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TITLE: HIGH-TEMPERATURE BOREHOLE INSTRUMENTATION

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HIGH-TEMPERATURE BOREHOLE INSTRUMENTATION

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ABSTRACT

Research in materials, equipment, and instrument development was required in the Hot Dry Rock Energy Extraction Demonstration at Fenton Hill located in northern New Mexico.

The new Phase II Energy Extraction System at the Fenton Hill Test Site will consist of two wellbores drilled to a depth of about 4570 m (15 000 ft) and then connected by a series of hydraulic-induced fractures. The first borehole (EE-2) was completed in May of 1980, at a depth of 4633 m (15 200 ft) of which approximately 3960 m (13 000 ft) is in Precambrian granitic rock. Starting at a depth of approximately 2930 m (9600 ft), the borehole was inclined up to 35° from vertical. Bottom-hole temperature in EE-2 is 317° C. The EE-3 borehole was then drilled to a depth of 4236 m (13 900 ft). Its inclined part is positioned directly over the EE-2 wellbore with a vertical separation of about 450 m (1500 ft) between them. The materials development programs were funded by DOE under the Hot Dry Rock Project, and cover all aspects of geothermal energy extraction. Research on drilling, hydraulic fracturing, and wellbore logging were necessary to determine the technical and economic feasibility of the hot dry rock concepts.

INTRODUCTION

Research and development concerning high-temperature materials has concentrated on the logging and hydraulic-fracturing hardware to complete the geothermal reservoir for the Phase II system.

The Phase II system, with boreholes to 4572 m (15 000 ft), bottom-hole temperatures of 300°C, and 69 MPa (10 000 psi) pressure, has placed very stringent requirements for the downhole instrumentation systems. The 35° inclination of the EE-2 and EE-3 wellbores also introduced new problems in well logging operations.

Many of the geophysical measurements needed to develop the hot dry rock concept are unique. Most of the routine instruments used in petroleum drilling fail in the hot and abrasive environment. New equipment developed includes not only the downhole sonde that houses the transducer and associated line driving electronics, but modifications also were needed on the entire data retrieval systems and associated data analysis technology.

Successful performance of wellbore surveys in the EE-2 and EE-3 boreholes depended upon the capacity of the sensors, instrument sonde, cablehead, and armored logging cable to work in this severe environment.

The major areas of materials development for surveying the boreholes in the high-temperature environment were on elastomeric seals, electrical insulation for logging cables, downhole sensors, and associated downhole instrument sonde.

DOWNHOLE TOOL DESIGN

Geometric constraints imposed upon the outside dimensions of the downhole sonde place severe restrictions on the space available for instrumentation. Fluid pressures up to 82.7 MPa (12 000 psi) are possible at depths of 4572 m (15 000 ft) in the EE-2 injection well. The fluid pressures are a summation of 44.8 MPa (6500 psi) hydrostatic head plus a 37.9 MPa (5500 psi) pumping capability. The high pressure combined with the high temperature (320°C) causes rapid deterioration of exposed components such as O-ring seals and electrical feedthrus.

The mechanical design concepts for packaging the downhole instruments and associated electronic signal conditioning used in the Phase II wellbores have been developed at the Los Alamos National Laboratory. The new design concepts take into consideration precautionary measures required in fabrication and assembly based on observations of commercial oil field well logging activities plus lots of experience in the fielding of the Laboratory instrument sondes. This experience was accrued in support of the Hot Dry Rock Project at the Fenton Hill site since 1974. Design criteria incorporating the precautionary measures for the downhole instrument sondes are listed for the seals, metals, and thermal protection components.

SEALS

- o The minimum possible number of pressure sealed joints and connections are used to reduce potential leak paths.
- o Static face seals are preferred over cylindrical seals, with redundant seals in cylindrical configurations whenever possible.
- o Leak test all first time sealed connections and all pressure weldment joints during initial tool assembly using a helium sensative mass spectrometer.
- o Protect all seal surfaces from damage during subsequent refurbishing operations that require breakout of connections. All seal surfaces must be carefully cleaned prior to reassembly.
- o Vigilant observation of seal performance is mandatory after each logging run to check for leakage or thermal damage of the elastomeric seal materials caused by high temperatures.

The guides used for design of the downhole instrument packages may deviate somewhat from standard practices but proved to be most effective in meeting the operational requirements in the severe geothermal environments.

The Laboratory has been conducting tests on seals for five to six years. Metallic seals of many configurations, along with elastomeric seals of various compositions and design, have been tested at temperatures of 275 to 300°C and pressures of 52 MPa (7500 psi). Years of testing have singled out a few seals that can operate in this environment; some of these seals, however, require complicated two-piece seal design, large radial clamping forces, extremely good surface finishes, or special assembly tools that may limit their compatibility in the field operations.

In attempts to keep seal design simple, the Laboratory funded L'Garde, Inc., Newport Beach, California, to adapt new elastomer formulations to yield an O-ring that will meet Phase II requirements.

L'Garde fabricated O-rings for the Laboratory's cablehead from the Y267 EPDM compound. The cablehead O-rings were tested in an autoclave with water and Mobil One oil. Cycles of 24 h, with the temperature and pressure on for 8 h and off for 16 h, simulated tripping in and out of the hole. The best prior performance achieved was with commercial fluoroelastomer O-rings which literally disintegrated after one cycle.

