STRIPA PROJECT 84-02

BUFFER MASS TEST – Heater Design and Operation

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INTERNAL REPORT

STRIPA PROJECT

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BUFFER MASS TEST –
HEATER DESIGN AND OPERATION

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This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

A list of other reports published in this series is attached at the end of this report. Information on previous reports is available through SKBF/KBS.

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SUMMARY

The nuclear waste is assumed to be contained in cylindrical metal canisters which will be inserted in deposition holes. Heat is generated as a result of the continuing decay of the radioactive waste and in the Buffer Mass Test (BMT) the heat flux expected from such canisters was simulated by the use of six electric heaters. The heaters were constructed partly of aluminium and partly of stainless steel. They are 1520 mm in length and 380 mm in diameter, and give a maximum power output of 3000 W. The heater power can be monitored by panel meters coupled to a computer-based data acquisition system. Both the heater and the control system were manufactured with a high degree of redundancy in case of component failure. This report describes the design, construction, testing, installation and necessary tools for heater installation and dismantling operation.

1 DESIGN CRITERIA

1.1 GENERAL

The criteria specified under sections 1.2 and 1.3 have been worked out in joint collaboration between SKBF/KBS, The Technical University of Luleå (LuH) and AB Jacobson and Widmark (J&W), Luleå. In order to clarify and better illustrate the design and construction of the heater units, a prototype at the scale of 1:10 was built in the laboratory of the Division of Soil Mechanics, University of Luleå. The purpose of the heater units is to simulate the heat flux from the canisters containing nuclear waste. In addition to the precise specifications concerning reliability and mechanical strength, consideration has also been taken, when designing the heaters, of the fact that the work of opening and sampling the deposition holes needs to be carried out under acceptable working conditions. In order to find a simple solution to the problem of deposition, each heater unit has been constructed on a basal plate on which stands a complete "package" consisting of heater elements, blocks of compacted bentonite, and instruments. The "package" has then been lowered into its deposition hole. When opening and sampling from the deposition holes, it is necessary that the units can be dismantled both horizontally and vertically to allow successive dismantling inwards, thus leaving the very interesting zone closest to the canister undisturbed. The geometrical positioning of the heater units within the test area, and at the test site, are illustrated in Fig. 1.

1.2 HEATERS

The following instructions were given concerning the design and construction of the heater units:

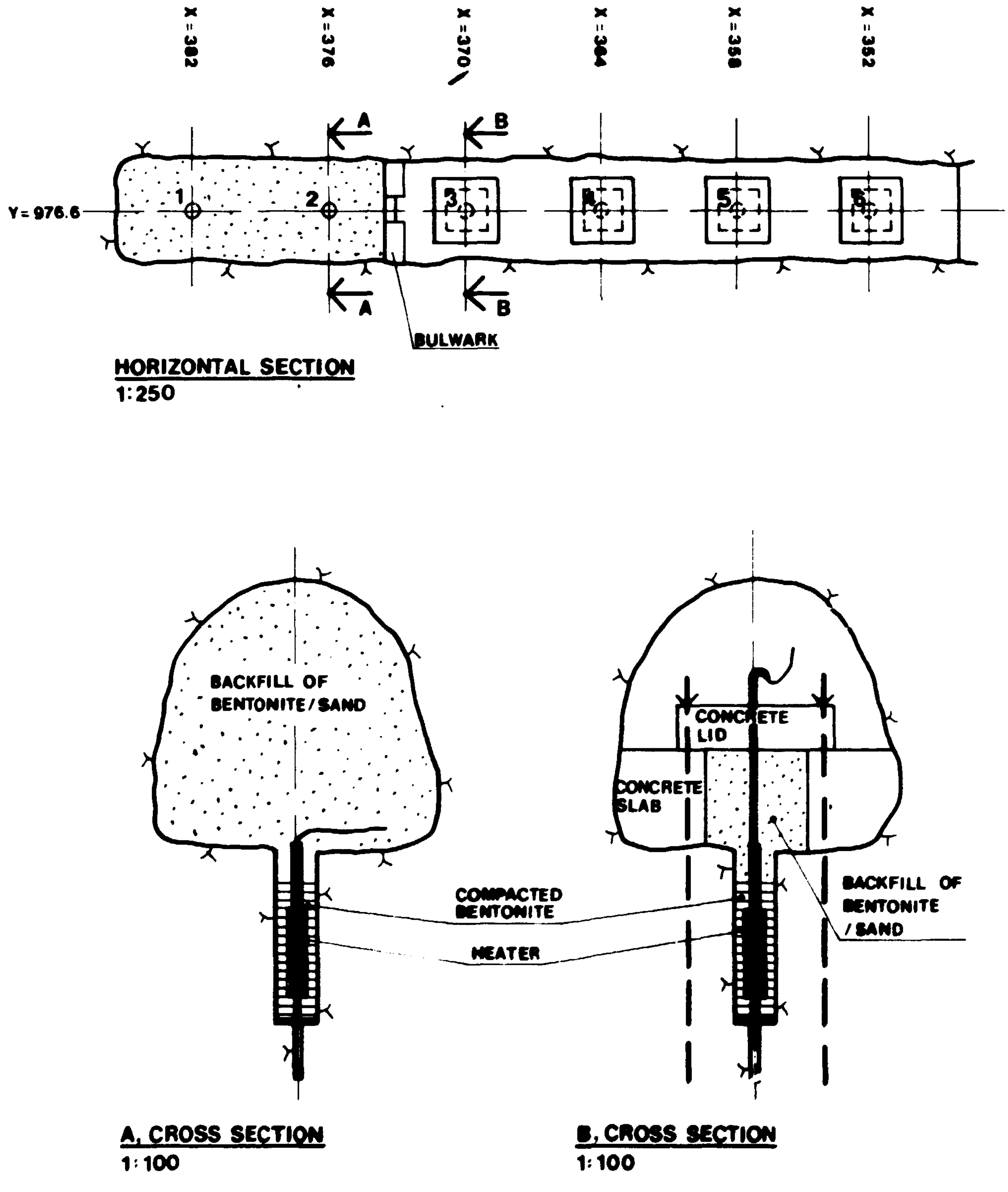


Fig. 1. Schematic sections through the BMT test site

- A test period of at least 4 years, possibly 10 years. Non-functioning heater units cannot be repaired without ruining the test.

- Dimensions of the units to be ca 1500 mm in length and 380 mm in diameter including protective tubing for connecting cables. The protective tubing should not function as a heater unit. A rod with a basal plate to be attached to the lower end of each heater unit. The rods must not function as heater units. The units themselves shall consist of 5 sections each about 300 mm in length. Each section shall be divisible lengthwise.

- The heater units shall be designed so that three quite independent heating possibilities exist.

- Maximum power output per heater unit 3000 W.

- Maximum casing temperature of $100^{o}C$, distributed as evenly as possible. The temperature at the interface between the heater unit and the compacted bentonite shall be $60-80^{o}C$ and the temperature gradient in the bentonite $1.5-3^{o}C/cm$.

- Maximum swelling pressure in the bentonite of 10.0 MPa.

- Possible effects of corrosion are not of prime interest. However, corrosion should not be so extensive as to interfere with the operating safety of the test.

- The connecting cables shall be protected and be heat resistant.

- Power source 220/380 V 50 Hz. The power supply of the mine and the test area is given in Fig. 2.

- Each heater unit shall be earthed. The earthing system for the mine is given in Fig. 3.

