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Experimental determination of the behaviour of irradiated P.W.R. fuel rods during simulated transients.

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EXPERIMENTAL DETERMINATION OF THE BEHAVIOUR OF IRRADIATED PWR FUEL RODS DURING SIMULATED TRANSIENTS

by

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SUMMARY

A programme of LOCA simulation tests on irradiated fuel rods was initiated at Windscale in 1978 in support of PWR safety assessment studies. Equipment was constructed in order to allow the mechanical stability of the unsupported fuel column to be examined after the cladding had bulged, in the temperature range 973-1073K, under the action of rod internal pressure.

The paper describes the LOCA test facility which incorporates an infra-red pyrometer and CCTV camera for measurement and control of cladding temperature diametral strain. Particular emphasis is placed upon modular design and construction in order to ease problems associated with repairs and maintenance under conditions of remote operation.

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1. INTRODUCTION

The effectiveness of emergency cooling during a large-break loss of coolant accident (LOCA) in a PWR could be adversely affected if the overheated Zircaloy cladding has bulged, prior to reflood, under the action of fuel rod internal pressure. The most serious restriction of cross-sectional area for coolant flow might be expected, for instance, if the cladding bulges were coplanar and axially extended.

Although there exists a considerable body of experimental data on the elevated-temperature deformation of internally pressurised Zircaloy cladding in the unirradiated condition there is little information relating to the behaviour of irradiated fuel rods. It is possible, for instance, that the deformation characteristics of the cladding could be modified by irradiation hardening or fuel-cladding interactions of a chemical or mechanical nature. Furthermore, the mechanical stability of the cracked fuel column must also be considered because separation and downward relocation of fragments from the fuel column within the bulged cladding might lead to localised overheating and a progressive downward extension of cladding deformation. The extent of fuel relocation could clearly be increased by mechanical impacts, that might result from cladding rupture, or by quench-induced vibrations during reflood.

This paper describes the test facility, equipment and techniques for LOCA simulation tests on lengths of irradiated PWR fuel rod with particular reference to the mechanical stability of the unsupported fuel column during and after the transient.

2. THE SHIELDED FACILITY

The equipment is set up in a general-purpose lead-shielded cell (250 mm wall thickness) provided with leaded-glass viewing windows; remote handling is by means of tongs and all major services are available, either in the cell or through easily accessible wall plugs. Because of the restrictions imposed by lack of manipulators for handling, and the fact that the general-purpose facility has very limited access, the use of modular components is of paramount importance and this aspect of the design will be described later.

The measurement and control equipment is housed in racks positioned in front of the facility allowing easy operating and access for maintenance (Fig. 1).

3. THE TEST-PIECE

The test-pieces (Fig. 2) are prepared from 450 mm lengths of fuel rod. After removing approximately one pellet length of fuel from each end, cylindrical metal plugs are inserted to contact the fuel stack (the one at the top end is provided with an axial hole to allow subsequent pressurisation). Closely fitting steel caps are then fitted over each end of the test-piece and compressed onto the cladding in a 500 kN hydraulic press to produce metal-to-metal seals. The top end-cap is grooved to accommodate a high-pressure O-ring and backing washer to allow connection to the pressurising head. Before insertion into the equipment the test-pieces are gamma-scanned and X-radiographed to establish the fuel distribution; unsatisfactory material is rejected at this stage.

4. LOCA SIMULATION EQUIPMENT

The test rig (Figs 3-6) is designed to fit in a steel-framed box 820 x 500 x 500 mm;

the top and three of the sides are Perspex, the base-plate and the remaining side (carrying the monitoring equipment) are of steel construction. The test-piece is mounted centrally and held in position by a pressure seal at the top and located in a bath of molten metal (Rose's alloy) at the bottom end (Fig. 5). The molten metal bath is fitted with adjustable lateral restraints, which allow the test-piece to move axially (as in a fuel element grid) but restrict lateral displacement. The steel side of the box carries the remainder of the equipment (Fig. 6): power cables for resistance heating, air-assisted filter, infra-red pyrometer, CCTV camera, pressure transducers, an accelerometer, a rotary vacuum pump, adjustable volume block, calibration thermocouples and entry points for controlled atmosphere testing and gas pressurisation.

The box also acts as a containment for any radioactive species released from the test-piece after rupture of the cladding. The air-assisted filter clears the exhaust gases from the containment box before they are drawn into the main extract system that serves the shielded facility.

The cladding is heated by the direct resistance technique (typically 300 amps at 6 volts) which maintains temperatures within $\pm$ 4K over a zone $\sim$ 250 mm long. A typical temperature distribution along the test-piece is illustrated in Fig. 7.

The infra-red pyrometer is directed at the mid-length region of the test-piece and has a target diameter of 2.5 mm at 250 mm and a response time of 5 ms. The temperature range for current work is 573-1173K and the output signal from the pyrometer is used to drive the Eurotherm International temperature controller which is capable of providing temperature ramp rates in the range 2-20 degrees K/s.

The monochrome TV camera is also fixed to view the mid-length point of the test-piece and provides a video signal for continuous monitoring and recording of cladding diameter during testing. (A moveable camera is used to monitor the whole of the test-piece as required.)

The two pressure transducers are of the Sangamo-Weston P180 type, 0-20 MPa. They are mounted on either side of a monitoring needle valve in order to enable differential pressure tests to be carried out when required; in general only one gauge is used for LOCA simulation testing.

An accelerometer, mounted in a magnet, is attached to the pressure head to monitor all movements of the test-piece throughout the test period. During fuel relocation tests it is used to identify any large or persistent vibrations that might affect the fuel stack before it is finally set in position with resin.

The rotary vacuum pump is connected through the pressurising line so that the system can be evacuated before pressure testing. The same pump is also used to clear fission gases from the pressure line in order to prevent leakage to the operating face of the shielded facility.

Because there is a variety of PWR fuel rod designs, arrangements have been made in the pipework to match the internal volume of the test equipment with that of the original fuel rod; volume blocks of different sizes can be plugged into the test system as required.

In order to ease problems associated with repair and maintenance under conditions of remote operation a modular design and construction plan has been followed. Equipment that is not associated with the pressure line can be simply unplugged and replaced as necessary, but the remainder required special attention. The need to maintain a fixed relatively small volume, to simulate the fuel rod plenum, rendered it essential that the additional volume associated with each individual coupling should be minimised but still allow a pressure-tight seal to be made without excessive application of force. In order to meet these requirements a special coupling has been developed (Fig. 8) which is a simple plug-in shaft sealed with standard O-rings and secured in position with a hardened steel pin; a large number of these couplings can be plugged into the pressure line without an appreciable increase in system volume.

