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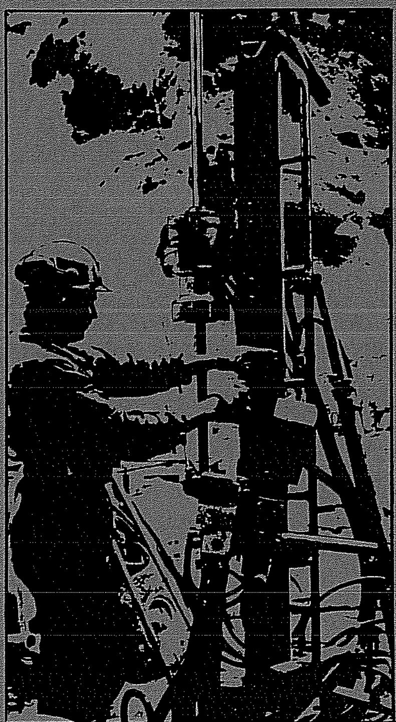
SAC-13

SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Information Report No. 13

ELECTRICAL HEATERS FOR THERMO-MECHANICAL TESTS AT THE STRIPA MINE

R. H. Burleigh, E. P. Binnall, A. O. DuBois,
D. U. Norgren, and A. R. Ortiz

January 1979

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January 1979

PREFACE

This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL).

The principal investigators are L. B. Nilsson and O. Degerman for SKBF, and N. G. W. Cook, P. A. Witherspoon, and J. E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previously published technical reports are listed below.

1. Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns by P. A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).

2. Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test by Lars Lundstrom and Haken Stille. (LBL-7052, SAC-02).

3. The Mechanical Properties of the Stripa Granite by Graham Swan. (LBL-7074, SAC-03).

4. Stress Measurements in the Stripa Granite by Hans Carlsson. (LBL-7078, SAC-04).

5. Borehole Drilling and Related Activities at the Stripa Mine by P. J. Kurfurst, T. Hugo-Persson, and G. Rudolph. (LBL-7080, SAC-05).

6. A Pilot Heater Test in the Stripa Granite by Hans Carlsson. (LBL-7078, SAC-06).

7. An Analysis of Measured Values for the State of Stress in the Earth's Crust by Dennis B. Jamison and Neville G. W. Cook. (LBL-7071, SAC-07).

8. Mining Methods Used in the Underground Tunnels and Test Rooms at Stripa by B. Andersson and P. A. Halen. (LBL-7081, SAC-08).

9. Theoretical Temperature Fields for the Stripa Heater Project by T. Chan, Neville G. W. Cook, and C. F. Tsang. (LBL-7082, SAC-09).

10. Mechanical and Thermal Design Considerations for Radioactive Waste Repositories in Hard Rock. Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Wastes by Neville G. W. Cook; Part II: In Situ Heating Experiments in Hard Rock: Their Objectives and Design by Neville G. W. Cook and P. A. Witherspoon. (LBL-7073, SAC-10).

11. Full-Scale and Time-Scale Heating Experiments at Stripa: Preliminary Results by Neville G.W. Cook and Michael Hood. (LBL-7072, SAC-11).

12. Geochemistry and Isotope Hydrology of Groundwaters in the Stripa Granite: Results and Preliminary Interpretation by P. Fritz, J.F. Barker, and J.E. Gale. (LBL-8285, SAC-12).

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ABSTRACT

Electrical heaters were installed at the Stripa mine in Sweden to simulate the heat flux expected from canisters containing nuclear waste. Three heater types were designed and fabricated: two full scale heaters, 2.6 m in length and 324 mm in diameter, supplying a maximum power output of 5 kW; eight peripheral heaters of 25 mm diameter, supplying 1.1 kW; and eight time scale heaters, one-third the size and power of the full scale heaters. The heater power can be monitored by panel meters as well as by a computer-based data acquisition system. Both the controller and the heater were designed with a high degree of redundancy in case of component failure. Auxiliary items were provided with the heaters to monitor borehole decrepitation and heater temperature, and to dewater the heater holes. This report describes the above systems and relates experience gained during testing, installation, and operation.

1. INTRODUCTION

An inactive iron mine at Stripa, Sweden is the site of a group of cooperative Swedish-American experiments designed to evaluate the suitability of a deep granite stratum as a permanent repository for nuclear waste. The nuclear waste is assumed to be packaged in cylindrical metal canisters which would be lowered into holes bored into a mine floor. Heat is generated in such containers as a result of the continuing decay of the radioactive waste. One phase of the Stripa experimental program evaluates the thermo-mechanical response of the surrounding rock mass to this predictable heat flux. Witherspoon & Degerman (1978) provide an overview of the Stripa program.

Three distinct experimental areas have been outfitted with electrical heaters which simulate the heat loads from waste containers. The first experiment was energized on June 1, 1978, the second in July, and the third in August. Although the heaters are scheduled to run for a period of at least one year, preliminary results have been discussed by Cook and Hood (1978). These results are based upon mechanical and thermal instrumentation (Schrauf et al., in preparation) placed in boreholes surrounding the heaters. Kurfurst, Hugo-Persson, and Rudolph (1978) show the borehole geometry for the heaters and associated rock instrumentation. McEvoy (in preparation) describes the data acquisition system to acquire and record the measurements and the heater power levels.

The electrical heaters are of three types: 1) full scale; 2) peripheral; and 3) time scale. The full scale heaters are designed to duplicate one of the possible geometries (324 mm diameter x 2.6 m long) of a single waste container, and to provide a heat load of up to 5 kW. Two such heaters have been installed within the mine. One heater will operate as a single isolated unit and the second will operate within the thermal field of eight peripheral heaters.

The peripheral heaters are small diameter (25 mm), 1.0 kW units whose heat output simulates the thermal environment that would surround a typical waste container located within a large field of containers. Eight of these peripheral heaters are installed in a 0.9-m-radius circular array around one full scale heater.

A group of time scale heaters are installed at a separate location within the mine. These heaters are approximately one-third the size and power of the full scale heaters. Modeling laws were used to select a scaling factor and the heater spacing that would create a thermo-mechanical response with a time constant one-tenth that for a full scale heater. Eight of these time scale heaters are arranged in a rectangular array to simulate the heat load and distribution of a large field of waste storage cylinders.

The principal elements of each heater installation are:

a. a vertical borehole in the mine floor for receiving the heater assembly;

b. a cylindrical enclosure (canister) which houses the electrical heater elements;

c. the electrical heater elements;

d. the electrical leads;

e. an upper tube to support the canister and the leads;

f. a thermal insulation plug to prevent heat loss up the borehole;

g. a power control and monitoring system.

The following auxiliary features are provided for some heaters:

h. temperature monitoring equipment;

i. a borescope and guide tubes for inspecting the borehole wall;

j. decrepitation sensing apparatus;

k. dewatering apparatus to remove either liquid or steam from the borehole.

2. FULL SCALE HEATERS

Design Criteria

a. Simulate a 324-mm (12-3/4")-diameter x 2.6-m (8'6")-long cylindrical canister filled with nuclear waste material, buried at the bottom of a 406-mm (16")-diameter x 5.5-m (18')-deep borehole in a hard granitic rock. Thermal output of the nuclear waste material will not exceed 5 kW.

b. Heater power will be provided by a 220 V, 50 Hz source. Heat will be uniformly distributed along the length of the canister, and centered 4.25 m (14') below the floor of the drift.

c. Provide maximum redundancy in case of heater element failure. Design equipment for a test duration of two years minimum.

d. Estimated maximum temperature of the wall of the borehole is approximately 500°C.

e. Provide thermocouples for monitoring the temperature of the canister.

f. Provide means for viewing certain internal features and the bottom of the cylindrical tank.

g. Provide thermal insulation to minimize heat loss up the borehole.

h. Design for installation in a drift having limited (5 m) ceiling clearance.

i. Design for easy removal from the borehole at the conclusion of the test.

j. Provide a dry collar surrounding the top of the rock borehole to prevent water on the tunnel floor from entering the borehole.

k. Design the equipment for air shipment.

l. Provide for viewing the heated portion of the borehole with a borescope.

m. Provide equipment to remove water and steam from the annular space between the cylindrical tank and the borehole, and to measure the incoming flow rate.

n. Provide wiring to monitor voltage drop directly across the heater elements, for accurate power measurements.

Chan, Cook, and Tsang (1978) describe the computer modeling which was used to predict the time vs. temperature history for a granite borehole subjected to a 5 kW continuous heat load and 8 kW of peripheral heat. Maximum borehole temperature of 500°C after two years was predicted by this model, using preliminary thermal properties for granite. This value was used as a boundary condition for design of the full scale heater. At this temperature, the dominant heat transfer mode, for a dry hole, is radiant. For the 500°C borehole, a maximum canister temperature of 527°C was predicted, based on an emissivity of 0.9 for the borehole and 0.7 for the oxidized stainless steel tube, and on a geometry factor of 0.8 for the concentric tube geometry. After laboratory measurements of the thermal properties of Stripa granite were available, the borehole temperature calculations were repeated. The limiting borehole temperature of 380°C predicted in this second iteration arrived too late to be considered in the heater design.

The installation of a full scale heater is shown in Fig. 1. The assembly is constructed in a modular fashion (Fig. 2) to facilitate its installation with limited overhead clearance, and to provide sub-units conveniently sized for shipping to a remote location.

The cylindrical heater enclosure (Fig. 3) used to simulate a waste canister is AISI 304 stainless steel, nominal 12", schedule-10 pipe. The actual outside diameter is 324 mm (12.75"), wall thickness 4.57 mm (0.18"), and length 2,590 mm (8'6"). It is closed at the bottom with a welded plate (with a small drain hole), and at the top by a demountable flange which is part of the heater element support.

Two 16-mm (0.63")-diameter thermocouple mounting tubes are provided along the inside wall of the canister. These tubes are parallel to the centerline of the canister and are welded to it. Prior to lowering the canister into the borehole, three type K (chromel-alumel) thermocouples are inserted in each tube. These extend to three different levels along the canister wall. Each thermocouple is mineral insulated inside an inconel sheath of 1.6 mm (0.065") diameter. As the leads from each set of three thermocouples emerge from the 16-mm-diameter tubes at the top of the canister, they enter flexible stainless-steel conduits. These flex conduits carry the leads to a thermocouple extension-wire transition junction near the top of the borehole. The type

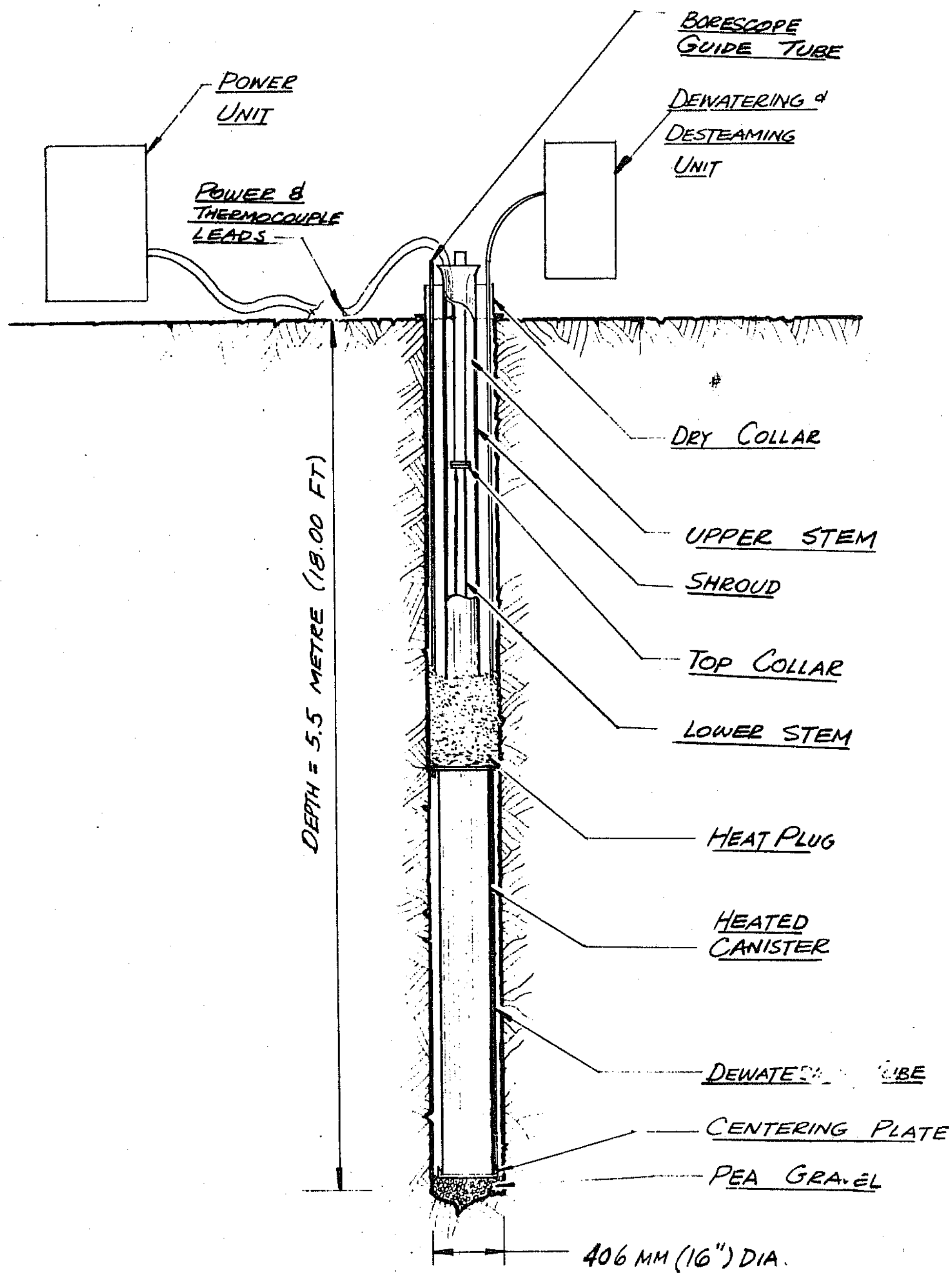

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Fig. 1. Full scale heater installation.

