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HIGH TEMPERATURE GEOPHYSICAL INSTRUMENTATION*

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Abstract

For a number of years Sandia National Laboratories has been working on the development of radically new scientific instruments for use in geophysical research. This work has been funded by OBES under the High Temperature Physics Program. The original purpose was to develop new geophysical instruments for research in thermally active regions of the crust and in particular, for applications related to CSDP. As this work proceeded, interest has appeared in other geophysical areas such as fossil energy and waste disposal where the earlier high temperature requirements were not critical.

An important theme of this project was that the instrumentation development program was to proceed in parallel with scientific research and was to be driven by the needs of researchers. The development of these instruments has therefore included numerous geophysical field tests, many of which have resulted in the publication of scientific articles. This paper is a brief summary of some of the major geophysical instruments that have been developed and tested under the High Temperature Geophysics Program. These instruments are briefly described and references are given for further detailed information and for scientific papers that have resulted from the use of these instruments.

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TABLE OF CONTENTS

DOWNHOLE PERIODIC SEISMIC GENERATOR

The Downhole Periodic Seismic Generator, commonly known as the downhole seismic source, has been under development at Sandia since 1980. The instrument was originally designed for basic geophysical research for CSDP, but recently has attracted considerable interest for evaluating oil and gas reservoirs. Although several versions of this type of instrument have been studied, our work has concentrated on the vertical dipole source version. This version produces vertical shear waves that are horizontally propagated. These shear waves are useful for detecting underground fluids and fractures. This type of downhole seismic source is normally used for HTH (hole-to-hole) tomography or for reverse VSP (vertical seismic profiling). The main features of this seismic source are: (1) it is a controlled downhole seismic shear wave source for HTH and reverse VSP work, (2) it does not damage the casing or borehole wall, (3) it is self-contained and compatible with standard logging cable, (4) it is designed for operation to temperatures of 250°C.

This instrument is a swept-frequency, controlled seismic source which is lowered into a hole and clamped to the casing or borehole wall by means of an electrically-driven clamp. Seismic waves are produced by the action of a pneumatically-driven piston which causes the instrument and adjacent geologic formation to oscillate. The oscillation rate of the piston is controlled by an electrically-driven rotary valve. The speed of the rotary valve can be controlled for monofrequency or swept-frequency runs in the 1 to 300 Hz range. All components and functions are operator controlled through either a standard seven-conductor or seventeen-conductor logging cable that extends from the surface to the tool. Because of the original application of this source for geophysical research in thermally active regions of the crust, the source was designed for continuous operation at temperatures to 250°C. The various components of the seismic source are shown in Figure 1.

There are currently two versions of this instrument. Both are vertical dipole sources that clamp to the casing or borehole wall. One is a slim-hole instrument, 5 cm in diameter, that operates at monofrequencies or swept-frequencies in the 10 to 100 Hz range. This instrument is supplied with gas from the surface and normally operates to depths of about 300 m. The larger version of the source is 13 cm in diameter and is designed for use in 15 to 25 cm diameter holes, either dry or liquid-filled. This source, shown in Figure 2, can operate at monofrequencies in the 1 to 300 Hz range. The sweep is computer controlled and virtually any type of time-varying sweep can be used. This source has a self-contained gas supply and can operate at depths to 3000 m.

The slimhole version of the downhole seismic source has been tested to depths of 250 m in both HTH and reverse VSP modes. Four field tests were conducted at Chevron Oil Field Research Company's LaHabra test facility and field tests were also conducted at Standard Oil Company's field test facility near Devine, Texas, and at Amoco Production Company's field test facility near Tulsa, Oklahoma. The slimhole seismic source has been shown to have a range of about 300 m in fairly attenuating weathered geologic media. The large downhole source has been tested in a gas well at a depth of 2000 m at the Multiwell test site near Rifle, Colorado. The theoretical range of the large source is 3 km or more but field tests to verify this have not been run yet. Future field tests are planned where the sources will be used in reverse VSP mode for oil reservoir characterization and in HTH mode for attenuation measurements in shallow weathered media in the 1 to 300 Hz band.

Patents have been issued for this seismic source in France (No. 8317184, 7/22/85), Canada (No. 1210125, 8/19/68), and United Kingdom (No. 2129559, 3/4/87). Patents are pending in the United States (No. A6437404), Japan (83-58-202485), and West Germany (DE 3339199 A1). Further information on the downhole seismic source can be found in the following references:

1. H. C. Hardee, J. C. Dunn, R. G. Hills, and R. W. Ward (1981). Probing The Melt Zone Of Kilauea Iki Lava Lake, Kilauea Volcano, Hawaii, Geophysical Research Letters, Vol. 8, 1211-1214.

2. H. C. Hardee, and R. G. Hills (1983). The Resonant Acoustic Pulser --A Continuous Frequency Marine Seismic Source, Geophysics, Vol. 48, 1082-1089.

3. H. C. Hardee (1983). Downhole Periodic Seismic Sources, Geophysical Prospecting, Vol. 31, 57-71.

4. H. C. Hardee, G. J. Elbring, and B. N. P. Paulsson (1987). Downhole Seismic Source, Geophysics, Vol. 52, 729-739.

5. H. C. Hardee (1987). Optimum Sweep Functions For Resonant Seismic Sources, submitted to Geophysical Prospecting -- October, 1987.

6. G. J. Elbring, H. C. Hardee, and B. N. P. Paulsson (1988). Results From A Test Of A Controlled Downhole Seismic Source, submitted to Geophysics --February, 1988.

7. Harry C. Hardee, Richard G. Hills, and Richard P. Striker (1983). Downhole Periodic Seismic Generator, U. S. Patent Application A6437404.

DOWNHOLE SEISMOMETER

A downhole seismometer has been developed for extended temperature capability to 250°C. This instrument, shown in Figure 3, contains dual sets of commercially available geophone elements in a triaxial array. The unique feature of this seismometer is the three-arm positive-locking mechanical clamp. This clamp locks to the casing wall with a force of 11,000 N and assures that a significant component of any incoming seismic wave will be transmitted to the seismometer elements where it can be detected. This seismometer is sealed for use in filled holes and is compatible with standard 7-conductor logging cable. An early version of this seismometer was field tested in Long Valley, California, for six months in 1984/85. The latest version, shown in Figure 3, has not yet been field tested. Plans are being made to use it soon in conjunction with the downhole seismic source in a series of HTH attenuation measurements. Although there are no patents filed on this seismometer, the main feature of the positive-locking mechanical clamp is covered under patents filed and issued for the downhole seismic source. In fact, the clamp for the downhole triaxial seismometer and the clamp for the downhole seismic source are interchangeable.

CONVECTIVE HEAT FLOW PROBE

A very sensitive convective heat flow instrument has been developed which uses a thermal perturbation technique to measure very small values of convective flow in permeable media. This instrument can measure both fluid direction and velocity in permeable media. In regions where a temperature gradient exists, such as a geothermal gradient, the instrument can be used to determine the convective heat flow. The convective heat flow instrument is inserted into an uncased borehole and a series of electric heaters are used to perturb the local permeable convective flow in the geologic formation adjacent to the borehole. Temperature sensors are used to record the degree of perturbation and this information along with the heater power can then be related theoretically to the local convective circulation in the formation in the absence of the perturbation. It is possible to distinguish both horizontal convective motion (hydrologic flow) and vertical convective motion (geothermal buoyantly driven flow or recharge/discharge flow). The features of this instrument are: (1) it can provide the full 3-D vector direction and magnitude of fluid motion in a permeable geologic media, (2) it is sensitive to permeable fluid velocities of order 1 m/year, (3) in thermal regions where heat flow is of interest, the instrument can measure convective heat flows as low as 1 to 2 HFU, although the usual application is where the convective heat flow is significantly larger.