5. GENERAL TEST PROCEDURE

Final preparation of test-pieces depends upon the type of test to be carried out; all are X-radiographed and gamma-scanned after end seals have been attached.

After setting the adjustable volume block to give a total effective plenum volume to suit the fuel rod type the test-piece is fixed in the pressurising head and pressure and vacuum tested for leak-tightness. It is then pre-pressurised and lowered into the molten metal bath to complete the electrical power circuit. The cladding temperature is raised to 773K and held for ∿ 120 seconds to allow the fuel to reach thermal equilibrium, after which the temperature is raised at a rate 2-10 degrees K/second to the required maximum. For fuel relocation tests the cladding is allowed to deform to ∿ 40% diametral strain (measured on the CCTV monitor) then the power is switched off before cladding rupture can occur.

After the test-piece has cooled, a hole is spark-eroded through the cladding, taking care to minimise mechanical impacts (all movements being monitored by the accelerometer, Fig. 9) and a low-viscosity epoxy resin (Appendix 1) introduced through the hole to fix the fuel in position. The spatial distribution of the fuel within the deformed cladding is then determined by further X-radiography and gamma-scanning followed by sectioning and optical examination.

6. SPARK-EROSION AND RESIN FILLING

The Materials Science spark-erosion equipment (Fig. 10) enables a hole to be electro-discharge machined in the ballooned cladding without disturbing the fuel stack. The system consists of a power supply unit, the spark-erosion head, the tool post carrying the machine tool and the dielectric drip feed; two reservoirs for resin and dielectric are fixed to the head (Fig. 11).

The use of the spark-erosion head in the horizontal position with a drip feed of dielectric (instead of the more usual approach involving submerging of the work-piece) is a non-standard technique that has been developed especially for the LOCA simulation test programme.

The spark-erosion tool is a 3 mm diameter, 0.6 mm wall copper tube which is also used to feed the resin into the ballooned test-piece after the hole has been machined. The tip of the tool is cut to present a vertical edge to the cladding wall. The perchloroethylene dielectric drip feed is through a similar copper tube positioned close to the tool tip, the rate of feed being controlled by a hypodermic needle fixed in the reservoir. A hole can be cut through 0.6 mm thick Zircaloy in approximately 30 minutes.

After machining the hole, the tool is left in position through the cladding wall and any perchloroethylene that has entered the test-piece is driven off by raising the cladding temperature to 373K over a period of 50 minutes. The temperature is controlled, in this instance, from the output of a clip-on Chromel-Alumel thermocouple attached to the top of the test-piece. After the perchloroethylene has evaporated, the test-piece is cooled to 323K and a low viscosity resin (Appendix 1) is introduced via the reservoir. The flow of resin through the gaps between the fuel fragments is improved by maintaining a temperature in the range 323-333K. When sufficient resin has been introduced, it is hardened by increasing the temperature at a rate of 30 degrees K/hour and heating for 20 minutes at a maximum temperature of 383K, after which the resin is completely hardened and the test-piece can be transferred for detailed examination.

7. SIMULATION OF CONDITIONS DURING REFLOOD

During the initial series of LOCA simulation tests, considerable care was exercised in order to avoid any impacts or vibration loading of the unsupported fuel column, after the cladding had bulged away from it, in order to determine the extent of fuel relocation under ideal conditions. During a PWR LOCA, however, it is possible that mechanical vibrations, due to quenching of the deformed cladding as the reflood water rises, may result in appreciable relocation of fuel fragments and, consequently, the LOCA simulation programme has been extended to include this. Unirradiated test-pieces were quenched from 1073K at a simulated reflood rate of 50 $mm.s^{-1}$ and the resulting vibrations were monitored by accelerometers and recorded. The recorded signals were then used to calibrate a white noise generator in order to produce closely comparable vibrations in the bulged irradiated test-pieces. The impulses are applied to the mid-length region of the cladding by means of a mechanical vibrator (Fig. 9) driven from the white noise generator. The vibrator is held in the spark-erosion head and connected to the mid-length of the test-piece with a mechanical clip.

8. CONCLUSIONS

The LOCA simulation test rig described here has been in service since 1978 and, during that period, the modular design has been a major factor in facilitating operations involving maintenance or replacement of equipment.

The results obtained on fuel stack relocation phenomena have contributed towards a better understanding of the behaviour of fuel rods under LOCA conditions.

APPENDIX 1

HOT-SETTING EPOXY-RESIN INFILTRATION MEDIUM

1. Composition of infiltration medium

Resin	MY 745	100 parts by volume	)
Hardener	HY 905	100 " " "	) Supplied by CIBA-Geigy
Accelerator	DY 063	3 " " "	)
Reactive diluent	DY 026	50 " " "	)

2. Viscosity of infiltration medium (approximate values)

Initial viscosity at room temperature	2 poise
Viscosity at room temperature after 1 day	5 poise
Viscosity at 343K	0.1 poise

3. Setting conditions

The infiltration medium is heavily loaded with low viscosity volatile components. Hence the exothermic setting reaction must be controlled or the volatile components will boil and a foam will result. Setting conditions therefore are: heat to 333K, heat to 388K $\pm$ 5K at a rate not exceeding 0.5 degree K/minute, cure one hour at 388K.