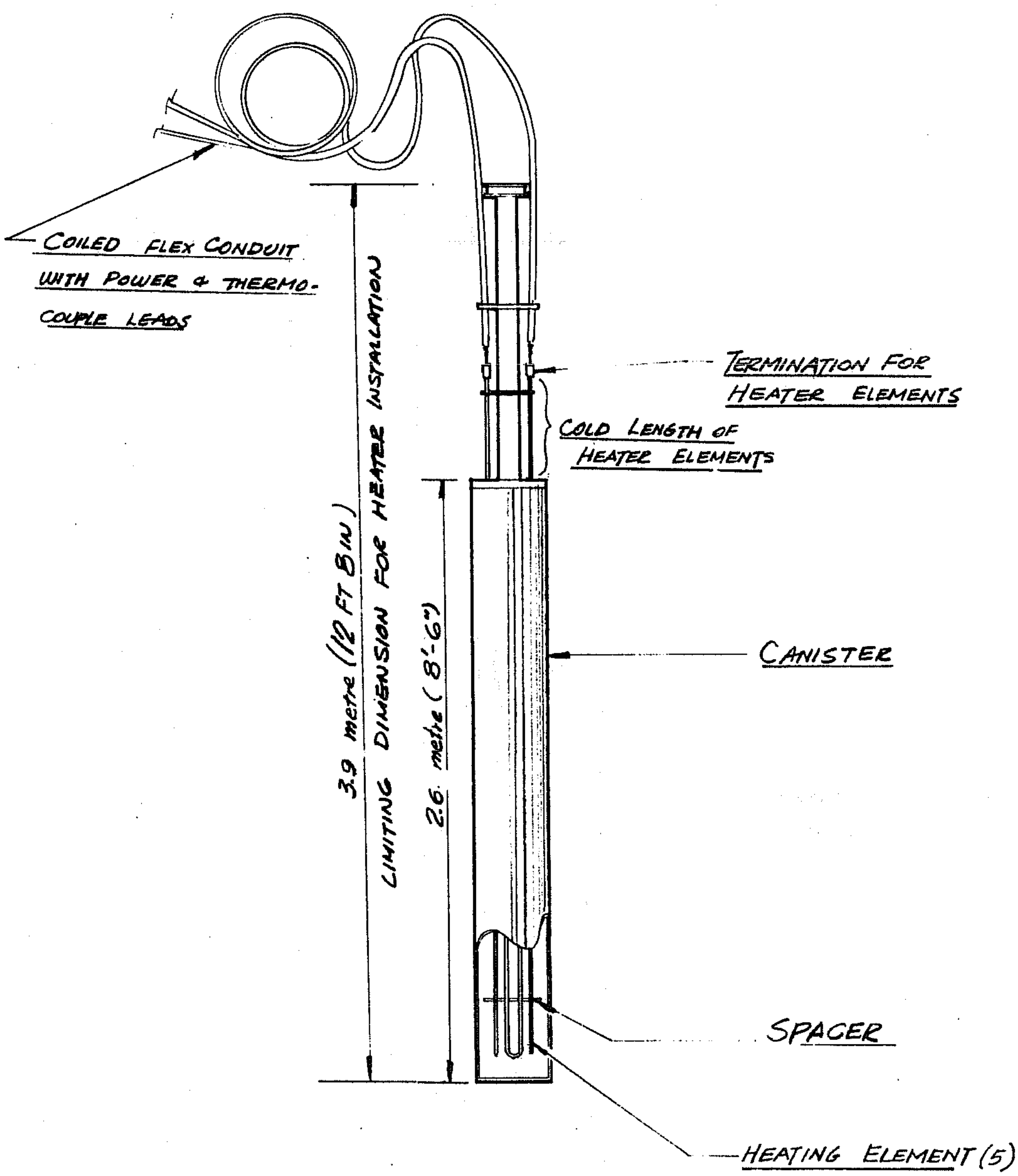

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Fig. 2. Full scale canister assembly ready for lowering into a borehole.

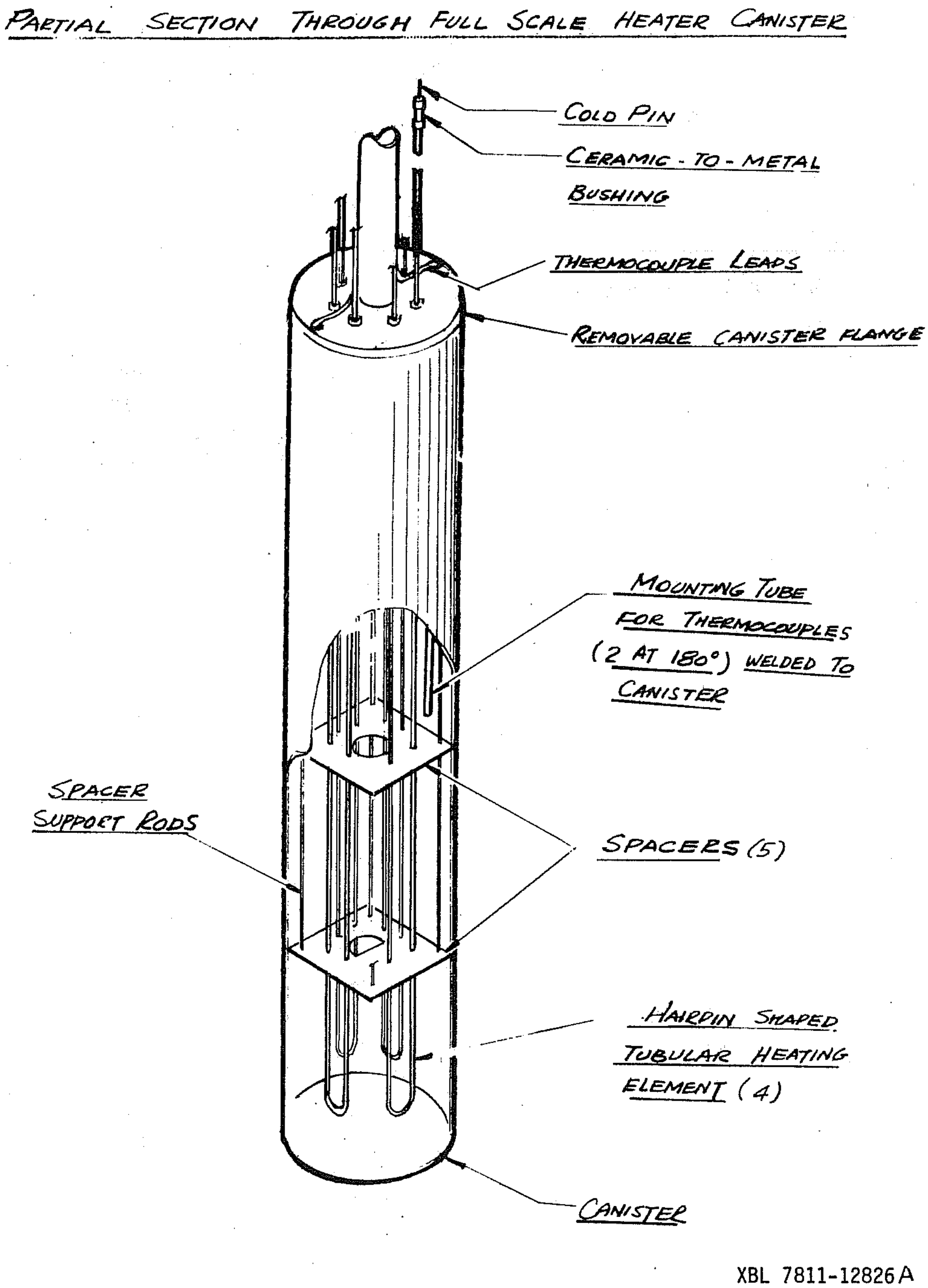

Fig. 3. Partial section through a full scale heater canister.

K extension wire then goes directly to an ice point reference located in the instrumentation racks.

Four separate electrical heating elements are suspended (in air) into the simulated waste canister (see arrangement shown in Fig. 3). Each heating element is in the form of a long hairpin. These elements are of a standard, commercially available type of construction. They are manufactured with a 12.5-mm (0.5")-diameter nickel alloy (Incoloy 800) sheath, mineral insulation, and a coiled central resistance wire. Each leg of the hot section has a 2.44 m (8') "hot" length plus a 1.20 m (47") "cold" length, and is terminated with hermetically sealed, high-temperature ceramic insulating bushing between the tubular shield and the nickel cold pin. The heating element is supported from a nickel-alloy collar brazed to each cold leg.

The total design load for the four heating elements is 5,000 W, normally portioned into 1,250 W per element. Each element is capable of delivering up to the full 5,000 W, to maintain program power in the event of failure of one or more heater elements.

Several tests were performed to verify the quality of each heater element. These tests consisted of:

- radiographic examination to verify that the mineral insulation (MgO) is free of metallic inclusions and voids, that the welds are sound, and that the resistance wire and cold leads are properly centered.
- cold resistance check for continuity and uniformity. Resistances were in the range of 10.8 to 11.0 Ω.
- measurement of insulation leakage current at 1,500 V. Measured leakage was in the range of 5 to 30 μA.

- before assembly into a canister, bench test for one hour at full 5,000-W power level, with thermal insulation surrounding the element to raise the sheath temperature to 700°C.
- over 400 hours operation in a simulated borehole.

The maximum heating-element sheath temperature of 605°C has been calculated for the case of a single heating element energized at 5 kW when mounted in a 527°C canister. Emissivities of 0.8 for the sheath and 0.7 for the canister, and a geometry factor of 0.7 for the enclosed ring of heater elements, were used to predict a maximum temperature of 605°C for the heater sheath. The long "cold" length of the element passes through a heat plug to locate the terminal connections in a zone which is well isolated from these maximum temperatures.

Attached to each cold pin of a heating element are two power leads, to provide redundancy and a conservative current density; plus a voltage sensing lead, to provide for measuring the net downhole power and to monitor power lead conditions. The voltage sensing lead is attached to the heater cold pin at a point below the power lead attachment (Fig. 4).

Since heater terminals are often trouble spots, particular care was taken to provide a conservative design for these connections. They must withstand ambient temperatures up to 200°C and a moist environment, while maintaining their mechanical and electrical integrity over a long period of time. A nickel ring was crimped around the cold pin and the leads to provide a strong mechanical joint. To assure that oxidation products could not build up between the leads and the cold pin, this crimped joint was brazed with a copper-silver alloy. The brazed joint was

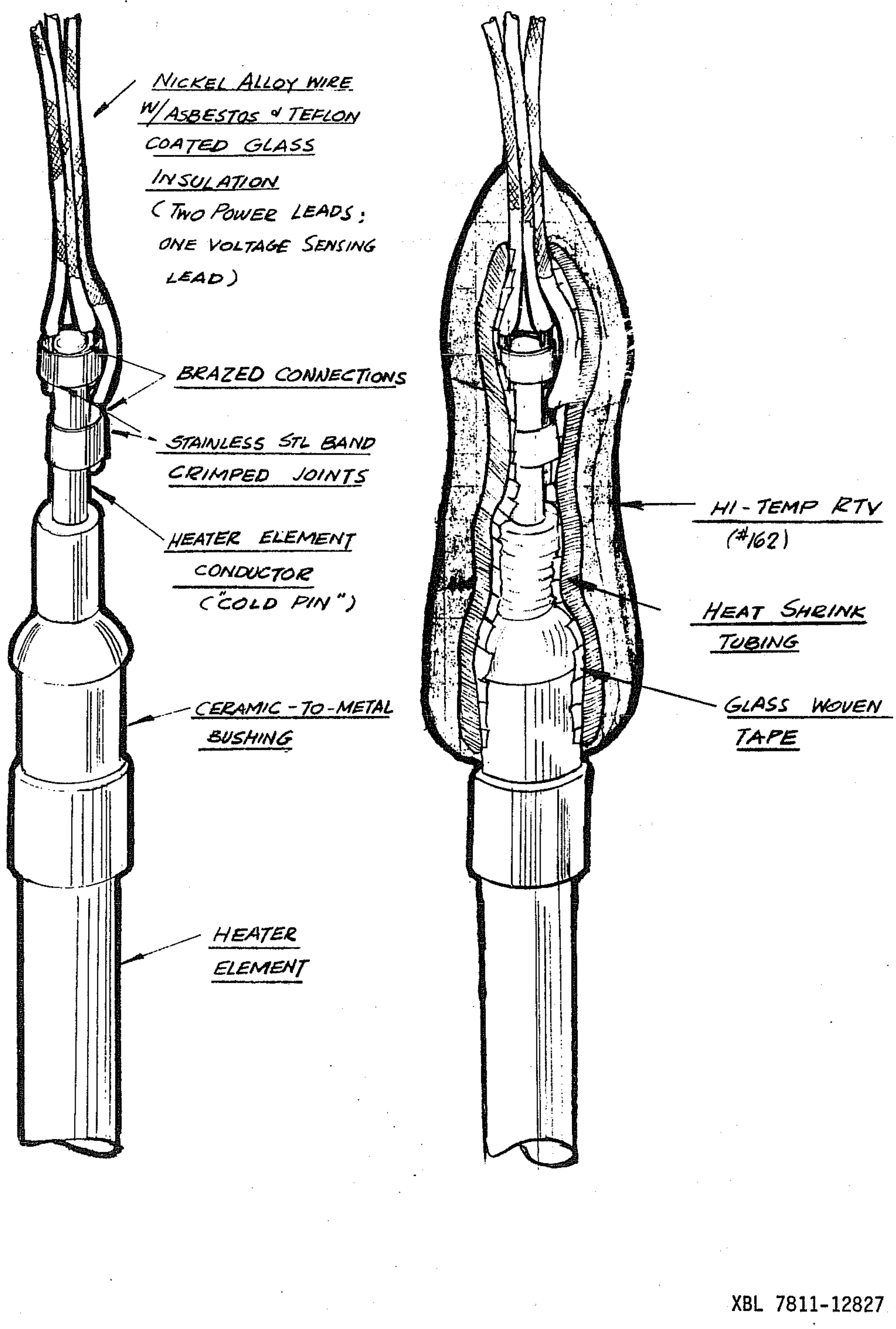

Fig. 4. Typical heating element connection:
(a) bare connection
(b) insulated connection.

wrapped with glass-woven tape and secured with a heat-shrink Teflon tube. The insulated joint was encased in a layer of silicone rubber (G.E. RTV-162) for waterproofing. This high-temperature silicone compound was selected because it cures without producing acetic acid.