The convective heat flow probe is shown in Figure 4 and also in the cut-away drawing in Figure 5. In a typical application a shallow hole (100 m) is drilled into the permeable geologic medium and the convective heat flow instrument is inserted into the hole and locked into position. A series of vertical cylindrical segments, shown in Figure 5, are driven and locked against the borehole wall by means of an internal electric clamp mechanism. Each segment contains an internal electric heater and several temperature sensors. When in contact with the borehole wall, the segments cover virtually all (95%) of the borehole wall. The same mechanism that locks the heater segment pads against the wall also activates two packers, shown in Figure 5, that further seal the borehole below and above the heater segments. Once the instrument is locked against the walls of the borehole, the heater pads are energized for a period of time and then are shut off or changed to a new power setting. The vertical and azimuthal temperature response is recorded during this time. The heater pads induce a localized vertical buoyant convective flow component in the surrounding geologic formation adjacent to the borehole. The magnitude of this induced convective flow varies depending on the amount of natural convection that already exists in the surrounding geologic formation due to other causes. It is possible then to use the measurements to infer the amount of natural convection that exists in the formation prior to the application of the instrument. The mathematics of this process are somewhat complicated and are covered in a paper by Carrigan et al. (1986). The instrument has been tested in a special calibration tank that was built at Sandia for this specific purpose (Carrigan et al., 1986). The instrument has also been tested twice in the field at Long Valley where both horizontal and vertical upwelling flows were known to exist (Carrigan et al., 1986). A U.S. patent has been issued for this instrument (No. 4547080, October 15, 1985) Further information can be found in the following articles:

1. C. R. Carrigan, J. C. Dunn, and H. C. Hardee (1986). A Tool And A Method For Obtaining Hydrologic Flow Velocity Measurements In Geothermal

Reservoirs, Proceeding of the Eleventh Workshop on Geothermal Reservoir Engineering, Stanford University, 231-236.

2. James C. Dunn, Harry C. Hardee, and Richard P. Striker (1985). Convective Heat Flow Probe, U. S. Patent No. 4547080, Oct. 15, 1985.

3. L. A. Romero (1983). Low Peclet Number Convection Past A Spheroid In A Saturated Porous Medium, Sandia Report (SAND83-0291), Sandia National Laboratories, Albuquerque, NM.

TRIAXIAL THERMOPILE ARRAY

The triaxial thermopile array (TTA) is an instrument that allows measurements of subsurface heat flow in three dimensions. It consists of three thermopile elements that are arranged in a three-dimensional array and placed in a cylindrical package that can be buried in a borehole. One of the thermopile elements is shown in Figure 6 prior to being sandwiched and assembled, as in Figure 7. The main features of this heat flow sensor are the following: (1) instantaneous estimates of heat flow can be obtained without detailed knowledge of the geologic thermal conductivity, (2) downhole heat flow readings are obtained in three dimensions--something that is not possible with conventional heat flow instruments, (3) numerous errors usually associated with an open hole are eliminated because the sensor is buried when the hole is backfilled.

Several versions of the TTA have been built and tested. An early version of the thermopile was tested at Puhimau Hot Spot, Hawaii (Hardee and Dunn, 1985). A permanent heat flow station using a TTA has been operating for several years at Indian Wells, California. DOE is in the process of filing a patent for the TTA.

Further information on the TTA can be found in the following articles:

1. H. C. Hardee and J. C. Dunn (1985). Surface Heat Flow Measurements At The Puhimau Hot Spot, Geophysics, Vol. 50, 1108-1112.

2. Charles R. Carrigan, Harry C. Hardee, Gerald D. Reynolds, and Terry D. Steinfort (1986). Triaxial Thermopile Array Geo-Heat-Flow Sensor, Patent Disclosure SD-4497, S-65224, Sandia National Laboratories, December 22, 1986.

3. C. R. Carrigan (1987). Estimates of Heat Flow in Indian Wells Valley, CA Using TTA, Sandia National Laboratories Internal Memo, C. R. Carrigan to H. C. Hardee, February 10, 1987.

HIGH TEMPERATURE LOGGING CABLE AND REEL

A high temperature (900°C) logging cable and reel unit was fabricated for primary use with a downhole temperature logging probe. This cable has also been used with other downhole instruments such as the downhole fluid sampler. The cable and reel are shown in Figure 8. This cable is commercially available stainless steel sheathed, magnesium oxide core with four copper conductors. The servo driven reel, also commercially available, was modified to handle this rather stiff cable. The servo driven reel is computer controlled which is an advantage when making automatic and continuous downhole temperature logs. The reel shown in Figure 8 contains 2 km of continuous high temperature cable. This cable unit was used several years ago in field operations at Coso, California, where temperature logs and fluid samples were taken in geothermal wells.

HIGH TEMPERATURE DOWNHOLE FLUID SAMPLER

A high temperature downhole fluid sampler, shown in Figure 9, has been developed which can take downhole equilibrium fluid/gas samples and seal these samples before they are returned to the surface. This sealed sample can then be transported to the lab where the sample can be heated to downhole conditions and the fluid/gas sample can be restored to its original in situ conditions prior to analysis. The fluid sampler consists of a one-half liter sample bottle, high temperature valve, and valve actuator unit. The bottle is evacuated and lowered into a well. At the proper depth the valve is opened; a sample is drawn and the valve is closed. The sampler is designed for continuous operation at 250°C or for limited operation (30 minutes) at 500°C. Four conductors are required for the logging cable. Two are for operation of the valve actuator and two are used for temperature monitoring of the valve actuator compartment. Several cable heads are available for use with this sampler, as shown in Figure 9, depending on the temperature requirements. The fluid sampler has been tested in two geothermal wells in California. Figure 10 shows one of these tests at Coso, California. Here the fluid sampler is inside the lubricator section at the top of the valve of a geothermal production well in the Coso Geothermal Field. The men in Figure 10 are connecting the high temperature cable from the high temperature reel, shown earlier in Figure 8, prior to lowering the fluid sampler into the well. In this test the fluid sampler functioned successfully after being exposed for six hours to temperatures in the well in excess of 225°C.

THERMAL INSTRUMENTS FOR USE IN LAVA FLOWS

Several instruments have been developed over the years for measuring physical properties of lava during or immediately after eruptions. A few of these instruments were modified or tested as part of the effort in Thermal Geophysical Research. These instruments include some convection heat transfer instruments and an electrical resistivity instrument.

A transient convection probe was developed to measure convective heat transfer rates in basaltic lava in the vicinity of the liquidus. The transient probe consists of a TZM (tantalum-zirconium-molybdenum) rod with an internal thermocouple. The probe is inserted into molten lava and the temperature response is recorded on a field-portable recorder. The temperature response is then used to determine the convective heat transfer rate to the probe. This information can be used to estimate the convective heat transfer rate to any body or heat exchanger that might be placed in the flow. This probe has been tested in laboratory samples of molten basalt and compared with a steady-flow convection probe. The transient probe was used to make a number of convection measurements in the lava flow from the 1983 Kilauea eruption. Figure 11 shows one of the laboratory tests of this probe, and Figure 12 shows the convection probe being used in the 1983 Kilauea lava flow.