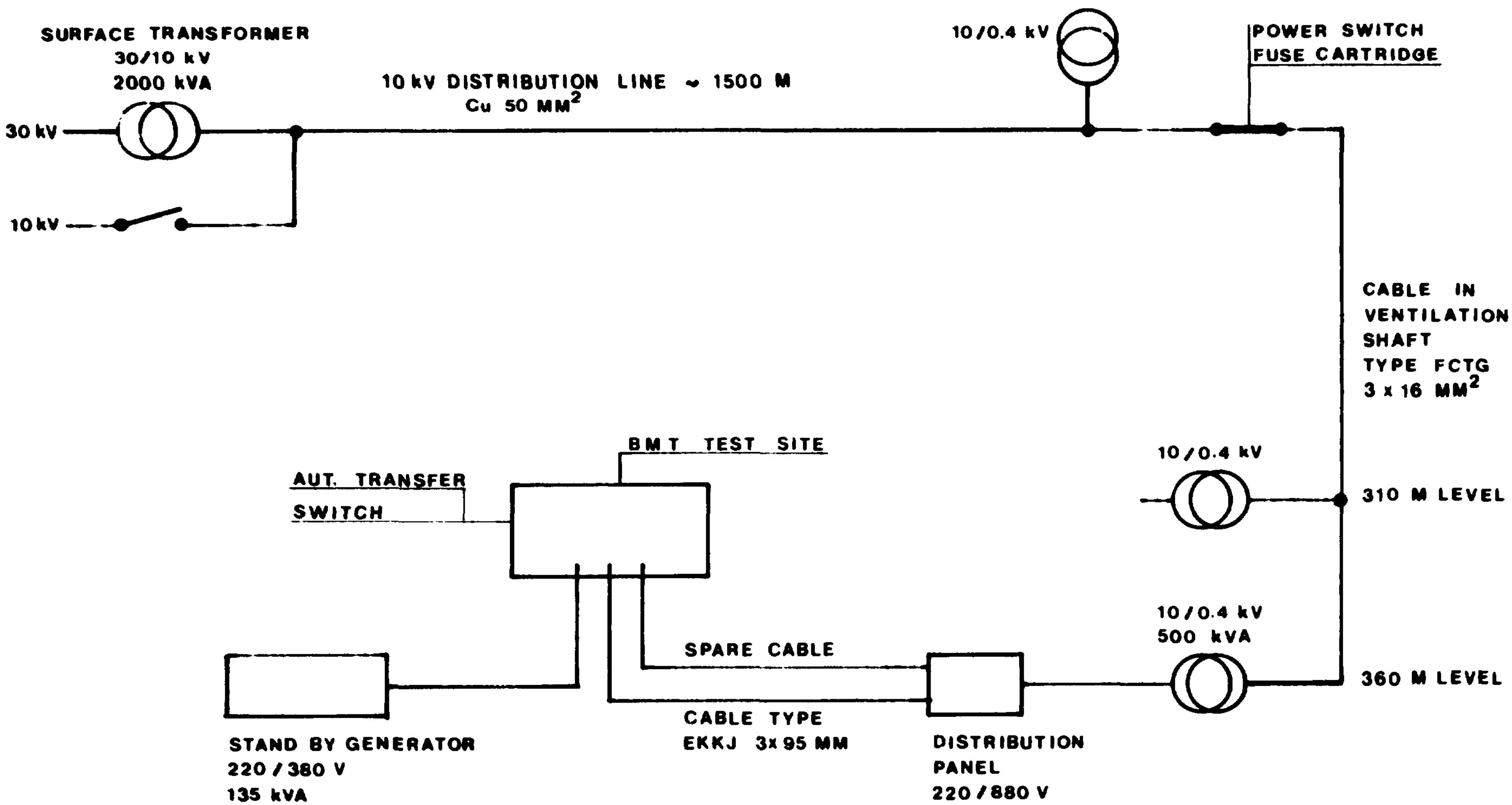


Fig. 2. Power supply of the mine and the test area

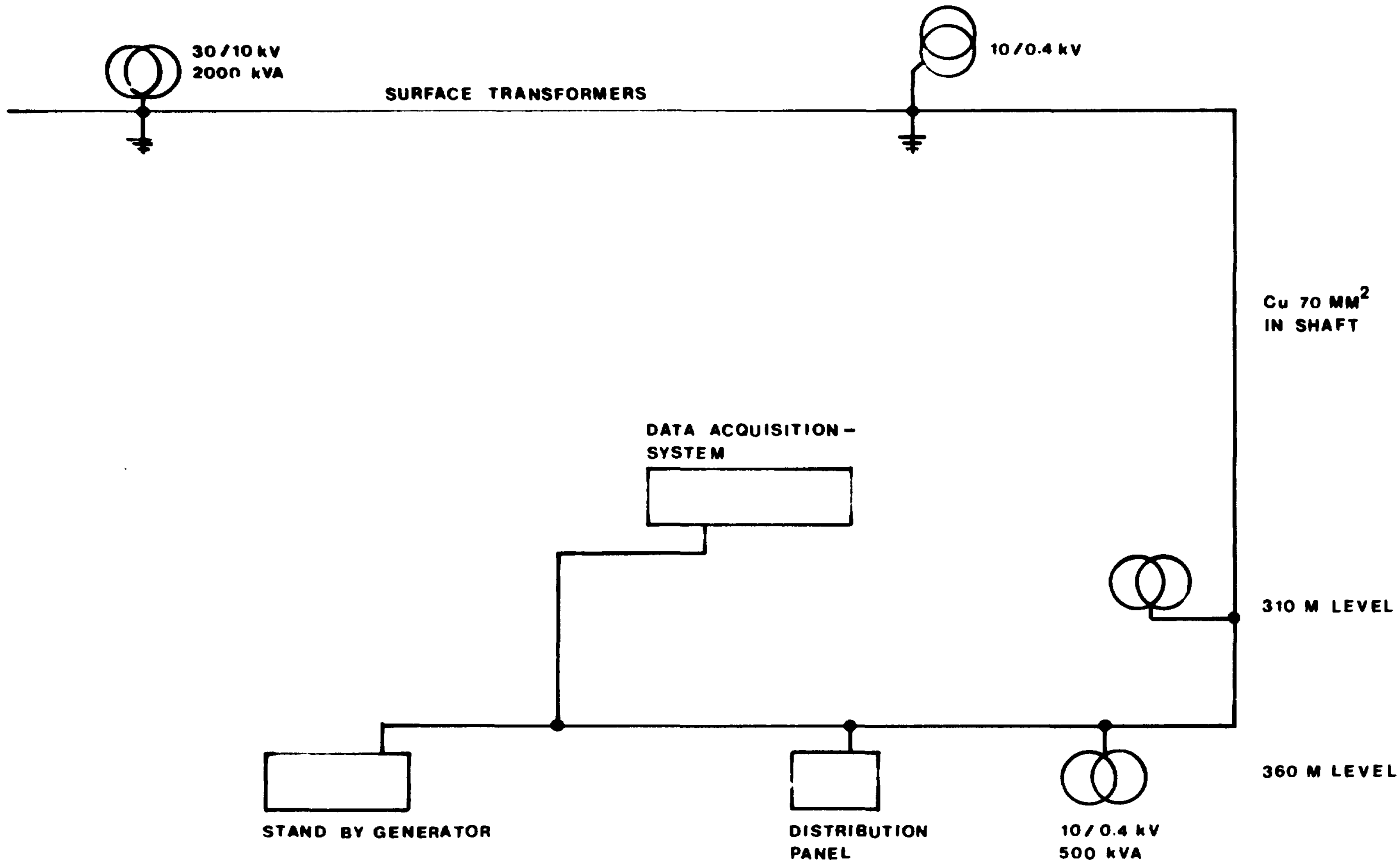


Fig. 3. Earthing system of the mine

- Suitable tools for construction and dismantling should be produced.

- Suitable transport containers should be built.

1.3 CONTROL SYSTEM

The following instructions were given for the control system:

- It is important for the interpretation of the results of the tests that the control system maintain the required heating effect as constant as possible during the whole test period. The system should be able to control and register the required effect and give warning if deviations are too great.

- The system shall be designed so that each unit can be supplied with 600 W while maintaining the possibility for variable adjustment if the regulation of other effects is required. Maximum power output 3000 W.

- Each unit to be supplied with three independent heating possibilities which all operate from the beginning, each giving 200 W. If one element fails to operate, the control system shall automatically increase the effect of the remaining two elements to give 300 W per element. If yet another fails, the remaining element shall give 600 W. Maximum permitted deviation ±10 W.

- Control and adjustment of the heater units should be automatic. Recording of, for example, power failures, deviation in heat supply, etc is to be carried out by using a computer. The measurement of the casing temperature, and temperature distribution in the compacted bentonite, is made by use of a comprehensive system of thermal elements /1/.

- In the case of a power failure, the reserve power source system for the mine shall come into operation within 10 seconds.

2 DESIGN AND CONSTRUCTION

2.1 GENERAL

Requests for tenders for the design and construction of the heater units were sent to several companies in Sweden. Several of the companies contacted felt that they could not make undertakings to a fixed price because the specifications given regarding durability, operational safety, strength etc for the heaters and the control system, were exremely high. The decision was then taken to place the order for both the design and construction of the units against a current account. The company which received the order was ASEA-ATOM. The order included:

- Detailed design of the mechanical and electrical equipment taking into regard the requirements and specifications already mentioned.

- Buying in of materials required for the mechanical and electrical components.

- Construction of 6 heater units and related electrical equipment.

- Laboratory tests in air of the casing and of the complete heater unit.

- Operational and dismantling tests in a sand-filled test rig with the same geometry as the depositional holes in the BMT.

- Installation of the control system in the BMT.

- Design and manufacture of special tools for assembling and dismantling.

- Delivery of drawings, operating instructions etc.

The agreement with ASEA-ATOM also included a clause stating that the parties concerned maintain continuous contact and discuss together, at monthly meetings, chocie of materials, suppliers, test programmes, costs etc. ASEA-ATOM commenced work on the project in February 1980 and delivered the first two heater units to Stripa in May 1981.

2.2 HEATERS

ASEA-ATOM has constructed heater units consisting of a centrally placed solid casing in which 3 symmetrically arranged hairpin-like elements are installed. The elements are fixed in place with brackets and cast in an aluminium alloy in order to give as even a heat flow as possible. Within the upper part of the casing, which protrudes from the heater unit, the elements are insulated with rock wool. The casing is surrounded by a central tube of stainless steel which is subdivided lengthwise into 5 parts. Around this tube are placed 2 half-moon shaped thick aluminium segments which are separated by 2 radial wedges of aluminium. These aluminium segments and wedges are subdivided lengthwise into 5 parts, in the same manner as the stainless steel tube. The segments, when mounted into place, were turned 60^{o} in relation to each other. Weight transfer from the aluminium segments and radial wedges to the central tube is accomplished by means of 4 wedges of stainless steel. The stainless steel tube, the segments and the wedge system are held together vertically by an upper and a lower plate and six crosswise bolts distributed lengthwise in accordance with the segments. These plates and the bolts are made of stainless steel. The basal support, under the complete heater unit, consists of a centrally fixed rod in a perforated basal plate of stainless steel.

The quality of steel used to construct the heater elements is Incoloy 800. SIS 2343 is used for all other steel parts. The aluminium alloy casting for the elements is of quality SIS 4261. The segments and radial wedges are made of string cast aluminium SIS 4244. All aluminium parts have been anodised after completion in order to improve their releasing characteristics.

Each element is supplied with power through a heat resistant cable.

The protective tubing for the cables to heater units 1 and 2 is made of plastic, and for the other heater units of steel.

The earthing system consists of stainless steel earth lines with a diameter of 16 mm which are attached to the basal plate and connecting box of each unit respectively.

The construction of the heater elements is illustrated in Fig. 4, of the casing in Fig. 5 and 6, and of the complete heater unit in Fig. 7 and 8. Fig. 8 also illustrates parts of the heater units. Fig. 9 illustrates the solution adopted for earthing.

2.3 POWER SUPPLY TO THE BMT TEST SITE

Special precautions have been taken with the design and equipment for the power supply system in order to ensure that the system is as reliable as possible. The only expected BMT-heater problem is actually short term power cuts. Stripa Mine is supplied with power from the national network (Fig. 2) by means of a 30 kV cable. In the event of lengthy power cuts in this supply, a 10 kV reserve supply from another company can be switched on manually. Cuts of this type are, however, very rare - hardly more than 1-2 times a year. A further reserve supply arranged for early projects exists in the form of a diesel driven power station mounted at the 360 m level in the vicinity of the BMT-area. This reserve