The tests were run for 5 cycles or 5 days with the Y267 EPDM O-rings assembled in the Laboratory's cablehead before stopping the test to examine the seals. On the fifth day this included a 24-h run which provided a total test time of about 56 h for this one seal. The temperature was nominally

275°C and the pressure was nominally 51.7 MPa (7500 psi). The O-ring condition was excellent after this test, and the ring obviously could have continued further cycling.

The EPDM seals in standard O-ring sizes are now used in a groove design as shown in Fig. 1. This face seal and cylindrical radial gap is used exclusively in all parts requiring O-ring seals where temperatures up to 320°C are expected.

When O-ring grooves are not suitable because of dimensional constraints, a static seal design using a spring loaded "C" shaped cross-sectional seal is used. The "C" shaped seals used in several of the downhole tools are supplied by Bal-Seals, Inc. The 505 series, S55 series, and the IS55 series have proven to be satisfactory for temperatures up to 320°C. The seal material is basically a graphite fiber-loaded Teflon. Typical groove design used in the downhole package is shown in Fig. 2.

All seal grooves and mating surfaces are carefully inspected to ensure compliance with print specifications. Protective end caps are attached to exposed surfaces during transport and storage of the instruments.

METAL MATERIALS

- o Conservative stress analysis is used to provide the constraints for rugged instrument housing in both high-temperature (320°C) and high-fluid pressure (82.74 MPa [12 000 pis]) environments and to withstand high impacts caused by rigging activities during tool insertion at the wellhead.
- o Pressure vessel materials are selected that are both machinable and weldable using standard machine shop tools and welding equipment.
- o Wear points are strengthened to withstand severe wear while tripping into and out of the abrasive boreholes. Logging rates up to 200 ft/min in the 35° inclined wellbores can cause considerable contact damage.
- o Connections must be sized to permit sonde assembly and disassembly on location by field personnel using conventional hand tools.

The specific metal materials and rated yield strength used to meet the structural requirements of the downhole sondes is listed in Table 1.

The aluminum usage is limited to internal portions of the instrument sonde for retainers, bushings, alignment sleeves, etc. Aluminum is not used in the external body portions and pressure seal joints where corrosion and thermal expansion differences caused by the chemical and thermal characteristics of the wellbore fluids can cause faillure.

Welding, when necessary, is limited to TIG procedures accomplished by qualified welders. Heat affected zones are kept to a minimum and alignment of the parts is controlled by designing all joints with shoulders for proper positioning at the weld interface.

Stress determinations for pressurized applications is based on cylindrical shapes and shown as plots in Fig. 3. Safety factors are adjusted upward usually by increasing the wall thickness as required after material selection and packaging sizes have been determined.

TABLE 1

Structural Materials

Metal	Yield Strength MPa	Yield Strength psi
Heat Treated Steel SAE-4340	896.3	130 000
Cold Drawn Seamless Tubing AISI C1018	448.2	65 000
Stainless Steel 304L	241.3	35 000
Aluminum 6061-T651	275.8	40 000

THERMAL PROTECTION

- o Thermal insulation of the internal electronics circuitry from pressure vessel surfaces heated by the wellbore environment is necessary.
- o High temperature electro-mechanical components and transducers are required for implacement in the instrument package which cannot be isolated from the wellbore environment.
- o Differences in thermal expansion coefficients of all metal linkage and connections are critical to avoid loosening at high temperatures.
- o Use of low melting temperature solder alloys for any electrical/electronics connections is prohibited.

Isolation of the electronics from the outer wall of the instrument sonde is accomplished by placing the electronic package in a stainless steel vacuum flask (dewar). A fusible alloy (eutectic temperature at 70°C) is inserted into the flask to provide a heat sink. Heat radiated into the dewar from the external environment contributes about 10 times the internal heat source as does the electronics. Heat pipes are used to conduct the heat from the electronics area to the heat sinks. A more efficient heat sink uses a container of ice coupled to a copper acceptor that is used to transport the thermal energy from the heat pipe to the water tank. The latent heat of the cerrobend fusible alloy is 14 as compared to the latent heat of water at 144. This thermal protection will allow continuous operation of a downhole sonde such as the acoustic detector to operate continuously in a geothermal environment of 250°C for 8 h.

DOWNHOLE SONDES

Continuing efforts in pursuing the development of high-temperature materials and components have resulted in significant advances in downhole instrumentation development. The upgrading of several instruments using the basic design guidelines is discussed below with emphasis on the high-temperature components and sensors which prompted the design.

Caliper Tool

An independent multiarm caliper tool began with the design and fabrication of a prototype three-arm sonde which can readily be modified to have six independent arms (Fig. 4). Arm lengths can be varied to measure hole diameter up to 762 mm (30 in.) or can be designed for maximum sensitivity at given diameters. The tool is sensitive enough to detect 1-mm variations along the borehole wall. Key components that led to the design for operation in the 300°C borehole environment are, in addition to the O-rings mentioned above, a high-temperature dc motor and a high-temperature 360° cosine, 5000-ohm potentiometer. The dc motor developed by AEI is used to extend or retract the arms on command from the surface. The 360° low-torque potentiometer shafts rotate with the feeler-arm motion indicating arm position. The low-torque, high-temperature potentiometers are made by Bowmar/TIC.

