no surface plant engineer or designer has ever encountered. It combines the worst process problems with the added criterion that measurement and control take place from a mile away – literally blind! Therefore future successes in *in-situ* processing will depend in large part upon the effectiveness of the measurement and control systems.

This document outlines in situ measurement needs and recommends research and development to establish feasibility of the proposed instrumentation systems to meet these needs. The development recommendations are the result of a five-month study made by the Joint EE/ME In Situ Instrumentation Group. The group consisted of a cross section of engineering and scientific personnel associated with the energy programs and with technical expertise important to the instrumentation concepts. The group addressed itself to the measurement problems of in situ coal gasification, in situ oil shale retorting, and geothermal energy conversion.

The following material covers the past practice for making in situ process measurements, present capabilities for providing these measurements, new concepts for improving our in situ measurements capabilities, and the Joint Study Group's recommendations and cost estimates for establishing feasibility of the instrumentation concepts.

Some of the measurement requirements that surfaced during the study can be filled with existing instrumentation. Emplacing these instruments in deep holes in a manner that will provide useful measurements, however, will require considerable design, laboratory, and field work.

Past in situ Measurements

Past in situ experimentation was done with only limited temperature and other underground measurements. Instead, the experiments depended heavily on aboveground measurements and post-experiment analysis of reaction products.

There are good reasons why only limited measurements were made in situ. The environmental conditions are severe because of high temperatures, reactive (either oxidizing or reducing) atmospheres, high pressures, and corrosive reaction products. Also, the measurements are hard to come by because of the remoteness or great depths of the measurables.

Despite these formidable obstacles there is a great need to understand in situ energy conversion process development and the associated critical parameters in order to optimize the processing techniques and provide the necessary guidance for future applications. As an example of a critical parameter, probably the most important and complex in situ measurement problem is definition or mapping of the coal gasification burn front.

Measurement Capabilities and General Needs

Well logging is an established capability for providing underground measurements of various types. It should be useful before a process is started, i.e. preburn, but it does not appear to be very useful after the coal or oil shale process is in operation. Therefore, future general needs require development of systems for:

- Most downhole measurements.
- Stand off measurements.
- Well-to-well measurements.

These systems should be generally applicable, as far as practicable, to all three energy programs.

Most downhole measurement systems need development because of the previously mentioned emplacement problems – great depth and severe environment. Thus, there appear to be no off-the-shelf measurement capabilities in in situ process development experiments. Even systems for simply measuring temperature in or near the burn front and reaction zone require careful engineering development.

Harsh conditions in the coal gasification experiment require very special materials to protect the measurements system. Temperatures range from 1000°C to perhaps 1700°C, in a strongly oxidizing atmosphere before the burn front and then a reducing one beyond. Furthermore, if the measurement system pierces the burn front it should do so without perturbing the process, e.g. without initiating a burn-front instability.

Hence stand-off measurements are preferable where possible. For example it appears possible to map the burn front by remote acoustic or electrical arrays. Resolution requirements, however, dictate placing the arrays as near as practicable to the measurables. Possibly these and other useful measurements can be made most effectively by well-to-well electrical or acoustic measurement systems in holes just outside the active zone.

Joint Study Group

The ad hoc in situ instrumentation study group was established last April to:

- Educate ourselves and communicate with energy-concerned persons.
- Identify measurement capabilities in house and elsewhere.
- Identify instrumentation needs that should be developed to support the energy programs.

The group identified measurement needs and possible instrumentation techniques for meeting most of these needs. Some of the less obvious ideas are explained in a following section and in greater detail in the references.

Recommendations for development to establish feasibility of the proposed instrumentation techniques are also contained in a later section together with cost estimates. Most, if not all, recommended instrumentation techniques are considered to be long term development challenges primarily because of the remoteness of the measurables and severity of their environment.

Because of this and the general lack of previous work on in situ instrumentation, the Joint Study Group concluded that development should be started as soon as possible. This is important not only because of the long term development requirements, but also in order to coordinate development with planned experiments and to take advantage of cost-sharing where possible.

Measurement Needs

COAL AND OIL SHALE

In situ measurement needs were found to be similar for both coal gasification and oil-shale retorting experiments, but the oil shale environment was considered to be less severe. The measurement needs include:

- Reaction zone temperature in 3-D.
- Burn-front location in 3-D.
- Burn-front instability detection.
- Gas pressure and distribution.
- Gas sampling and distribution.
- Horizontal stress at depth.
- Fracture progression/location.
- Permeability—gross and incremental.

Representative temperature profiles from the burn front through the reaction zone are important to an understanding of the process. However, the unknown perturbation caused by the measurement system's penetration of the active area, not to mention the expense of each temperature-sampling installation, suggests that these samples be kept to a minimum.

Burn front location in three dimensions would provide not only an indication of the reaction progression but also, if the method has adequate resolution capability, a warning of the development of an instability or localized high rate-of-burn progression.

Gas pressure and samples at various locations are important to process development and, as in the case of temperature measurements, should be made with a minimum of samples.

Horizontal stress, fracture progression and location, and permeability measurements are important preburn parameters. Stress is important to modeling and prediction of the fracturing process which in turn controls the degree of permeability. These measurements are needed to assure the desired uniform and adequate permeability.

GEOTHERMAL

The geothermal environment is generally less severe than those of coal gasification or oil shale retorting. The measurement needs include:

- Temperature at depth.
- Pressure at depth.
- Brine analysis — sampler.
- Flow velocity.
- Detection of reservoir flashing.
- Replenishment time.

The temperature and pressure sampling would be somewhat similar to the coal and oil shale systems but, because the medium is fluid, would require far fewer sampling systems.

The brine *in situ* sampler is a device for bringing a sample of brine to the surface and analyzing it with negligible change in its temperature and pressure. The sampler should permit optical analyses and visual observation. A means of extracting micro quantities of the sample without significantly affecting its environment is also desirable.

Flow velocity is an important measurement that presents a special challenge because the fluid consists of both liquid and vapor. In general these two phases will be flowing at different velocities and in variable proportions.

Instrumentation to detect reservoir flashing and the need to replenish reservoir fluid is also important to the geothermal process development.