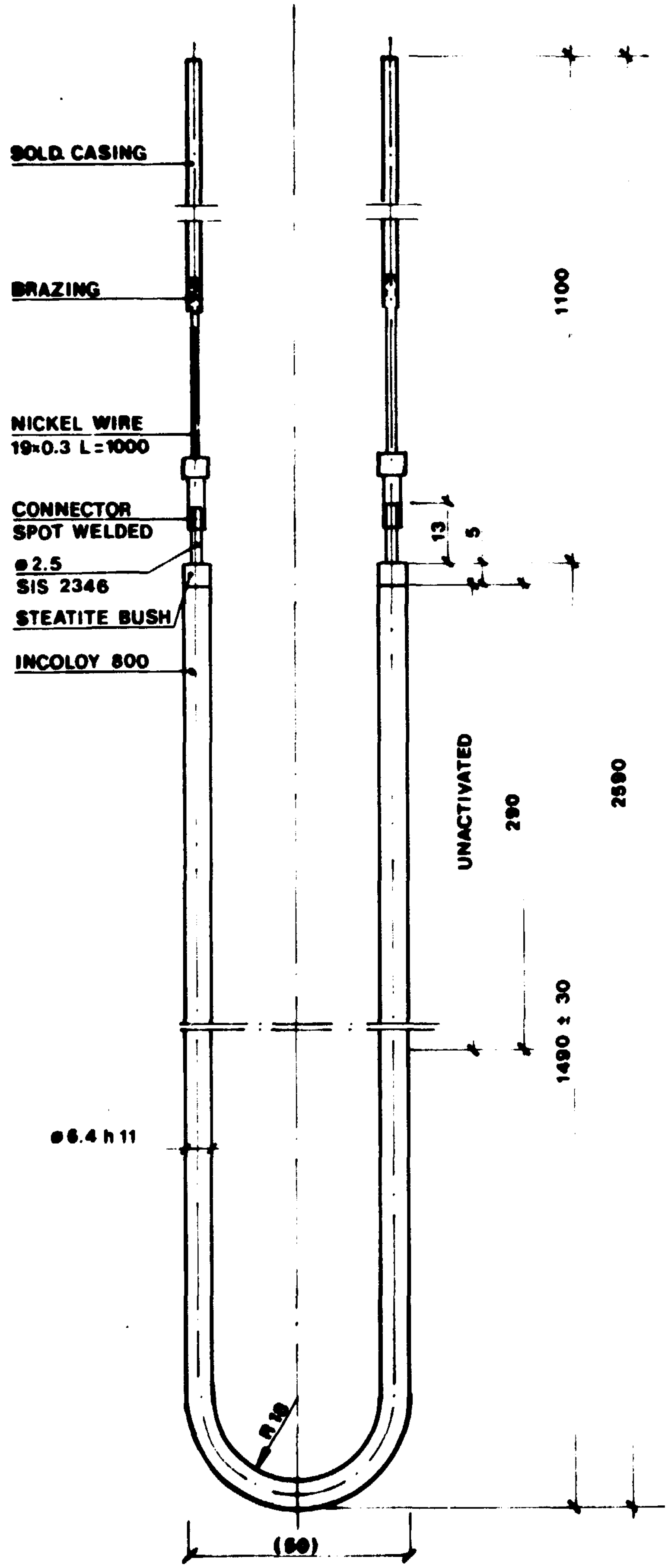


Fig. 4. Hairpin shaped tubular heating element

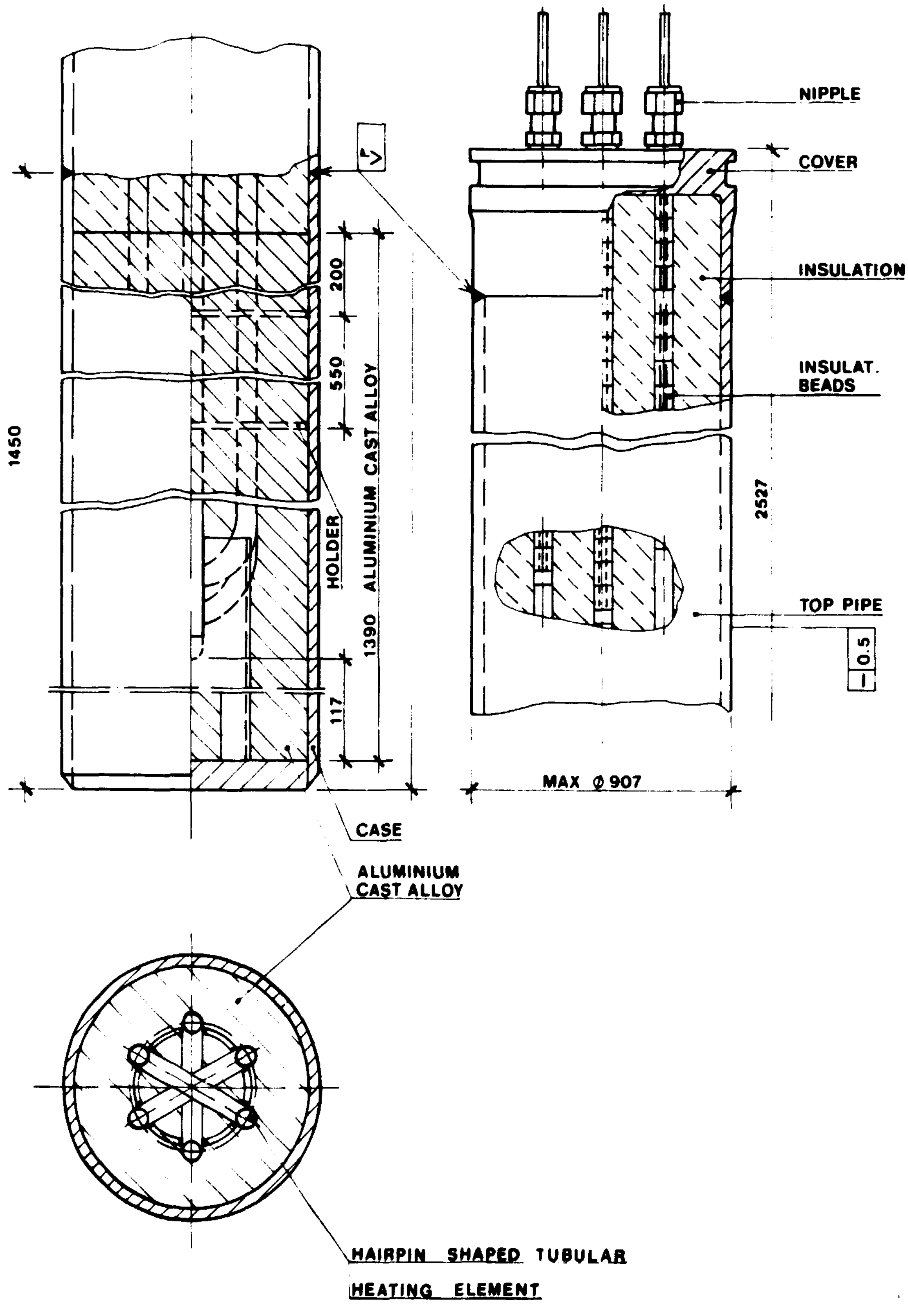
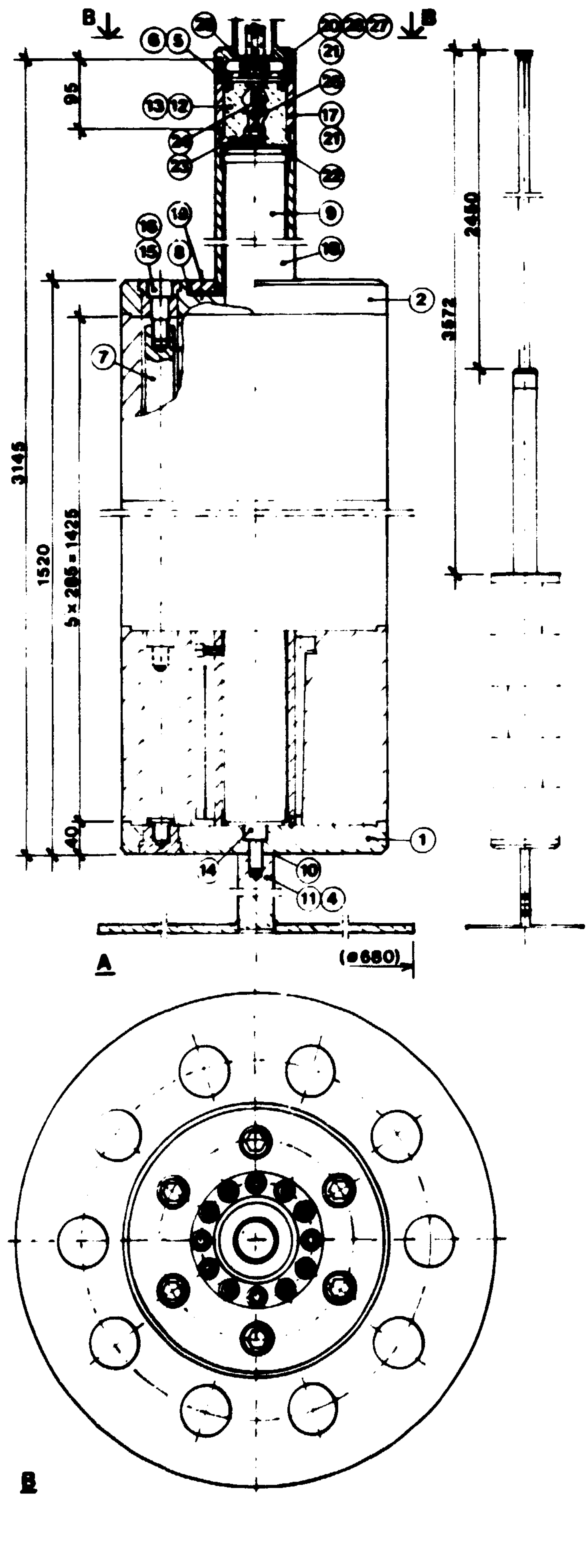
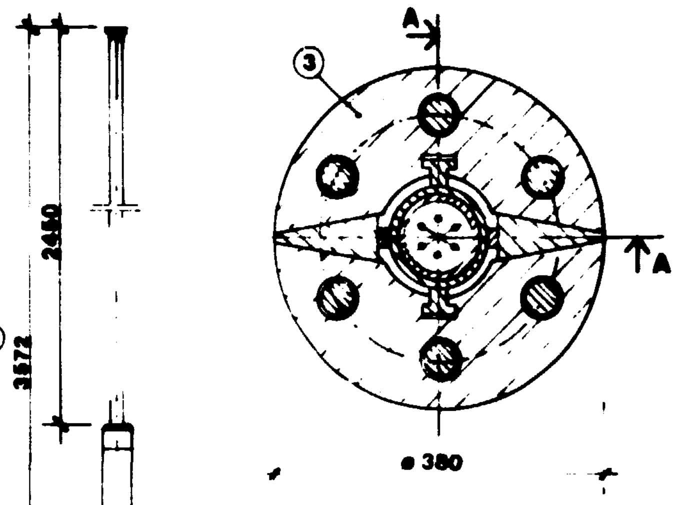


Fig. 5. Heater casing with heating element

Fig. 6. Heater casing





POS	NAME OF ITEM
1	BOTT. CABLE
2	COVER
3	HEATER PART
4	BOLT
5	BRACKET
6	SCREW
7	SCREW
8	GASKET
9	HEATER
10	GASKET
11	BOTT. SUPPORT
12	RUBBER DOUGH
13	HARDENER
14	SCREW
15	SCREW
16	RING
17	CASING
18	PROTECT. TUBE
19	SCREW
20	PROTECT. TUBE
21	RING
22	RING
23	SCREW
24	CLIP
25	CABLE FITTING
26	SHRINK PLAST
27	PROTECT. TUBE
28	PROTECT. TUBE
29	PROTECT. TUBE

Fig. 7. Heater

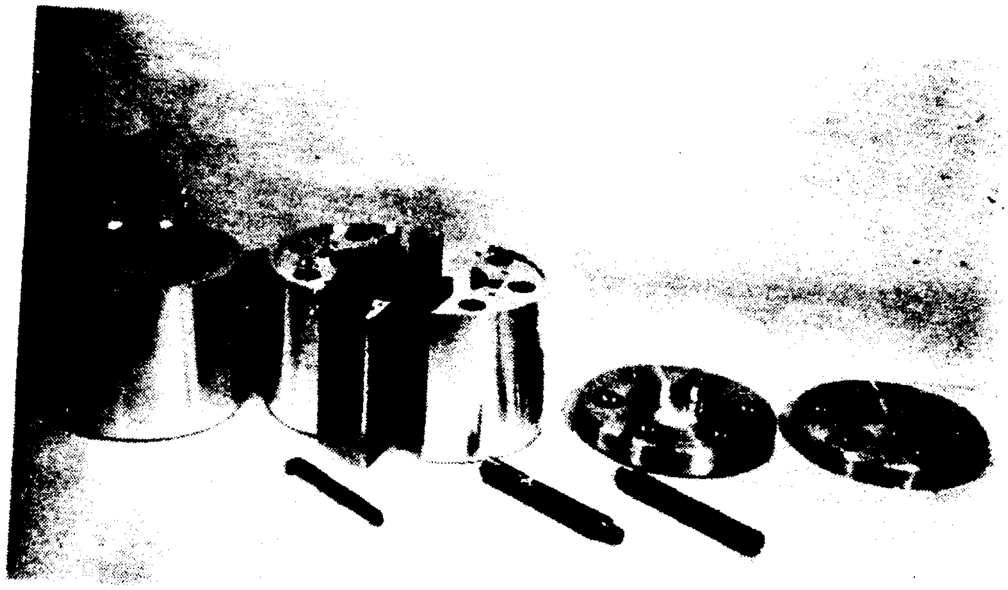


Fig. 8. Heater details and assembled heater

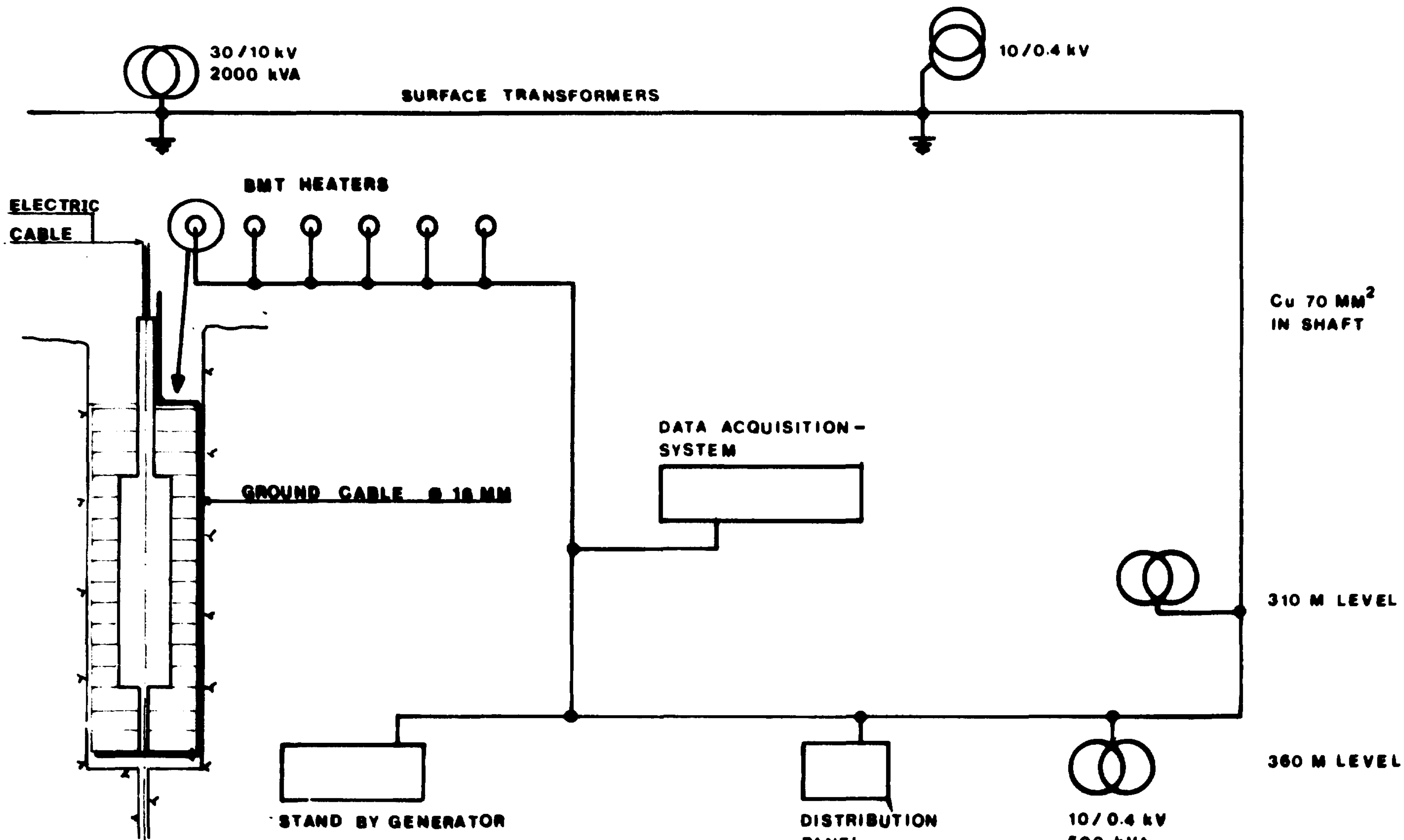


Fig. 9. Earthing system of the mine and heaters

supply is equipped with an automatic system which continously checks the power supply to both the heaters and computers.