An electrical resistivity probe, originally designed by T. L. Dobecki for the Magma Energy Program, was modified for use in an active lava flow. The probe consists of a penetration tip, shown in Figure 13, with four electrodes on an insulating substrate. The electrodes are configured in a Wenner array. This probe was inserted into a molten lava flow from the 1983

Kilauea eruption, as shown in Figure 14. This field test indicated a resistivity value of 40 ohm-m for the molten basaltic lava in this flow.

Additional information on the convection probe and the electrical resistivity measurements can be found in the following references:

1. H. C. Hardee and J. C. Dunn (1981). Convective Heat Transfer In Magmas Near The Liquidus, Journal of Volcanology and Geothermal Research, Vol. 10, 195-207.

2. H. C. Hardee (1981). Thermal Property Measurements In A Fresh Pumice Flow At Mt. St. Helens, Geophysical Research Letters, Vol. 8, 210-212.

3. H. C. Hardee (1983). Heat Transfer Measurements Of The 1983 Kilauea Lava Flow, Science, Vol. 222, 47-48.

4. L. C. Bartel, H. C. Hardee, and R. D. Jacobson (1983). An Electrical Resistivity Measurement In Molten Basalt During The 1983 Kilauea Eruption, Bulletin of Volcanology, Vol. 46-3, 271-276.

POSTFACE

This paper has briefly described a series of special purpose scientific instruments, developed with a modest budget, for use in basic geoscience research. A number of these instruments have been used for scientific measurements during the course of their development. In the remaining cases, the developers have submitted, or plan to submit, proposals to use these instruments in future research. These instruments also have potential applications for scientific research by other agencies and universities, and the instruments have potential applications for commercial measurements by industry. Unfortunately, there is a wide gap between the development of a new research instrument and the acceptance and common use of the instrument by the scientific community and industry. Success in this area will depend on our ability and resources to publicize these potential applications and to educate the scientific and commercial communities regarding the applications and advantages of these instruments. Until this happens, the full potential of these new instruments will remain unfulfilled.

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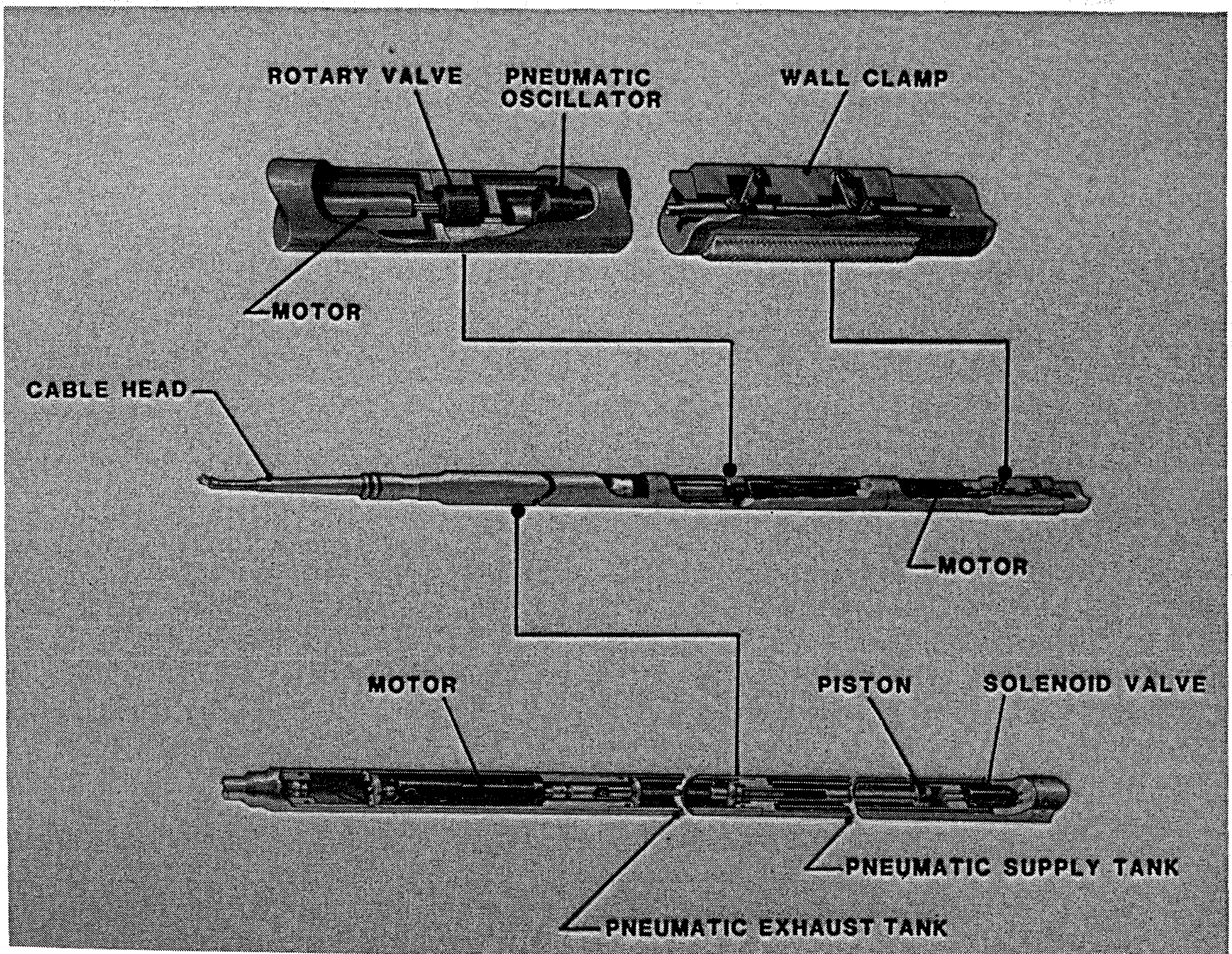

Figure 1. Downhole Periodic Seismic Generator (Downhole Seismic Source).

Figure 2. Downhole Seismic Source (Full Scale Model) Undergoing Tests at Buffalo Hill Test Site, Albuquerque, New Mexico.