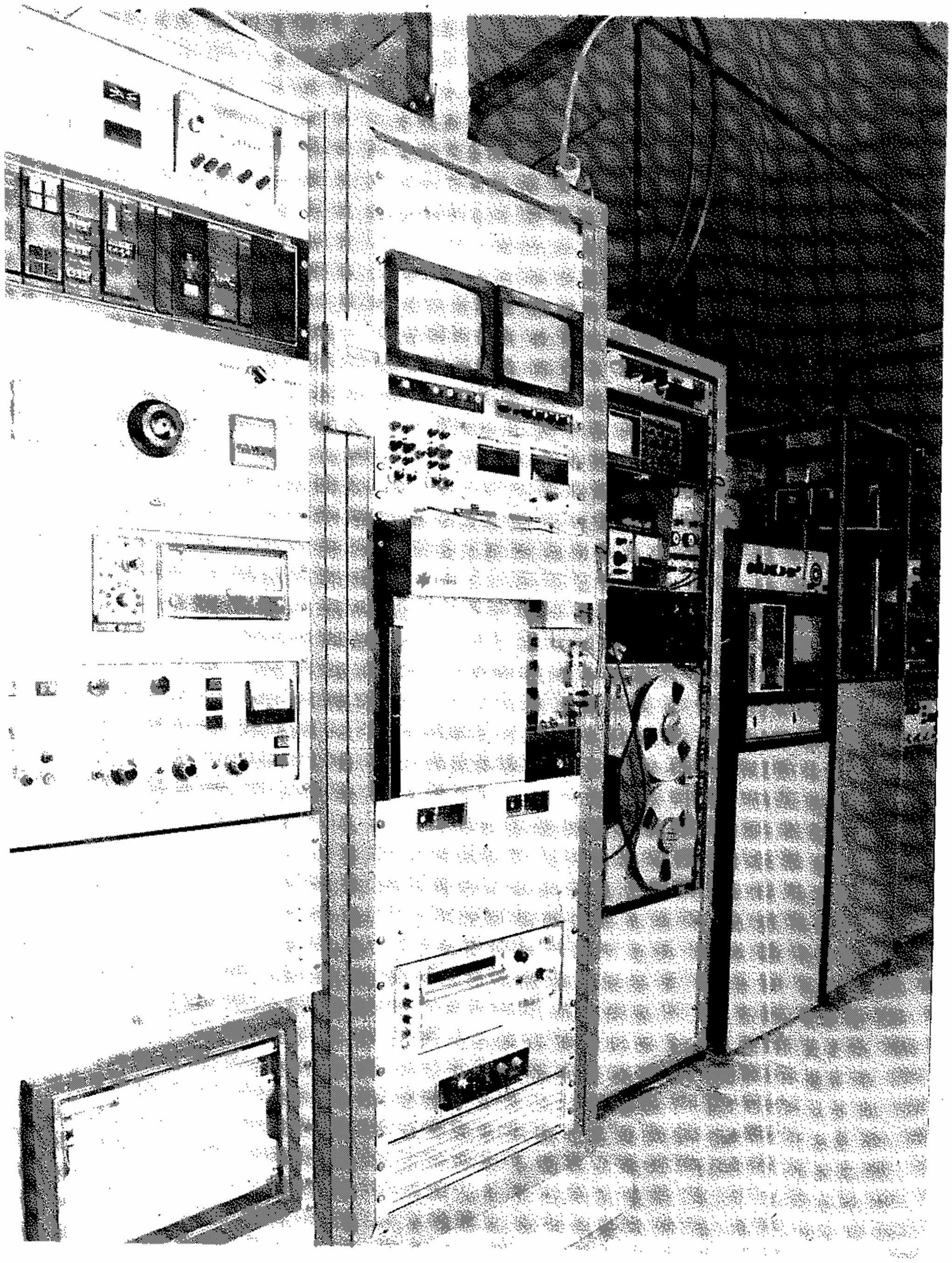


FIG. 1 MONITORING AND CONTROL SYSTEMS

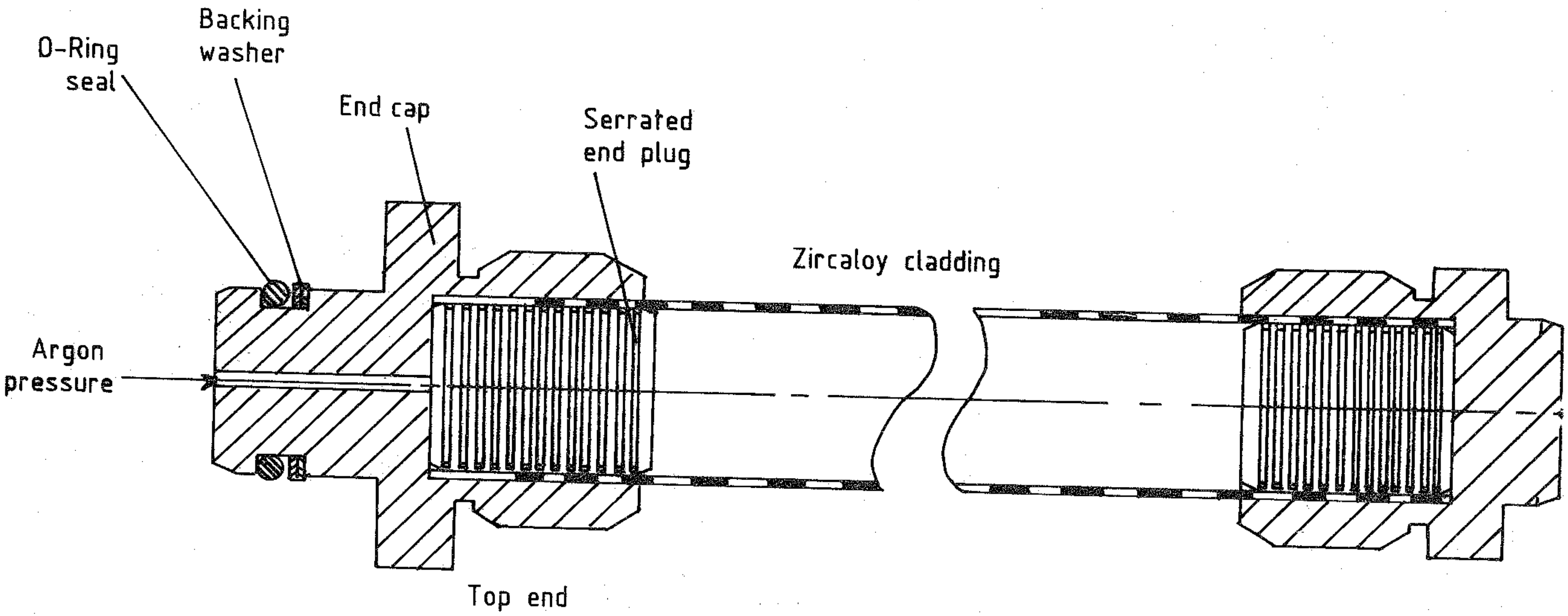


FIG. 2 LOCA TEST-PIECE - VACUUM/PRESSURE END-SEAL ARRANGEMENTS