If the supply decreases below a given voltage, the diesel engines are started and the reserve supply is available within 15 seconds. This reserve supply can normally operate, supplying the whole area, for 3-4 days without fud refill.

When the ordinary power supply is reconnected, it is automatically switched on while the diesel driven supply is still in operation. This change-over takes place so quickly (≃30-40 ms) that the control system for heaters remains operative. This means that the interruption in heating is negligible in the case of normal cuts in power supply. This type of disturbance may occur about 5-7 times a year.

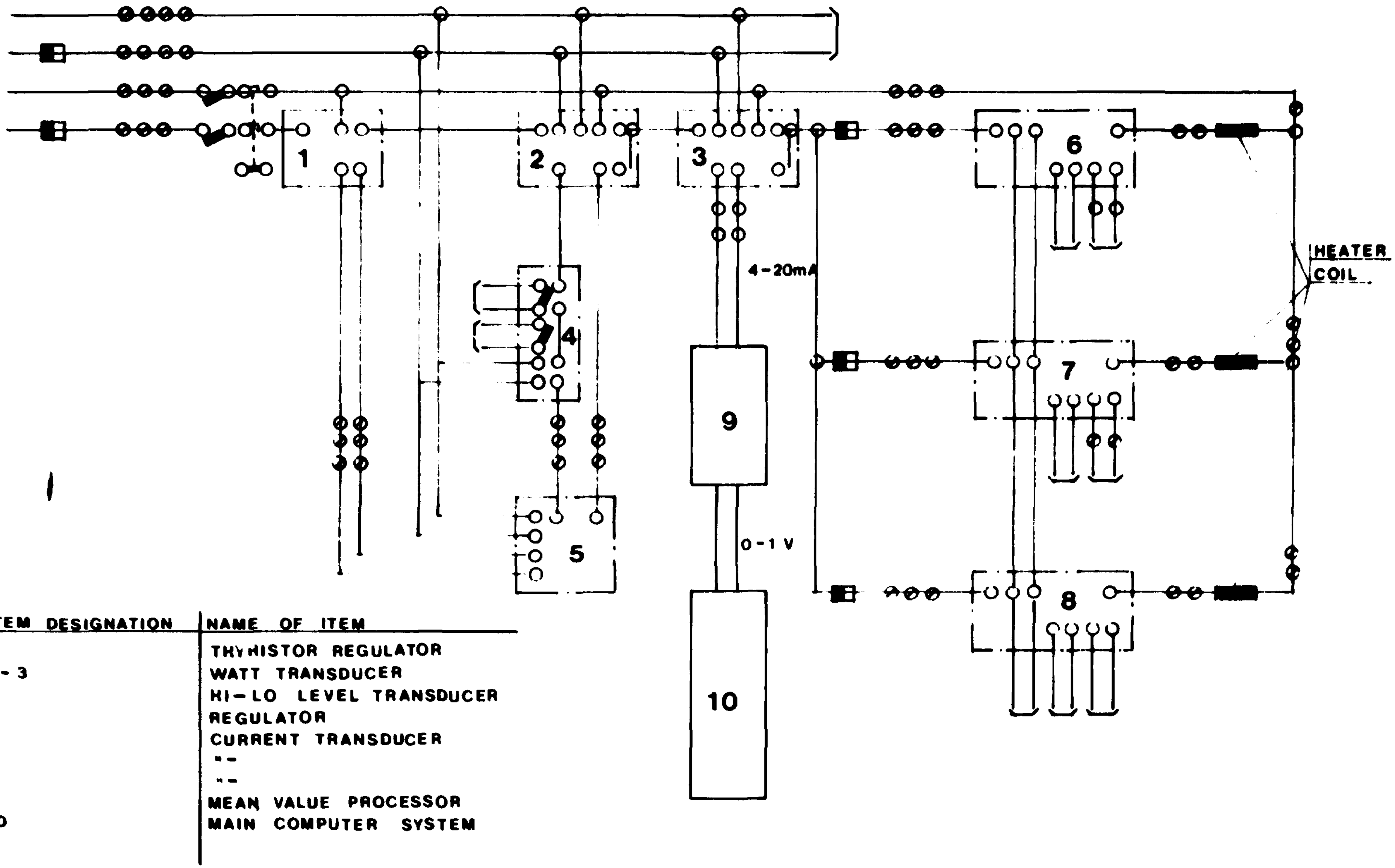
2.4 POWER CONTROL SYSTEM

2.4.1 Function

The control system is divided into two sub-systems, one for regulating and one for measurements. They are separated from each other as much as possible, i.a. the two systems use separate, identical transducers to convert electric power to current.

2.4.2 The Regulating System

The system consists of three main parts: the transducer, the electronic control unit, and the thyristor commutating switch (Fig. 10). The transducer is connected to the cables supplying power to the heater. It converts the power that is supplied to the heater to a current (4 - 20 mA). The control unit can be set at the desired amplification, integration time, etc. and it



ITEM DESIGNATION	NAME OF ITEM
1	THYRISTOR REGULATOR
2 - 3	WATT TRANSDUCER
4	HI-LO LEVEL TRANSDUCER
5	REGULATOR
6	CURRENT TRANSDUCER
7	" -
8	" -
9	MEAN VALUE PROCESSOR
10	MAIN COMPUTER SYSTEM

Fig. 10. Block diagram of the control system

produces a control current (4 - 20 mA) that feeds the thyristor switch. The switch turns on the AC mains to the heater at a certain phase angle every half period of the AC voltage. The control current determines this angle which also dictates the power that is fed to the heater, thereby completing the loop.

2.4.3 Measurement System

For each heater there is a second transducer identical to that of the regulating system (Fig. 10). This produces a current (4 - 20 mA) that is proportional to the power. The transducer is very sensitive - it responds to power variations in just a few milliseconds (settling time = 300 ms). If this current is sampled directly, the recorded value is very unstable for reasons that are discussed later. It was therefore necessary to use the mean value of the current over several minutes to obtain a stable signal. A microcomputer with an A/D converter is used to calculate the mean value and feed the result to the main computer that collects data from all testpoints in this experiment. The main computer was unable to make the mean value calculations simultaneously to recording the data.

2.4.4 System Components

A more specific description of the function, in principle, of each component is given below.

Each of the six electric heaters used in this experiment contains three resistors that do the actual heating. Each resistor is supplied with power from a separate power cable, so that if one resistor or cable breaks down there are still two left. The resistors are designed to discharge 1000 W of power each but the actual power supply for one heater during this test is only 600 W. This means that one resistor alone can supply the power to the heater. Normally the three resistors operate parallel and discharge 200 W each.

As mentioned above, the transducer measures the electric power and discharges a current that is proportional to the power. The method is this:

The voltage and current are transformed to a suitable level by two separate transformers. The transformers also provide galvanic isolation between input and output of the transducer. The momentary values of the current and the voltage are then multiplied using the "pulse width/pulse amplitude" method, which means that the width of each pulse is proportional to the voltage and the amplitude proportional to the current. The pulses are then lowpass filtered and the result is a signal that is proportional to the momentary product of the current and the voltage. The pulse frequency determine the highest permitted frequency of the input. As the pulse frequency is about 5 kHz, input frequencies of up to 500 Hz are measured with retained accuracy.

The input in this case is not a true sinus voltage as the thyristor switch considerably distorts the sinusoide. When sampling this distorted voltage the result is very unstable and varies with time. However, as there is no synchronisation between the pulse frequency (5 kHz) and AC frequency (50 Hz), the mean value is correct. Experiments showed that an integration time of 5 to 10 minutes gives a stable signal within 0.2%.

The control unit is a general purpose differential amplifier with adjustable characteristics. The reference value as well as the gain and integration time are adjustable by knobs which are manipulated at installation until the power of the heater is correct. As the power is supervised during the test period by measurement system, there is no need to adjust the control unit as long as the power is correct. Any inaccuracy in the control unit will immediately be monitored.

The thyristor switch turns on the AC voltage 100 times a second. The exact moment to turn on the voltage is controlled by the current fed to the control input of the switch.

The mean value processor is a specially built unit which contains a one-chip microprocessor. The unit processes the signals from all 6 transducers and discharges 6 analogue voltages that are to be sampled by the HP data acquisition system which collects all measurement data during the experiment.

The signal from each transducer is at first transformed from current to voltage. This voltage is low pass filtered in a simple RC link with a time constant of 0.1 seconds. All six signals are then multiplexed and fed to an A/D-converter. The digital values are added during a period of time that is chosen by a switch to one of 14 values from 0.125 seconds to 8.5 minutes. The sums are stored for each signal in a cyclic way so the last 8 sums are available in the memory. The mean value of each signal is computed from the eight sums and fed to a D/A-converter. After demultiplexing and buffering, the six computed values are discharged to the HP. The precision of the A/D and D/A conversions are 12 bits.

As a result of the computations, the mean value is calculated over 1 s if it is updated every 0.125 s. The mean time value can consequently be set to one of fourteen values between 1 second and 1.14 hours.

2.4.5 Data Acquisition System

The system has been designed by the Computer Department, University of Luleå, and manufactured and delivered by Hewlett-Packard.

The hard- and software of the system are described in detail by Björn Hagwall in Reports IR 82:02 and IR 82:03.

3 FUNCTION TEST IN LABORATORY

3.1 GENERAL

The following tests were carried out in the laboratory at ASEA-ATOM:

- Testing of the heatflow of the casing in air.

- Testing of the heatflow of the entire heater unit in air.

- Assembly, trial operation for 14 days and dismantling. These tests were carried out in a sand-filled test rig equipped with thermocouples and with the same geometry as the deposition holes.

3.2 LABORATORY TEST OF THE CASING IN AIR

Following assembly, the distribution of temperature in the casing was tested with 1, 2 and 3 elements in operation and with a total effect in all cases of 600 W. The temperature was measured, when a stable situation was reached for each combination, using a contact thermometer at 18 levels with 8 points at each level. The room temperature was measured simultaneously. As illustrated in Figures 11 and 12, a casing temperature of about 110°-130° was attained at a room temperature of $22^{\circ}C$, the elements being cast in aluminium. Over the upper part of the casing, where the elements are insulated with rock wool, the temperature decreased rapidly from about $110^{\circ}C$ near the cast-in part to about $30^{\circ}C$ at the top. Exactly the same heatflow picture was noted whether one, two or three of the elements were in operation.