A variety of lead wire constructions were evaluated, including solid or stranded wire, copper, nickel-plated copper, or alloy wires, as well as ceramic bead, sleeve type, or braided type insulation. The lead construction selected was stranded #12 nickel-alloy wire with Teflon tape plus asbestos and Teflon-coated glass braid insulation (see element "B" in Table 1). This lead wire is rated for 600 V operation at 250^{o}C. The alloy was selected because it is more resistant than copper to corrosion at elevated temperatures. While the electrical resistance of the alloy is substantially higher than that of copper, the power loss in the leads is negligible. The Teflon and braid insulation is compact, flexible, low in friction, and suitable for long life at elevated temperatures.

To verify the ability of this insulation to resist a high temperature, moist environment, a 10-m length of the lead wire, with 110-V AC applied, was placed in a 70^{o}C salt solution for 72 hours and, later, in a 70^{o}C cupric sulfate solution for 96 hours. In both cases the leakage from conductor to test container remained less than the minimum sensitivity (5 mA) of the instrumentation. For protection against mechanical abuse, all leads are encased in flexible, stainless-steel conduits. These flexible conduits are anchored, to isolate them from strain, at a collar 100 mm (4") above the heating element terminal.

Each heater assembly was operated in a simulated borehole for a minimum of 408 hours with 1,250 W applied simultaneously on all four elements, plus 24 hours with each element singly at 5,000 W. Typical temperatures reached were 540°C on the canister wall and 150°C at the heater element connection. All leads tested (Table 1) showed little or no heat effect; however, the ease of installation was markedly better for the asbestos Teflon-glass braid insulation.

Table 1. Voltage drop for 7.6 m (25') lead wire.

Element	Wire type	Insulation	Voltage drop @ 5 kW
A	Copper 2-#12	Asbestos Teflon-glass	0.7
B	Ni-alloy 2-#12	Asbestos Teflon-glass	1.3
C	Ni-alloy 1-#12	Asbestos	2.4
D	Ni-alloy 1-#12	Ceramic bead	2.5

The tubular heater-assembly stem (Fig. 5) is constructed in two parts. The lower part, with heating elements and leads, is attached to the canister at the time of original assembly. The upper part of the stem is attached after the canister is lowered part way into the borehole. The demountable arrangement allows the heater assembly to be installed within a drift which has 4.5 m (15') of vertical clearance. This stem provides:

- support for the heating elements
- support for the electrical leads
- support for the thermocouple leads
- clearance for the optical pyrometer view line

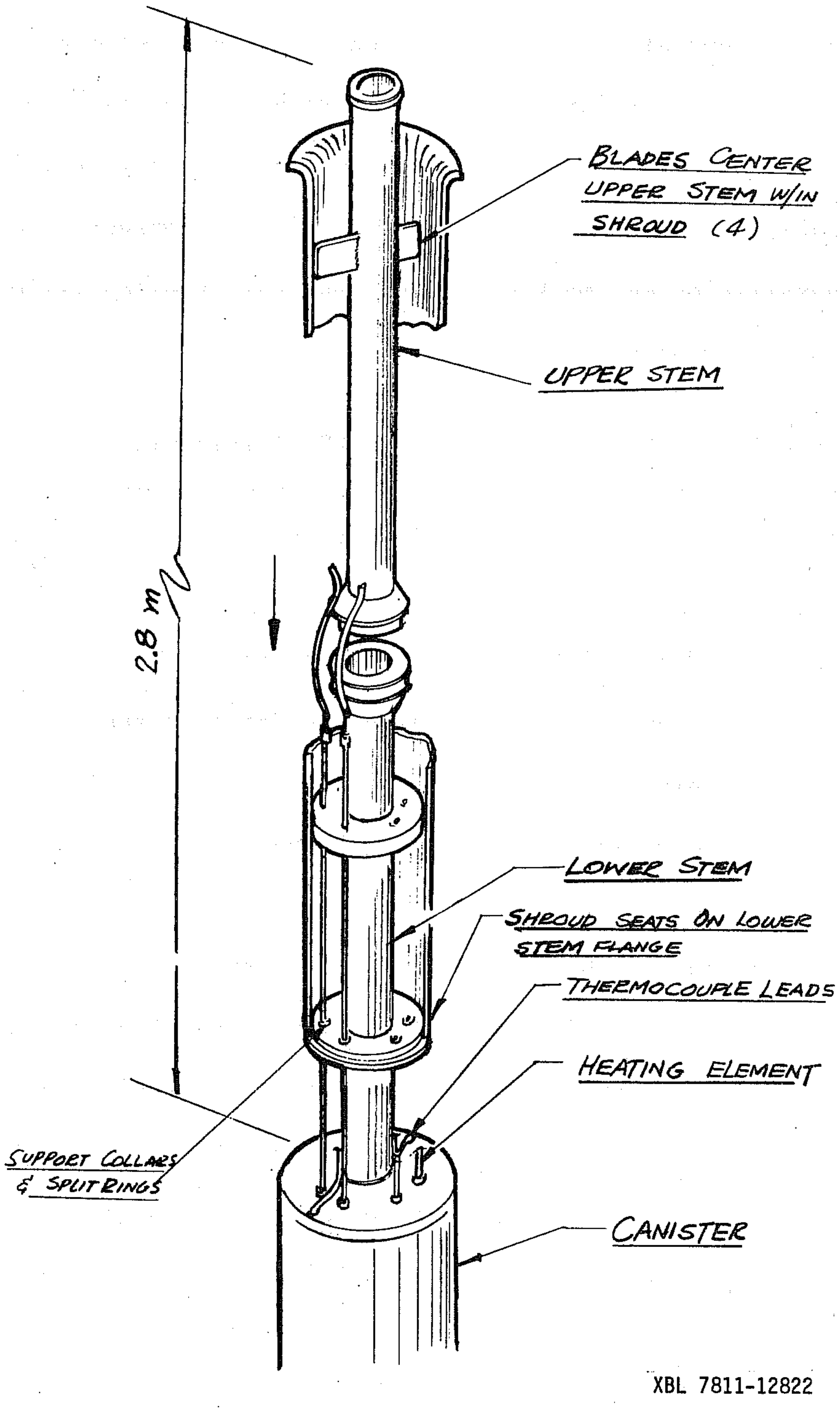

Fig. 5. Full scale heater stem showing mounting of the upper stem and shroud.

- means for supporting the canister as it is lowered into the borehole.

A ring-shaped thermal insulation layer (Fig. 6) rests on top of the canister to block convective heat transfer up the annular region between the tabular stem and the borehole. This heat plug consists of:

- a wire screen fastened to the top of the canister
- a layer of wire-reinforced asbestos cloth, fastened to the top of the canister
- a 300-mm (12")-thick layer of vermiculite--a granular high temperature insulation--poured into place after canister installation.

During normal heater operation a cylindrical plug is lowered into the tabular stem to prevent convective heat loss. When this plug is temporarily removed, a clear optical pyrometer viewline is available from the top of the borehole into the interior of the canister. This viewline intercepts a portion of one of the sheet-metal spacers which are positioned along the heating elements (Fig. 3) and the bottom of the canister.

At the top of the borehole, a metal collar is grouted in place with portland cement, to prevent surface water from entering the hole. Radial screws in this collar center the stem within the collar. Four struts, which are clamped onto the top edge of the collar, support the upper ends of four vertical guide tubes. The lower ends of these tubes terminate just below the thermal insulation layer. Either a borescope or a dewatering tube may be passed down these guide tubes into the annulus between the canister and the borehole.

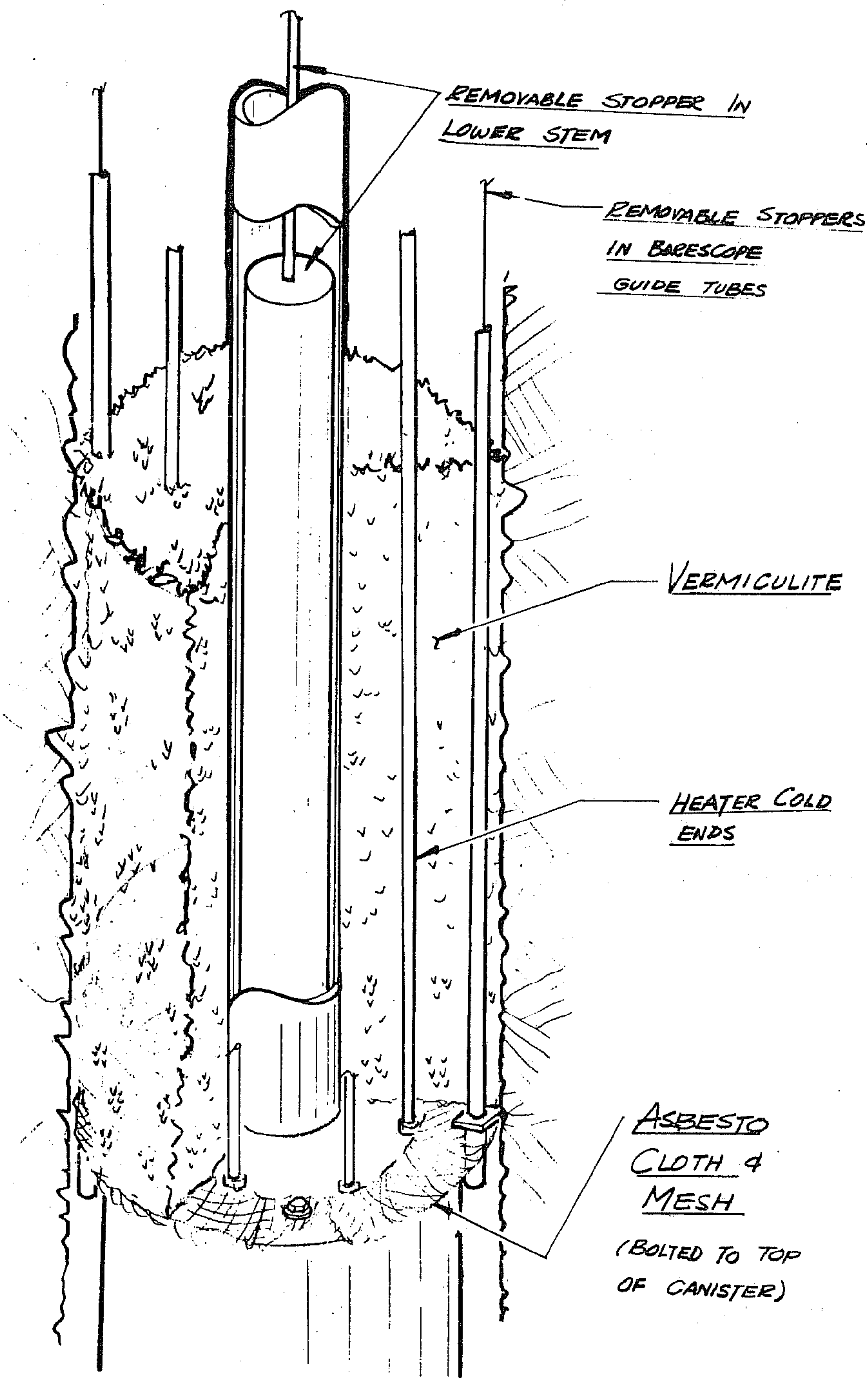

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Fig. 6. Details of heat plug for full scale heater.

3. PERIPHERAL HEATERS

The peripheral heaters (Fig. 7) are much simpler than either the full scale or the time scale heaters. They include no downhole instrumentation or dewatering apparatus.