Instrumentation Concepts

The Joint In Situ Instrumentation Group discussed various ideas for providing the above-mentioned measurements summarized below. In some cases, e.g. thermocouples and pressure transducers, the recommended development consists of solving the emplacement and survivability problems. In other cases, such as acoustic arrays, the concept needs development to establish its feasibility. To repeat, it was the Group's opinion that no existing instrumentation system was entirely suitable for in situ measurements of an operating energy conversion experiment. The remoteness and severe environment of the measurables requires at least special emplacement development of each system.

The following ideas evolved from the Group:

- Acoustic arrays.
  - Active.
  - Passive.
- Electrical techniques.
  - Low frequency resistivity.
  - Electromagnetic effects.
  - Probabilistic potential theory (PPT).
- Time domain reflectometry (TDR),
  - Electrical.
  - Temperature sensing dielectric.
  - Acoustic.
- Thermocouples.
- Pressure transducers.
- Geothermal brine sampler.
- In situ chromatography.
- High temperature electronics.

Acoustic arrays, both active and passive, and electrical resistivity together with the PPT interpretation technique should be useful for mapping the burn front and detecting burn-front instabilities for both coal gasification and oil shale retorting.

It appears practical to trace the progress of hydraulic fracturing as it occurs using a passive acoustic array. Post-fracture measurements, either electrical or acoustic or both, might also provide useful data on the extent of fracturing. For high-explosive fracturing post-shot measurements clearly would be essential. Pre- and post-fracturing electrical and acoustic measurements might also provide a useful correlation with the fracture-induced change in permeability.

Geothermal underground structure information can be obtained with acoustic and electrical techniques. Size and shape of geothermal reservoirs to depths of 3 km have been obtained using electrical resistivity measurements. Possibly flashing and the need for reservoir replenishment can be monitored by electrical means.

Time domain reflectometry or thermocouples can provide in situ temperature data, e.g. the reaction zone temperature profile at selected points in the active area for both coal gasification and oil shale retorting processes.

Pressure would be sampled at various depths, in coal gasification and oil shale retorting and would share the instrumentation hole with the thermocouples. Also, at these pressure sampling points, a small gas chromatograph could provide in situ gas analysis data for these energy conversion processes.

In the geothermal energy process, pressure samples vs depth could be continuously monitored in a manner similar to the coal and oil shale processes. Because of the fluid nature of the medium, however, probably fewer sample points would be needed both for temperature and pressure in situ.

A possible special need for the geothermal experimental work would be a means of analyzing reservoir brine under in situ conditions of temperature and pressure. The geothermal brine sampler would provide this capability. With this self-contained device, a sample of reservoir brine from a specified depth could be withdrawn for laboratory analysis without changing its original conditions of temperature and pressure.

High temperature electronics would be needed for in situ gas chromatography and possibly the geothermal brine sampler.

These ideas are described briefly in the following sections and in more detail in the references.

ACOUSTIC ARRAYS

Acoustic arrays[1] were considered by the In Situ Instrumentation Group as a means of mapping the coal gasification burn front. Burn front mapping is needed as an indication of the reaction's progress and for detecting the development of burn front instabilities. An area where the burn front progresses much faster than the average could, if allowed to persist, prematurely terminate the gasification process by shunting the input reactants directly into the output reaction products.

Figure 1 illustrates the idea of using a passive acoustic array of sensors to define and follow the burn front as it progresses through a coal seam. In this concept, which was suggested by Professor T. V. McEvilly, UC Berkeley, the heat from the burning process causes local fracturing of the coal just ahead of the burn front. The fracturing generates microseisms or acoustic impulses detectable by the acoustic sensors. By measuring the arrival time differences of an impulse at the various sensors, the impulse source can be determined by triangulation. The impulses would be generated at random times and we estimate that within a few hours enough impulses would be received to adequately define the entire burn front. This should make it possible to follow the burn front's expected 0.3-m/d progress. If the arrival times of the impulses can be measured to ± 2 ms, a spatial resolution of 1.5-3 m could be achieved.

Successful development of this scheme would not only provide information useful to the normal monitoring of the process, but also it would show the development of a burn-front instability and its location. Thus corrective measures could be instituted and, more importantly, the causative mechanism could be studied. This might make it possible to prevent the instability by suitable process control.

There is some experimental evidence supporting the feasibility of passive burn-front monitoring. Recent experiments