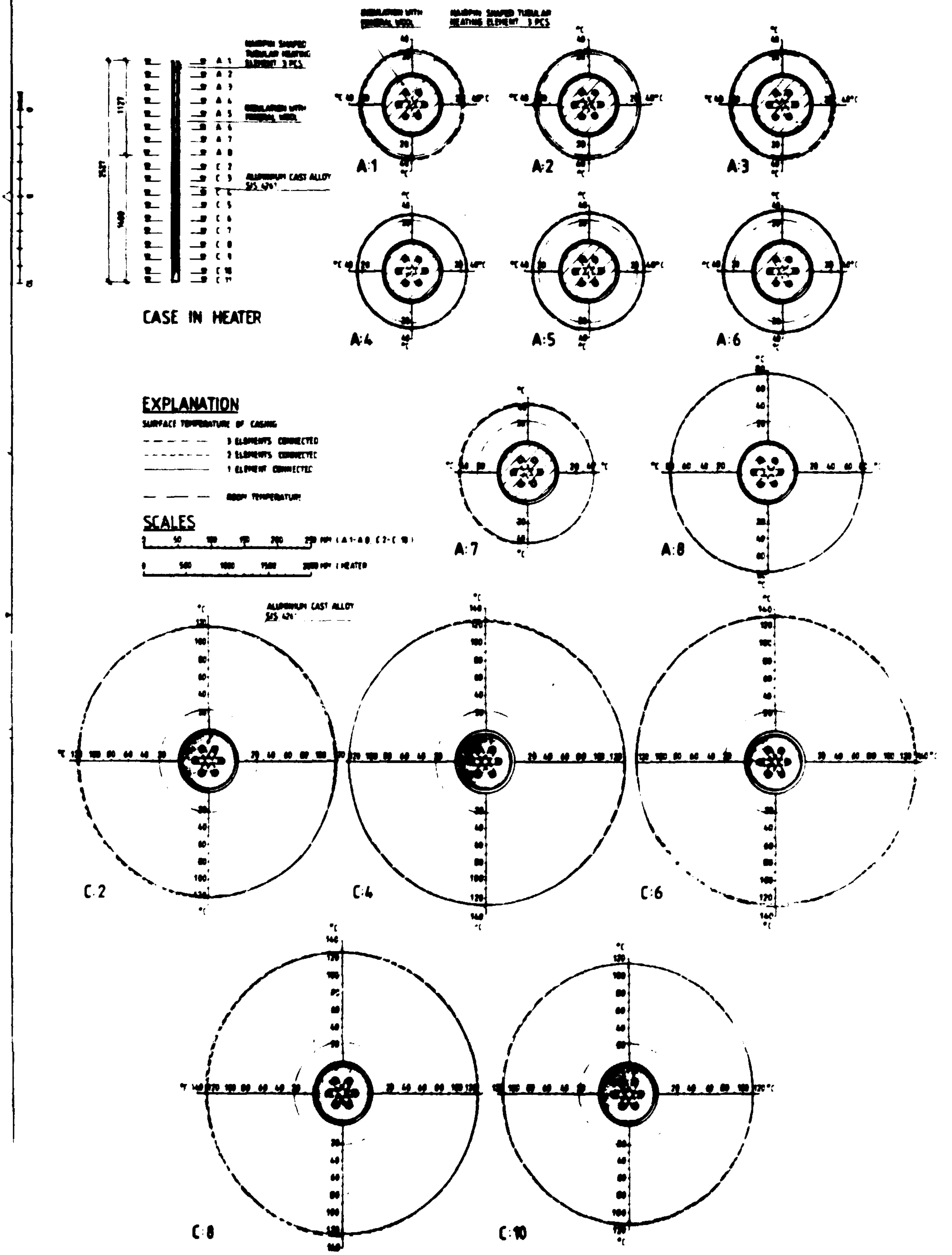


Fig. 11. Laboratory test of casing in air. Horizontal sections

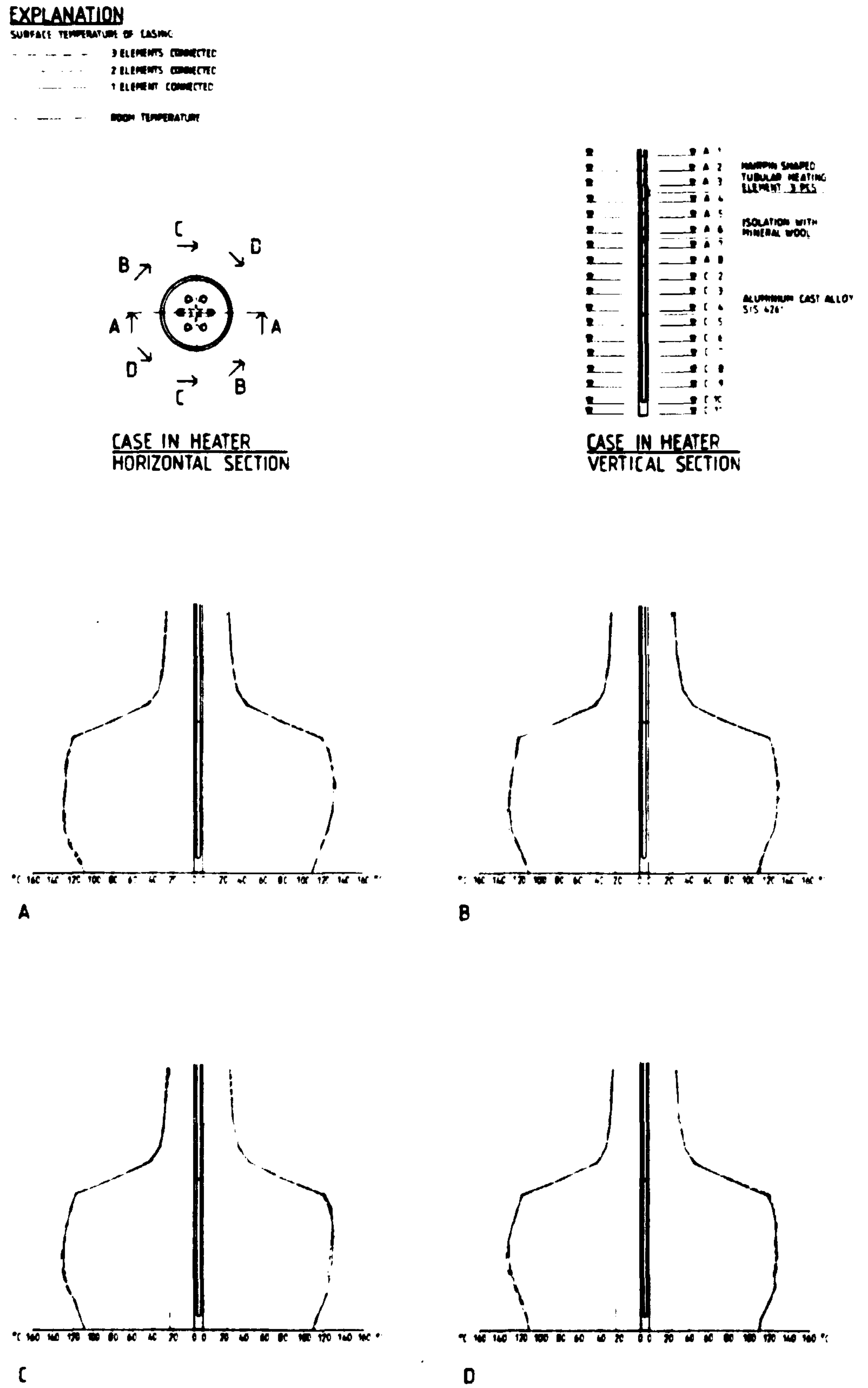


Fig. 12. Laboratory test of casing in air. Vertical sections

3.3 LABORATORY TEST OF HEATER IN AIR

A complete heater unit was tested in the same manner as the casing. As shown in Figs. 13 and 14, the same even radial heat-flow picture was obtained as for the casing. The temperature distribution along the upper part which protrudes from the casing, and along the rod between the base of the heater and the basal plate varied from about 70°C nearest the encased part of the heater, to about 25°C at both the top and bottom of the entire unit. Fig. 15 illustrates both the assembly of the heater and the way in which the temperature measurements were made.

3.4 LABORATORY TEST OF HEATER IN "DEPOSITION HOLE" OF STEEL PIPE FILLED WITH SAND

One heater unit was installed in a test rig Fig. 16 consisting of a steel pipe with the same dimensions as a deposition hole. The pipe, which was insulated with rock wool, was filled with water-saturated olivine sand. The instruments consisted of 39 thermocouples placed at 5 levels, the positions of which are shown in Fig. 17. The primary purpose of the test was to check the reliability of the equipment over a longer period and to check that the units could be dismantled in the intended manner. The trial period was at first planned for one month. When a stable situation for temperature distribution was attained after 10 days, it was decided to end the trial after 14 days. It was very interesting to note that thermocouples 11 and 12 at the base of the heater unit, 19 and 20 in the middle, and 27 and 28 at the top all showed almost identical temperature increases. Thus an even radial heat-flow picture was also obtained with this test.

Dismantling of the heater unit showed that the construction functioned as planned. Several stages are illustrated in Fig. 18 and 19.