Fluid Velocity Sensor

A fluid velocity sensor (spinner) uses an impeller that is rotated by the vertical flow of fluids in a borehole (Fig. 5). The impeller is fixed to the lower end of a connecting shaft that rotates two magnets. The rotating magnets actuate a reed switch attached to the protected side of a pressure bulkhead which generates pulses that are recorded at the surface. The lightweight stainless steel impeller is 76.2 mm (3 in.) in diameter and has eight blades. The blades have pitch angles of 20° which maximize its rotational speed for a given fluid velocity. The pressure-point impeller pivot bearings are made of heat-treated steel to reduce friction drag and resist wear. The simplicity of the bearings allows this tool to measure flow rates of 50.8 mm/sec (10 ft/min) up to 2450 mm/sec (350 ft/min) over a working range up to 300°C and 103.3 MPa (15 000 psi).

Acoustic Detectors

A triaxial geophone array is assembled in a downhole instrument package and used to detect microseismic activity resulting from rock failure during fluid injection into the fracture reservoir. The cumulative number of microseismic events, the microseismic occurrence rate, and the distance from the injection point of microseismic force reveal much information about the size and location of the geothermal reservoir. High-temperature geophones are arranged in a cradle assembly in an orthogonal set. A dewar system combining a stainless steel vacuum bottle (manufactured by Vacuum Barrier) and heat sink material is used to protect electronic signal conditioning, 2 axis inclinometers, and the battery pack associated with the geophone instrumentation. Laboratory tests demonstrate that the dewar's instrument compartment temperature remains below 85°C for 12 h in an external temperature environment averaging 275°C. A source in the cavity dissipated 15 W of heat during each of the tests to simulate the output of an electronic package. A high-temperature dc motor and lead screw assembly drive a locking arm mechanism which forces the geophone cradle against the borehole wall to improve mechanical coupling (Fig. 6).

A new downhole acoustic detection system will use high-temperature accelerometers in place of the geophones. The geophones are mechanically limited to 14° angle of tilt from the axis prohibiting their use in the high-angled boreholes. The accelerometers are insensitive to axis orientation or tilt and have a higher frequency response.

Downhole Injector and Gamma-Ray Detector

Water circulation in the geothermal boreholes is studied with the injector-tracer sonde. High-purity ammonium bromide is prepared by irradiation with neutrons at a nuclear reactor in Los Alamos. The ^{82}Br has a half life of 35.4 h and its principal gamma energies are from 554 to 1474 keV. For irradiation the solid NH_4Br is sealed in a quartz ampule. To protect personnel working with the sonde, the ^{82}Br is transported in a lead pig. The sonde is bolted onto the upper portion of the pig, which then comes apart to become part of the sonde (Fig. 7).

When the sonde has been placed in the borehole at the desired location, a high-temperature dc motor propels a rod into the quartz ampule, smashing it. The ^{82}Br is then flushed into the geothermal fluid by 199.39 mm^3 (7.85 cu in.) of water. The gamma-ray detector (which is part of the sonde) then follows the path of the ^{82}Br and is readout on the surface. The sonde has been upgraded for operation at 300°C. The gamma detectors have been packaged in the dewar assembly similar to that used in the geophone acoustic detector. Additional shock mounting has been added to protect the instrumentation in the severe vibration environment.

CONCLUSION

Development of the high-temperature materials, components, and sensors discussed has paved the way for upgrading all required downhole instrument systems for the Fenton Hill Phase II measurements. The specific survey sondes described illustrate the use of the techniques that have been expanded to a number of downhole instruments including temperature probes, acoustic transceivers, water samplers, and explosive devices. The development of the TFE Teflon electrical insulation for armored cable fabrication, the EPDM O-rings, and the thermal protection device has increased the capability to survey geothermal boreholes where temperatures exceed 300°C.