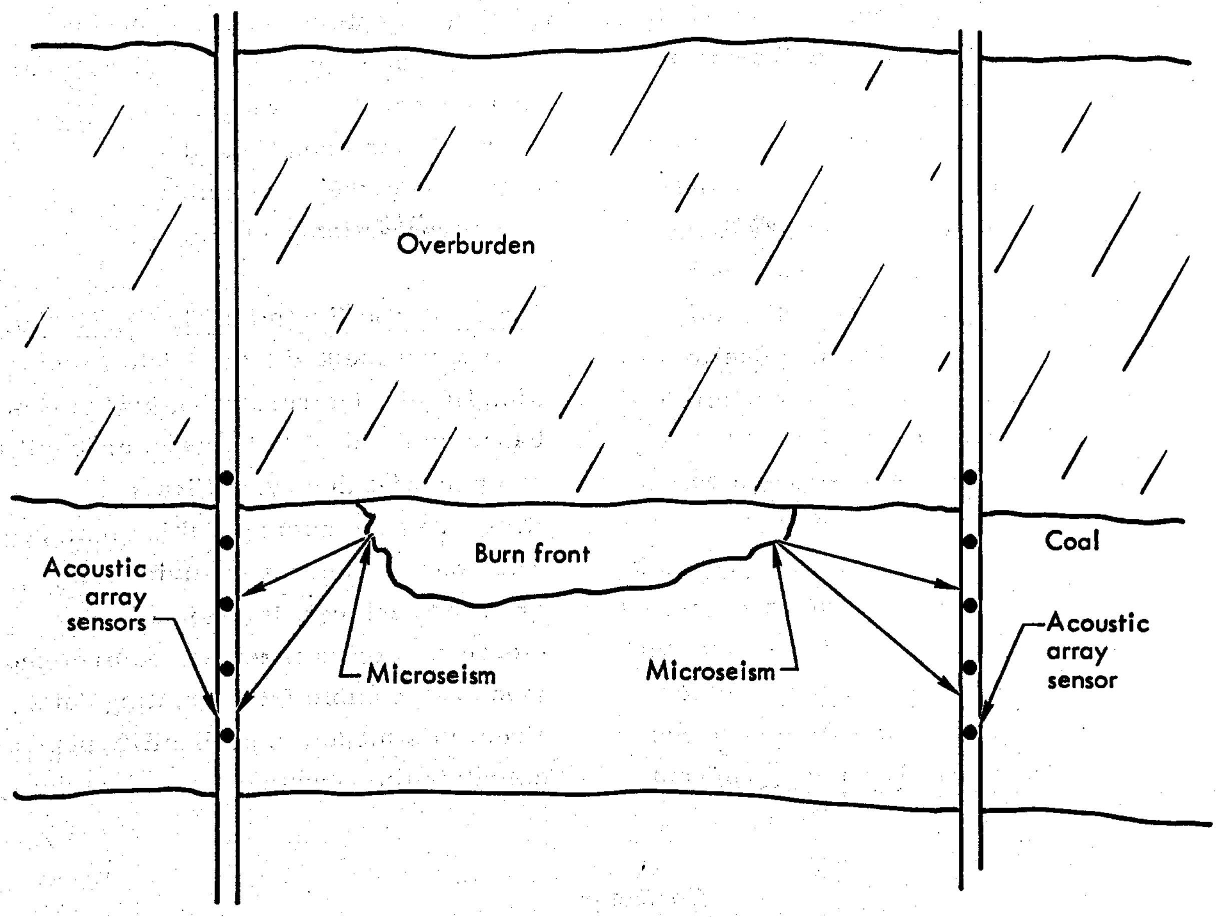

Fig. 1. Burn front location using passive acoustic arrays.

by the U. S. Bureau of Mines at Hanna, Wyoming were monitored by personnel of Sandia Corp., Albuquerque. They were able to hear the burn front and detected a few discrete noise pulses that correlated with the assumed burn-front location.

If for some reason the passive acoustic method proves unfeasible, an active acoustic method with an impulse source might be used to define the burn region. The change in acoustic impedance at the burn-front interface should be enough to produce strong reflections from the incident impulse. The arrival times of these reflections at the various acoustic sensors would provide data for defining the burn front.

On the whole, however, the active acoustic method is less attractive than the passive. It appears much more difficult to interpret the multiple reflections than the direct impulse from a single source.

Despite this apparent drawback, the active acoustic method should be amenable to useful interpretation, especially for the in-situ processes involving continuous use. In this case familiarity, i. e. comparing before and after pictures, provides a significant advantage.

ELECTRICAL RESISTIVITY

Electrical methods for geophysical prospecting, e. g. surface resistivity measurements, have been used extensively to determine certain types of subsurface structures.

The four-probe electrical resistivity technique shown in Fig. 2 is commonly used with various probe configurations. Current, I, is injected into the ground by metal electrode, A, and collected at B. The potential difference due to the current flow in the ground is measured by probes V_1 and V_2. From the values of V_1, V_2, and I, the resistivity can be determined.

As the spacing of the current probes is increased in this configuration the current penetration increases in depth. Thus the effects of deep features can be detected by wide probe spacings. In a homogeneous medium, approximately half the current is below a depth equal to the probe spacing. In the usual case the medium is inhomogeneous, however, making interpretation complicated. The following section describes a technique for easing the interpretation problem.

Probabilistic Potential Theory (PPT)

A novel method that should greatly simplify the interpretation problem is based on the duality between probability and potential theory.[2] Figure 3 illustrates the nature of this technique. The zone of interest is divided into a grid and each cell is assigned an electrical conductivity, σ, determined as much as possible from existing data. From this model, a probability number is calculated for each cell based on the

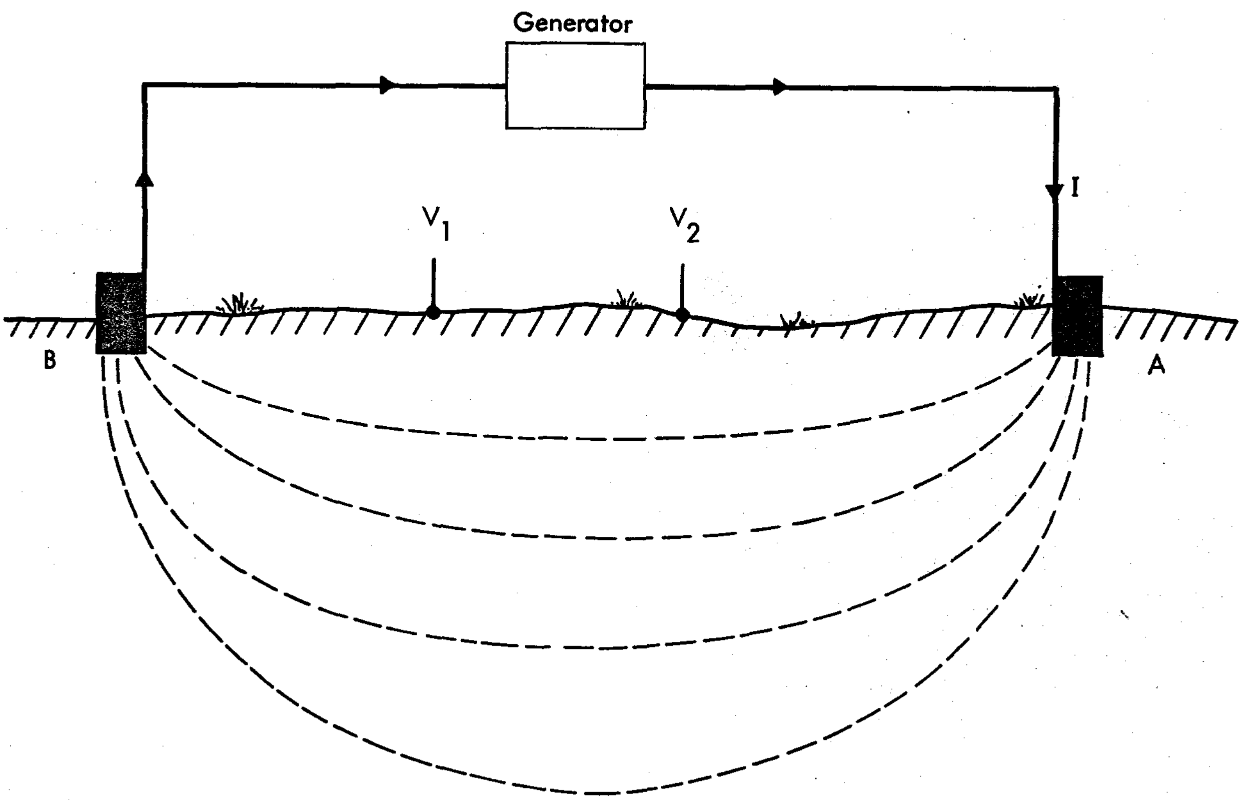

Fig. 2. Four-probe resistivity system for locating underground discontinuities.