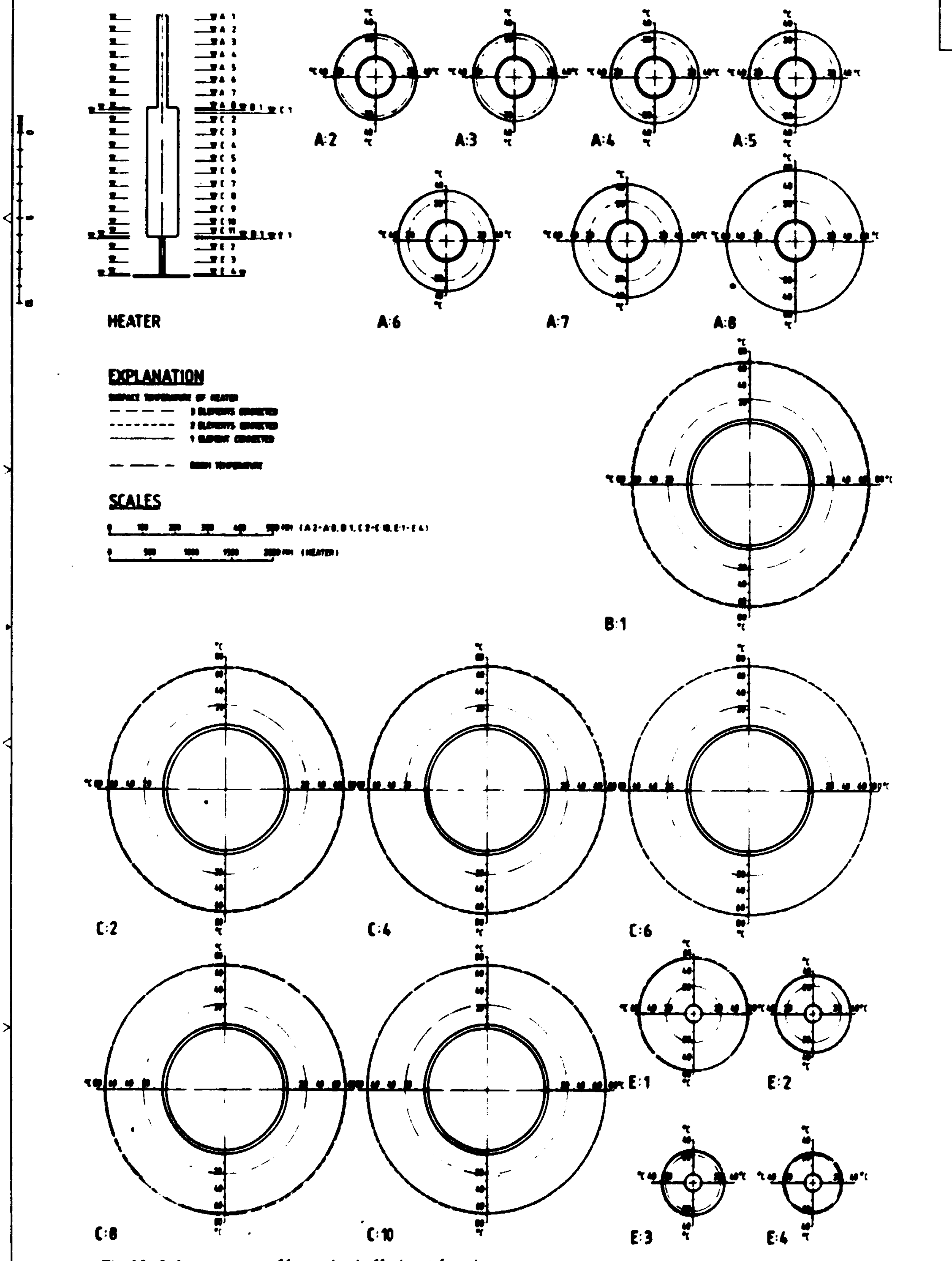


Fig. 13. Laboratory test of heater in air. Horizontal sections

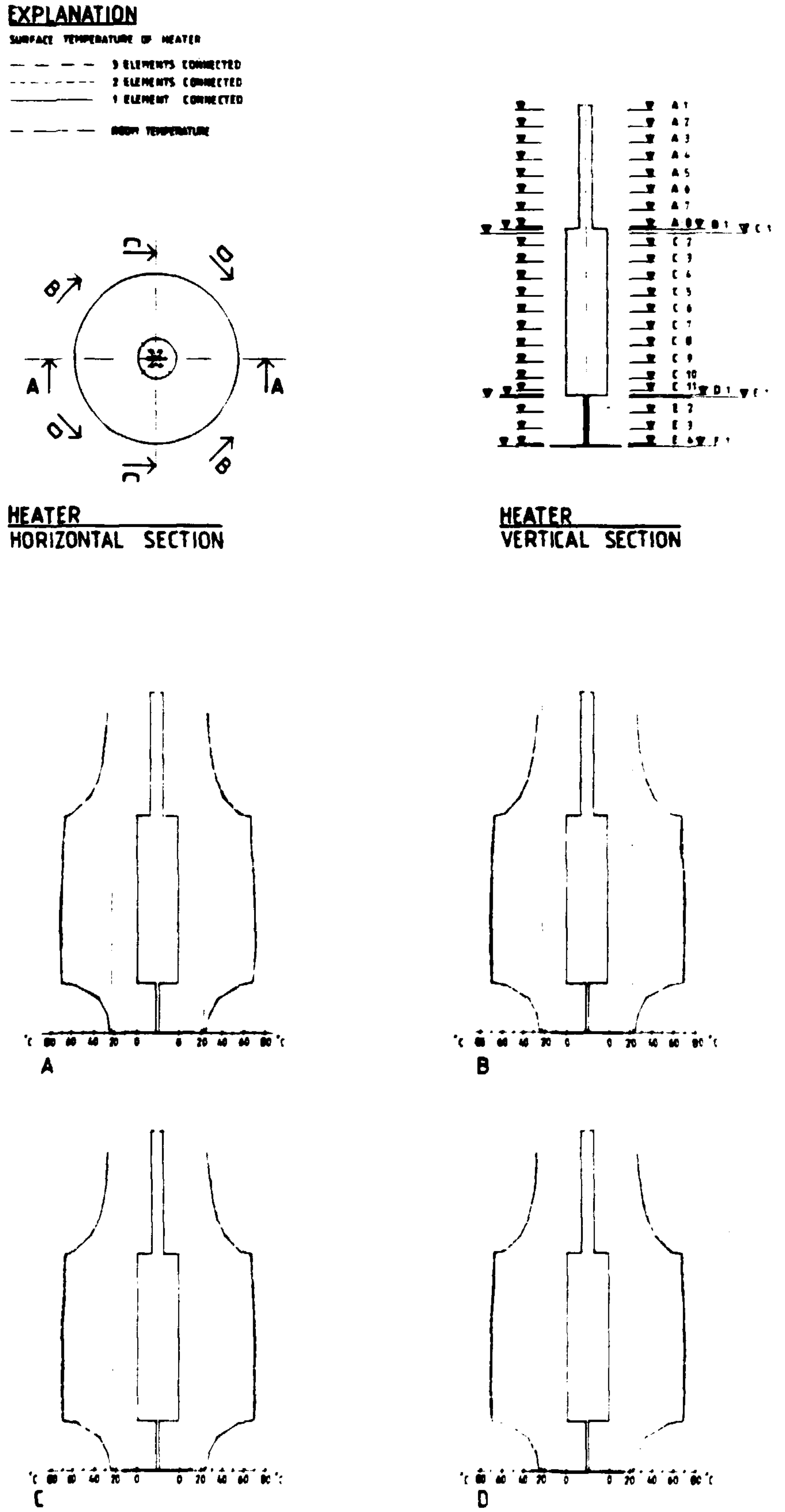


Fig. 14. Laboratory test of heater in air. Vertical sections

Fig. 15. Laboratory test of heater in air

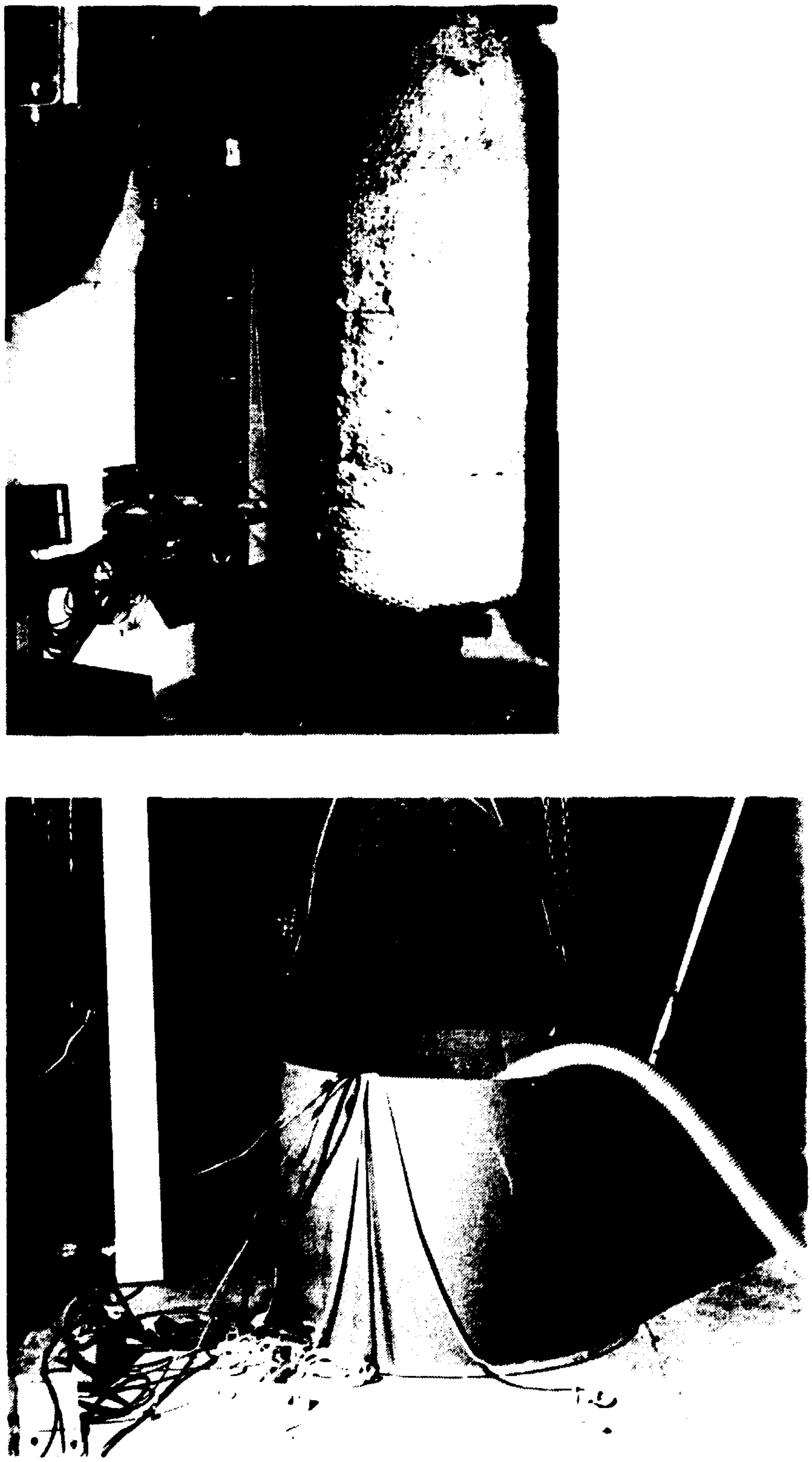


Fig. 16. Laboratory test of heater in test rig

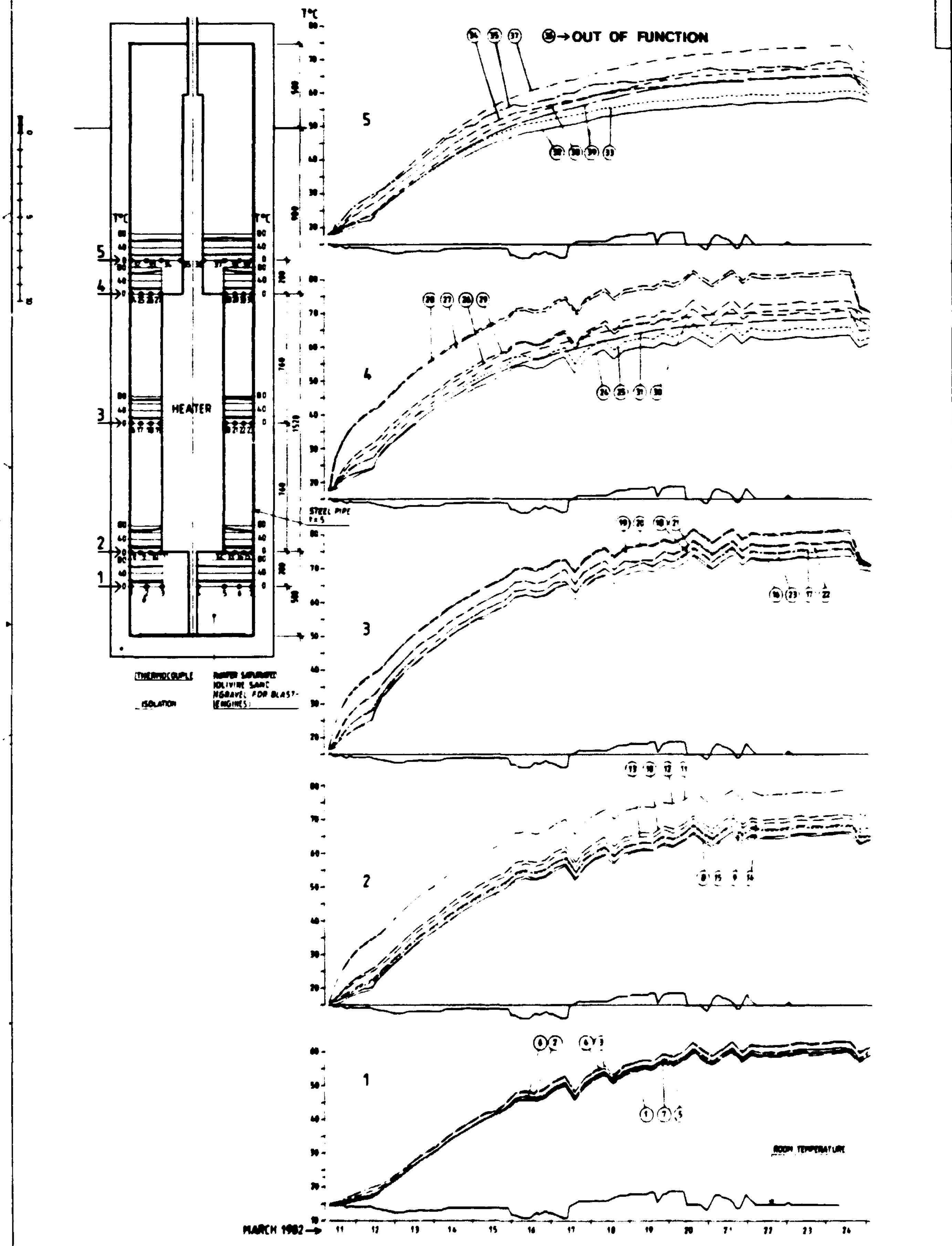


Fig. 17. Temperature distribution in test rig

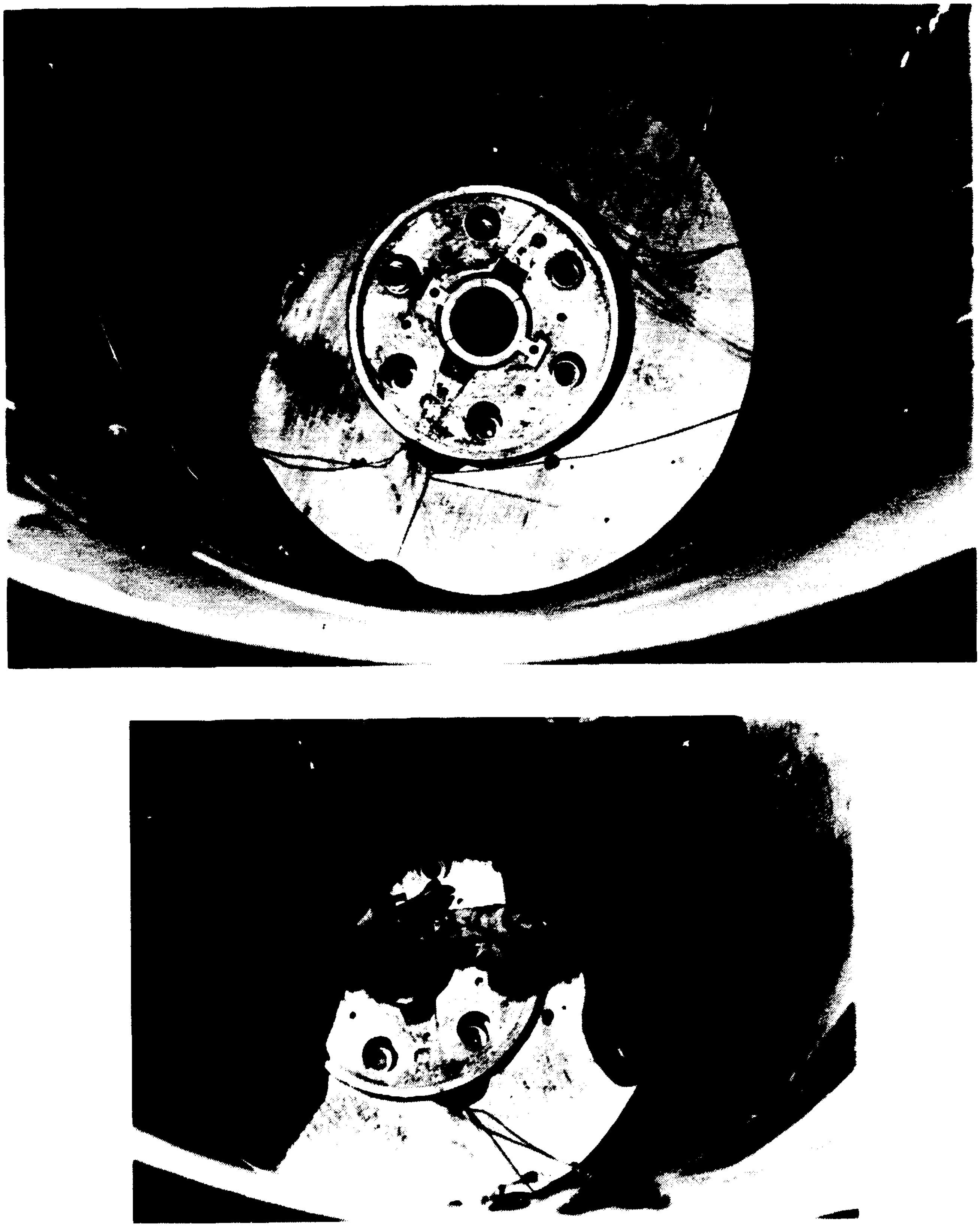


Fig. 18. Dismantling of heater in test rig

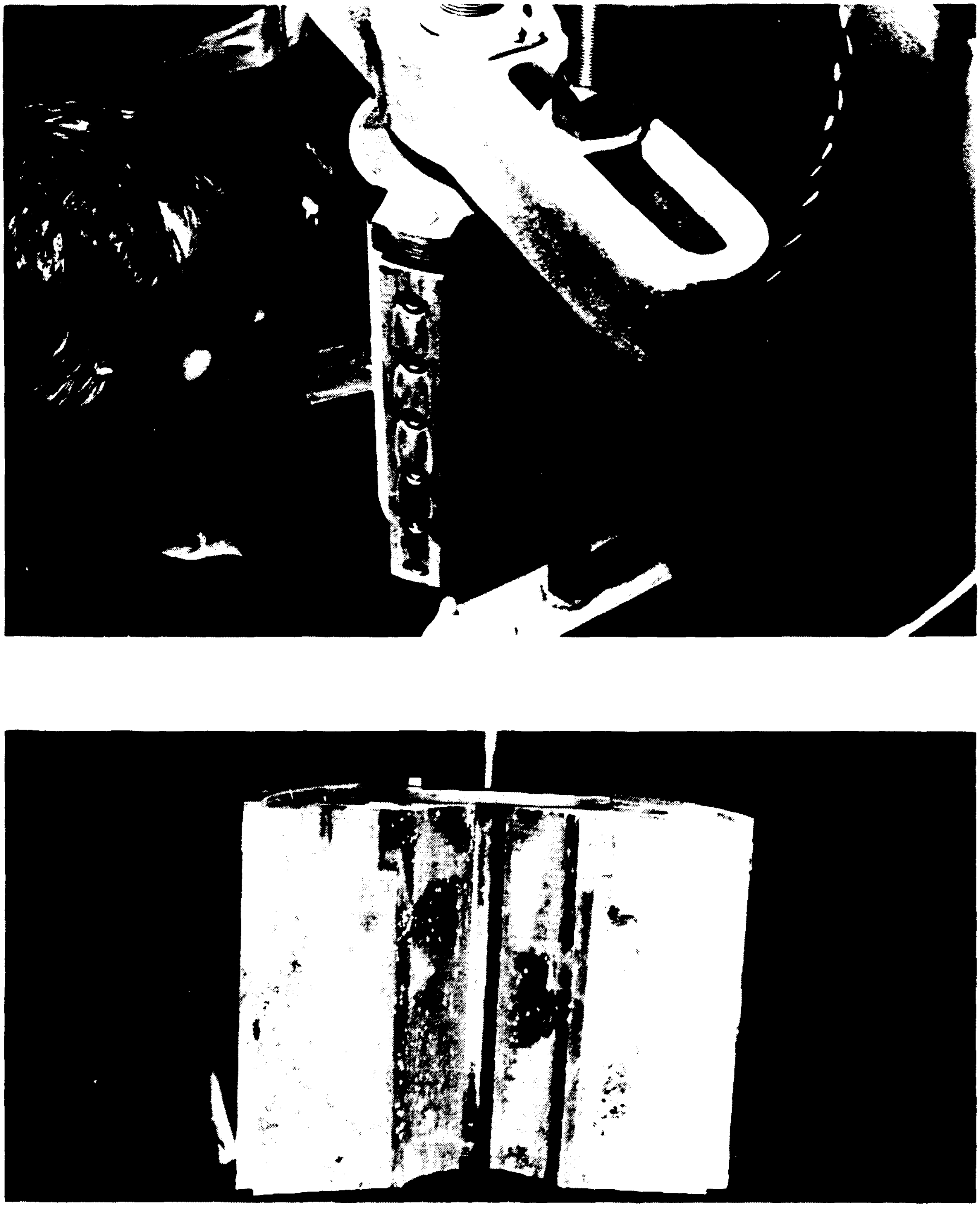


Fig. 19. Heater parts with lifting equipment

4 INSTALLATION OF CONTROL SYSTEM

This equipment has been installed in the underground data acquisition and control center, with the exception of the computer which is situated above ground. This center is close to the test area, and was originally established for the Lawrence Berkely Laboratory (LBL). Fig. 20 illustrates the relationships between the components of the system. Fig. 21 shows the three cabinets for the power control system. Two of the cabinets contain thyristors and the alarm panel, and the third contains the controls for the heating effect. The measuring equipment which is connected directly to the computer is shown in Fig. 22.