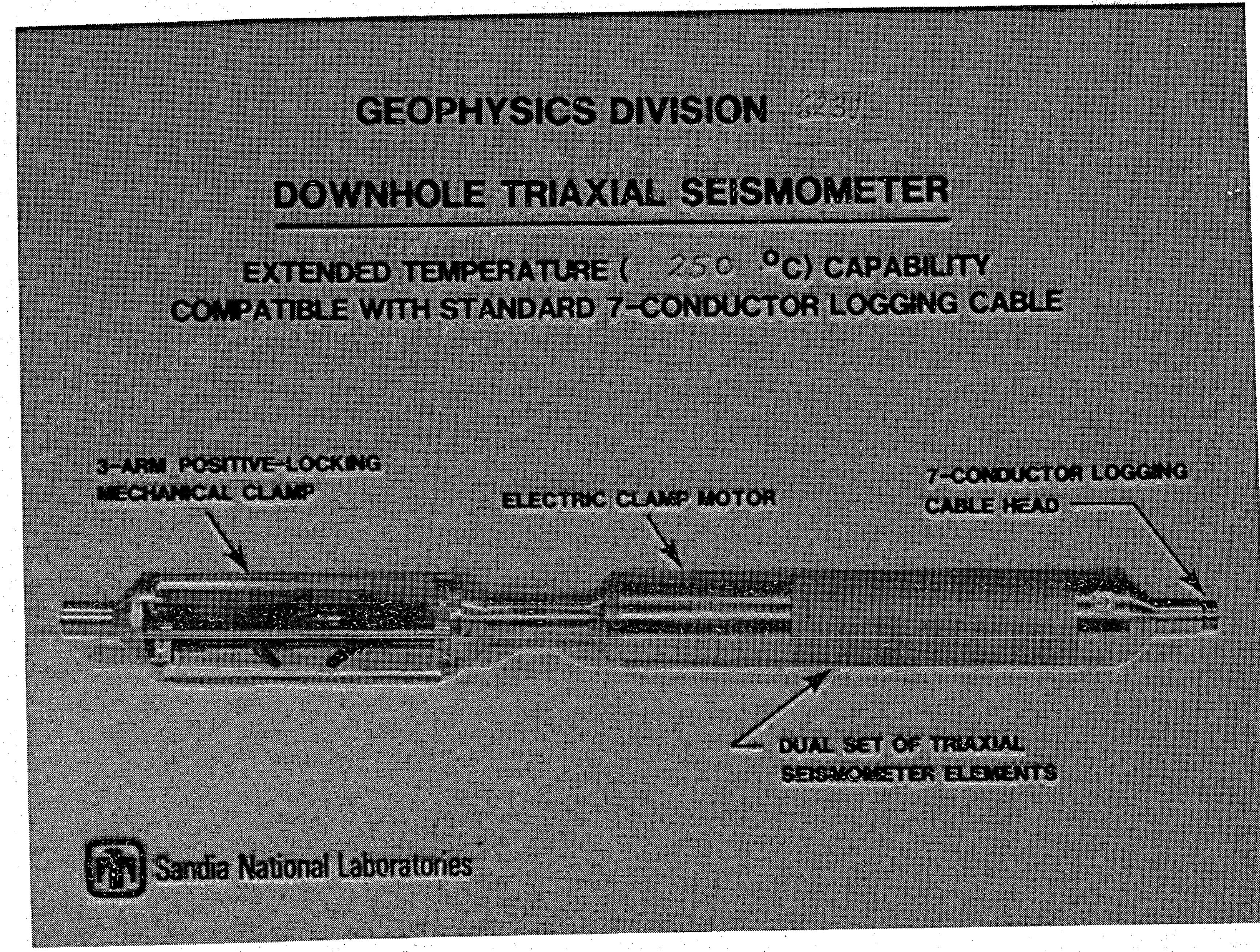

Figure 3. Downhole Triaxial Seismometer.

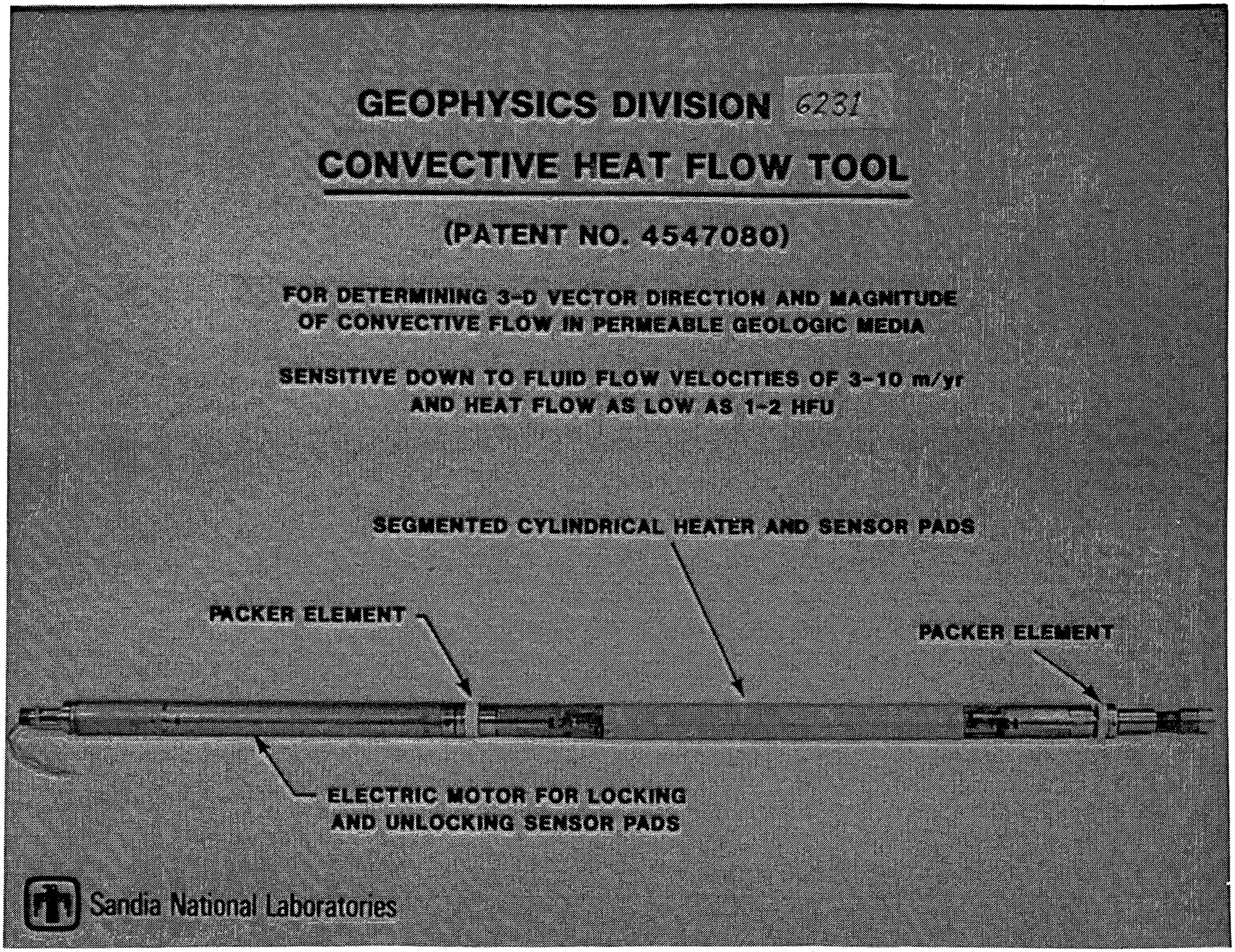

Figure 4. Convective Heat Flow Probe.