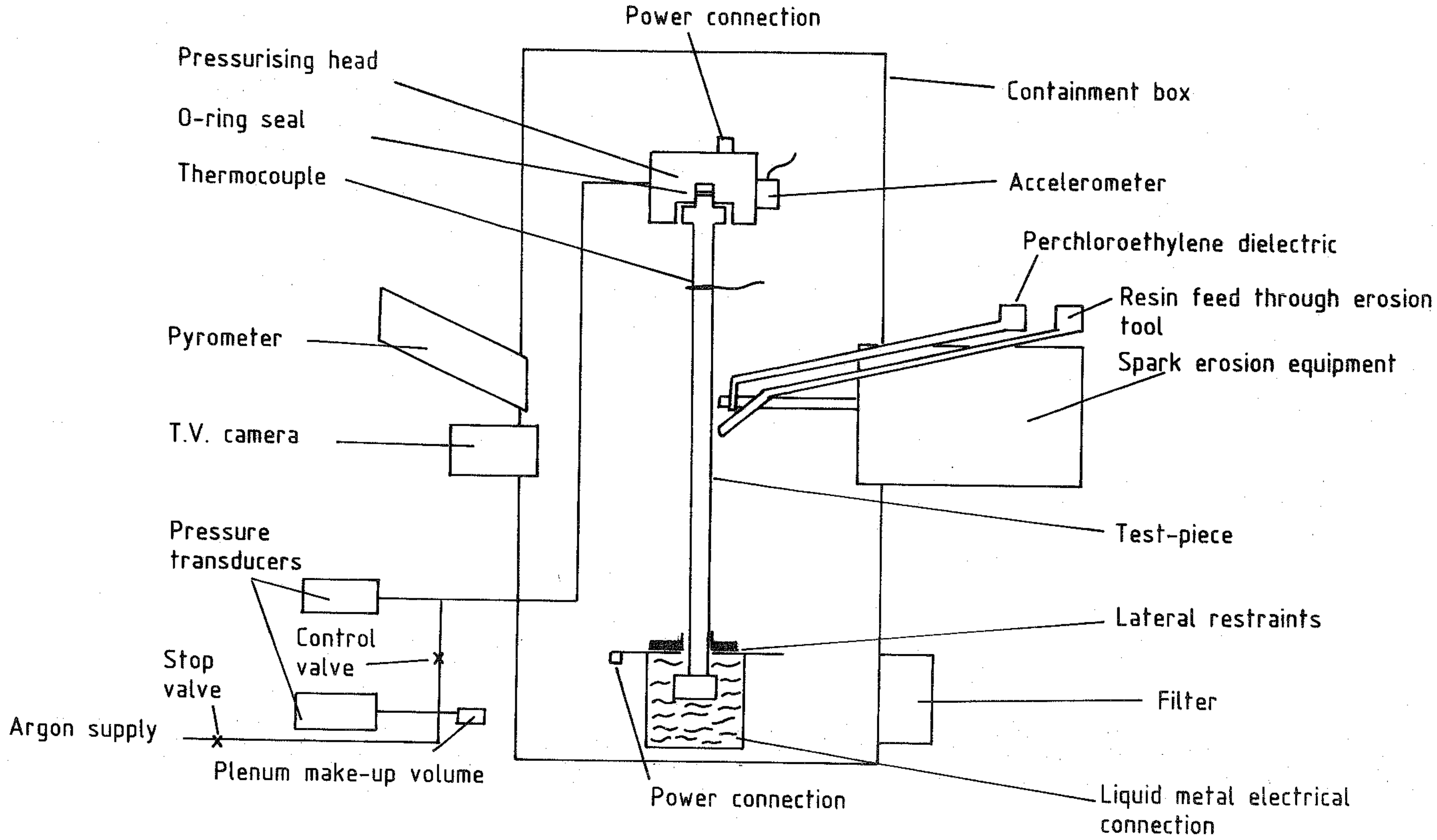


FIG. 3 SCHEMATIC DIAGRAM OF EQUIPMENT FOR LOCA SIMULATION TESTS

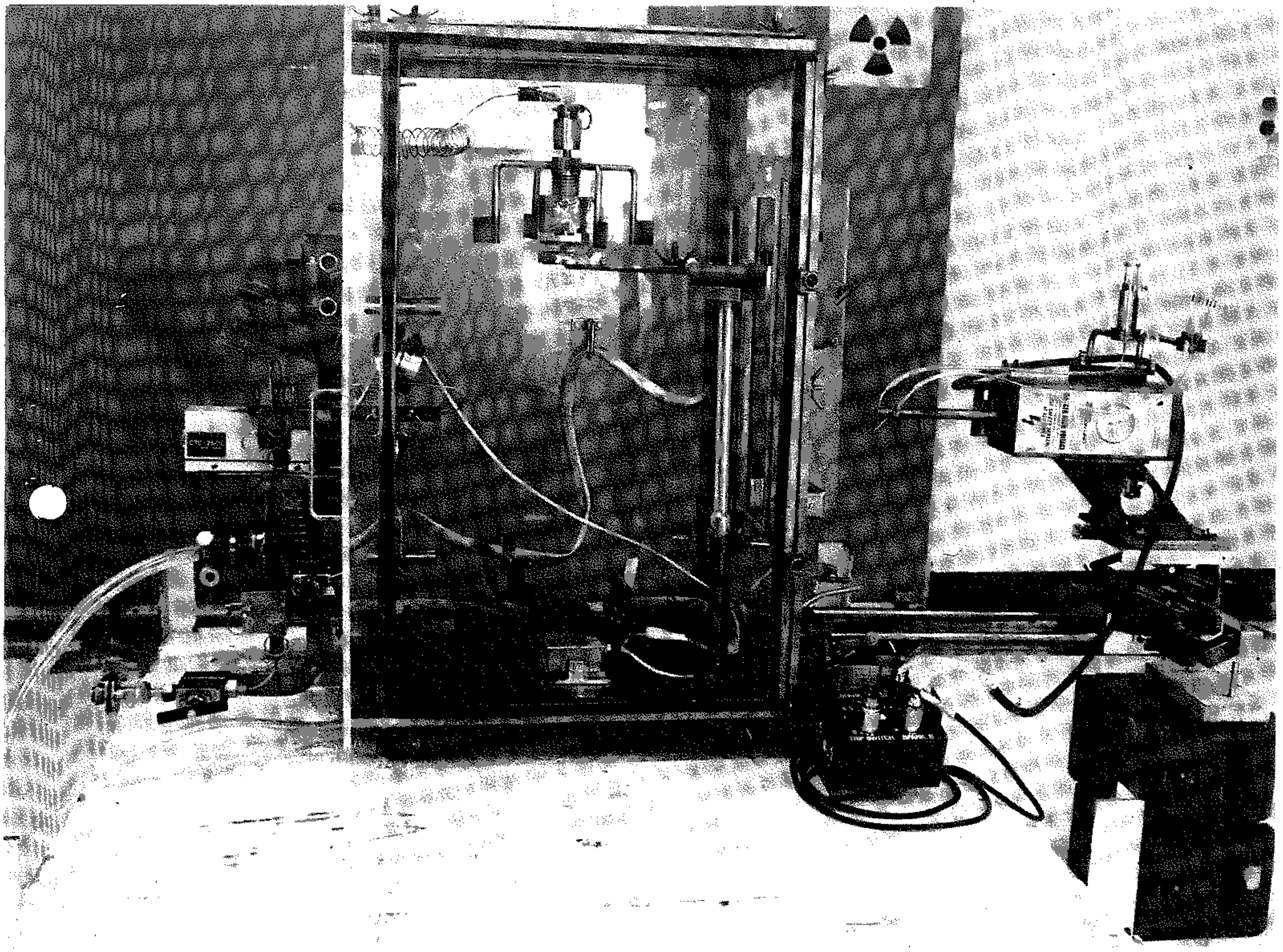
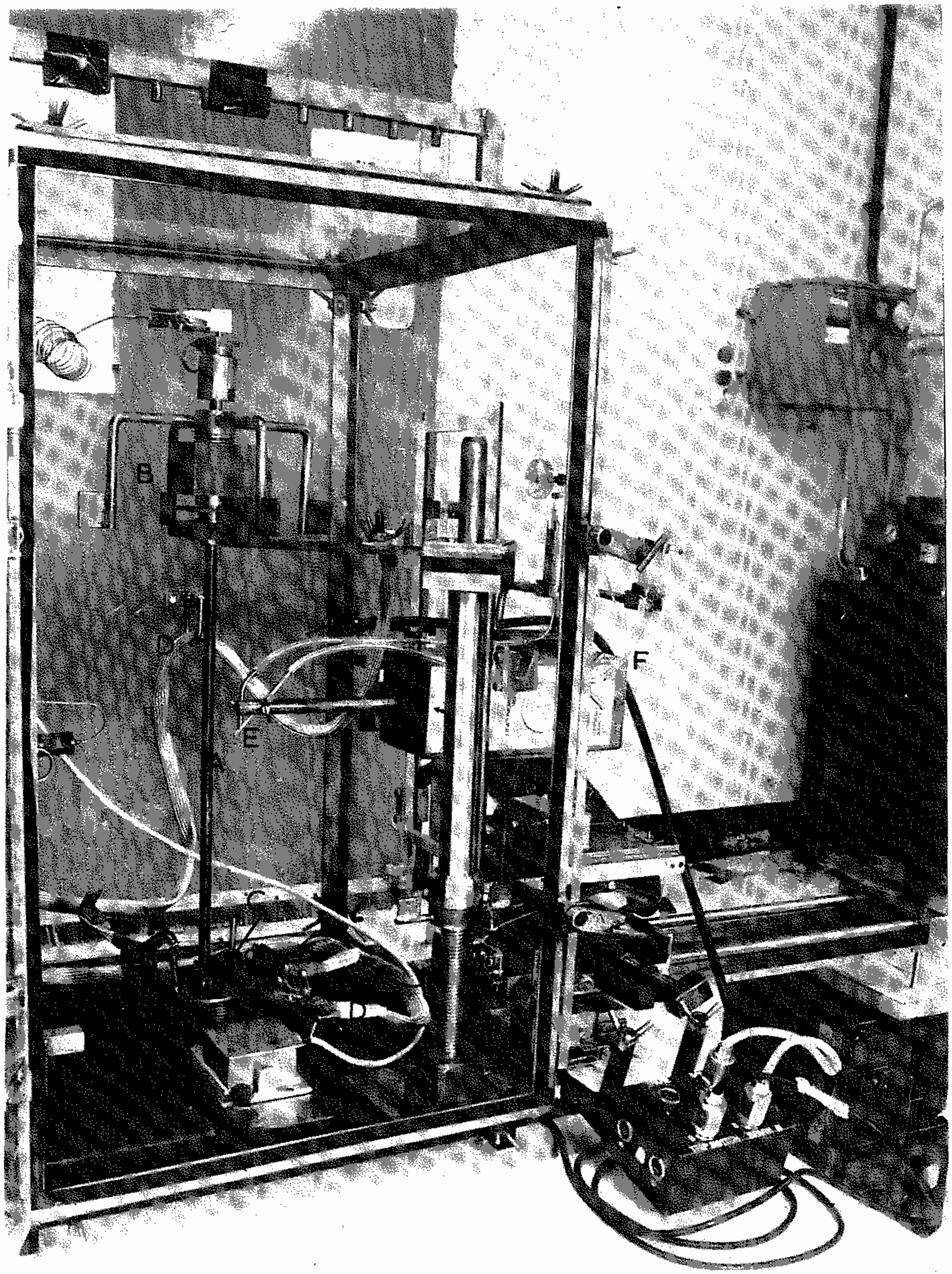


