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ACOUSTIC SENSOR DEVELOPMENT FOR GEOTHERMAL BOREHOLE TELEVIEWER

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INTRODUCTION

The Borehole Televiewer[1] (BHTV) is a well logging tool which provides an acoustic image of the borehole surface, delineating such important features as wall discontinuities, formation dip, fracture patterns, vugs, and washouts. Demonstrated capabilities include mapping of fracture zones, bedding planes, and other borehole manifestations of the geology. BHTV has also been used in cased wells as an inspection tool to map cavitation, pitting, perforation plugging or enlargement, casing breaches, and other production-related parameters. It is generally agreed that BHTV would be extremely useful during many phases of geothermal resource development.

USGS/Water Resources Department[2] has been conducting field evaluations of BHTV in geothermal reservoirs for some time. Their cooperative efforts with Simplec[3] have resulted in an improved BHTV with extended temperature tolerance. However, efforts to operate the improved tool at temperatures as high as 500°F have been largely unsuccessful to date. The most serious geothermal tool deficiencies appear to be concentrated in the acoustic sensor portion of the tool, as it must withstand direct exposure to the borehole fluid.

Westinghouse[4] is currently under contract with DOE/DGE to develop a geothermal BHTV sensor. Environmental design goals are operation at 275°C (525°F) and 7000 psi and sufficient tolerance to the corrosive borehole fluid. The primary project objective is to demonstrate the operation of a BHTV sensor under simulated geothermal borehole conditions. The developed sensor configuration will follow that of the improved BHTV sensor package so that the resulting technology can be readily incorporated into an experimental geothermal BHTV design.

The basic approach selected is to provide geothermal replacement components for the improved BHTV embodiment rather than completely redesigning the tool. This decision was made for several reasons 1.) sensor problems are essentially materials problems and solutions are considered to be realizable, 2.) the basic BHTV configuration is believed to be functionally effective in geothermal logging, 3.) an improved BHTV tool is available for experimentation, 4.) the approach facilitates relatively low-cost investigation of the usefulness of BHTV in the geothermal environment.

GEOTHERMAL BHTV SENSOR PROBLEMS

The cross section diagram of Figure 1 indicates the various components comprising the sensor. The lead metaniobate piezoceramic disc used to transmit and receive acoustic pulses provides good electroacoustic performance at temperatures exceeding 275°C and therefore is not a problem. The piezoceramic disc is mounted on a damping material to minimize structural reverberation within the tool which could mask weak received signals. The commonly used damping material is absorptive rubber which is unsatisfactory at 275°C and 7000 psi and must be replaced. Efficient acoustic communication between the piezoceramic and the borehole fluid is accomplished through a protective acoustic window and an intermediate coupling fluid. Traditional BHTV windows are fabricated from temperature intolerant elastomers. Recent efforts toward a high temperature window have focused on polyimide plastics such as Vespel by DuPont. While this material has permitted

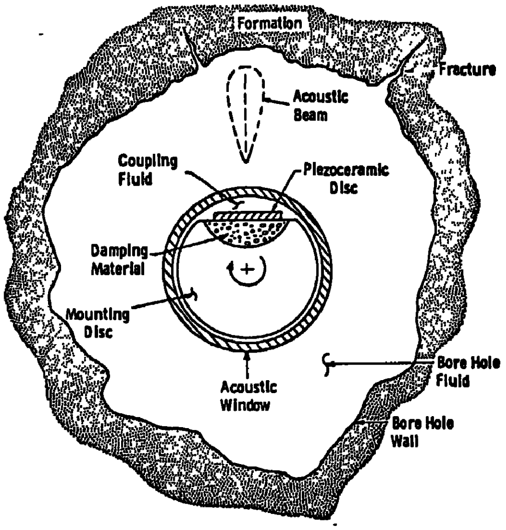

Figure 1 - BHTV Sensor Cross-section

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[1] Patented by Mobil Research & Development Corp.

[2] U.S. Geological Survey-Water Resources, Denver.

[3] Simplec Manufacturing Co., Inc., Dallas, Texas.

[4] Westinghouse R&D Center, Pittsburgh, Pa.

logging in hotter wells, frequent window failure is reported and the window is initially viewed as a likely problem. A typical internal coupling fluid is synthetic lubricating oil formulated for jet engines. The performance of this fluid is considered questionable under geothermal conditions and is therefore viewed as a potential problem.