Design Criteria

a. Mount in a 38-mm (1.5")-diameter x 6.4-m (21.1')-deep borehole.

b. Provide 1,100 W of heater power over a 4.3 m (14') length--centered in the same horizontal plane as the center of the full scale heater.

c. Provide a single heating element to mount inside a protective housing, with provision for easy replacement.

d. Estimated maximum borehole temperature is 235°C.

The peripheral heaters do not utilize a canister, but do incorporate a protective housing which occupies the full length of the borehole. This protective mounting tube is made in two parts, for installation where there is limited overhead clearance. The lower section is a type 304 stainless-steel pipe (27 mm or 1.05" o.d.) with a chamfered plug welded into the bottom, and a collar having external threads welded to the top. This collar mates with an internally threaded collar welded onto the lower end of the upper tube. A rubber gasket is assembled between the collars, for a water-tight joint. The upper tube is larger (42 mm or 1.66" o.d.) to provide clearance for the electrical heating terminals.

This style of heater assembly uses two linear heating elements joined together at the bottom. This assembly is rated for operation at up to 1,500 W and, in case of failure, it can be quickly replaced. It is similar to the heating elements in the full scale heater,

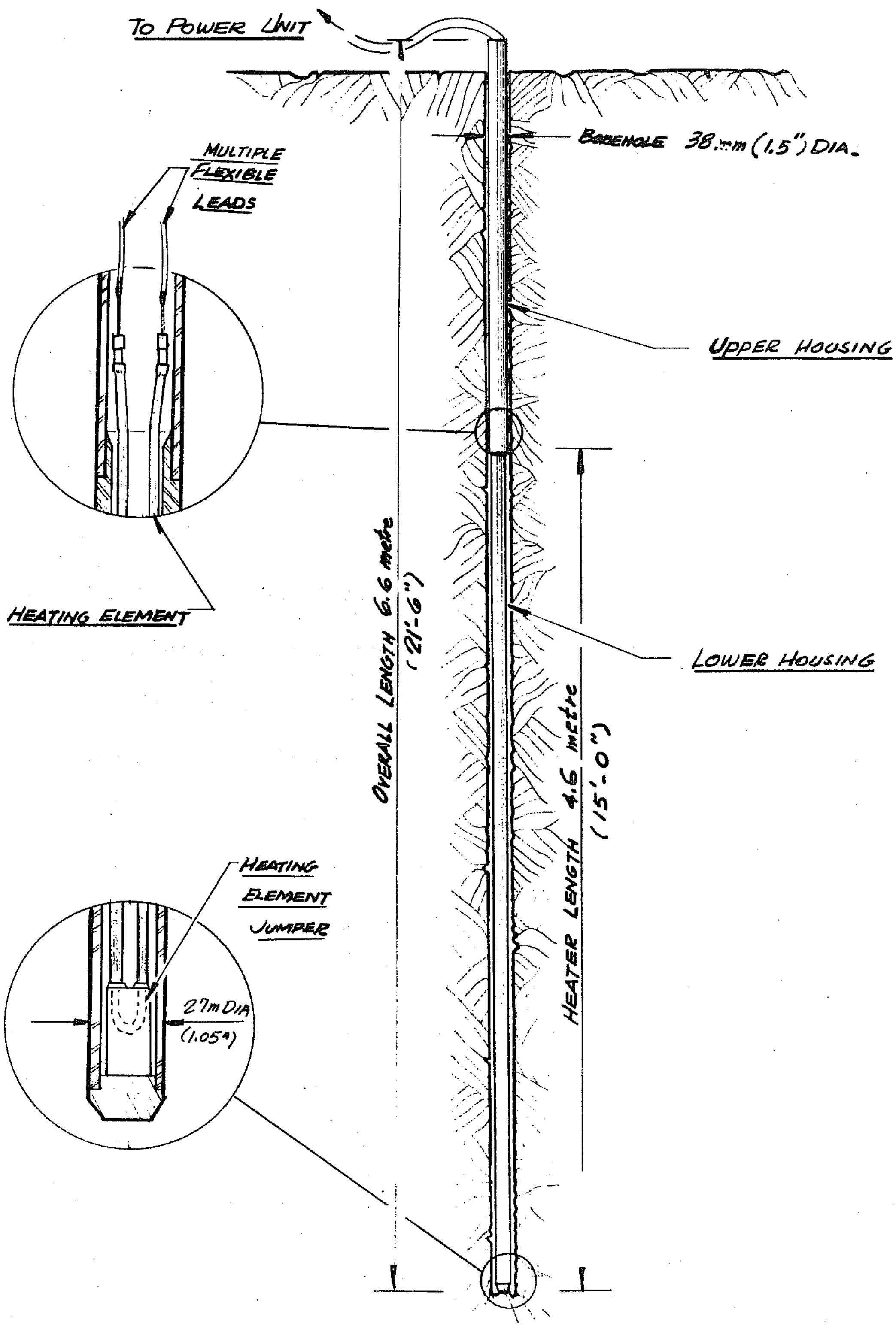

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Fig. 7. Peripheral heater installation.

except that the return bend is replaced by a cylindrical stainless-steel junction box within which the two legs are welded. This change was required because the housing did not provide enough space to accomodate a "U" bend. Sheet metal discs are welded to the legs at four locations along their length, to space them within the protective mounting tube. Each disc has two additional holes so that thermocouples could be inserted if desired. These peripheral heater elements operate in a lower temperature environment than do the full scale heaters, and require a "cold" length of only 300 mm (12") to separate the terminals from the hot zone.

The leads, connections, and protective flex conduit are similar to those described for the full scale tests (see Section 2).

4. TIME SCALE HEATERS

A time scale heater (Fig. 8) is a simplified version of a full scale heater, and approximately one-third of its size. There are eight basically identical time scale heaters. Minor variations are noted in Table 2.

Design Criteria

a. Mount in a borehole which is 125 mm (5.0") diameter x 11 m(36') deep.

b. Maximum predicted borehole temperature is 210^{o}C.

c. Heat to be uniformly distributed over 0.76 m (30") of borehole length centered at 10.2 m (33.5') below the floor of the drift.

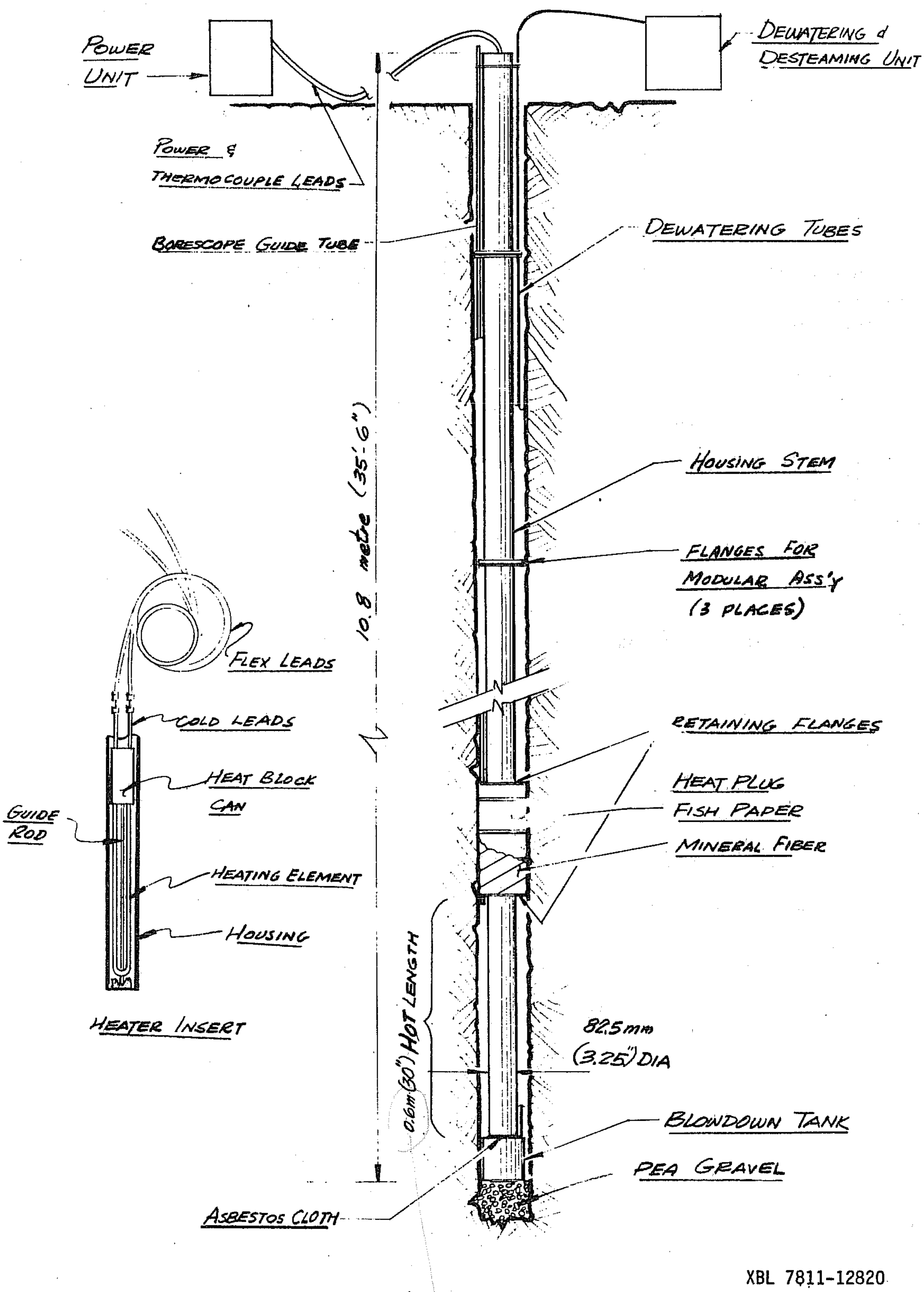

Fig. 8. Time scale heater installation.

Table 2: Variable features of time scale heaters.

Heater number	Special instrumentation[a]	No. borescope guide tubes	Housing length[b]	Blowdown tank volume[a] (liter)
1	caliper	3	10.7	1
2	none	1	11.1	3
3	weigh pan	3	10.7	1
4	none	1	10.3	1
5	none	1	10.7	1
6	none	1	10.7	1
7	none	1	10.7	1
8	none	1	10.7	1

[a]Described in Section 5.5.

[b]This is a length adjustment to compensate for uneven and sloped floor in the drift. The centers of the heated lengths of all of the heaters are located in the same horizontal plane.

d. Use two heating elements for 1,100 W total load, with leads as constructed for the full scale heater. Each element is to be capable of handling the full load.

e. Design for a test duration of two years minimum.

f. Minimize heat loss up the borehole.

g. Design for installation in a drift having a 5 m roof clearance.

h. Design for easy removal of heating elements from the borehole.

i. Provide thermocouple monitoring of the temperature of the protective heater housing.

j. Provide equipment to remove water and steam from the annular space between cylindrical heater housing and the borehole, and to measure the flow rate.

k. Provide means for optically inspecting the heated portion of the borehole with a borescope.

Although the time scale heaters are reduced size simulators of the full scale heaters, the details of construction are different. For example, the time scale heater housing extends the full length of the borehole. This housing is made in four sections of 82.5-mm (3.25")-diameter stainless steel tube. These sections are bolted together by their welded end-flanges at the time of installation.

To accomodate out-of-straightness of the rock bore, the flanged joints are joined with a flexible fastening system. Belleville (conical) spring washers are captured under the flange bolts and a rubber gasket of narrow cross-section is clamped between the flanges. Under test these joints have remained water tight with a misalignment of 0.5°. The lower end of the heater housing is closed by a welded plug which has a central recess to engage and center a rod on the heating element assembly. A removable bellmouthed collar is provided at the upper end of the housing to prevent chafing of the electrical leads. To compensate for the fact that the center of all time scale heaters lies in the same horizontal plane while the drift floor is rough and sloped, the length of the upper section of each heater housing is tailored to suit its individual location.

To prevent heat loss up the annular space between the heater housing and the rock bore, an external insulating plug is provided on the heater housing above the "hot" zone. This insulating plug consists of a mineral-fiber blanket wrapped around the tube and confined length-wise by two external flanges. To assure that the plug may be easily lowered into the bore, the fiber blanket is wrapped with a layer of "fishpaper" electrical insulation and is held in a compressed state by adhesive tape. When the heaters are turned on, the fishpaper and tape burn off, allowing the mineral wool to expand and make contact with the rock bore.

The thermocouple, dewatering, and borescope guide tubes are similar to those described for the full scale heater. However, sections of these tubes are welded to the individual sections of the heater housing. The housing flanges are keyed to assure that the tube centerlines are aligned. The thermocouples are inserted after the housing sections are joined. This threading of the thermocouples proved to be a very tedious operation. Two thermocouples are provided for monitoring the housing temperature adjacent to the center of the "hot" section. One thermocouple is in each of the guide tubes. The thermocouples are the same as those described for the full scale heater.

The heating elements and their flexible leads are made into an assembly which can easily be lowered (by the leads) into the previously installed housing. The materials of construction for the leads, the heating elements, and their terminations are the same as for the full scale heaters. The elements have a 720-mm (30")-long "hot" section and a 432-mm (18")-long "cold" section. They are each rated for 1,500 W operation but will normally be energized at 550 W per element, with both elements operating.