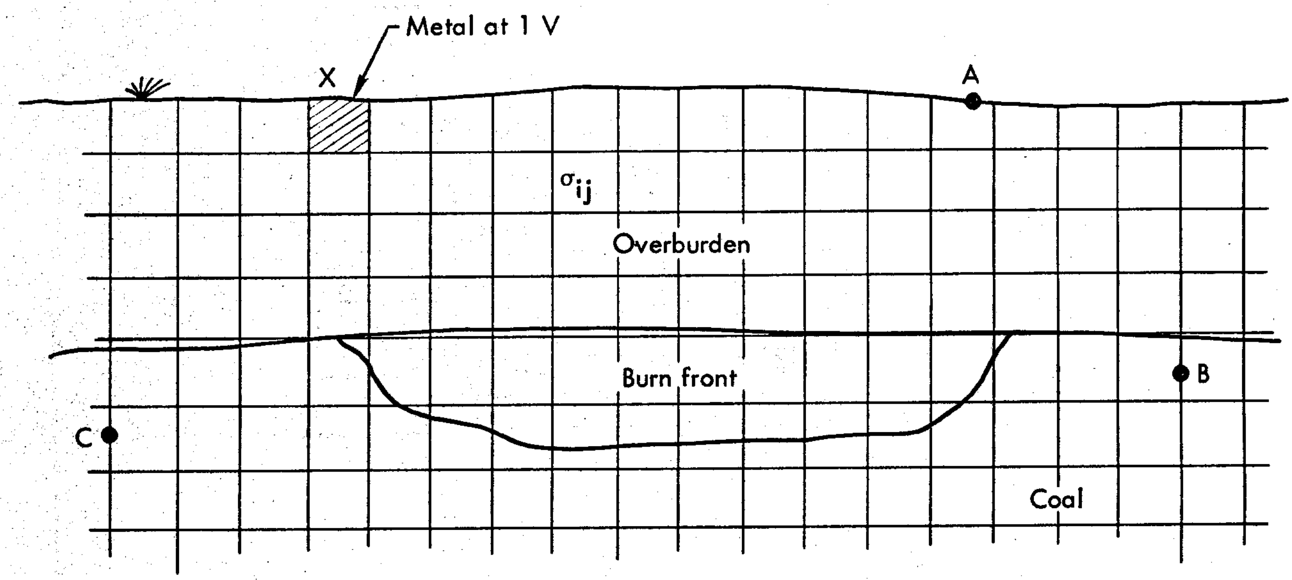

Fig. 3. Electrical method of locating the burn front using the probabilistic potential theory.

conductivities of the cell and its immediate neighbors.

From the grid or matrix of probability numbers, the potential at any point can be determined in a relatively simple way. The potential at a point is equal to the probability that a test particle starting at that point, for example A, will arrive at the 1-V electrode, X. Thus, if the probability of going from A to X is 0.2, point A is a potential of 0.2 V. The same procedure applies to points B and C. Although shown in two dimensions, the technique applies equally well to three-dimensional models.

The model can be refined by comparing the calculated potentials with the experimental data. Model improvement might be facilitated by using a suitable inversion technique.

High Frequency Electromagnetic Measurements

Electrical resistivity measurements are usually made with direct or very low frequency current, e.g. 20 Hz. Useful measurements also can be made with high frequency electromagnetic energy – typically in the region of 1-100 MHz. Even though propagation losses in most underground media are severe at these frequencies, good measurements can be obtained through media several hundred feet thick using only a few watts of transmitted power.

Figure 4 illustrates the experimental setup for subsurface electromagnetic measurements performed in the Brooks Range in Northern Alaska.[3] The measurements used the swept-frequency technique. In this manner, subsurface reflecting interfaces can be located by the constructive and destructive interference effects produced at the receiving antenna as the frequency is swept.

The experimental procedure consists of positioning one of the antennas, e.g. the transmitter dipole, at a fixed depth while varying the depth of the other

