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EXPERIENCE AND TECHNIQUES IN MAINTENANCE AND REPAIR OF REACTOR COMPONENTS ON THE DOUNREAY FAST REACTOR

by

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SYNOPSIS

Since the DFR first went critical in November 1959, radioactive maintenance and repair work has ranged from relatively minor tasks such as control rod maintenance and damaged element recovery to major undertakings like changing the core tube nest, dealing with 600 swollen breeder elements and repair of a primary circuit leak. Some tasks were eased by far sighted design and simplification by operators of initially complicated equipment has reduced down time. The end result is a fund of valuable experience covering a range of techniques in the maintenance and repair of reactor components in a highly radioactive liquid metal contaminated environment.

EXPERIENCE AND TECHNIQUES IN MAINTENANCE AND REPAIR OF REACTOR COMPONENTS ON THE DFR

CONTENTS

EXPERIENCE AND TECHNIQUES IN MAINTENANCE AND REPAIR OF REACTOR COMPONENTS ON THE DFR

INTRODUCTION AND SUMMARY

1. Since the DFR first went critical thirteen years ago a considerable amount of radioactive maintenance has been carried out. The work has ranged from relatively minor tasks such as control rod maintenance to major undertakings like the changing of the complete core tube nest, dealing with 600 swollen breeder elements and repair of a primary circuit leak.

2. The changing of the core tube nest, which has been described by Hayden and Pearce(1) involved gaining access to the reactor core with the liquid metal still present. The plant was only lightly active at the time and while the reactor was shut down for the work, the opportunity was taken to modify control rod mechanisms and gas blanket pipework. This early work proved to be invaluable to the development of equipment and techniques in a low radioactive liquid metal contaminated environment well in advance of the highly active maintenance problems which had to be faced after high power operation commenced in 1962.

3. Maintenance and modification work on the DFR reactor, which is typical of that likely to be encountered in any fast reactor, is influenced by the fully vented metallic driver fuel charge which causes heavy fission product contamination of both cover gas and coolant. The long term radioactivity makes it impossible to merely wait for radioactive decay to occur before maintenance work begins. It also leads, for example to requirements for extremely high standards of leak tightness to be achieved in the maintenance of gas blanket equipment and when inactive components such as fuel grabs are inserted into the liquid metal, maintenance must be carried out remotely or after decontamination. In spite of these particular problems and the general problem with a liquid metal coolant, ie its chemical activity and its opacity, experience during the ten years since power operation began has shown that major radioactive maintenance and modification tasks can be undertaken mainly with simple techniques. For instance,

i. Highly active components of control rod mechanisms have been removed and overhauled after decontamination using local shielding techniques.

ii. Control rod carriers have been discharged and replaced by assemblies capable of carrying instrumented experiments and advanced fuel sub-assemblies in operations no more complicated than a routine fuel change.

iii. In 1965 some outer breeder elements were found to be excessively swollen and 600 were removed during a three month shut down. The normal charge machines were used, supplemented by simple heavy equipment for 400 elements. The remainder could not be removed until sections of the upper support plate inside the reactor vessel had been cut away using cutting equipment operated through a normal charge plug hole. The reactor coolant was only partially dumped during the operation which has been described in detail by Phillips(2).

iv. As a follow up from the changing of the core tube nest, the reactor centre has recently been modified yet again to enable longer fuel sub-assemblies to be irradiated.

v. In 1967 a small leak of active NaK occurred from the primary circuit into its leak jacket and the reactor was shut down to locate and repair the fault. Ten months later the plant was re-commissioned after a section of the main circuit pipe inside the biological shield had been cut out and replaced and seven other primary circuits had been modified. 148 stainless steel welds inside the main shield had been completed; 40% of these being on active primary pipework. All this repair work was done using simple bagging and glove box techniques and restricting the access for individuals to a strictly controlled time limit. The operation had been described in detail by Matthews and Henry(3).