The "cold" lengths of the "U"-shaped heater elements pass through a stainless steel can, which blocks the loss of heat upward through the center of the housing. The interior of the can is filled with vermiculite, and its removable top flange captures a heavy glass-cloth disk. The edge of the cloth conforms to the inside diameter of the housing to prevent air circulation around the loose-fitting can. The heating elements are attached to the removable top flange of the can by collars brazed to the "cold" legs of the elements. A central vertical rod is welded to the bottom of the can, and several stainless steel discs with clearance holes--for the rod and for the heating elements--are secured by cotter pins along the length of the rod. These discs guide the heating elements within the housing. The central rod engages the bottom plug of the housing to center and support the heating element assembly.

5. AUXILIARY SYSTEMS

There are five auxiliary systems used with the various heaters: (1) borescope, (2) optical pyrometer, (3) borehole caliper, (4) weighing pan, and (5) dewatering pump.

5.1 Borescope

The borescope is a custom built (Lennox Instrument Co.) assembly for viewing the surface of a borehole. It is used periodically, during the life of the tests, to inspect the heated wall of each of the full scale and time scale heater boreholes for evidence of decrepitation.

The borescope consists of a high-intensity lamp, a prism, and a number of coaxial lenses--all mounted in a 12-mm (0.5")-diameter stainless steel tube. The lamp is at the bottom of the assembly to illuminate the borehole wall. It is powered by a variable-voltage power controller which plugs into the eyepiece at the top of the assembly. The prism is positioned to rotate the optical path approximately 80° so that it passes up through the lenses to the eyepiece at the top of the borehole. A camera adapter may be attached to the eyepiece.

The borescope can be rotated and raised or lowered within the guide tubes which are on the exterior of a heater assembly. These guide tubes end just below the layer of thermal insulation at the top of the heated zone. By moving the borescope, the scope's 55° field of view can be translated along the length of the borehole and rotated about its axis to scan the portion of the borehole which is below the guide tube. Only a portion of the periphery is visible from each guide tube position, since the canister itself occupies the center of the borehole.

To view the heated length of the time scale boreholes requires an optical path over 10 m long. Therefore, the borescope assembly is provided with five 2-m-long extenders. These are screwed together as they are lowered into the guide tubes.

To make the unit useful for continuous observations within a 300°C environment, and for short observations in hotter surroundings, the lower section of the borescope tube is polished and silver plated to create a highly reflective surface. A supply of dry-nitrogen purge gas enters the assembly near the eyepiece and exits near the lamp and prism. This gas provides internal cooling. External cooling is provided by a second purge-gas supply which flows through the annulus between the guide tube and the borescope.

5.2 Optical Pyrometer

A hand-held optical pyrometer is used periodically to measure temperatures within the full scale heater canisters. The pyrometer is a pistol-type unit made by Raytek of Mountain View, California.

Its temperature range is 350° to $700^{\circ}C$. Its angle of view is 0.4°.

To make a temperature measurement, the operator temporarily removes a thermal plug which is suspended inside the stem of the heater assembly. This clears a view line into the center of the canister. Temperature readings were made during the heater tests described above. The heat flux up the heater stem was minor and did not interefere with comfort of the operator. The surfaces whose temperatures are measured are (1) the lowest of the stainless steel spacers which position the heating elements within the canister, and (2) the bottom of the canister itself. A central hole in each spacer provides a clear path to the lowest spacer. The lowest disc has a "D"-shaped hole to provide an optical sighting target while maintaining a clear path to the bottom of the canister.

5.3 Calipers

This device and the weighing pan described below were last minute additions, included primarily to evaluate the techniques involved in their use. One of the time scale heater assemblies is provided with calipers to sense changes in the diameter of the rock bore. Two caliper assemblies are installed at different levels on the one heater (Fig. 9).

Each caliper comprises:

- An Invar ring surrounding the heater housing
- Three spring fingers attached to the ring
- Strain gauges on the fingers to detect their deflections
- Fusible pins to restrain the fingers during installation
- Fusible links to secure the ring to the heater housing during installation.

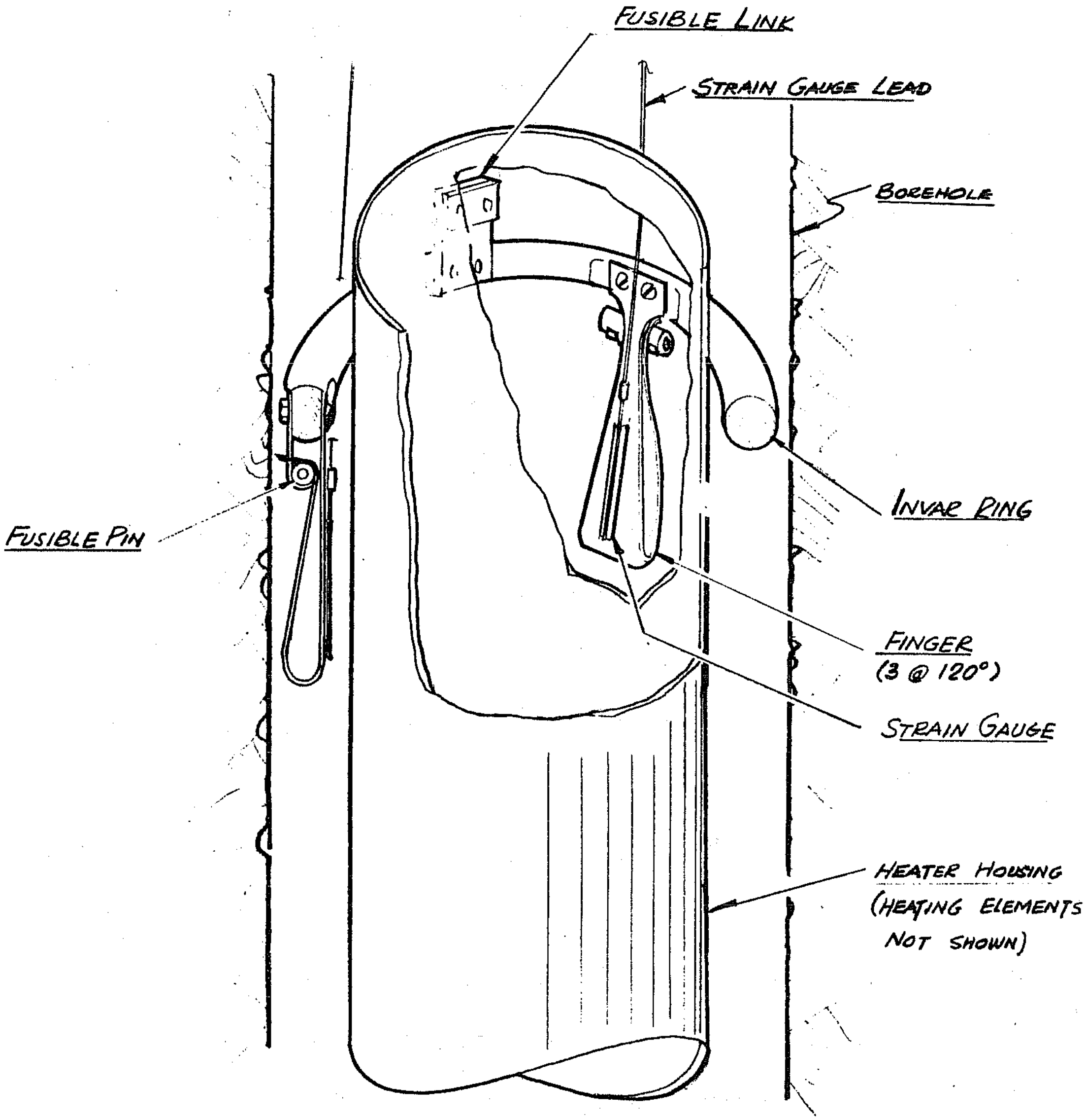

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Fig. 9. Caliper assembly installed in the time scale heater borehole.

Each spring-loaded finger is a hairpin leafspring of stainless steel, coming to a point where it contacts the rock surface. The strain gauge is spot welded to one leg of the finger. The finger width is tapered where the strain gauge is attached, so that a constant stress acts throughout the length of the strain gauge.

The hermetically sealed platinum-tungsten strain gauges are of a standard commercial type (Ailtech Mod #SGH425-01HF-37-304SS), totally enclosed, with a thin flange for welding in place. They have mineral-insulated leads in a stainless-steel sheath. They are designed to work at temperatures to 800°C and in a wet environment. They are partially temperature compensated by the inclusion of a compensating resistor within the hermetic sheath.

The fingers are restrained during installation by a hollow fusible pin of Cerrobend alloy with a melting point of about 50°C. During installation the Invar ring carrying the fingers is attached to the housing through three fusible links of Cerrobend alloy with a melting point of about 120°C. When the heater is turned on, the pins restraining the fingers melt first. This action releases the fingers to spring out against the rock surface. Next the links supporting the Invar ring melt, leaving the ring floating freely, supported only by the fingers. With this arrangement, the readings on the strain gauges are sensitive to movements of the fingers, but are undisturbed by movements of the heater housing. During bench testing, the gauge demonstrated a sensitivity of .025 mm (.001") and a maximum range of 3.6 mm (0.14").

5.4 Weighing Pan

One of the time scale heaters is provided with a weighing system to measure the amount of rock which spalls from the heated portion of the borehole. The unit uses a strain-gauge system, and during bench testing was demonstrated to have a sensitivity equivalent to a single 10-mm (0.4")-diameter granite sphere. The maximum load which can be weighed is 10 kg. This device, shown in Fig. 10, consists of:

- A support ring attached to the heater housing above the heated zone
- Three cantilever beams mounted on the ring
- A strain gauge attached to each cantilever beam
- An annular pan surrounding the heater housing near its lower end
- Three weigh-pan support cables (braided bronze wire) which are attached to the cantilever springs at their upper ends and to the pan at their lower ends.

Each cantilever beam is formed by machining a slot in a block of stainless steel. Part of the upper surface of the cantilever is machined away and each end of a strain gauge is spot welded to one of the remaining upper surfaces of the cantilever, thus bridging the machined gap. This construction puts the strain gauge into the same tension throughout its length, and increases its sensitivity. The strain gauges are of the same type as those used on the caliper described above. A screw-adjustable stop is provided to limit the deflection of the cantilever and prevent damage to the strain gauge.

A hole drilled in the end of each cantilever receives the upper end of one of the weigh-pan support cables. The pan hangs from the bottom of the cables. The cables pass through small tubes which pierce the thermal insulation at the top of the "hot" section of the heater assembly. The annular pan is formed from

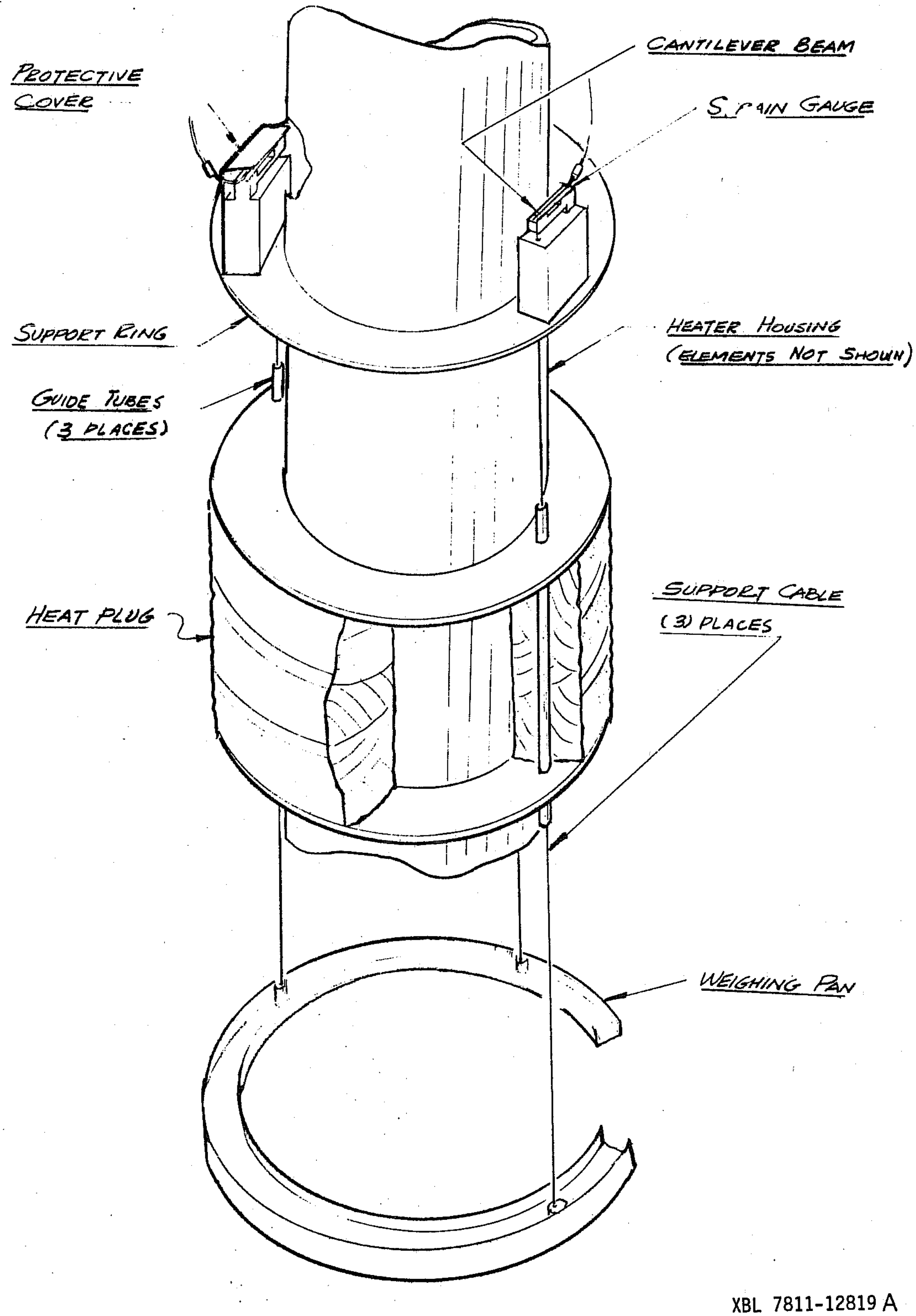


Fig. 10. Weighing pan assembly installed on the time scale heater.

a thin stainless-steel sheet with inner and outer lips. The cables are attached to the pan with adjustable connections, so that the pan may be leveled before the heater assembly is lowered into the borehole.