FIG. 4 GENERAL VIEW OF LOCA SIMULATION TEST RIG



A. Test-piece

B. Pressurising head

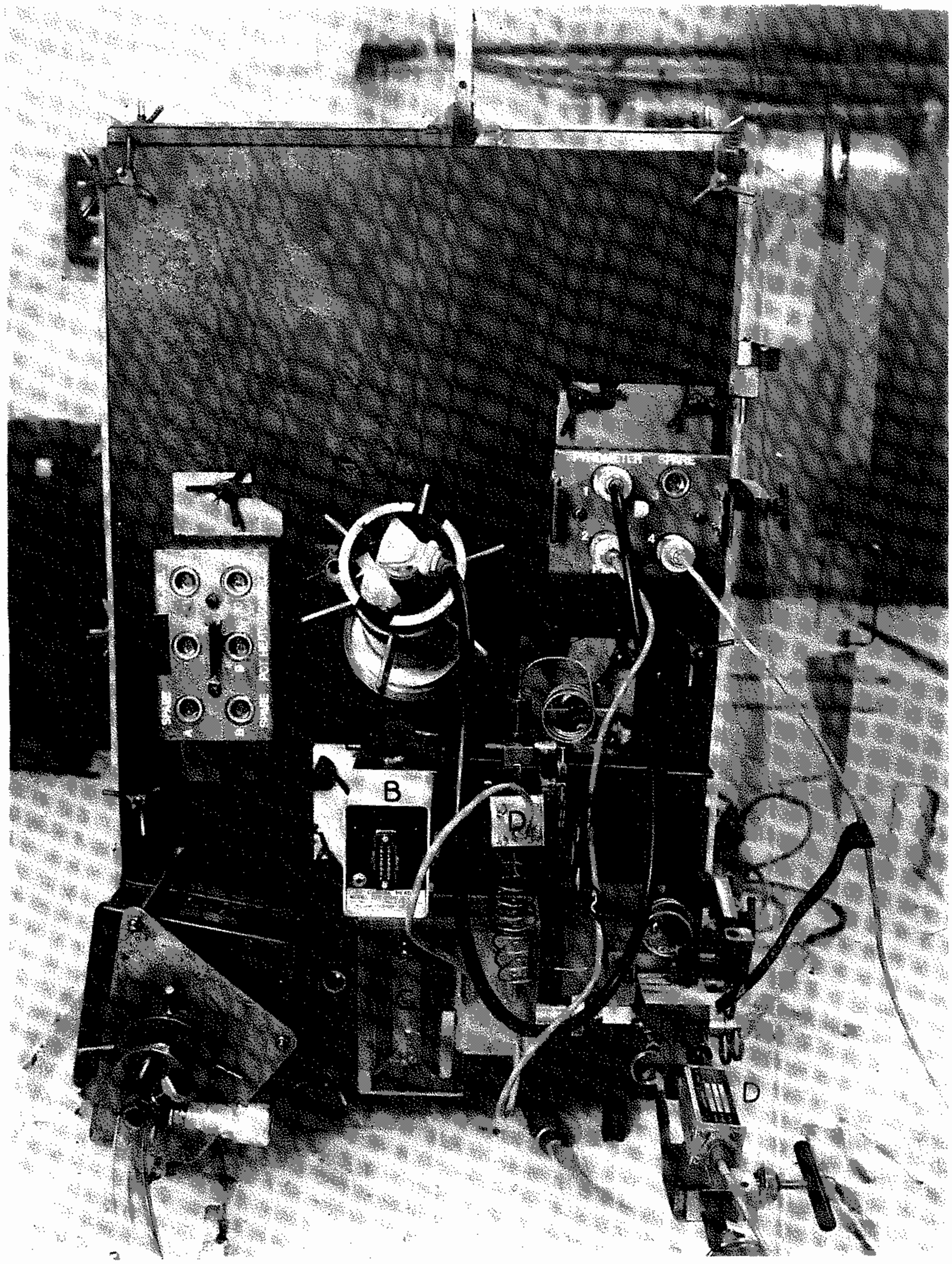
C. Liquid-metal bath with lateral restraints