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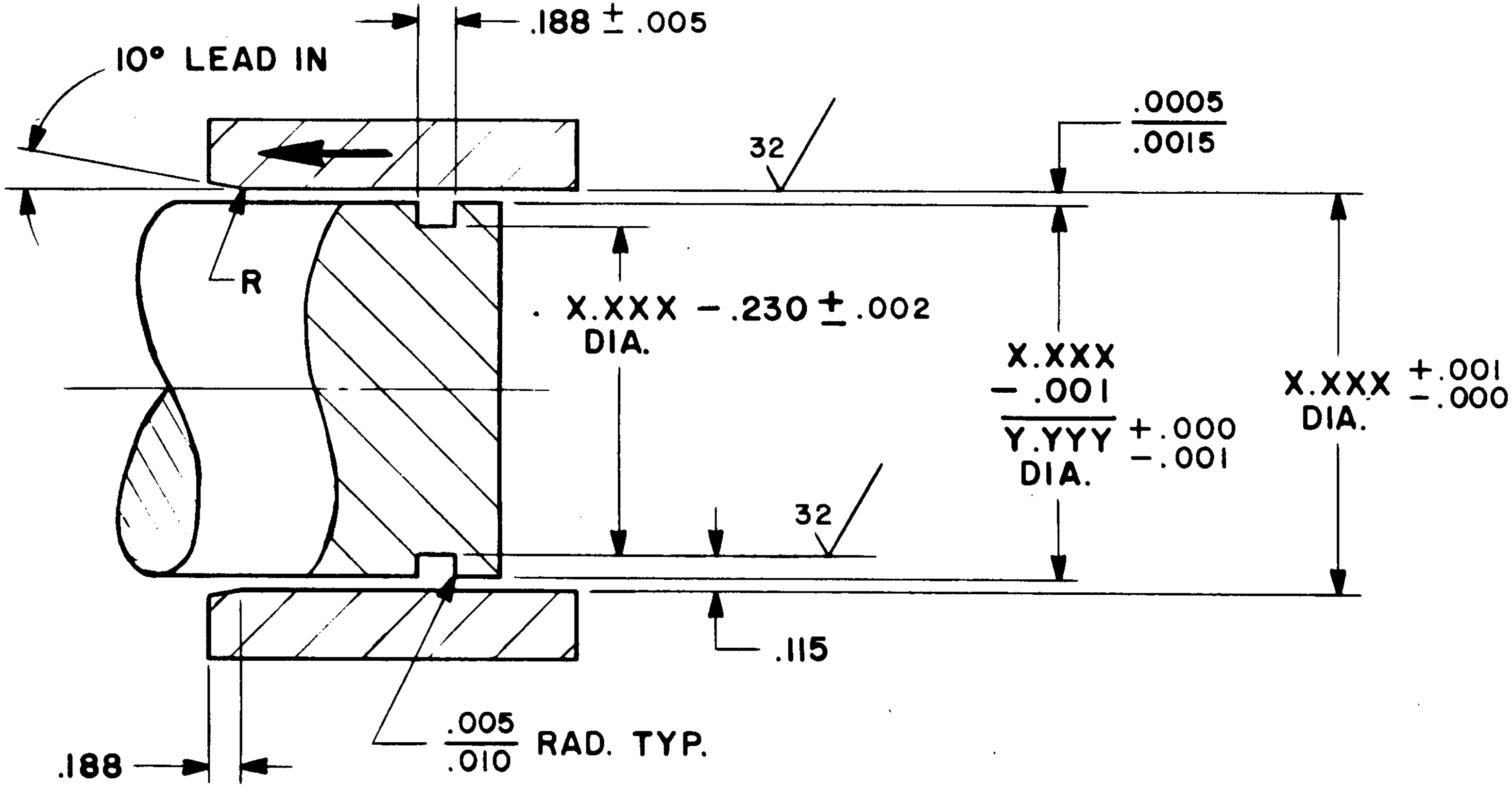
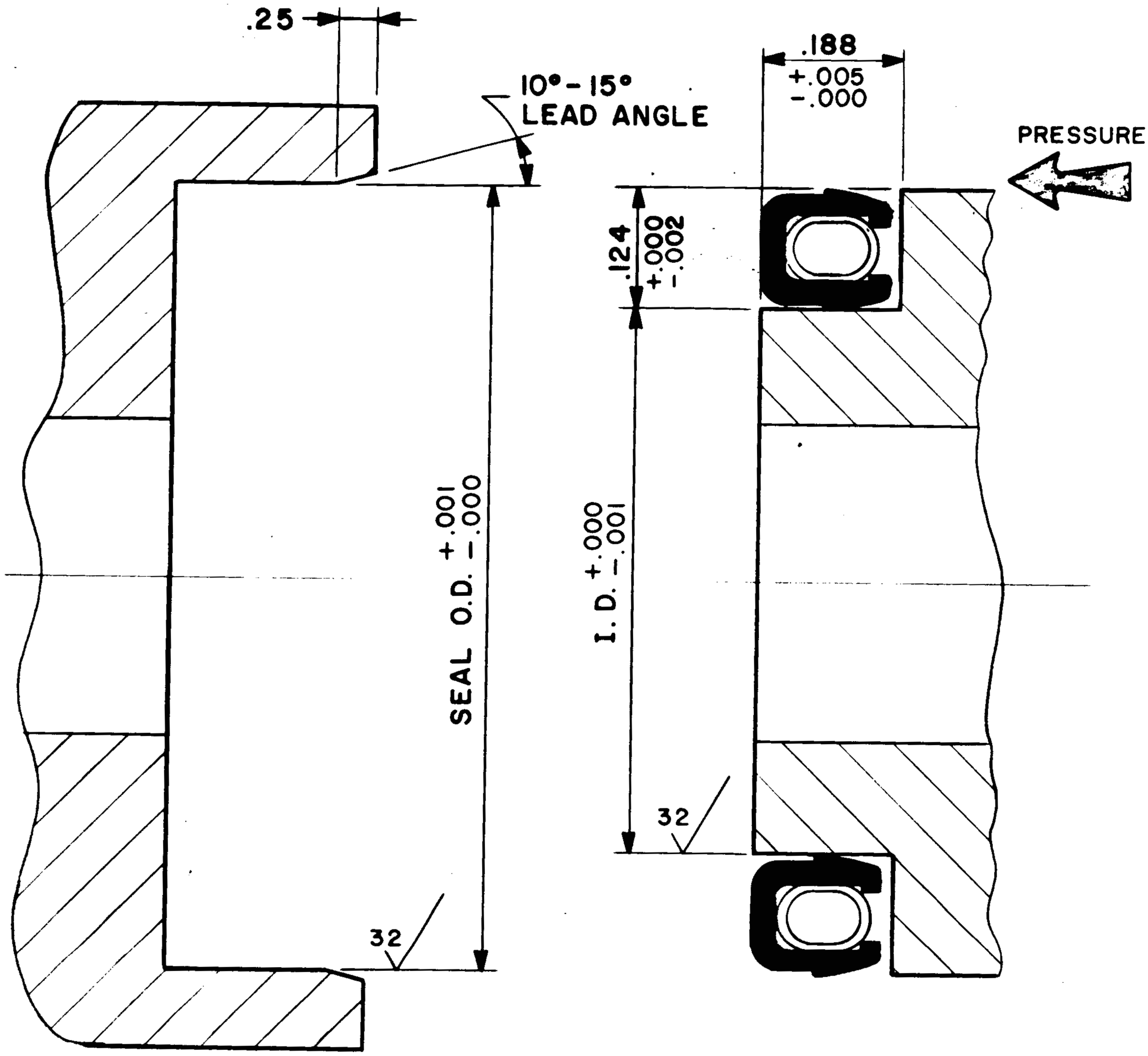