BHTV SENSOR DEVELOPMENT PROGRAM PLAN

Three phases of 275°C, 7000 psi, simulated borehole fluid autoclave tests are planned. The final phase involves comprehensive performance testing of a working BHTV sensor package. Prior to this, a sensor replica is to be tested to demonstrate all non-acoustic functional requirements. The initial phase consists of screening candidate materials, components, and fabrication methods necessary to conduct the test program.

Supportive investigation and development of appropriate acoustic materials and location of critical mechanical components are to be conducted in parallel with initial autoclave work. Earlier project work had included a detailed study of two improved Simplec BHTV tools. The major purpose was to establish acoustic performance reference data against which our experimental sensor could be compared. The exercise also provided familiarization with tool embodiment and operation.

Phase I - Screening Tests: A special capsule (Figure 2) was designed to expose candidate sensor materials and components to service-simulative conditions. Capsules were fabricated from 6-inch lengths of 1-inch, Schedule 80, SS 316 pipe, threaded on both ends to accept threaded caps. The end caps compress the perimeter of the candidate window material against a series of concentric sealing grooves machined in the pipe end faces. 1-inch diameter axial holes through the center of the end caps provide simultaneous exposure of window materials to internal coupling fluid on one face and autoclave fluid on the other. The capsule interior is charged with various samples of candidate sensor internal components and then filled with a candidate coupling fluid. Total fluid volume was minimized to reduce volume expansion and the accompanying risk of window rupture. This was done by charging the capsule interior with tabular alumina before installing the coupling fluid.

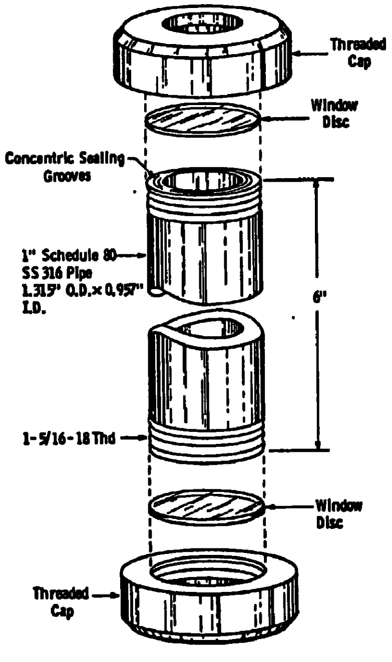

Figure 2 - Assembly diagram of screening test capsule.

Free-flooding capsules were also constructed by replacing the window disc with a perforated stainless steel disc. These capsules were used to evaluate survivability of numerous items requiring direct exposure to the corrosive fluid.

Phase II - Non-acoustic Sensor Tests: Tests are to be accomplished using a replica of the envisioned final form sensor. The replica design is shown in Figure 3 and consists of a SS 316 spool enveloped by a cylindrical shell window. The window will be sealed around the circumference of both end flanges of the spool using a SS hose clamp or equivalent device. The resulting interior chamber will be charged with prototypical transducer assemblies and a coupling fluid. An Inconel bellows will be used to minimize pressure differential across the window as the fluid volume changes. Fill-hole sealing will be accomplished using a metallic or elastomeric o-ring or a Bal-seal. Overall integrity and durability of the replica will be evaluated by testing several versions in the subject autoclave environment.

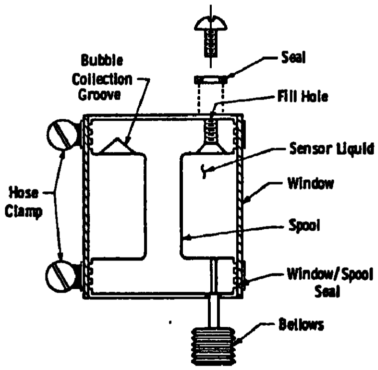

Figure 3 - Cross-sectional view of cylindrical structure comprising sensor replica.

Phase III - Acoustic Sensor Tests: Final tests will be accomplished by providing a special replacement autoclave agitator shaft. This hollow shaft will penetrate the existing packing seal in the autoclave head and will support an operating BHTV sensor package designed around previously demonstrated methods, materials, and components. Sensor leads will be brought out through a special electrical penetration. One or more arrays of stationary acoustic targets (reflectors) will be attached to the autoclave internals. The test concept is indicated in Figure 4.