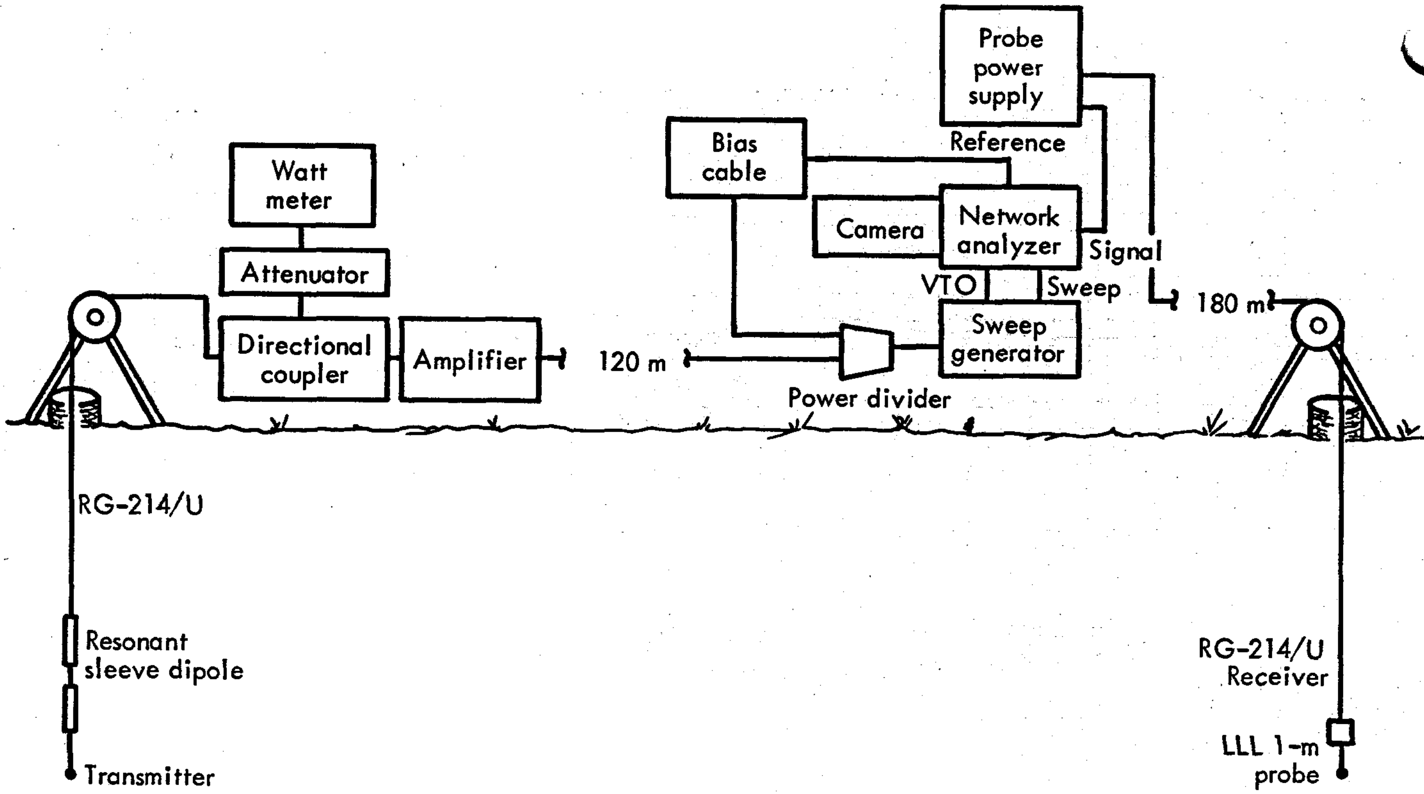

Fig. 4. Transmitter-receiver setup for the swept-frequency hole-to-hole experiments.

antenna in steps and sweeping through the useful frequency range at each step. Then this procedure is repeated, with the fixed antenna at a different depth each time, until the region of interest has been thoroughly covered. Reduction of these data can yield high frequency relative dielectric constant and conductivity figures as well as the subsurface geological features.

TIME DOMAIN REFLECTOMETRY (TDR)

Temperature can be measured in a variety of ways. For in situ measurements electrical TDR, acoustic TDR, and thermocouples were considered to be the most practical competing techniques.[4] At this time thermocouples appear to be easier, less expensive, and adequate for the needs. However, it seems premature to eliminate the TDR techniques from consideration, so they are described briefly in the following two sections. On the other hand it seems unnecessary to describe the thermocouple technique here; it is treated in Ref. 4.

Electrical TDR

Time domain reflectometry is widely used to locate discontinuities or anomalies in electrical transmission lines. In this technique, a narrow voltage pulse is transmitted. If the line is electrically uniform and properly terminated the pulse will not be reflected. If a discontinuity is present, however, part of the transmitted pulse energy is reflected and can be displayed on an oscilloscope. The time of arrival of the reflected pulse locates the discontinuity and the magnitude and shape of the reflected pulse give an indication of the size and character of the discontinuity.

To locate and measure temperature using the TDR technique, the transmission line characteristics must be temperature sensitive and, desirably, cause pulse reflections which are proportional to the magnitude of the temperature. In Fig. 5, the ceramic insulators are used as temperature-sensitive elements. At low temperature the ceramic has very high electrical resistivity and its presence causes only a slight capacitive effect. As the temperature increases, the resistivity decreases and the ceramic becomes less an insulator and more of a discontinuity. For example, zirconia with a stabilizer can exhibit a relatively smooth resistivity decrease of five orders of magnitude when heated from 300°C to 900°C.

As shown in the figure the largest reflected pulse is at the burn front, which indicates the highest temperature. The other two ceramic insulators are at lower temperatures and cause smaller reflections. The round-trip time of transmitted and reflected signals locates the depth of each reflection. The TDR technique for locating and measuring temperatures in situ is shown in Fig. 6.

Acoustic TDR

The acoustic TDR technique for measuring and locating in situ temperatures is similar to the electrical TDR technique. An acoustic waveguide, e.g. a solid rod, would be used, with acoustic impedance discontinuities or fiducials at the locations for temperature measurements as shown in Fig. 7. In this technique, however, the physical locations of the fiducials are known and essentially fixed, but the time-spacing of the reflections from these fiducials increases

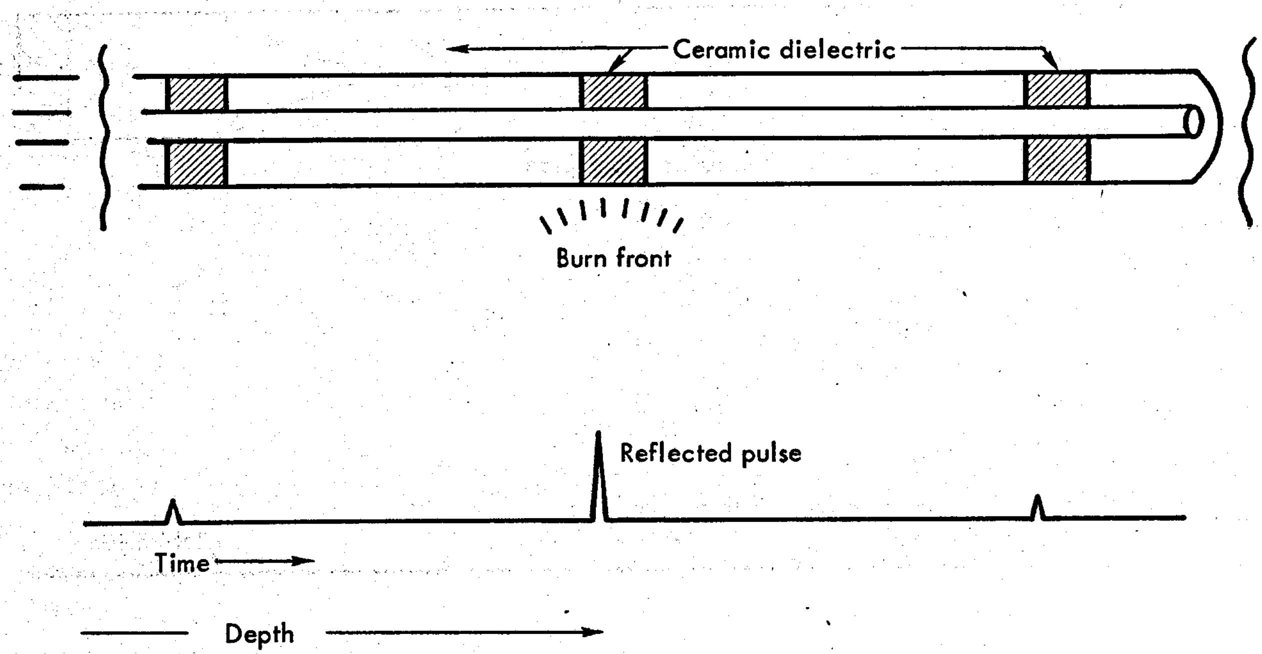

Fig. 5. Time domain reflectometry (TDR), electrical.