5.5 Dewatering Pump

The original heater design criteria were based upon a prediction that the borehole would be dry: A dewatering retrofit was required when, during the borehole drilling phase, most of the boreholes were found to accumulate seepage water. This water (see Table 3) seeps into the holes through intersecting fractures in the granite. At the turn-on of a heater experiment, the boreholes are cool and the water accumulates as liquid. Later the rock temperature becomes high enough so that only steam could be present. If the water vaporized, a large heat loss could occur from the lower portion of the borehole. Therefore, there could be a large uncertainty in the amount and distribution of the heat flux reaching the granite. To cope with this water inflow, each full scale and each time scale heater borehole was equipped with a pumping and water-collection system. By collecting and measuring the condensed steam, a power correction can be calculated and a compensatory increase made in the heater input power. No dewatering was provided on the peripheral heaters, as the heat distribution is less critical for these boreholes.

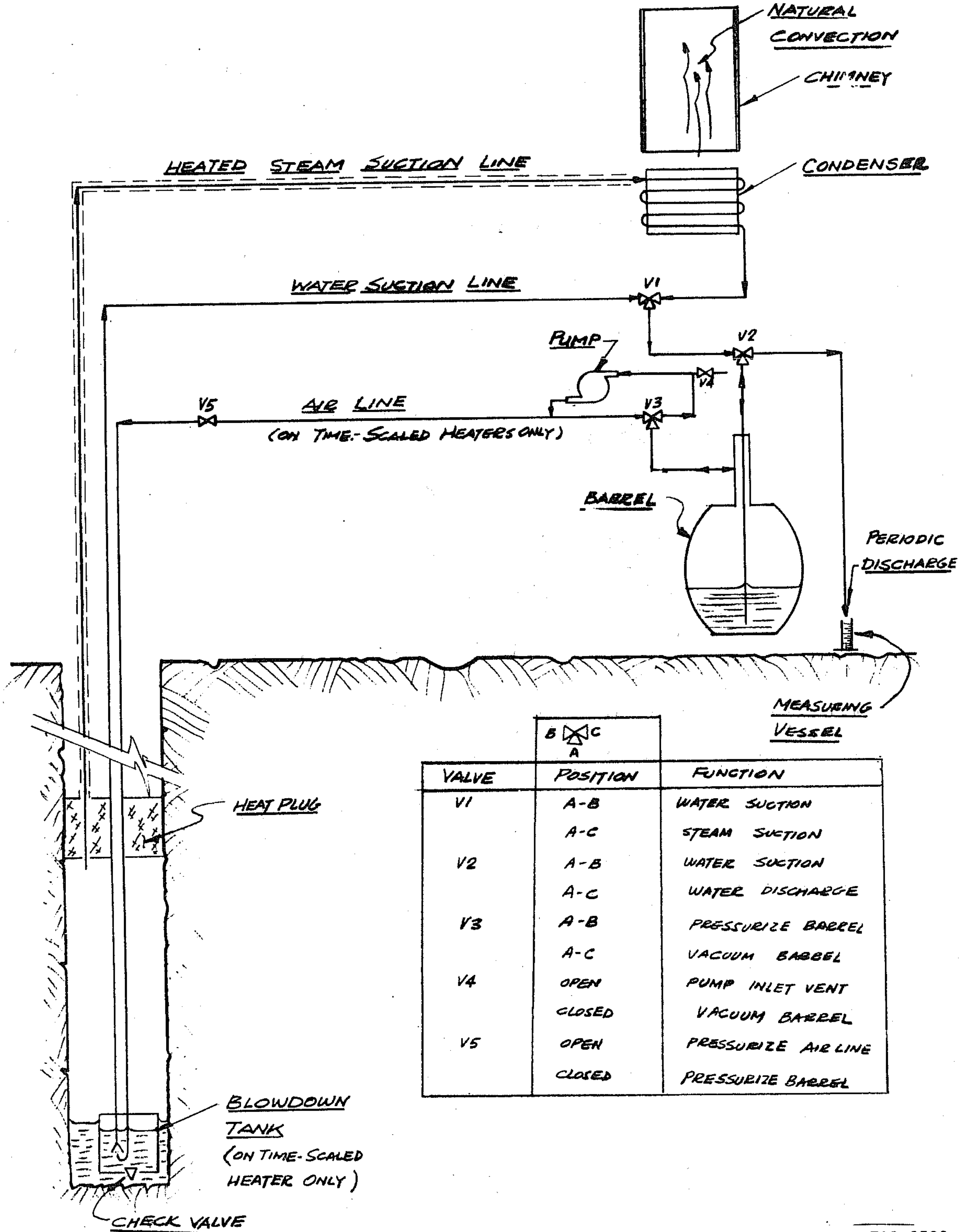
Table 3. Borehole number vs. water influx.

Heater type	Time scale							Full scale		
Borehole No.	1	2	3	4	5	6	7	8	9	10
Flow(liter/day)										
on 5/10/78[a]	1.0	17	140	14	14	1.9	3.4	0.1	1.3	0
on 7/18/78	0.8	9.0	0.2	1.8	0.6	0.4	1.2	0.1	0	0
on 9/21/78	0.6	8.4	0.2	2.1	0.4	0.2	1.1	0	0	0

[a]Before installation of heaters the water influx was large as a result of nearby drilling activities. Later flow rates may have been influenced by hydrology experiments occurring in an adjacent drift. FS9 and FS10 delivered water for a few days after these heaters were turned on and then returned to a dry condition.

The hostile downhole environment dictated that the active pumping apparatus should be at the top of the borehole. This uphole apparatus is nearly identical for both types of boreholes, although it is operated in a different mode for each type. A schematic of the apparatus is shown in Fig. 11. It consists of a two-stage, diaphragm-type vacuum pump (which evacuates the air from a reservoir), the evacuated aluminum-barrel reservoir (which draws in and stores the water), an air-cooled condensor (for condensing steam), and various valves, plumbing, and instrumentation.

Each system is designed to remove either liquid or steam, but not both simultaneously. Spare pumping units are available and the existing units can be modified by the addition of a second collection barrel so that both phases can be pumped simultaneously.



VALVE	POSITION	FUNCTION
V1	A-B	WATER SUCTION
	A-C	STEAM SUCTION
V2	A-B	WATER SUCTION
	A-C	WATER DISCHARGE
V3	A-B	PRESSURIZE BARREL
	A-C	VACUUM BARREL
V4	OPEN	PUMP INLET VENT
	CLOSED	VACUUM BARREL
V5	OPEN	PRESSURIZE AIR LINE
	CLOSED	PRESSURIZE BARREL

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Fig. 11. Schematic of dewatering pump installation.

As the experiment progresses, the number of holes requiring dewatering and the presence of steam or liquid will determine how this need will be met.

The technique for liquid removal is somewhat different for the full scale heaters than for the time scale heaters, due to the difference in their borehole depths. The full scale borehole depth of 5.5 mm (18') is such that water can be removed by direct suction. The 11.2 m (35') depth of the time scale boreholes requires a more complicated technique.

On each heater assembly, one of the borescope guide tubes is adapted for removing steam. Both steam and air are drawn from the borehole through this tube. The guide tubes extend from the top of the hot zone (just below the heat plug) up to the top of the borehole. At this top end another tube is attached. The opposite end of this extension tube is attached to the inlet of an air-cooled steam condenser which is in turn connected into the evacuated reservoir. The thermal insulation layer at the top of the canister has a sufficient impedance to the inflow of air to maintain a negative static pressure in the borehole. Both guide and extension tubes are wrapped with thermal insulation, and an electrical heating tape is threaded through their full length. This tape provides 18 W (maximum) per foot to prevent the steam from condensing and refluxing in the tubes. An autotransformer powering the heat tape is adjusted until the steam temperature at the entrance to the condenser is 2^{o}C above the boiling point.

Liquid removal from the relatively shallow, full scale heater borehole is accomplished with a simple suction tube which passes from the collection barrel to the bottom of the borehole. A fine-mesh screen protects the inlet of the tube.

Liquid removal from the time scale heater borehole requires two tubes, as shown in Fig. 11. One of these tubes carries air from the outlet of the pump, and the second tube is a water suction line similar to that used for the full scale heater. These two tubes terminate in a blow-down tank at the bottom of the borehole. The blow-down tank has a 1-liter volume for all time scale heaters except #2. This #2 unit was provided with a 3-liter tank, because early information indicated a larger seepage rate into that hole. The blow-down tank has an inlet ball check-valve. This ball-type valve closes when the pressure in the tank exceeds that in the surrounding borehole. The check valve is protected by a two-stage filter. A 50-mesh screen is located just below the valve. Water flowing to the screen passes through a narrow gap between the tank bottom and a circular plate spaced 1.1 mm below. A layer of asbestos cloth insulates the blow-down tank from the heater housing. A pipe plug is screwed into the top of the blow-down tank. Since no thread sealant was used on the threads of the plug, a high-impedance bleed resulted. Any air trapped at the top of the tank slowly bleeds off.

The initial concept for operation of this two-tube system envisioned that the air line would supply a very small flow of air into the water suction line. This air would form a string of bubbles in the water-filled suction tube, thereby reducing the average density of that two-phase fluid head. With a reduced density, the fluid could be sucked out of the 10-m (35')-deep hole. The blow-down tank made system start-up easier, and provided a second mode of operation. In this second mode, the air line could be cyclicly pressurized to close the check valve and then force the accumulated liquid up the tube. These operating modes were demonstrated at the time of manufacture. In the field a third mode was found that did not require as critical an air flow adjustment as did the bubble lift, and did not require cyclic valve operation. In this third mode a slightly higher air flow rate allowed the liquid to be aspirated up the suction tube.

The water which is collected by each of the dewatering units is emptied once each work day. The operator manipulates the various air and water control valves (Fig. 12) so that each barrel is pressurized with air and the water is forced out the barrel discharge line. The operator then measures and records the amount of water collected from each borehole. Depending upon whether the water was collected as liquid or steam, the borehole heat loss can be estimated, and an appropriate correction can be applied to the heater input power.

6. ELECTRICAL HEATER CONTROL SYSTEMS

Electrical control systems are required for two full scale heaters, eight peripheral heaters, and eight time scale heaters. The design critera for these control systems are:

a. 50 Hz power at 220 V

b. 5 kW minimum power per element for full scale heater, and 1.5 kW minimum power per element for time scale and peripheral heaters

c. voltage regulation for stability of power setting

d. sensors for monitoring voltage, current, and power levels for both visual inspection and data acquisition

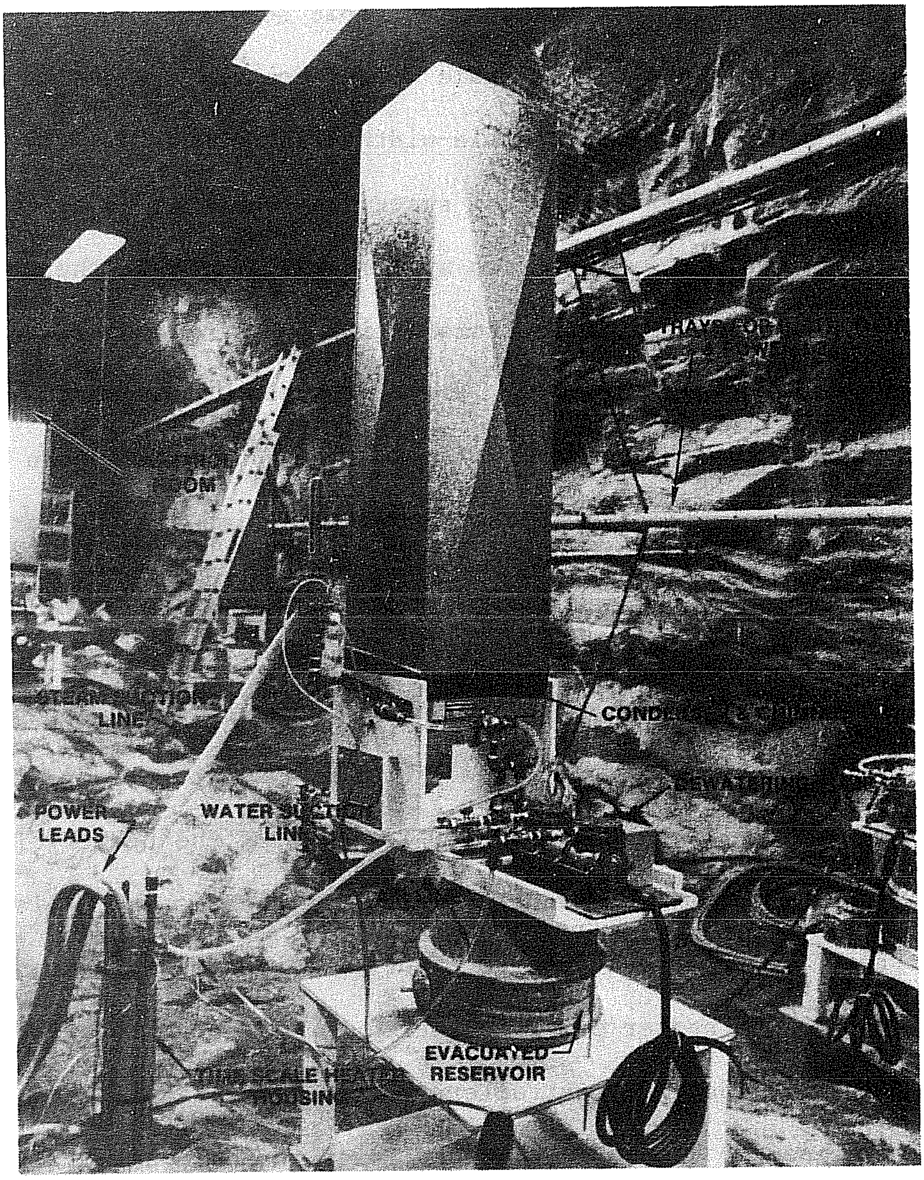

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Fig. 12. Time scale heater drift.

e. manual power control with continuously variable adjustment

f. conservatively rated elements for high reliability

g. redundancy of components and system configuration

h. modular construction for rapid service.