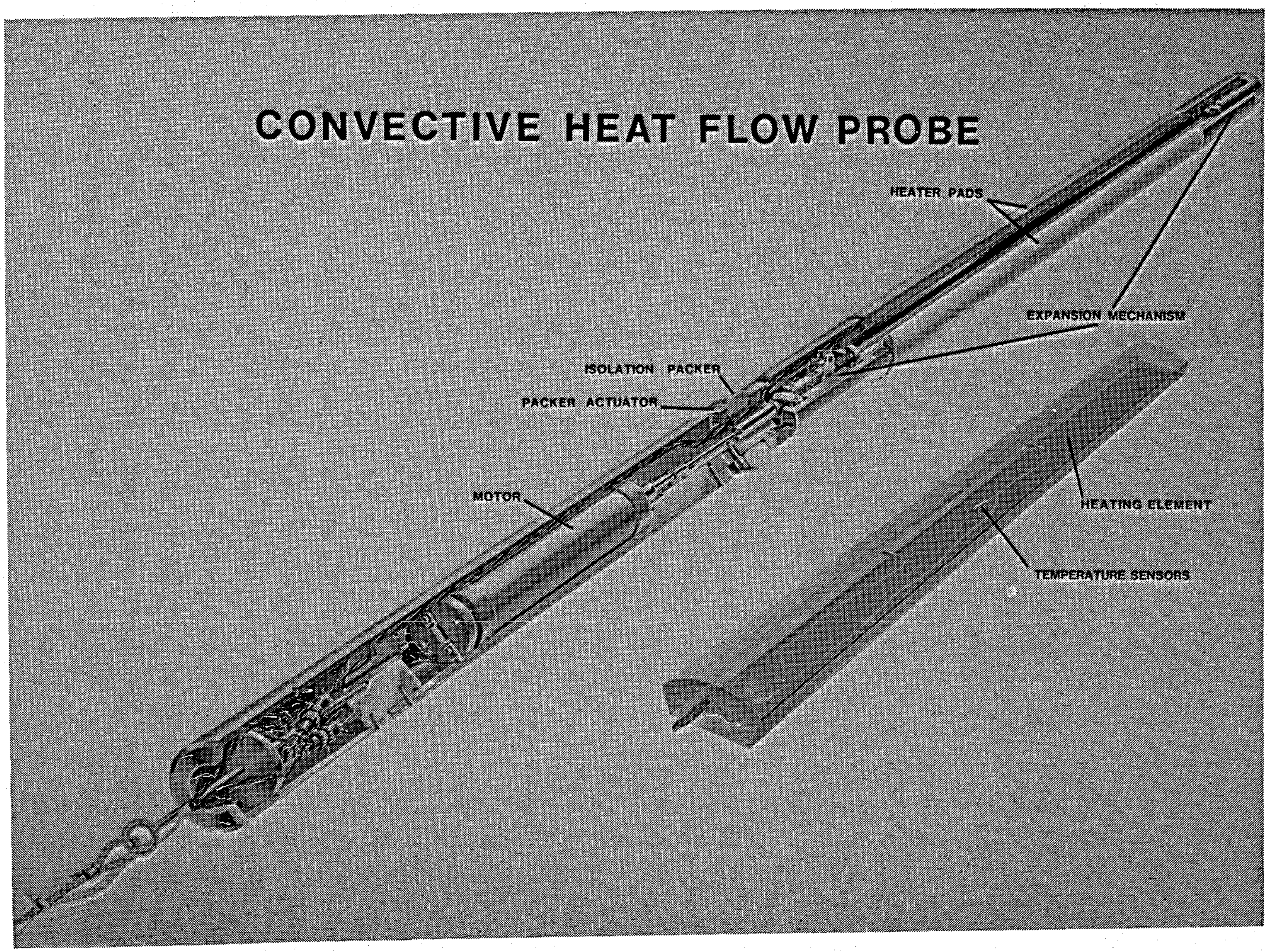

Figure 5. Convective Heat Flow Probe-Cutaway Showing Internal Mechanism.

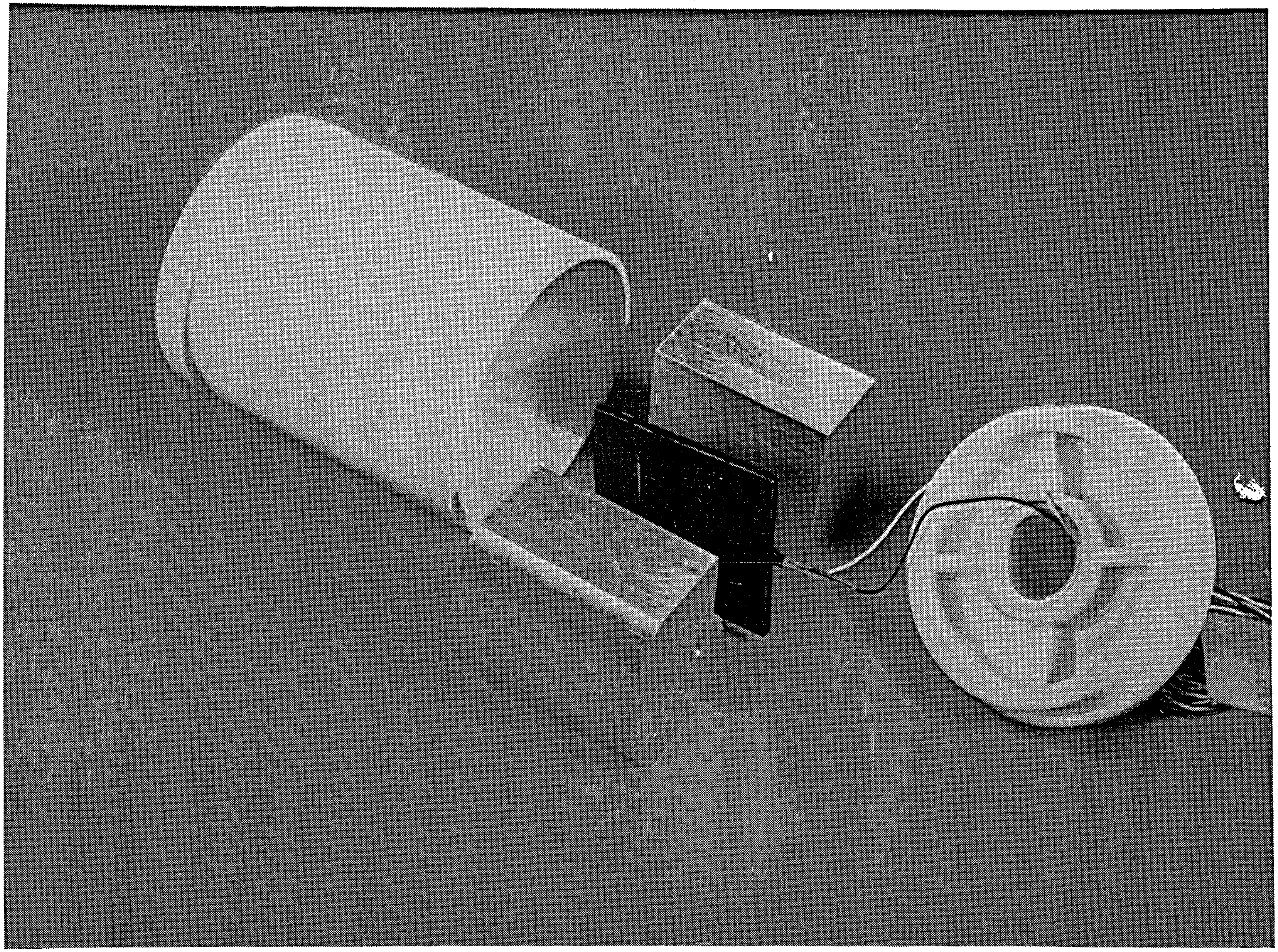

Figure 6. Triaxial Thermopile Array Prior to Assembly Showing Thermopile Element.