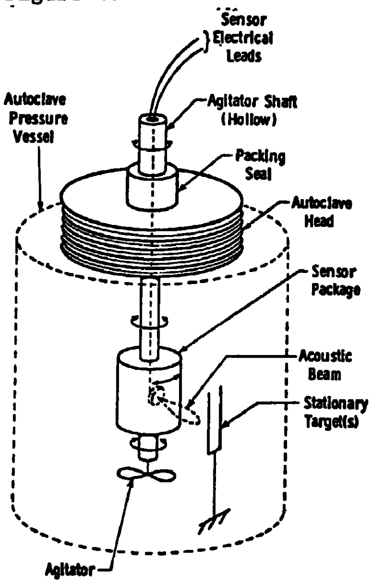

Figure 4 - BHTV sensor evaluation concept.

Since the support shaft permits rotation of the sensor, this apparatus will provide a complete analysis of sensor operation including beam pattern, resolution, and sensitivity measurements. The experimental sensor will be evaluated by comparison with the reference characteristics previously measured on actual BHTV tools.

Satisfactory sensor performance will provide the basis for incorporating the developed technology into an experimental geothermal BHTV tool.

FACILITIES

Autoclave: Fundamental to the development program is availability of specialized autoclave facilities. A commercial autoclave service was located, having a 316 stainless steel vessel capable of achieving 275°C, 7000 psi, and tolerant to simulated geothermal brine. The 10 gallon vessel (Figure 5) is cylindrical with interior dimensions of 11-½" diameter and 19" height. The vessel is resistance-heated from the outside and the internal temperature is controlled by circulating a moderating fluid through spiral wound tubing coils suspended inside the vessel. Continuous or intermittent mixing of autoclave fluid is provided by an agitator affixed to a rotary shaft which penetrates the autoclave head. Temperature and pressure within the vessel can be continuously monitored. An argon cover gas is being used to pressurize the autoclave fluid. Exact volumes of brine and cover gas under room conditions are noted to permit computation of dissolved gas liquid-vapor phase partition at elevated temperature and pressure.

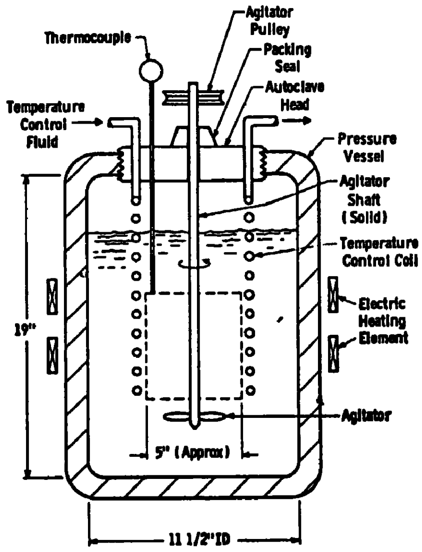

Figure 5 - Cross-section diagram of autoclave.

Simulated Geothermal Brine: Of similar importance was formulating an autoclave fluid representative of the borehole environment. DOE/DGE provided the essentials of a recipe developed for similar evaluations of other geothermal components (elastomers). The following composition is being used:

H_2O = 990 g/l
NaCl = 25.4 g/l
$NaHCO_3$ = 1.94 g/l (0.023 M)
$Na_2S \cdot 9H_2O$ = 2.15 g/l (0.00895 M)
HCl(1M) = 41.0 ml/l (0.041 M)

MATERIALS AND COMPONENTS EVALUATED

Acoustic Windows: 1.) Kalrez high-temperature elastomer by DuPont, 2.) ALFAS-150 high-temperature elastomer by ASAHI Glass Co., 3.) Vespel polyimide by DuPont, 4.) TFE Teflon by DuPont, 5.) Graphite-carbon-glass-filled TFE Teflon supplied by Bal-Seal Engineering, 6.) PFN phosphazene supplied by Firestone Tire and Rubber.

Coupling Fluids: 1.) Mobil Jet Oil II, synthetic jet engine lubricant, 2.) Dow Corning DC-210H Silicone oil, 3.) DC-550 high-phenyl silicone oil, 4.) DC-710 high-phenyl silicone oil.

Transducer Assemblies: Rudimentary transducers were constructed consisting of pieces of silver-electroded lead metaniobate bonded to three candidate damping materials using EPOTEK H-20E electrically conductive epoxy. Candidate backing materials were tungsten-filled Stycast 2762FT epoxy, tungsten-filled Duralco 700 epoxy, and a novel tungsten-filled refractory cement. All three materials exhibit excellent damping properties.

Potting/Encapsulating Materials: Cubical samples of two high-temperature epoxies were fabricated, Stycast 2762FT and Duralco 700.