Each of the two full scale heater control systems is mounted in one side of a shared double-width electronics rack (Fig. 13). The peripheral heater control system is contained in a similar double-width rack. These two systems are housed in the full scale experiment drift in an instrumentation building constructed between the two full scale heaters. The time scale heater control system is mounted in a triple-width rack (Fig. 14) located in an instrumentation building at the rear of the time scale experiment drift.

6.1 Full Scale Heater Control System

The control system for the full scale heater is shown in Fig. 15. Each of the full scale heaters has four separate heater elements (see Section 2). Power for each of the heater elements is provided by an independent controller chassis which also provides current, voltage, and power monitoring circuitry. Under normal operation the heater power is shared by the four heater elements and their respective controllers. Each element and controller is designed to handle full heater power in the event of failure of up to three of the four heater elements and/or controller channels. Moreover, each controller is a modular unit capable of replacement within a few minutes.

Though the controller chassis are the work horses of the heater power-control systems, there are also several other types

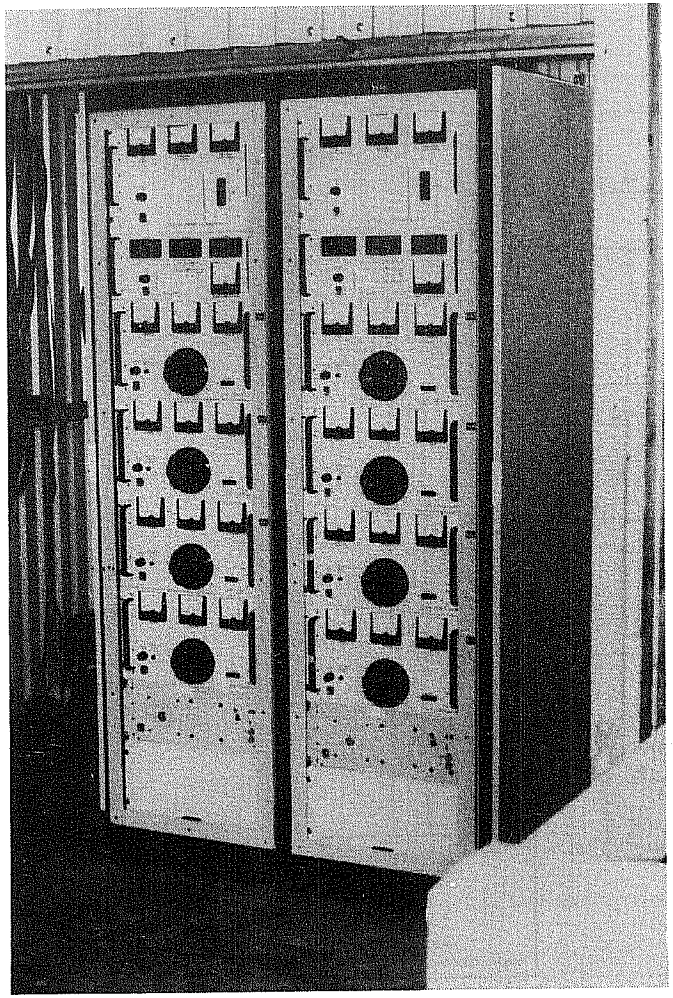

Fig. 13. Full scale heater control system.

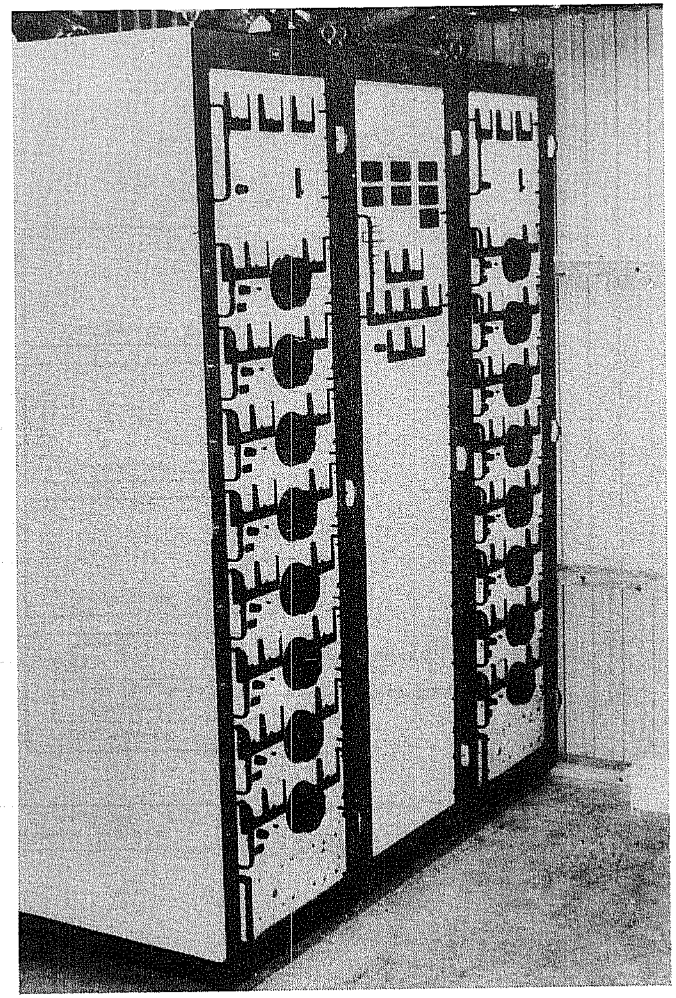

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Fig. 14. Time scale heater control system.

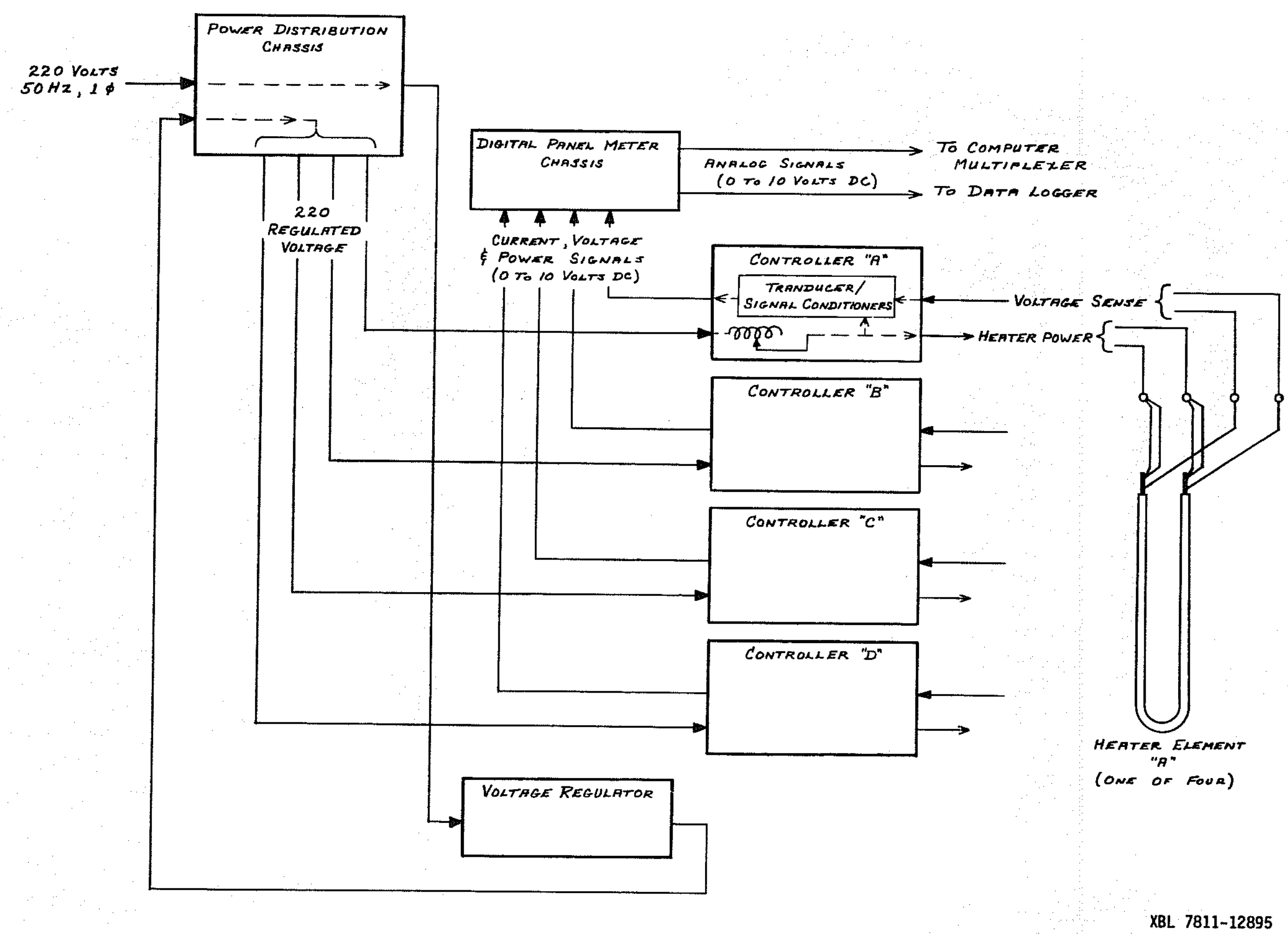

Fig. 15. Block diagram of the full scale heater control system.

of chassis required for a complete system. A full scale control system is composed of:

- one power distribution chassis;
- one voltage regulator chassis;
- four controller chassis; and
- one digital panel-meter chassis.

These chassis are mounted on slides in a standard 19" electronics rack. A block diagram (Fig. 15) illustrates the general power routing to the various chassis that make up a full scale heater control system. Analog monitoring signals are derived in the controller chassis and supplied to the digital panel-meter chassis for use there, and for further distribution to a data logger and the computer multiplexer. A more detailed description of each of the four types of chassis is given in the following paragraphs.

The power distribution chassis is mounted in the top part of the electronics rack. Raw 220 V, 50 Hz mine power is brought in through a connector in the rear of the chassis, then to the main circuit breaker mounted on the front panel of the chassis. This circuit breaker also serves as the main power switch to the full scale heater control system, and is located to be easily accessible for killing all power to the system and the heater elements in the event of emergency. Power is then routed from the power distribution chassis through a voltage regulator located in the bottom of the rack, then back up into the power distribution chassis. Four connectors are provided to distribute this regulated power to the four full scale heater controller chassis. There are three AC meters on the front panel of the power distribution chassis to monitor unregulated input voltage, regulated 220 AC voltage, and regulated current to the system.

The voltage regulator is a GenRad Variac type 1582-AH capable of 9.8 kVA with an output voltage regulation of ±0.25%. These units employ a "Buck-Boost" transformer fed by a servo-motor driven autotransformer. Each regulator used in Sweden was wired for 50 Hz operation and set for 220 V output with a nominal 220 V input. Regulators were also fitted with rack slides and electrical connectors for rapid replacement in the event of failure.

Each of the four heater controller chassis received regulated 220-V AC power from the power distribution chassis through a rear panel connector on the controller. From there power is fed through a front-panel mounted switch/circuit breaker to a GenRad type W50H Variac autotransformer capable of 7.8 kVA and 25 A. The autotransformer is mounted horizontally with a 90^{o} gear drive to the front panel/knob, thus allowing us to limit the vertical dimensions of the controller to a maximum of 10.5". The adjustable output of the autotransformer is brought to an output connector on the rear panel of the controller, to facilitate cabling to one of the four heater elements within a full scale heater canister. Heater voltage-sense wires, brazed to heater element connections downstream from the power-input wires (as shown in Fig. 4), are brought back into the controller chassis through a separate connector. This signal is used to accurately monitor the heater-element voltage and power dissipation.