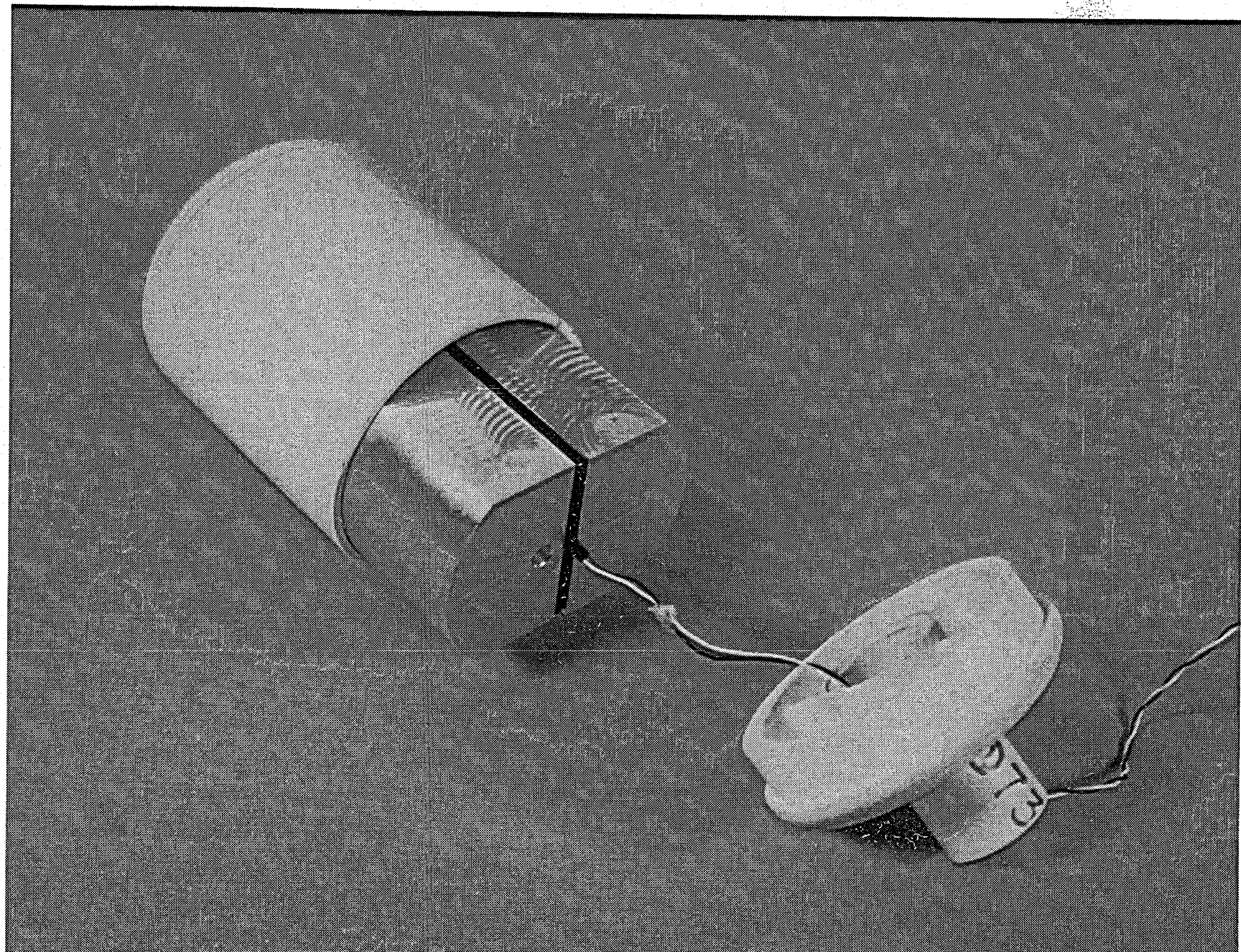

Figure 7. Triaxial Thermopile Array Showing Assembly

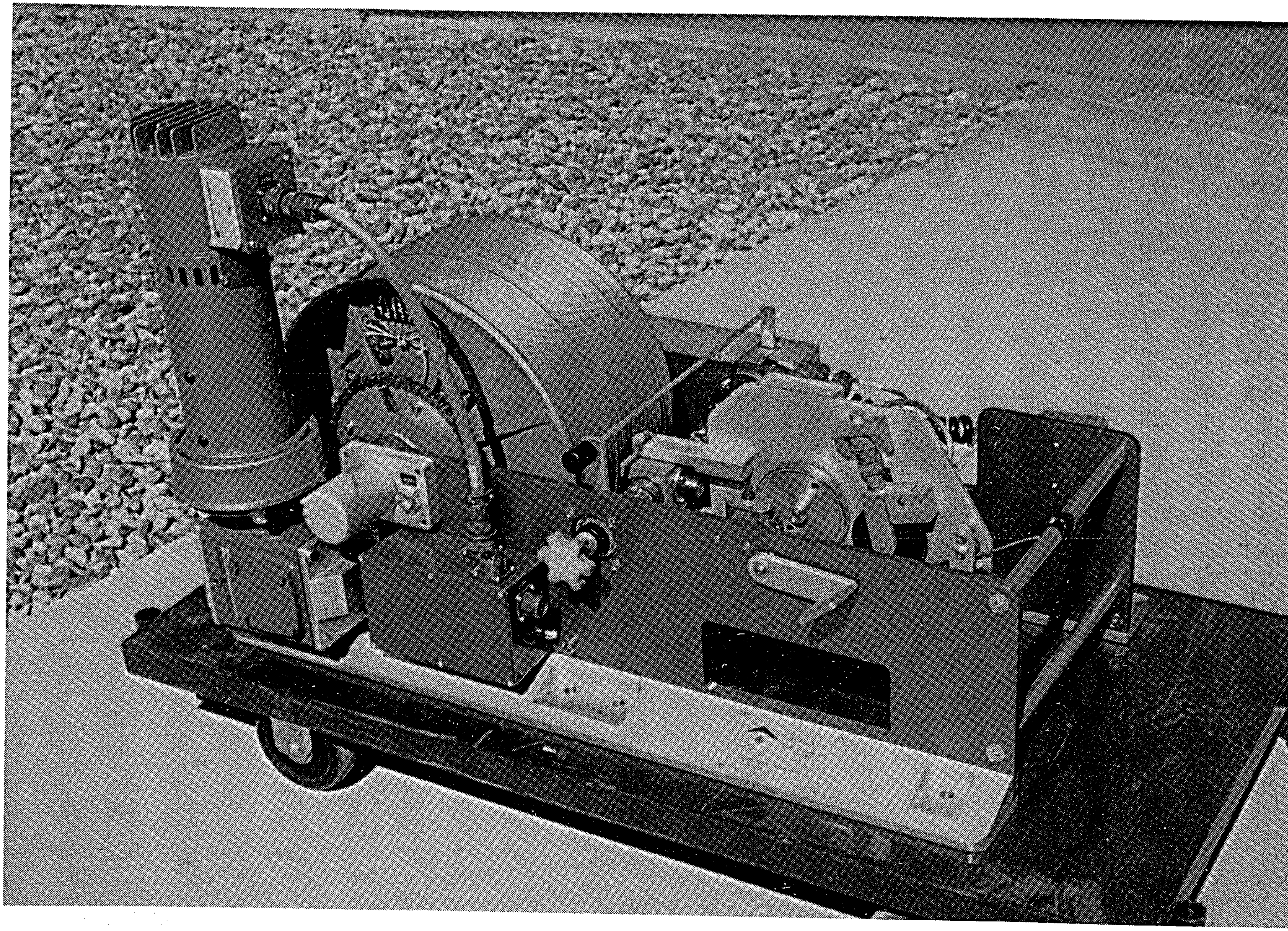

Figure 8. High Temperature Logging Cable and Reel.