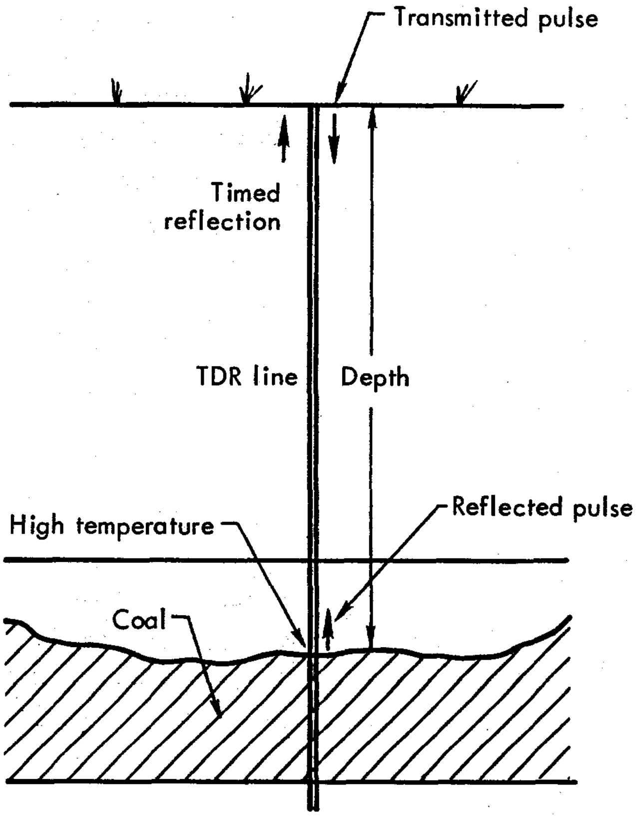

Fig. 6. Time domain reflectometry for locating and measuring temperature anomalies.

as the temperature increases because of a corresponding reduction in the acoustic velocity. Thus, the change in time between any two pulses can be used as an indicator of the average temperature change of the waveguide between the fiducials that produced these pulses. It should be noted that the temperature-caused elongation of the waveguide is small compared with the temperature effect on the acoustic velocity.

GEOTHERMAL BRINE SAMPLER

Development of geothermal energy resources requires analysis of the reservoir brine. Some of the analytical techniques require examining the brine sample at its in situ temperature and pressure conditions.[5] For example, dissolved gases are important and isotopic ratios of H, C, and O are valuable tools in tracing the source. If

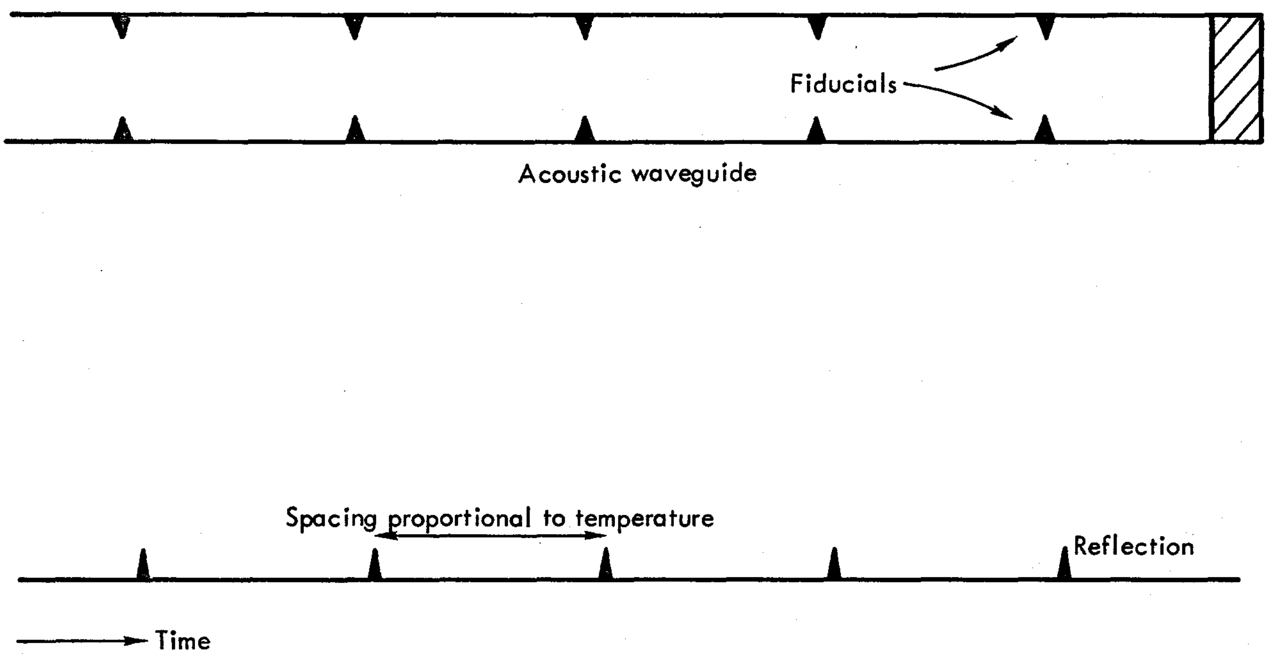

Fig. 7. Time domain reflectometry (TDR), acoustic.

the sample is permitted to boil, however, the dissolved materials might precipitate. Even if it were possible to redissolve them this could disturb the isotopic ratios and cause errors in source identification.

The geothermal brine sampler would hold the sample at its in situ temperature and pressure through its trip to the surface and during analysis in the laboratory. The principal features of the sampler are shown in Fig. 8. The sample tube is made of fused quartz to permit visual and optical analysis without changing the sample's original pressure and temperature. Temperature control is automatic and facilitated by the evacuated annulus which eliminates convective heat loss. Because of their shape, the ball valves introduce no pressure change on closing. Pressure is monitored by the strain gages but not controlled, since the ball valves should provide adequate seals.