Insulated Wire: Specimens included Mica-glass insulated nickel, silicone dioxide insulated nickel, TFE Teflon insulated copper, FEP Teflon insulated copper.

An assortment of other interesting materials were also evaluated over the course of the screening tests: ethylene propylene (elastomer), Astrel 360 (3M-plastic), Polybutadiene, doryl-glass-mica, 304 SS, Inconel 718, a bellows sample, two Bal-Seals, and 316 Swagelok tubing couplings.

AUTOCLAVE TEST CYCLE

The temperature of the autoclave-liquid system is first slowly raised to 250°F during an overnight period of 12 hours, while the pressure is maintained at 100 psig. The temperature of the autoclave-liquid system is next raised to 525°F over a 7 hour period, during which time the autoclave liquid is continuously stirred. During this time the autoclave pressure rises of its own accord from 100 to 1200 psig. With the autoclave fluid temperature at 525°F, argon gas is used to increase pressure from 1200 to 7000 psig. The total elapsed time from the start of initial heating to the attainment of 525°F, 7000 psig test conditions is 19 hours. The next three hours of testing can best be described as a test-condition stabilization period. The last 14-½ hours of testing can be described as being the specified test period itself. During this time the pressure and temperature are maintained at 7000 psi and 525°F, respectively.

PROJECT STATUS AND RESULTS

Two iterations of screening tests have provided sufficient data for design of the sensor replica. At this time, replica design is complete and components are being fabricated. The following materials, components, and fabrication techniques have been selected for the sensor replica.

Acoustic Window: TFE Teflon, selected for its superior retention of mechanical properties combined with attractive acoustic properties. Carbon- and graphite-carbon-glass-filled TFE Teflon is also being considered but is expected to be more porous.

Coupling Fluid: All four fluids tested appear to be equally satisfactory. Mobil Jet Oil II is slightly favored since it has been successfully used at elevated temperature in direct contact with auxiliary sensor components such as the motor and slip rings. The four subject coupling fluids will be carried over into sensor replica testing.

Transducer Assembly: Lead metaniobate piezoceramic will be used exclusively with silver electrodes replaced by gold. Damping material will be tungsten-loaded refractory cement, selected for its inherent immunity to the environment, its excellent acoustic loss characteristics, and machineability. Piezoceramic elements will be bonded to damping blocks using EPOTEK H-20E electrically conductive epoxy.

Miscellaneous: An Inconel bellows is being incorporated into the replica design to minimize differential pressure across the acoustic window. The bellows will be connected to the replica housing using 316 SS Swagelok tubing fittings. A stainless steel hose clamp is being used to provide the sealing force between the Teflon window and concentric grooves around the housing. TFE Teflon Bal-Seal will be used to seal the fluid fill-hole.

Other screening test results of general interest are as follows: Vespel, the acoustic window material presently used for improved BHTV, virtually disintegrated over the subject test cycle. All non-Teflon plastics and elastomers evaluated are judged unsuitable as acoustic windows. Kalrez sheet exposed to autoclave fluid swelled approximately 100%. Astrel 360 was totally consumed. The two epoxies tested varied from partially to totally consumed. 316 SS Swagelok tubing couplings have provided excellent seals against the autoclave fluid.

CONCLUSIONS

The objective of this work is to demonstrate feasibility of a BHTV sensor having sufficient durability for geothermal use. Results to date indicate that suitable materials, components, and construction methods are available for achieving that goal. Confidence is sufficiently high to permit preliminary design of the Phase III test apparatus. Figure 6 indicates a cross-section of the apparatus which is expected to provide the final sensor verification tests.

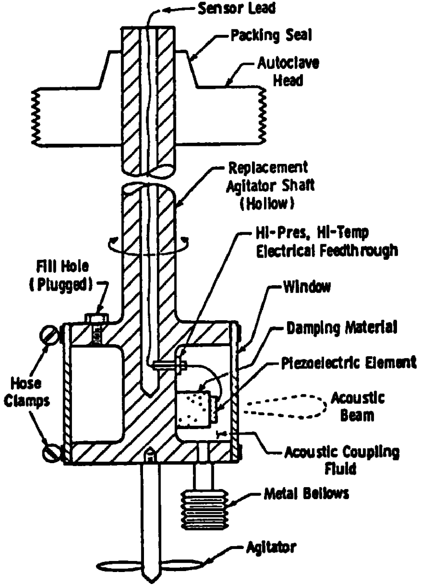

Figure 6 - Apparatus concept for geothermal BHTV sensor feasibility tests.