FOR .139 O' RINGS ONLY

RADIAL GAP

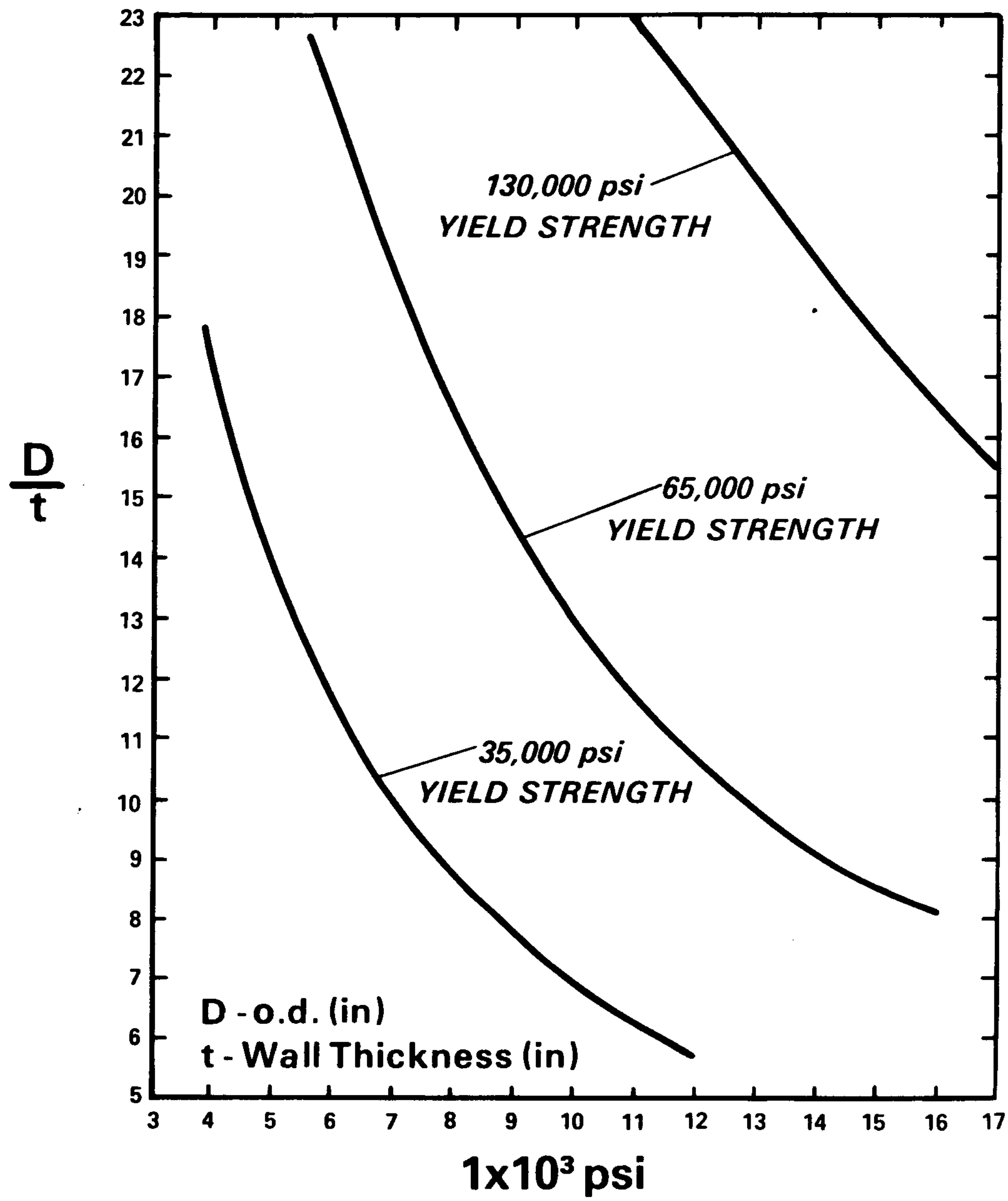
FIGURE 1.