The sampler connects to an automatic control and power supply assembly. The two parts, when joined, make up a completely self-contained automatic sampling package about 1.2 m long, 0.13 m in diameter and designed for pressures to 14 MPa (2 ksi) and temperatures to 450°C.

In use the sampler would automatically cycle itself at some predetermined depth, opening the ball valves to permit flushing and thermal equalization of the sample tube, closing the valves after a preset time, and actuating the automatic temperature control system.

IN SITU GAS CHROMATOGRAPH

A gas chromatograph is an instrument that separates and analyzes gases by differences in their surface adsorption properties. A small quantity of the material to be analyzed is injected into a stream of gas flowing through a long tube filled with a porous substrate. The rates at which components of the material drift down the tube depend on their differing affinities for the substrate material. Drifting at different rates, the components become separated and reach a detector at different times. Unknown compounds may be identified by their

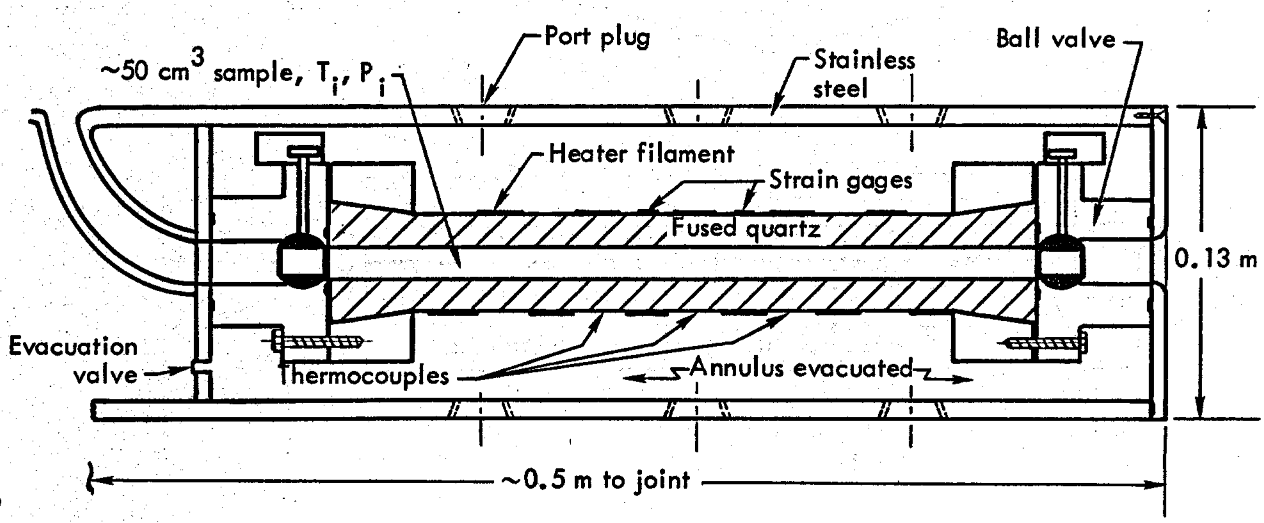

Fig. 8. Geothermal brine sampler.

characteristic times-of-arrival at the detector. Furthermore, the size of the detector pulse corresponds to the amount of material detected. Hence the analysis is both qualitative and quantitative.

For in situ analysis of gases it appears possible to make a miniature high temperature chromatograph.[6] Figure 9 gives an idea of the size attainable. With dimensions as shown, a 6.9-m column in the form of a spiral groove about 60 μm wide × 40 μm deep could be made. The groove would be chemically milled in silicon and covered by a bonded quartz plate. The unit with dimensions as shown would contain microvalving, filter, and detection electronics.

One of the most difficult aspects of this unit is making the column. To test our capability we etched a 2.1-m-long spiral groove in a 25-mm-diam silicon wafer.

HIGH TEMPERATURE ELECTRONICS

Some proposed in situ measurements require high temperature electronics in the measurement system.[7] The use of high temperature electronics for the gas chromatograph and the geothermal brine sampler was mentioned earlier. Other uses also could develop.

Generally, electronic packages can be produced using more or less off-the-shelf active and passive components that operate up to about 600°C. The dimensions of these components permit functional cylindrical packages of 50 mm or less diameter.

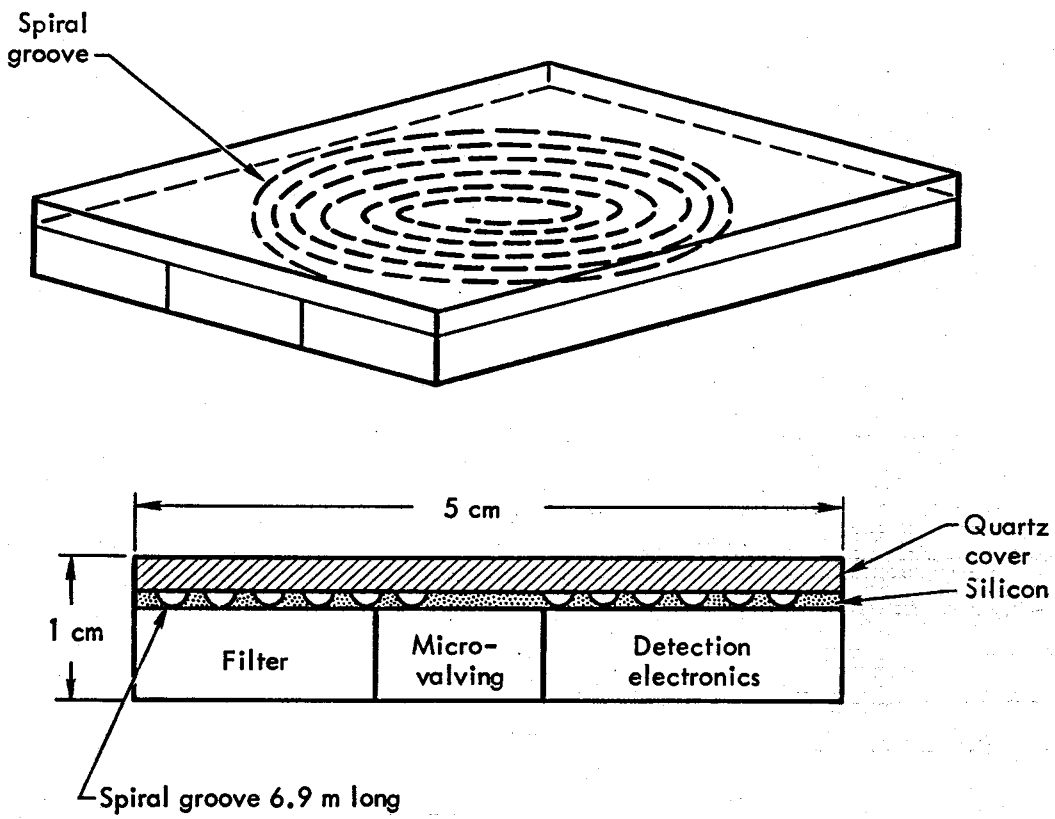

Fig. 9. In situ gas chromatograph.