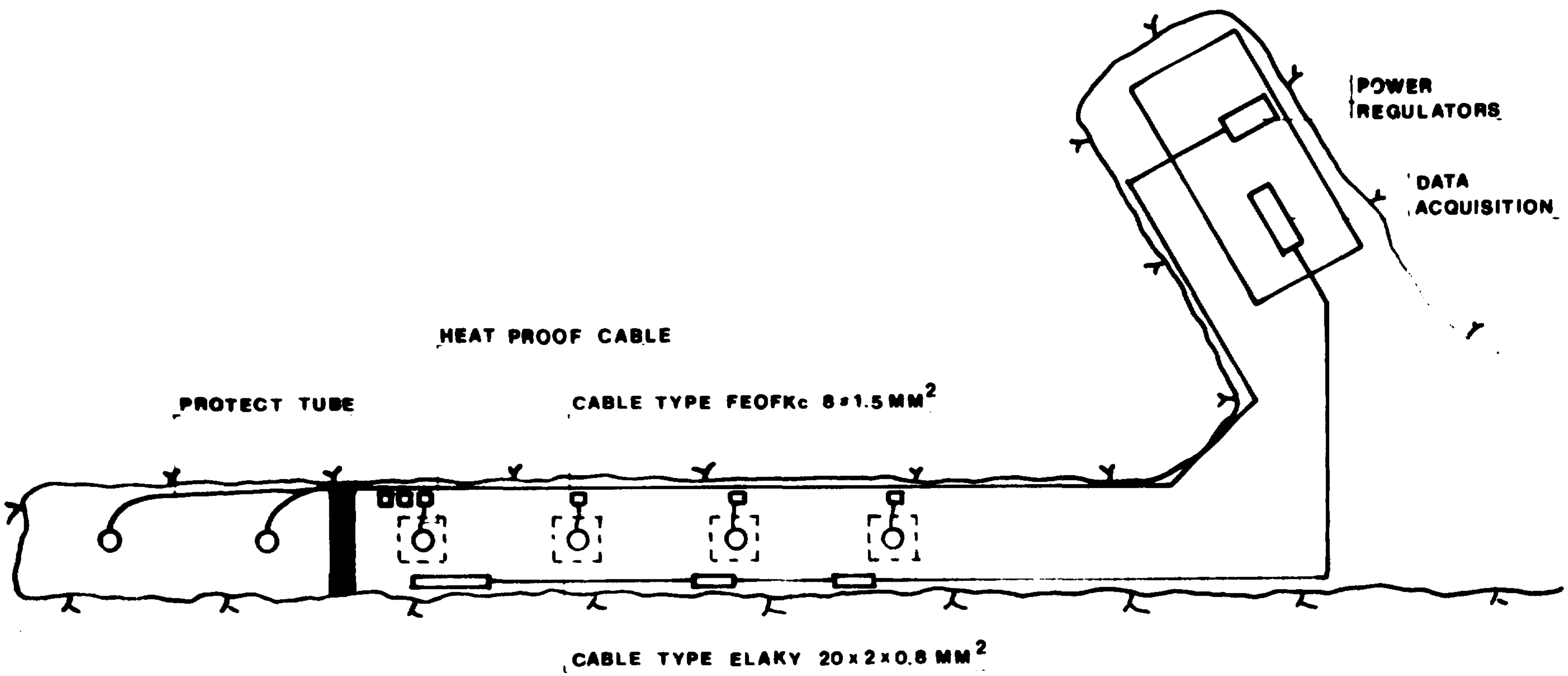


Fig. 20. Relationships between the components of the control system

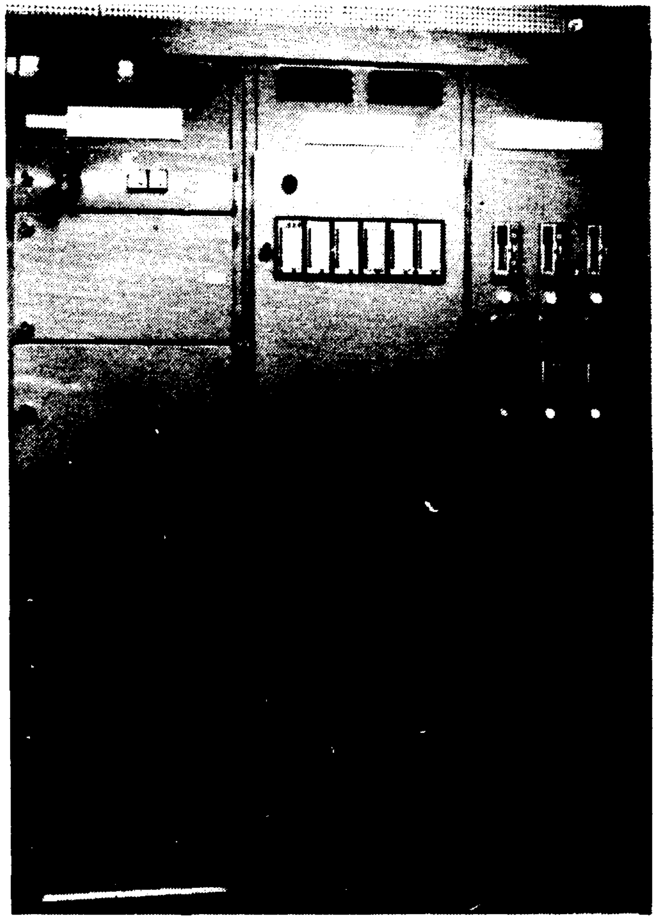


Fig. 21. Cabinets for the power control system

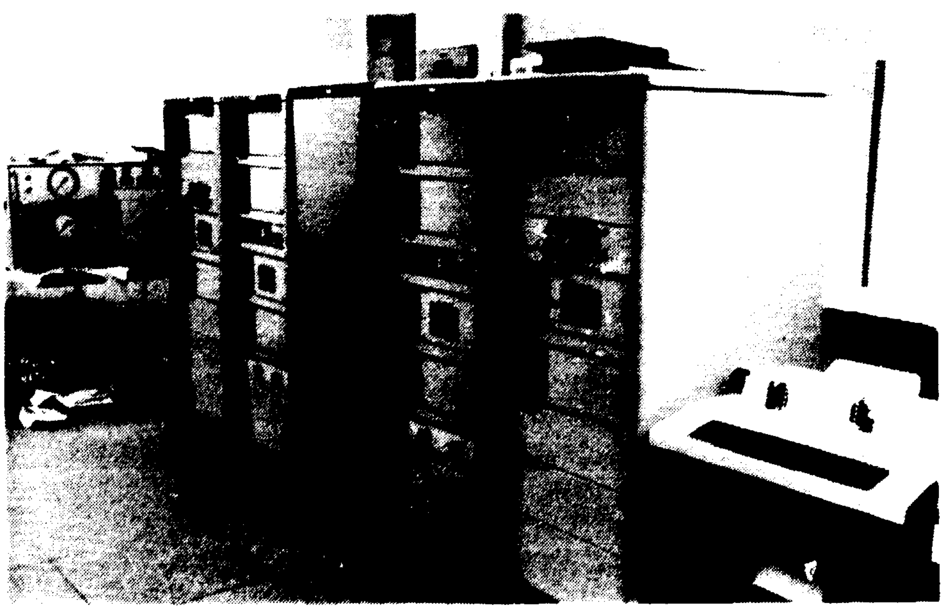


Fig. 22. Cabinets for the measuring equipment

5 INSTALLATION OF HEATER IN DEPOSITION HOLE

ASEA-ATOM's undertaking also included delivery to Stripa Mine of all six assembled heater units in special transport containers.

The work of installing the heaters was carried out as follows:

Each transport container was placed on a working platform directly over a deposition hole, using a hoist block. The container was opened and removed. A means of attachment for the hoist block was screwed into the uppermost protruding part of the heater casing. The perforated basal plate was then fixed into position. Blocks of compacted bentonite containing instruments were placed around the heater and fixed into position using plastic bands, producing a package weighing a total of about 3 tons. The package was then lowered into the deposition hole and the attachment for the hoist removed and replaced by protective tubing for the electric cables. The protective tubing for heater units 1 and 2 is made of plastic, and for heaters 3-6 of steel piping. Figures 23-26 illustrate some of the various stages of installation.

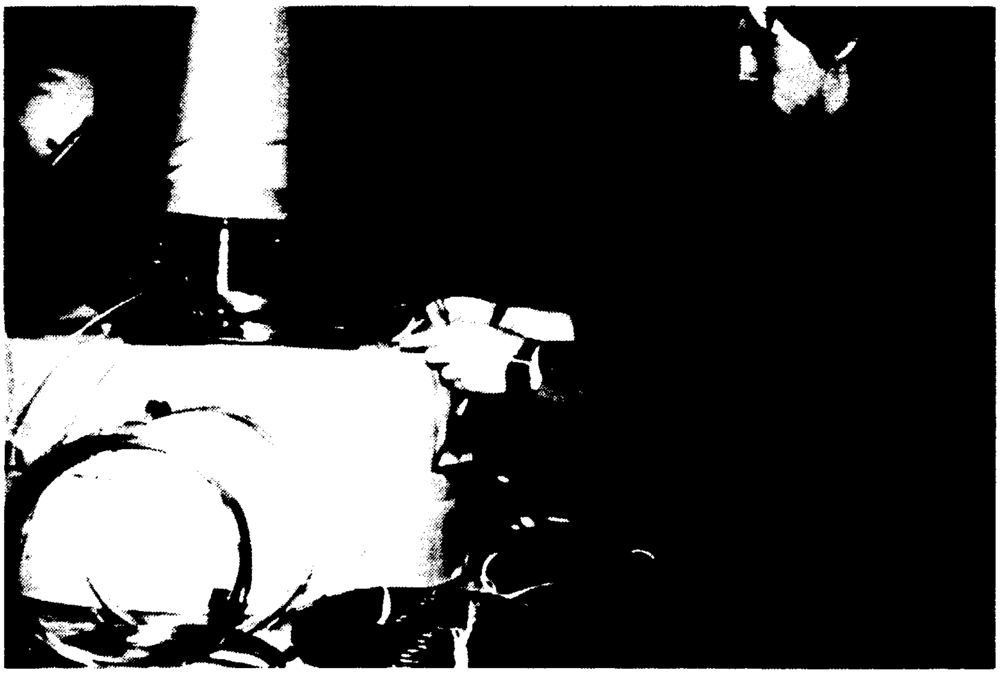


Fig. 23. Blocks of compacted bentonite containing instruments

Fig. 24. Package lowering into the deposition hole

Fig. 25. Casing with plastic cover of electrical cables extending from heater. The plastic cover has only been used in heater holes no 1 and 2.

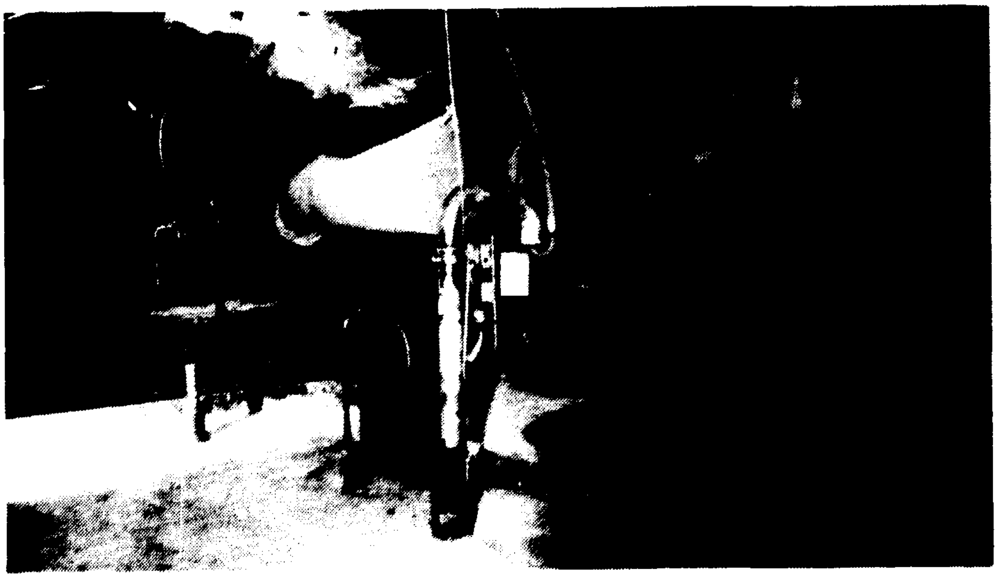


Fig. 26. Steel casing for protection of cables from heaters no 3. 4, 5 and 6

6 OPERATING EXPERIENCE

6.1 HEATERS

The six heater units were put in operation on the following dates: nr. 1, October 5, 1981; nr. 2, October 7, 1981; nr. 3 and nr. 4 January 20, 1982; and nr. 5 and 6, March 24, 1982. Hole 3 was opened during week 15 1983 and hole 4, week 48, 1982. The remaining holes have not yet been opened. All the heater units have functioned quite satisfactorily and according to the plans, both with respect to installation, operation, and dismantling.

6.2 CONTROL SYSTEM

The control system, once properly adjusted, has worked very well and reliably. The following errors were estimated for the various components.

6.2.1 Errors

Errors in the control system will affect the constancy of the power supply, both on a short and long term basis. Variataions of less than 10 to 20 minutes are not significant to the test results as long as the mean value is recorded. The temperature of the heater will not be affected by shorter variations. Long term variations, weeks or months, will be monitored by the measuring system and can be compensated for manually if necessary. The variations during times between those time limits is expected to be very small, about 1 W.

An attempt to estimate the maximum errors in the measurements is based on the data sheets for the various components.

6.2.2 Power Losses

The transducers record the power in the heaters and the power in the power cables. The power in the cables has been calculated by ASEA-ATOM in a report 1981-12-23 for each heater. The maximum error in the calculated power losses is 1 W. After the experiment, the values can be verified whereby the power in the cables will be known with greater accuracy.

6.2.3 Transducer Errors

The data sheet for the transducer shows that the accuracy is about 0.5 %. It has been verified by experiments that the transducer is not significantly affected by the fact that the power voltage is distorted. The maximum error from the transducer is then 0.5 % x 1000 W = 5 W. Careful calibration should improve this figure as the circumstances of the measurement are very stable.

6.2.4 Mean Value Computation Error

The mean value processor is designed to produce an error of less than 0.1 % of FSR which means 0.1 % x 1000 W = 1 W. This has been verified at the time of installation.

6.2.5 Total Error

From the above it can be conducted that the heating power is measured with an absolute error of less than 5 + 1 + 1 = 7 W. Much smaller variations in power will of course be detected, and as the power is very constant, the equipment can be calibrated to measure the power just around 600 W with greater accuracy. The actual heater power is given in the following table:

Heater no	Power loss, W	Nominal power, W
1	24.9	600
2	22.3	600
3	18.6	618.6
4	16.9	616.9
5	14.9	614.9
6	12.9	612.9

The power loss through cable resistance etc, was compensated for in the case of heaters no 3, 4, 5 and 6, while this was not the case for heaters no 1 and 2. Thus, the net power was 600$\pm$7 W for heaters no 3-6 and about 575 $\pm$7 W for heater no 1 and 577 $\pm$7 W for heater no 2.

7 DISMANTLING OF HEATER AT OPENING OF DEPOSITION HOLE

Deposition holes 3 and 4 were opened week 15, 1983 and week 48, 1982 respectively. Extensive sampling of the box filling and compacted bentonite was carried out. Dismantling of the heaters followed the procedure described for the test rig without problems. Fig. 27 and 28 illustrates the situation in a deposition hole when the uppermost layer of compacted bentonite was exposed and sampling commenced. Fig. 29 shows the upper plate (lid) exposed and Fig. 30 the basal plate. These figures illustrate that the limited space makes it necessary to construct the heater units so that they can be dismantled successively lengthwise and inwards to make the sampling possible.

Fig. 27. Steel plate jig for sampling at the excavation of the heater holes

Fig. 28. Dismantling of heater to give access to the clay for sampling purposes

Fig. 29. Upper end of heater exposed in the course of the excavation of hole no 4, 10 months after test start

Fig. 30. View of exposed sampling level in hole no 4 before application of the jig

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