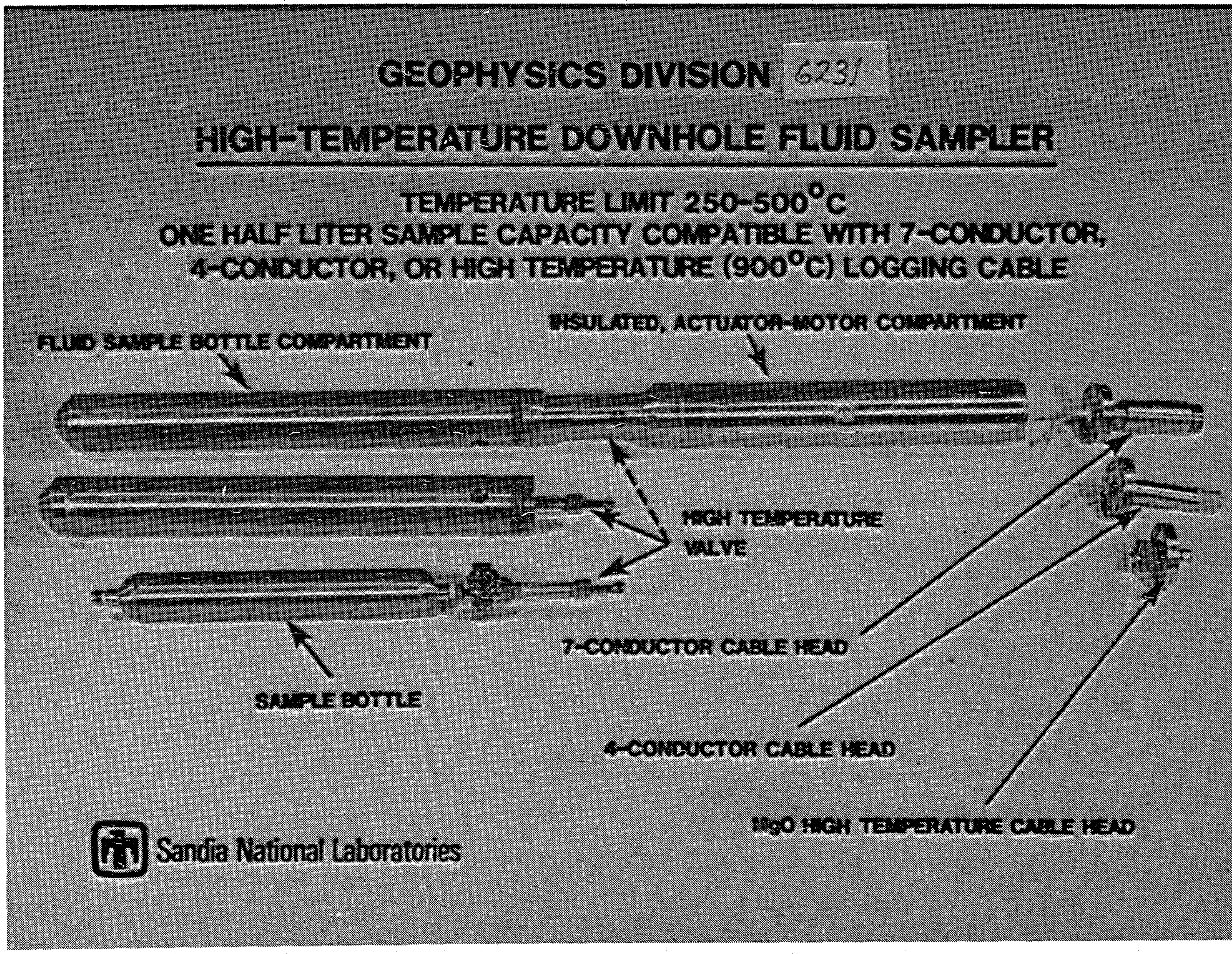

Figure 9. High Temperature Downhole Fluid Sampler.

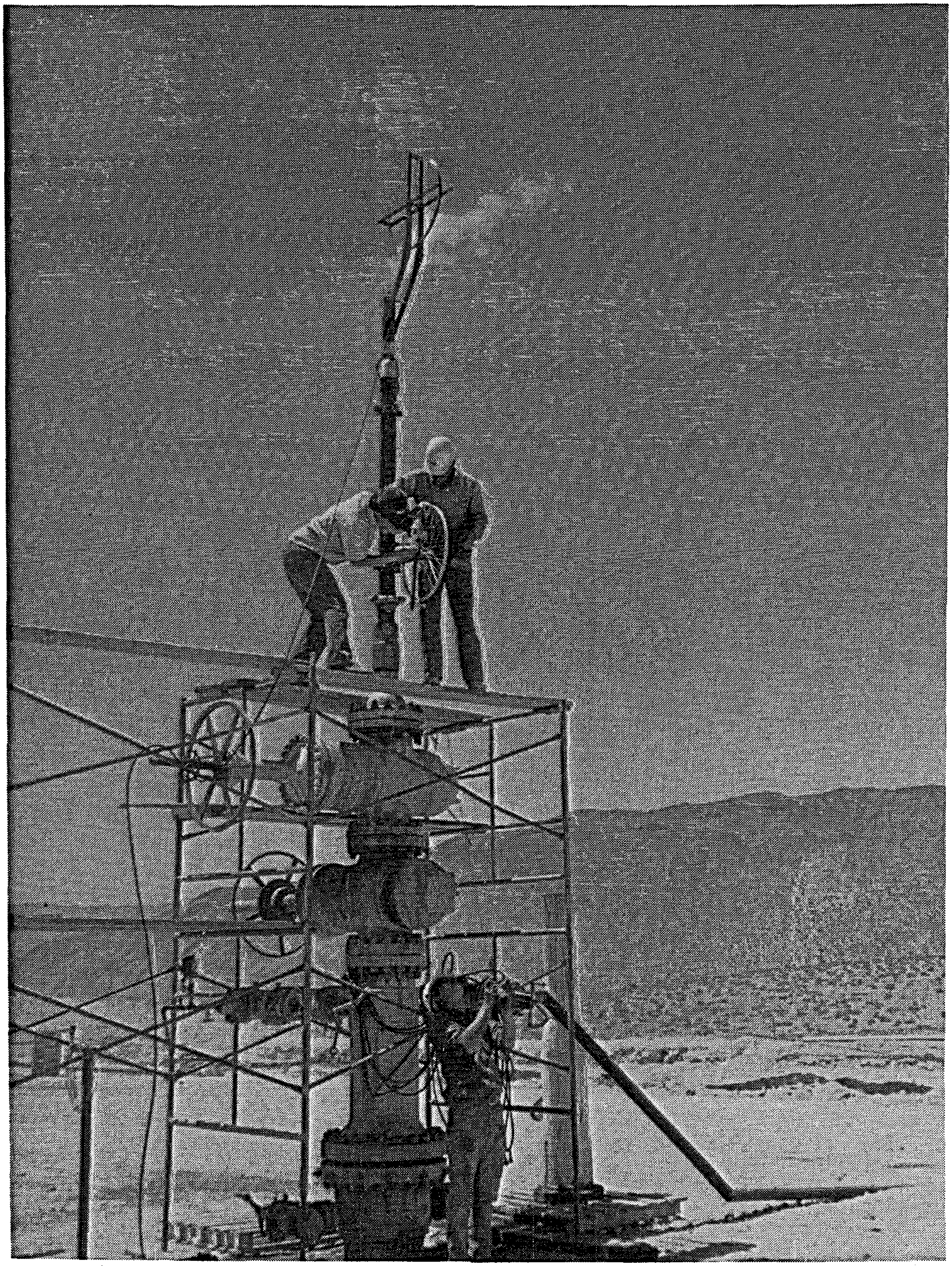

Figure 10. High Temperature Downhole Fluid Sampler Being Used to Sample in Producing Geothermal Well in Coso Geothermal Field, CA.