D. Power leads

E. Spark-eroding tool

F. Spark head

FIG. 5 DETAILS OF EQUIPMENT WITH TEST-PIECE IN POSITION



A. Pyrometer

B. T.V. camera

C. Power connections

D. Pressure transducer

E. Filter

F. Low-volume couplings

FIG. 6 DETAIL OF EQUIPMENT MOUNTED ON THE CONTAINMENT BOX

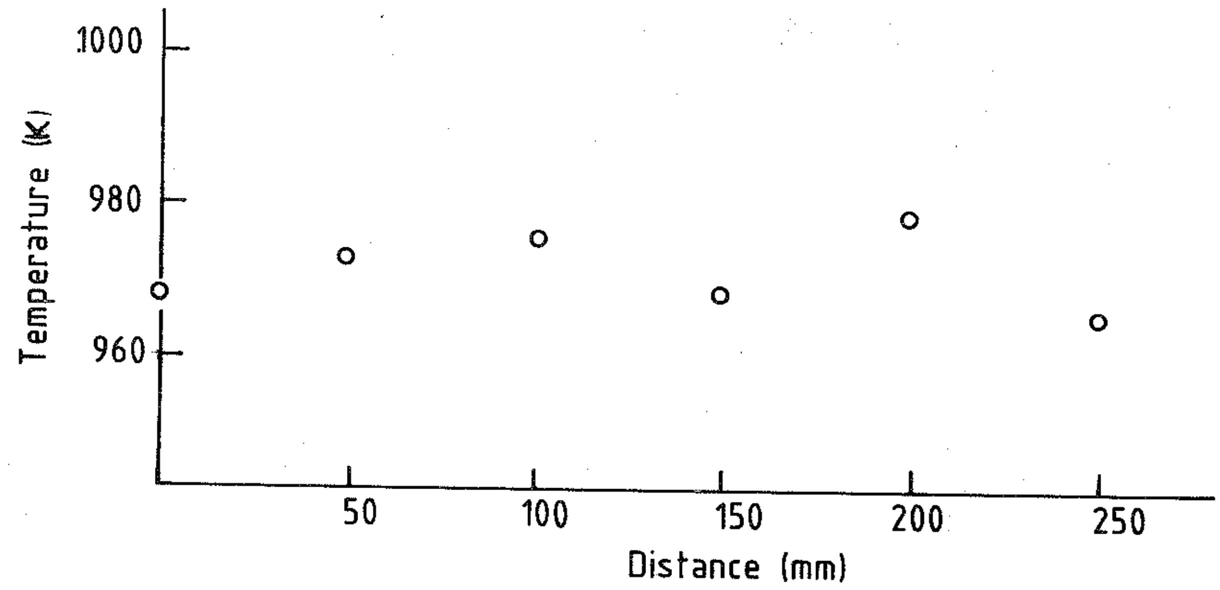


FIG. 7 TEMPERATURE DISTRIBUTION MEASURED ALONG THE CENTRAL 250mm OF A ZIRCALOY TUBE.