505 SERIES

BAL-SEALS

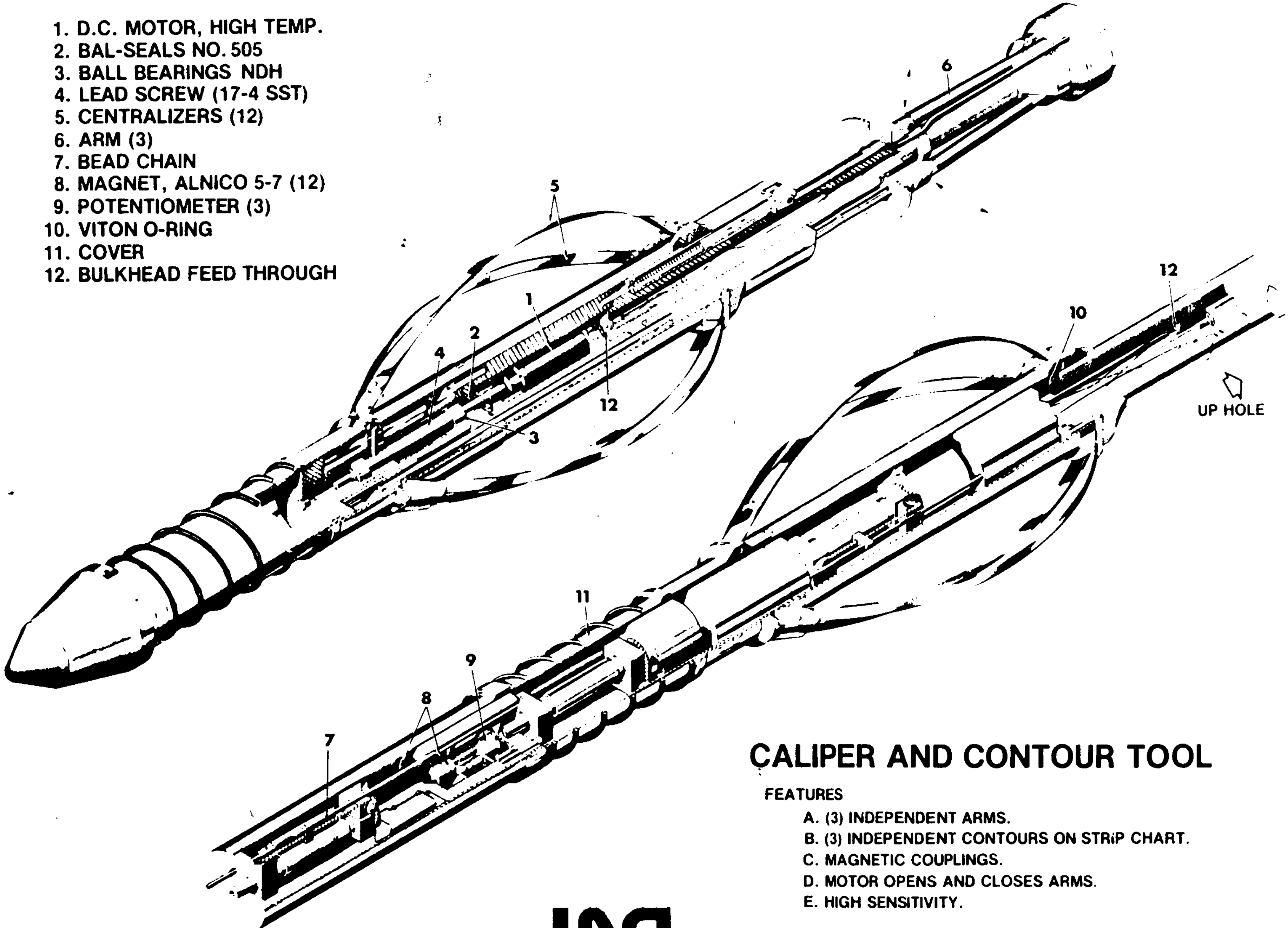
FIGURE 2.



Material Selection Stress Analysis

FIGURE 3.

1. D.C. MOTOR, HIGH TEMP.
2. BAL-SEALS NO. 505
3. BALL BEARINGS NDH
4. LEAD SCREW (17-4 SST)
5. CENTRALIZERS (12)
6. ARM (3)
7. BEAD CHAIN
8. MAGNET, ALNICO 5-7 (12)
9. POTENTIOMETER (3)
10. VITON O-RING
11. COVER
12. BULKHEAD FEED THROUGH



CALIPER AND CONTOUR TOOL

FEATURES

A. (3) INDEPENDENT ARMS.
B. (3) INDEPENDENT CONTOURS ON STRIP CHART.
C. MAGNETIC COUPLINGS.
D. MOTOR OPENS AND CLOSES ARMS.
E. HIGH SENSITIVITY.

FIGURE 4.