Figure 11. Laboratory Test of Transient (TZM) Convection Probe.

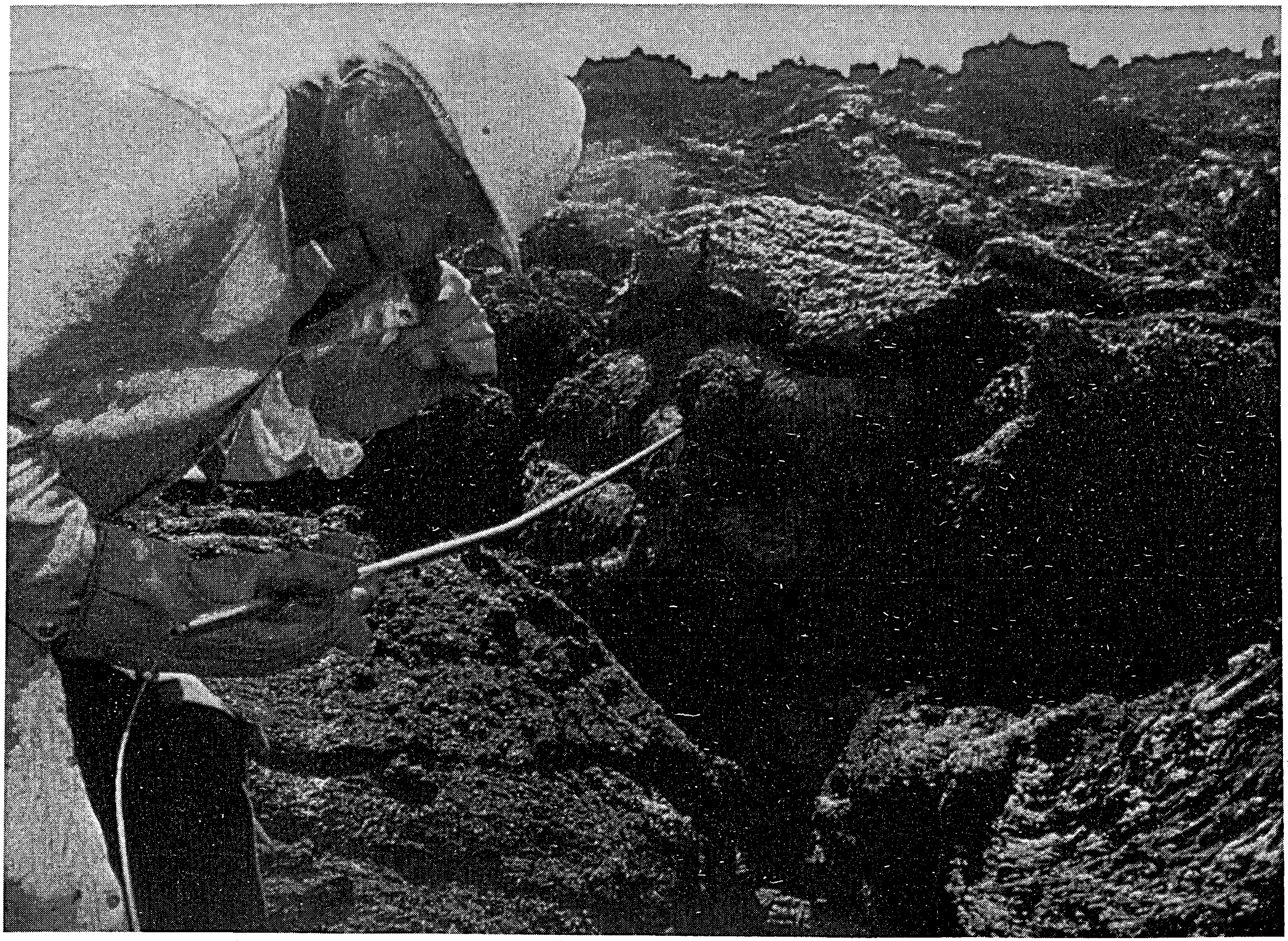

Figure 12. Transient Convection Probe in Operation in 1983 Kilauea Lava Flow.

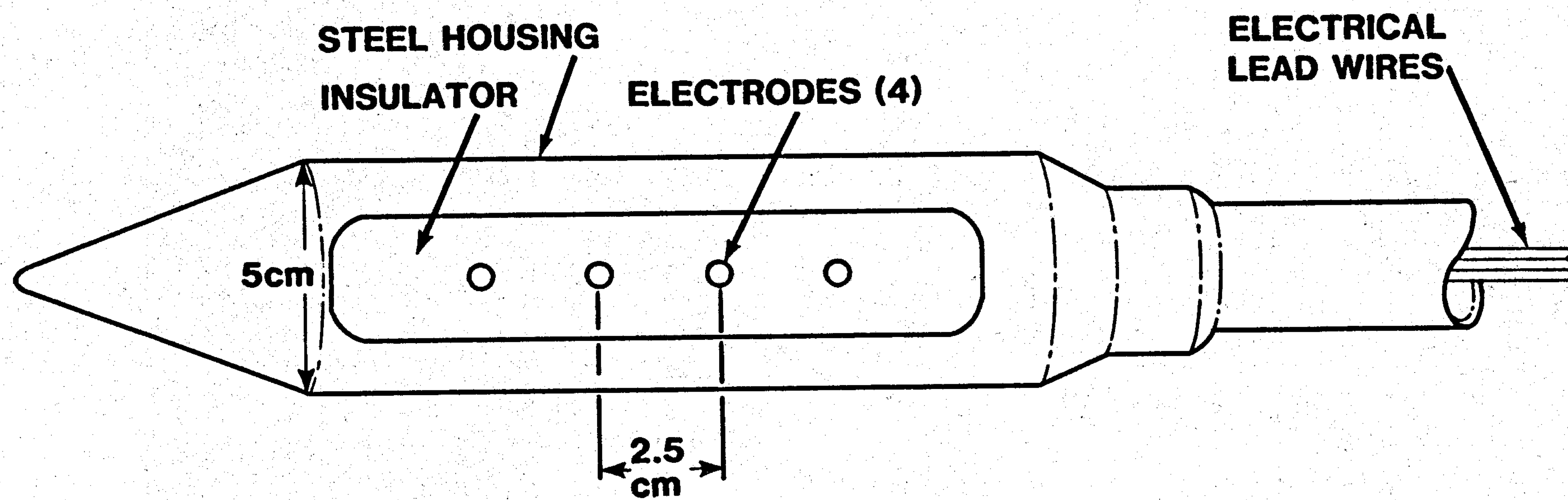

Figure 13. Electrical Resistivity Probe Sensing Elements.

Figure 14. Electrical Resistivity Probe in Operation in 1983 Kilauea Lava Flow.