Each controller also contains four transducer/signal conditioner modules to monitor heater current, autotransformer output voltage, heater-element voltage, and heater-element power. These modules, in conjunction with operational amplifier buffers, provide a 0- to 10-V DC normalized analog representation of the four measured parameters. Heater-element current, voltage, and power are displayed on three analog meters mounted on the front panel. Autotransformer output voltage can optionally be displayed on the voltage meter for diagnostics by pressing the push button switch on the front panel. The four analog signals are also wired to a connector on the rear panel for cabling to the digital panel-meter chassis.

A single digital panel-meter (DPM) chassis with three digital meters is used to accurately monitor and display current, voltage, and power from all four heater controller chassis. These signals are brought in through four rear-mounted connectors, one for each controller. Power signals are summed using an operational amplifier summing circuit to provide a 0- to 10-V DC analog representation of total heater canister power. This parameter is continuously displayed by an analog meter on the front of the DPM. The digital meters display parameters from only one controller or the summed heater power at any one time. A ganged assembly of five push-button switches is used to make this selection. All analog parameters, except for autotransformer voltages, are wired to two 32-pin output connectors on the rear of the DPM chassis. One of these connectors provides signals to the data logger and the other to the computer multiplexer (McEvoy, in preparation).

The controller systems for the peripheral and time scale heaters (Figs. 16 and 17) differ in detail from the full scale

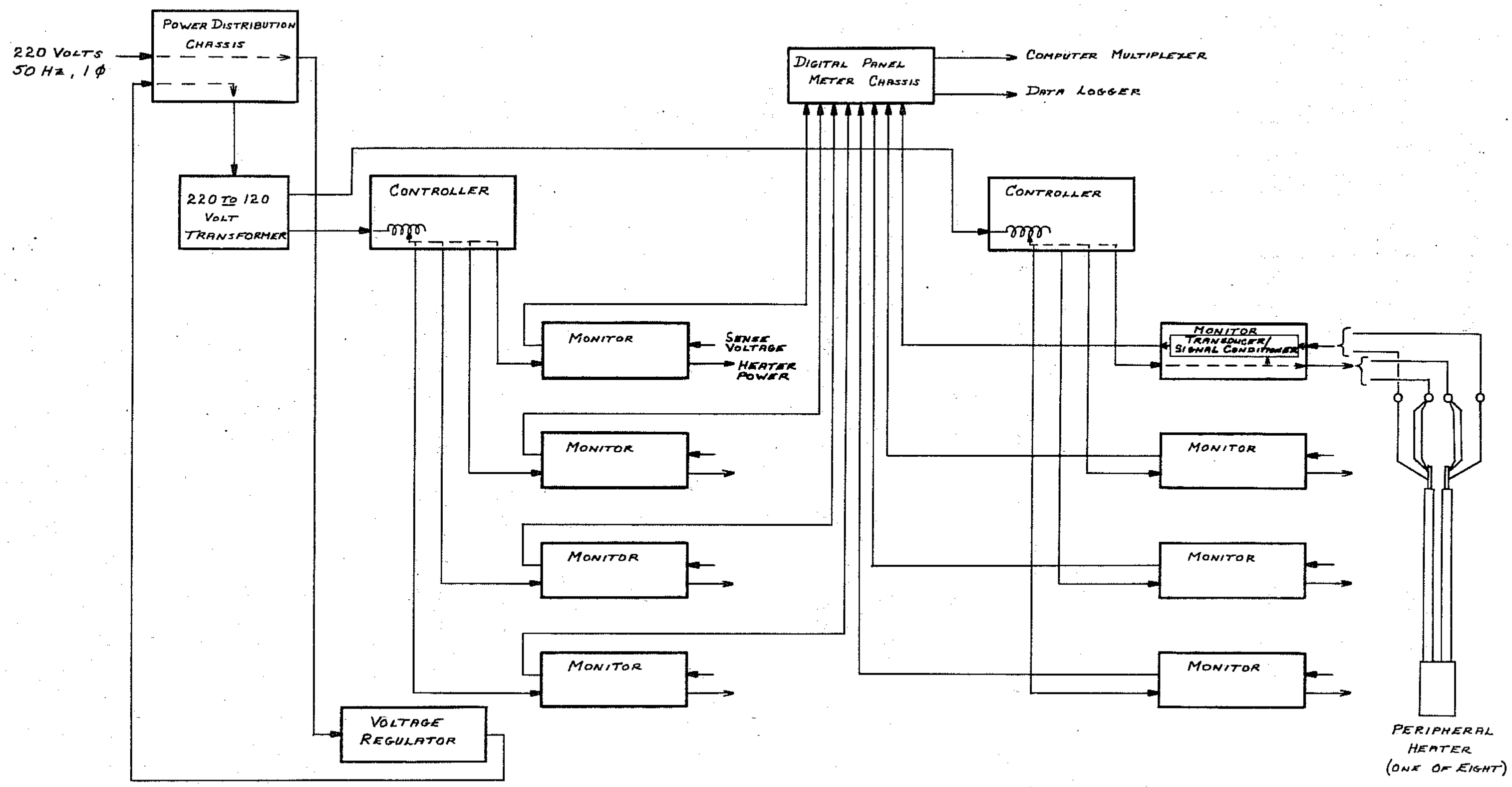

Fig. 16. Block diagram of the peripheral heater control system.

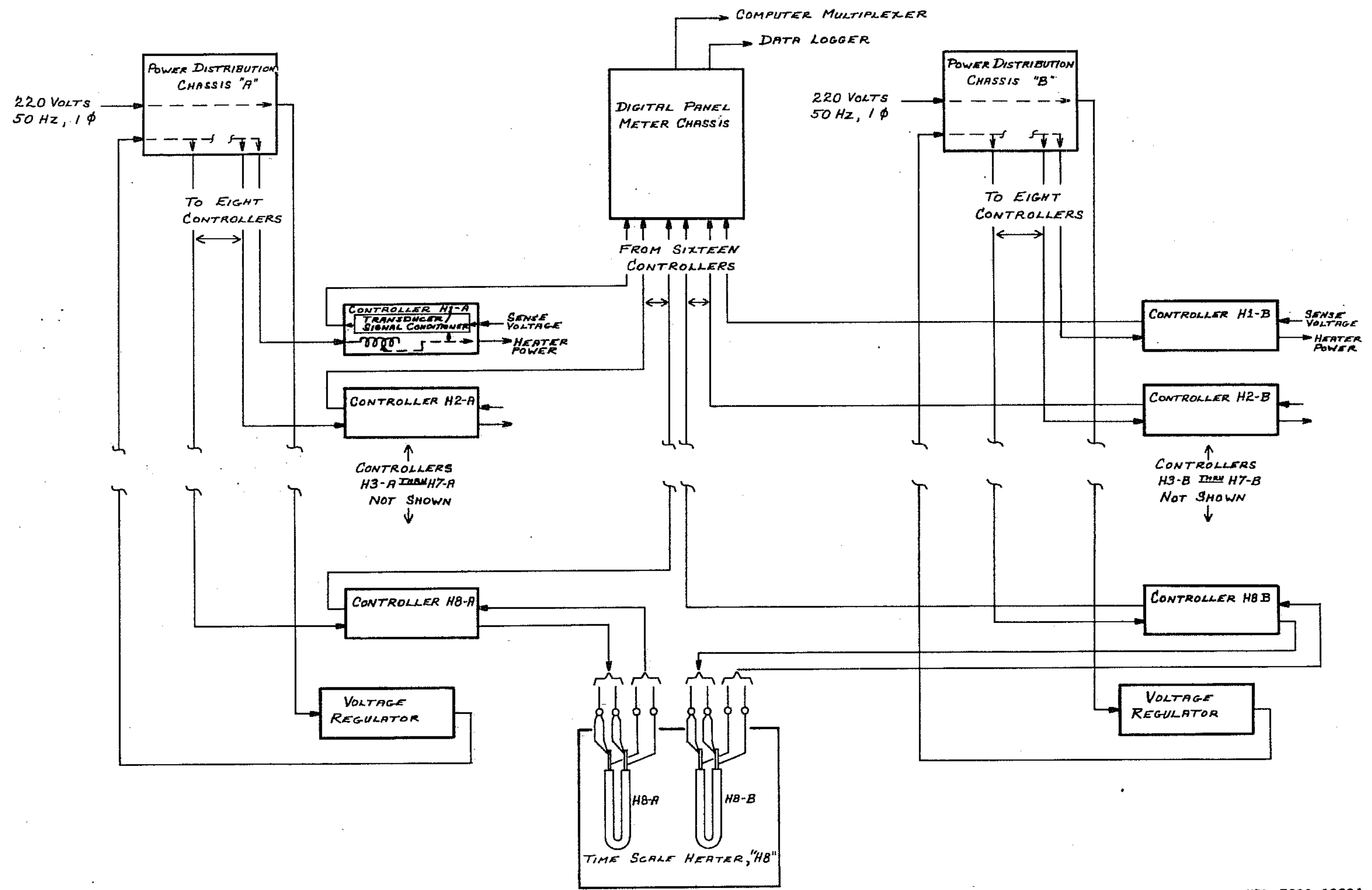

Fig. 17. Block diagram of the time scale heater control system.

controller system. Some of the primary differences are pointed out in the following paragraphs.

6.2 Peripheral Heater Control System

Each of the eight peripheral heaters uses a single electrical heater element designed to operate at 1 kW with a nominal 120 V input, thus requiring an additional 220- to 120-V transformer following the voltage regulator. It was decided in the early stages of the project to use only two peripheral controllers, each powering four peripheral heaters in parallel. However, unlike the full scale controller system, eight separate monitor chassis are used to monitor the current, voltage, and power dissipation of each heater.

6.3 Time Scale Heater Control System

Each of the eight time scale heaters has two elements. Like the full scale controller system, power for each heater element is provided by an independent controller chassis containing current, voltage, and power monitoring circuitry. Under normal operation, the heater power load within any one canister is shared by the two elements and their respective controllers. However, each element and controller is capable of handling the full load in the event of a heater or controller failure. Chassis are distributed in the racks and interconnected for maximum redundancy; that is, any one rack can completely fail without loss of power capability to any of the eight time scale heaters.

7. INSTALLATION AND OPERATING EXPERIENCE

The full and time scale heaters were mechanically installed during the period of May 15 to May 22, 1978 by two to four technicians. An additional week was required for two people to assemble and install the dewatering systems. The installation was relatively uneventful. One problem experienced was the difficulty in obtaining, locally, certain installation materials and parts compatible with the American design.

The very rough floor of the heater drift made handling the heaters awkward, and rendered some installation aids ineffective. A flat concrete collar around the top of each heater borehole would have been very useful. Some minor design changes would reduce the number of small fastener parts which needed to be assembled at the site. A miner wearing a hard hat, heavy clothing, and gloves in a poorly lighted drift is at something of a disadvantage when assembling small parts. Many of the boreholes required dewatering before installation. Power for the dewatering pumps was required immediately to keep the holes and heaters dry.

Insufficient provision had been made for protecting the many instruments and their leads from the foot traffic necessary for installation. A narrow walkway directly on the floor of the drift, with provision for crossing instrument and heater leads, would have been helpful.

The time scale heater experiment was turned on June 1, 1978, with both heating elements of each assembly at 0.56 kW for a total of 1.12 kW per assembly. The first full scale heater was energized on July 3. Four heating elements at 1.25 kW yielded a total of 5 kW. The second full scale heater was energized on August 24. The four elements of that unit were energized at 0.9 kW for a total of 3.6 kW. The peripheral heaters associated with this second full scale heater are scheduled to be installed and turned on about February 1, 1979. Currently the full scale and time scale heaters have been operating continuously, except for three very brief power outages. The time scale heaters have operated over 3,600 hours and the first of the full scale heaters have operated 2,800 hours. There have been no failures of either heater or power supply, with the exception of an intermittent short in the wiring of one of the time scale heater elements (H3B) during the first weeks after turn-on. The short was repaired by reinsulating the electrical connection at the heater element.

The controller systems have proven to be very reliable. There have been no electrical or electronics failures in any of the chassis or the associated wiring, with the exception of the previously mentioned intermittent short. While we were working on that problem, the H3 time scale heater was operated at full power using only one element for a period of hours. Other than this, none of the redundancy built into the controller systems was used, except to cross-check heater power readings.

In any future designs, two basic electrical changes are suggested to the peripheral heater controller system:

- Use a standard voltage for all heater elements throughout the experiment (e.g., 220-V AC).
- Use a single controller for each peripheral heater with monitoring circuits included within the controller chassis, as was the case for the full scale and time scale controller chassis.

Had this philosophy been followed, the time scale controller design could have been used in the peripheral heater control system, thus eliminating the special peripheral controller and separate monitor chassis design.

The time scale heater dewatering operation had several failures during the first month of operation, because of improper air flow adjustments. After these adjustments were corrected, there were no further failures. There has been no significant collection of steam. The temperatures at the bottom of the time scale boreholes have not reached the boiling point, and the full scale heater boreholes are dry.

8. ACKNOWLEDGMENTS

The assistance of William M. Wong in providing his observations regarding the heater testing and installation and in generating the mechanical illustrations for this report is gratefully acknowledged. We also acknowledge Charles A. Arthur and Gerald W. West, who designed and installed much of the electronics and electrical equipment described, and Philip H. Nelson, who provided guidance for the preparation of this report.

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