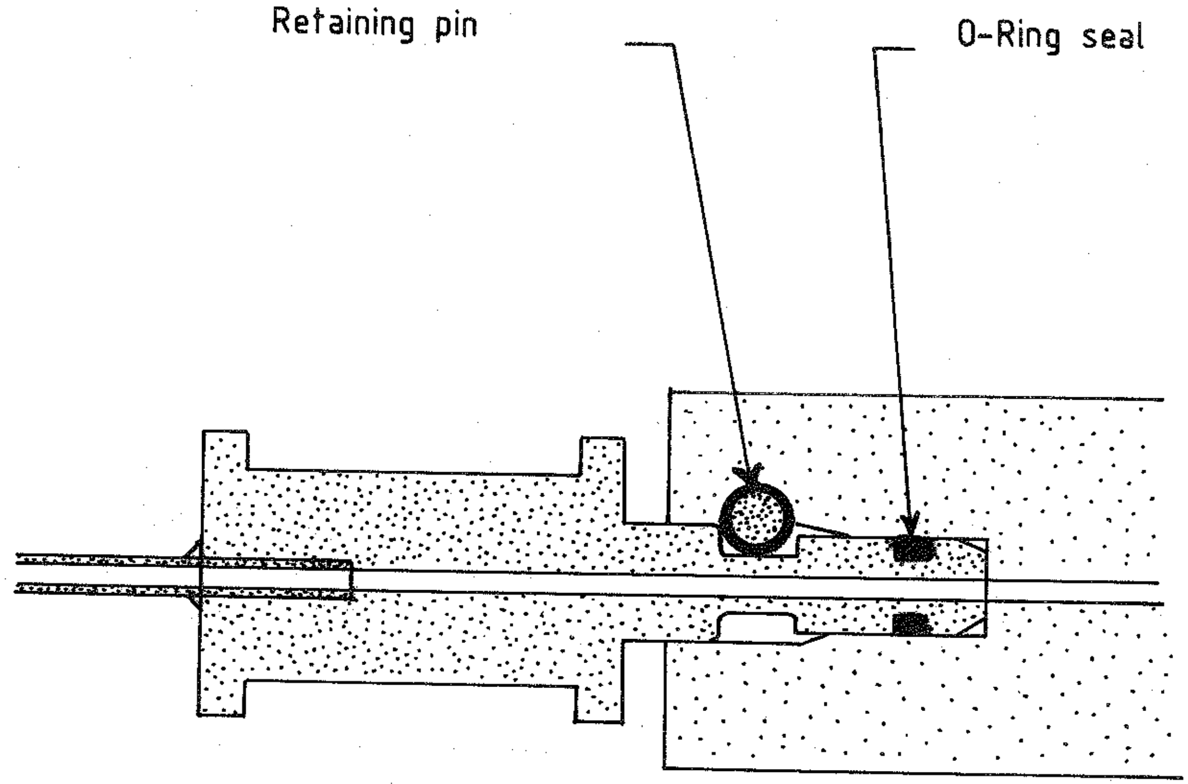


FIG. 8 LOW-VOLUME VACUUM/PRESSURE COUPLING

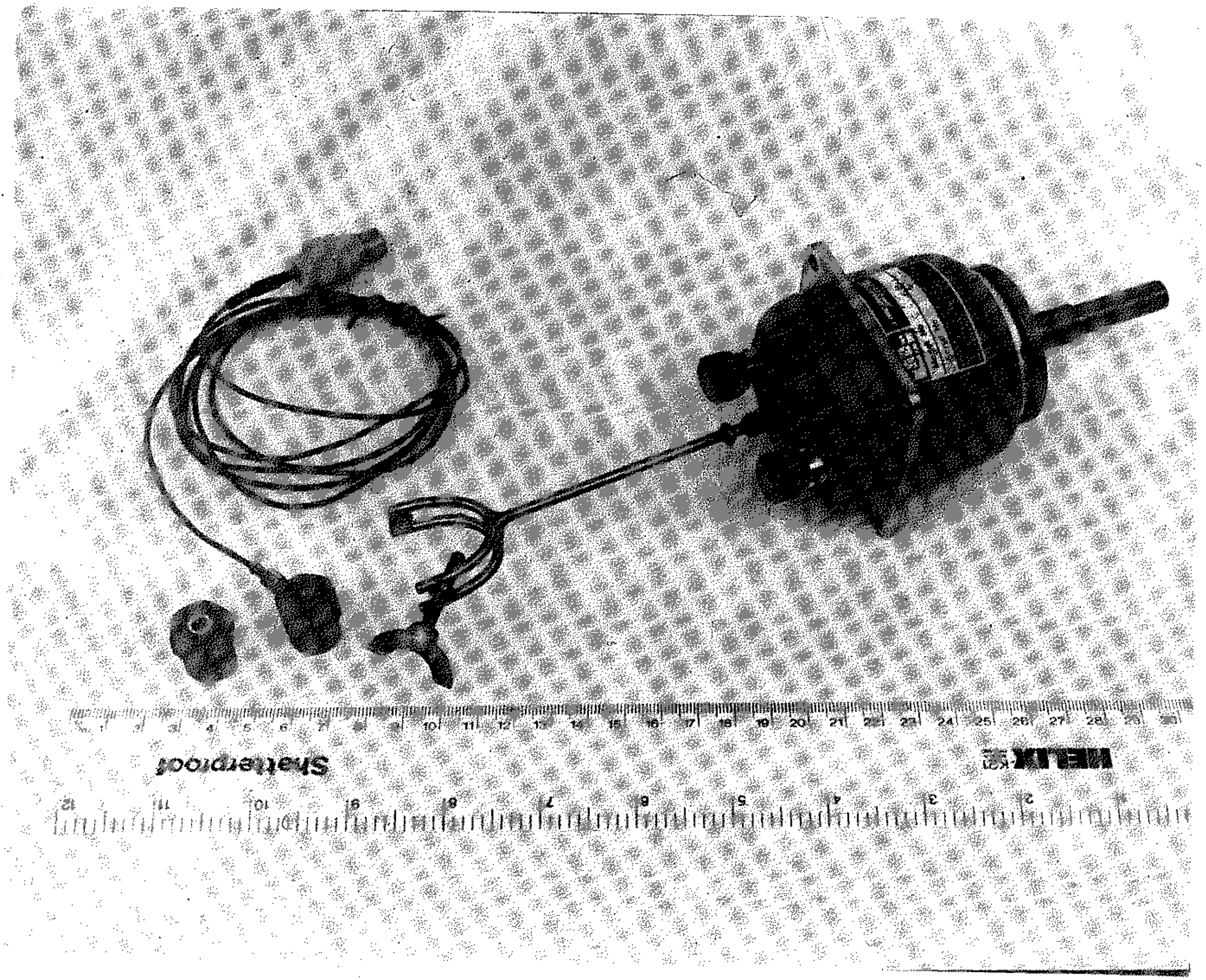


FIG. 9 ACCELEROMETER AND VIBRATOR FOR RE-FLOOD SIMULATION TESTS

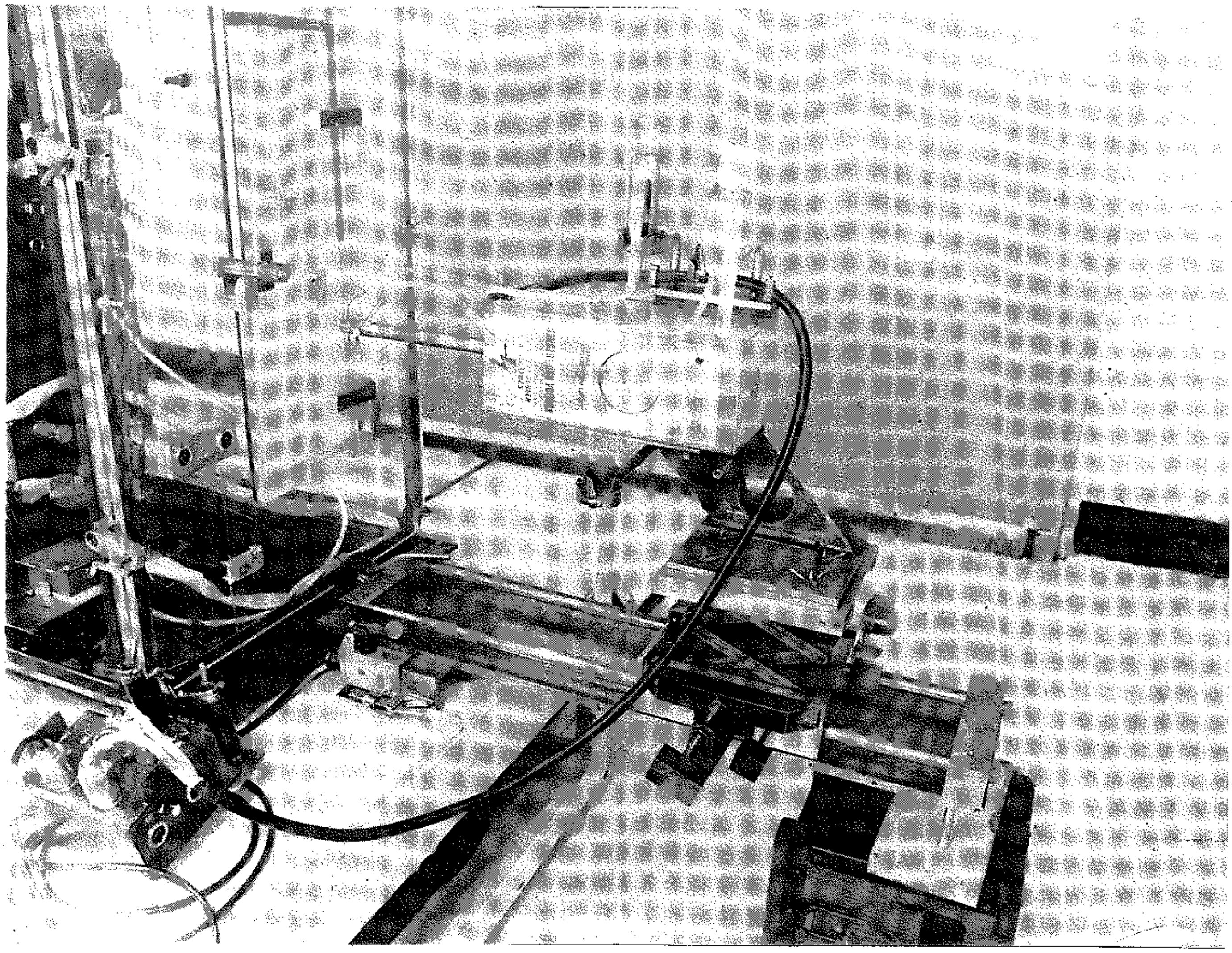