FLUID VELOCITY SPINNER PROBE

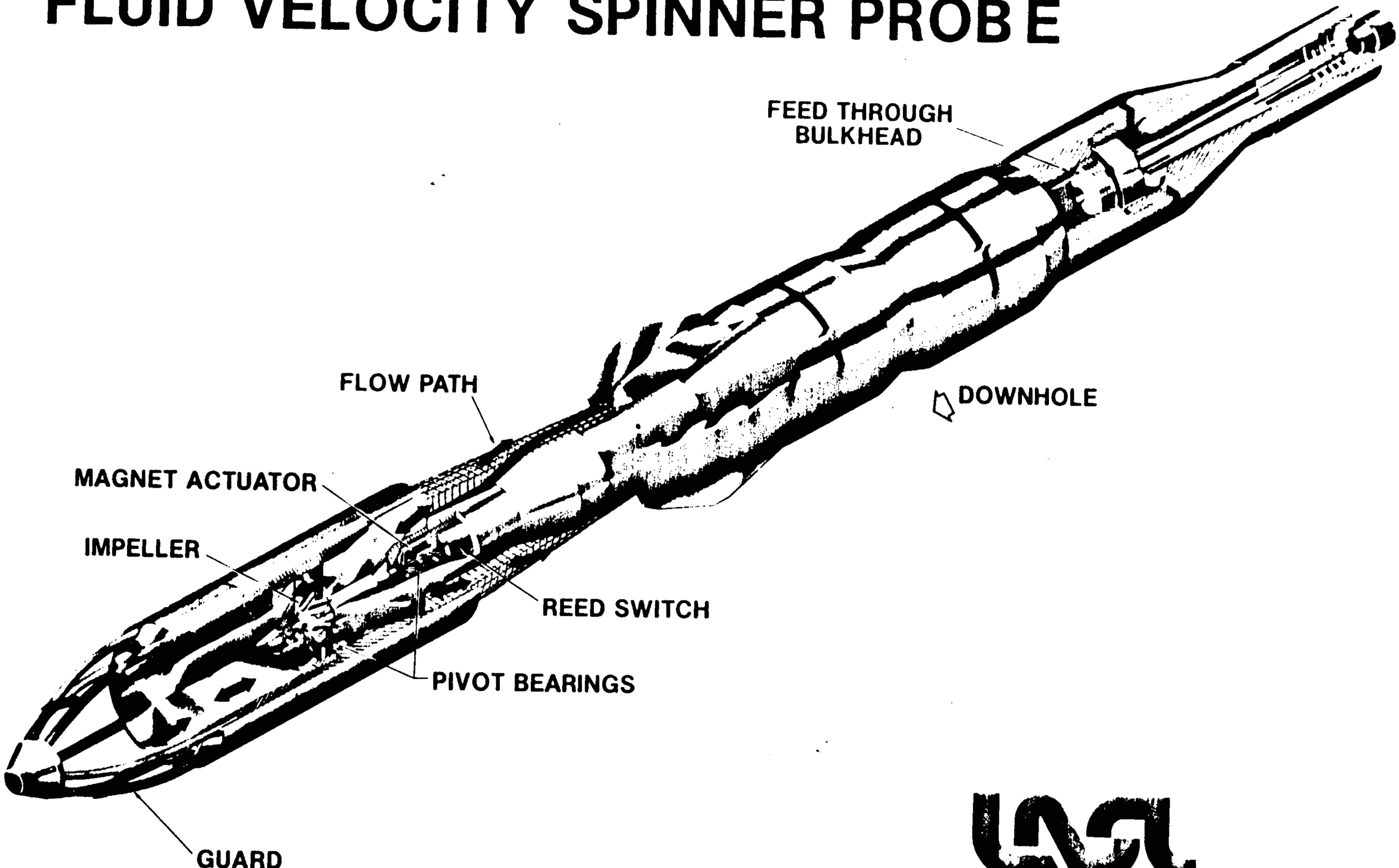


FIGURE 5.