One disadvantage of present-day high temperature electronics is that its active components are relatively bulky (about 10 triodes per cm^2 in. a plate less than 10-mm thick) electron tubes, rather than semiconductor devices. This limits the complexity that can be built into a given volume. Such tubes have the advantage, however, that we can fabricate them in house. We can therefore meet particular electronic requirements within a wide range of choices.

Given more lead time than needed for producing ceramic tubes, we also can develop semiconductor active devices that operate up to about 600°C using existing facilities. As a long range project, we can consider the development of electronic components that operate in the range 1000-2000°C.

Recommendations

Further study and development are recommended on:

- Acoustic arrays.
- Electrical arrays.
- Interpretation methods.
- Thermocouples or TDR.
- Pressure transducers.
- Gas chromatograph or sample tube.
- Brine sampler.

Although it appears that the thermocouple system should be used for temperature measurements, the TDR techniques are presented for further consideration. Similarly the gas sample tube appears to be more economical to develop than the chromatograph, but both are left for further consideration.

At this time development effort on both the electrical and acoustic array techniques is recommended. If the passive acoustic technique proves effective and sufficient for coal gasification needs, the electrical array technique might still be necessary for geothermal and oil shale use. The development of interpretation methods applies to both techniques.

Cost Estimates

Figure 10 shows the cost estimates in man-years or thousands of dollars, with one man-year set at $50, 000. Except for drill hole costs, the major part of each estimate is in-house manpower requirements.

As mentioned previously, both electrical and acoustic techniques are recommended for development at this time. Although a burn test, such as the planned Bureau of Mines experiment at Hanna, Wyoming, might indicate that the passive acoustic method will be sufficient to define or map the burn front for coal gasification, the need for other techniques in oil shale and geothermal experiments seems apparent. Both estimates are shown in Fig. 10 as coordinated effort with the scheduled and planned coal gasification experiments

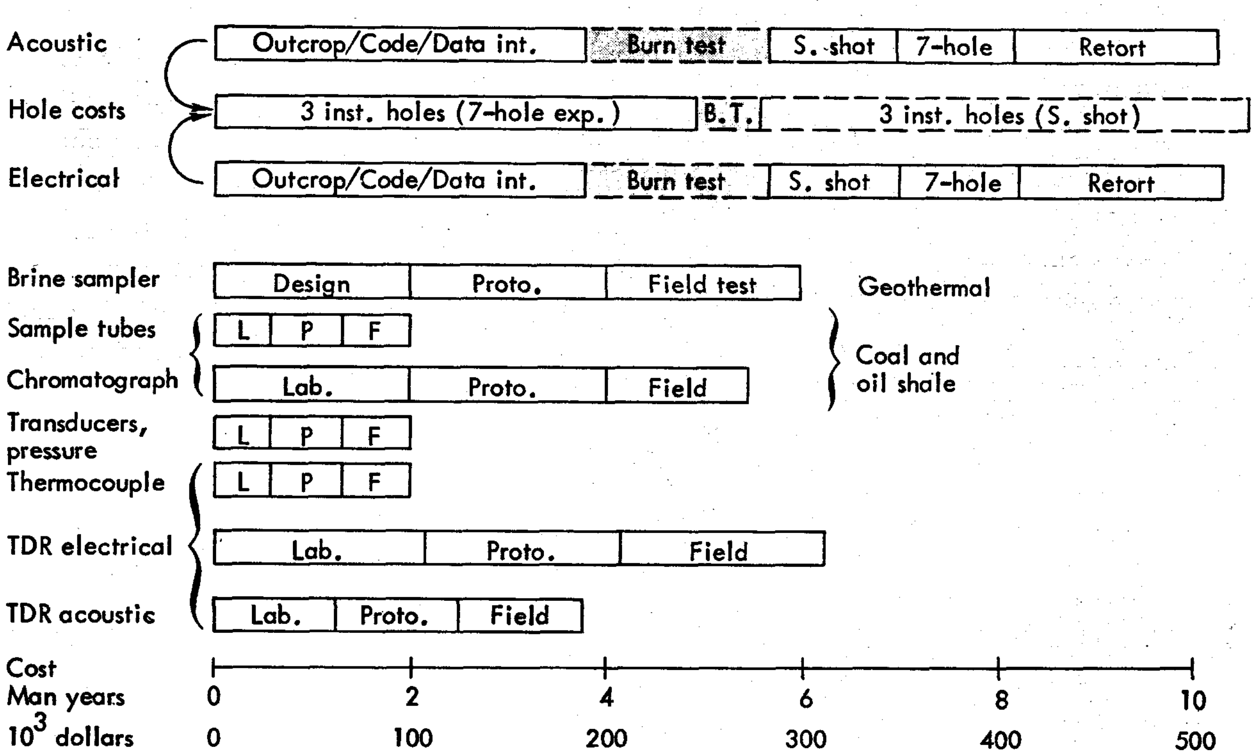

Fig. 10. Proof-of-concept cost estimates for various in situ measurement techniques.

except for the burn test. This is a recommended early test, such as the Hanna experiment, to evaluate the passive acoustic technique. Otherwise, the first planned experiment that would evaluate this technique would be the LLL Retort experiment 2-3 y from now.

A large part of the hole costs can be shared with other instrumentation systems as presently planned. These shared costs are shown with dashed lines. It might be necessary, however, to drill as many as three additional holes outside the planned burn area in the Seven-hole experiment in preparation for the Retort experiment.

Also as mentioned previously, choices must be made based on the relative merits of sample tubes vs chromatography and of thermocouples vs one of the TDR techniques.

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