FIG. 10 SPARK-EROSION HEAD WITH RESERVOIRS AND FEEDERS IN POSITION

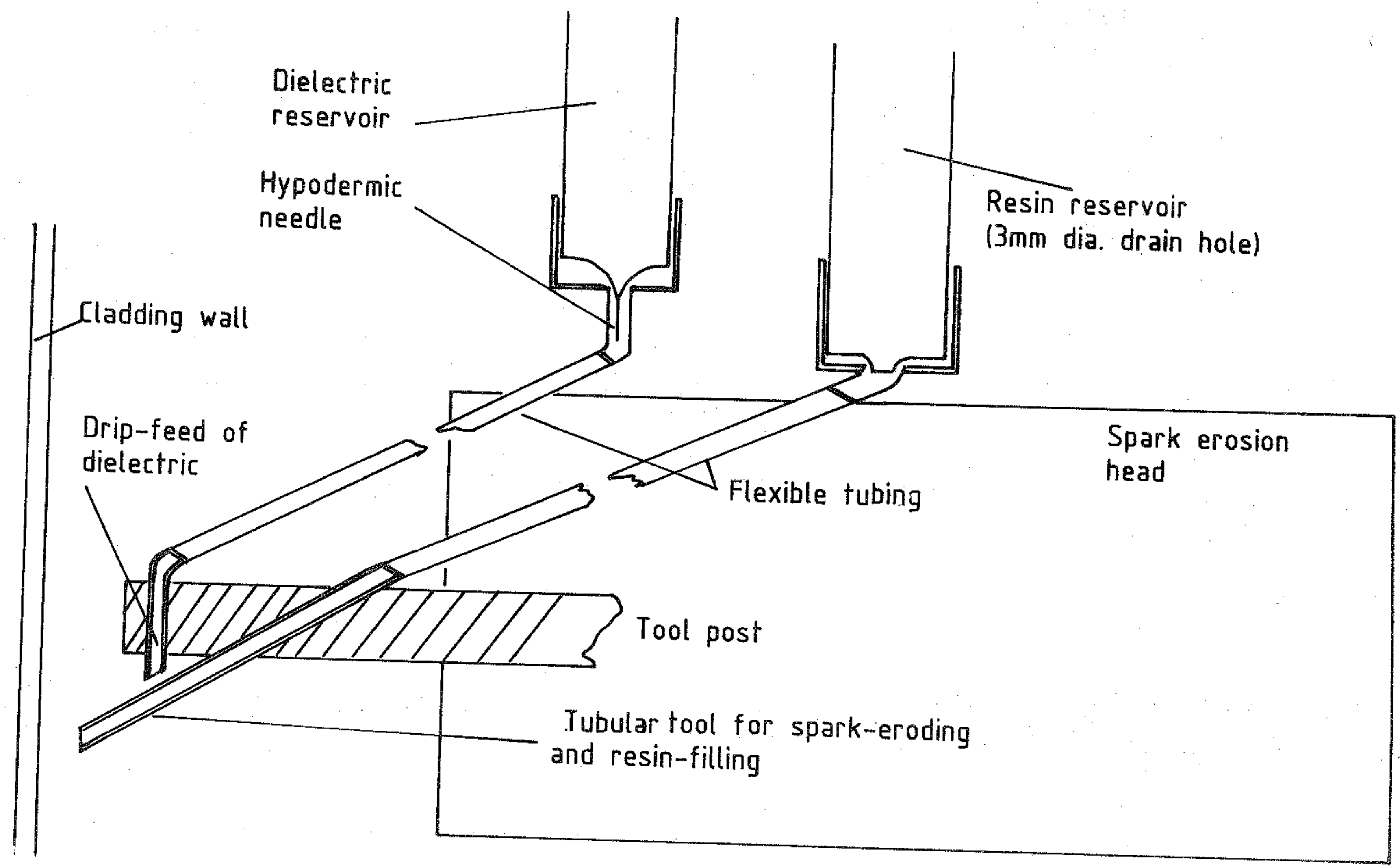


FIG. 11 SCHEMATIC DIAGRAM OF SPARK-EROSION AND RESIN-FILLING EQUIPMENT

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