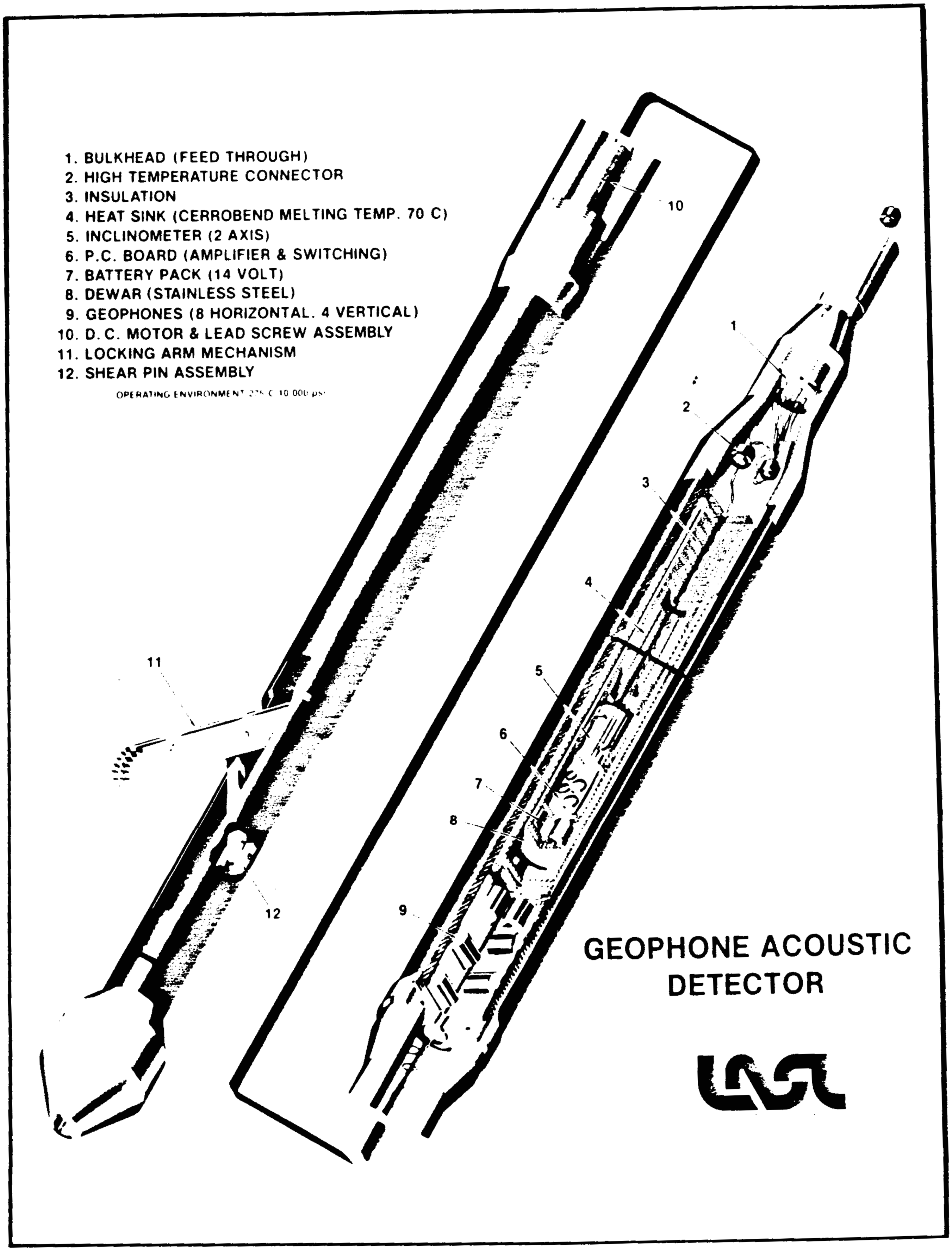
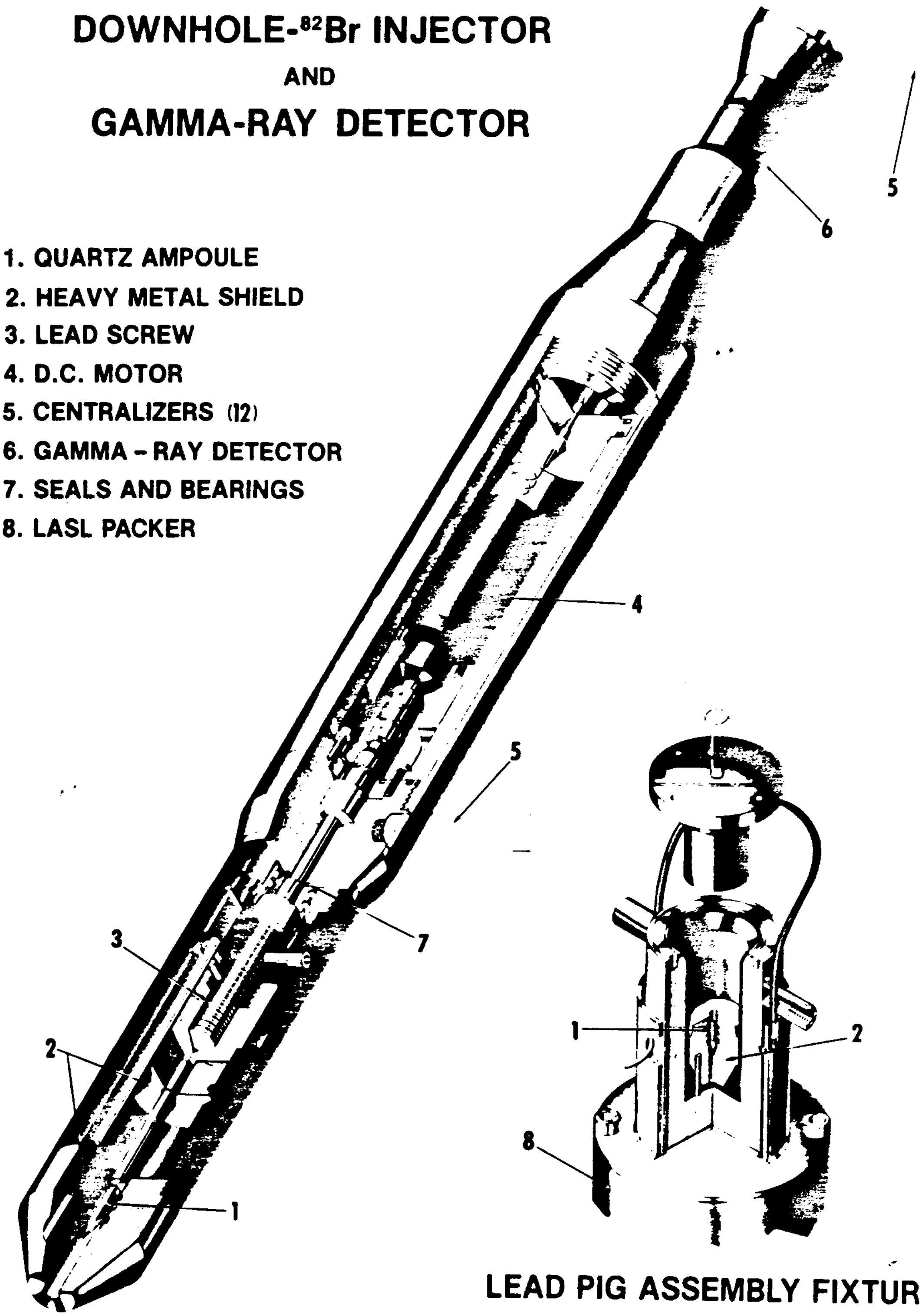

1. BULKHEAD (FEED THROUGH)
2. HIGH TEMPERATURE CONNECTOR
3. INSULATION
4. HEAT SINK (CERROBEND MELTING TEMP. 70 C)
5. INCLINOMETER (2 AXIS)
6. P.C. BOARD (AMPLIFIER & SWITCHING)
7. BATTERY PACK (14 VOLT)
8. DEWAR (STAINLESS STEEL)
9. GEOPHONES (8 HORIZONTAL. 4 VERTICAL)
10. D. C. MOTOR & LEAD SCREW ASSEMBLY
11. LOCKING ARM MECHANISM
12. SHEAR PIN ASSEMBLY
OPERATING ENVIRONMENT
10
1
2
3
4
5
6
7
8
9
11
12
GEOPHONE ACOUSTIC DETECTOR

FIGURE 6.

DOWNHOLE-^{82}Br INJECTOR
AND
GAMMA-RAY DETECTOR

1. QUARTZ AMPOULE
2. HEAVY METAL SHIELD
3. LEAD SCREW
4. D.C. MOTOR
5. CENTRALIZERS (12)
6. GAMMA - RAY DETECTOR
7. SEALS AND BEARINGS
8. LASL PACKER



LEAD PIG ASSEMBLY FIXTURE

FIGURE 7.