DESIGN FOR MAINTENANCE

4. In the design of the DFR (fig 1), it was accepted that at some time during the life of such an experimental reactor it might be necessary or desirable to remove the whole of the core and breeder structure in order to carry out maintenance or modification work. The reactor vessel internal structure and each individual component of core and breeder were constructed so that dismantling would be a relatively easy task. For example, the vessel structure ends at the vessel internal flange (fig 2) on which the breeder coolant outlet header box rests loosely. This header box in turn supports the breeder gagging skirt and inner breeder from which components the outer breeder plates are supported. The inside rim of the inner breeder carries the core skirt which in turn supports the last item, the core tube nest. The double rotating top shield system includes a central plug of 840 mm diameter which can be removed to allow discharge of the core tube nest and skirt. For the removal of any larger items it would be necessary to remove one or both of the rotating shields. No handling flasks were provided for any of the items listed. It was intended that any equipment required would be designed and built only if the necessity arose.

5. Control rod maintenance was one of the tasks to which the designers of DFR devoted considerable attention, and handling flasks were provided to enable any component to be replaced. There are three main control rod components inside the primary tank,

a. The 'carrier' which is essentially a movable section of the core with channels for ten driver fuel elements.

b. The control rod mechanism which comprises a horizontal arm supporting the carrier with a vertical screw mechanism for raising and lowering.

c. The 'top hat' which comprises a stainless steel enclosure for the windings of the electro-magnet which supports the mechanism and an electro-magnetic clutch through which the rod drive is transmitted to the screw mechanism from the external electric motor.

After the primary circuit had been charged with NaK, but before the reactor went critical, at least one each of the above components was discharged and recharged to test the equipment under circumstances which were intended to be as realistic as possible.

6. It was anticipated that, after the final closure of the primary circuit vault towards the end of the construction phase, this area would never be entered again but, as a precaution, a sheet steel walkway was erected all the way round the inner circumference of the main biological shield just below the level of the bottom of the heat exchangers. Furthermore, the last four access points

3366 n

Skilled craftsmen and mates 202

to the vault which were used during construction were filled with blocks rather than cast concrete. The access points and walkway proved to be invaluable eight years later.

WORK DURING LOW POWER PERIOD

Changing the Core Tube Nest (fig 3)

7. In 1960, after the reactor had operated at low power, it was decided that the core tube nest would be changed to provide a number of core channels more suitable for the irradiation of sub-assemblies of ceramic fuel pins which were already envisaged as the basis of the UK's fast reactor fuel development programme. Although radiation and radioactive contamination levels were low, this project presented the maintenance team with its first large handling problem involving NaK. In April 1960 the 840 mm plug was removed from the inner rotating shield and the core tube nest was removed. The simplest possible equipment was used. An unshielded gas tight hand operated valve was erected over the top of the 840 mm plug and a simple flask was placed above it. The interior of the flask and valve were purged with inert gas and a lifting rod was lowered through a gas tight rubbing gland in the top of the flask and attached to the top of the plug which had already been unbolted leaving its own weight to compress the gas seal. The plug was lifted into the flask and removed. A lifting frame was lowered from a second flask through the large access hole onto the core tube nest which was easily raised and allowed to drip before being lifted fully into the flask and removed. The new tube nest was installed four months later, most of the intervening time being spent upon other work, not directly connected with the tube nest changeover. The primary circuit NaK was in the reactor during both phases of the operation.

8. During this initial period when the equipment was only slightly radioactive it became necessary to remove all the control rod carriers, mechanisms and top hats to carry out a number of modifications.

i. The loose connection between the carrier and the horizontal support arm was changed completely after a few cases of misalignment had occurred.

ii. The screw mechanism itself was modified so that all bearings would be submerged in NaK at all times. This was to prevent jamming of the screw which had occurred during initial operation when the NaK fell below the level of the bearings and left oxides on their surfaces (fig 4).

iii. The top of the tube which enclosed the screw mechanism was modified to make a gas tight joint together with the top hat. This isolated the mechanisms from the main gas blanket system and prevented the NaK coolant pressure difference over the length of the tube drawing blanket gas down into the coolant.

9. One longer term benefit from this relatively large volume of work was the simplification of the handling flasks which evolved. For example, all electrically and pneumatically operated grabs on flexible wires and cables were found to be more complicated than necessary and required considerable maintenance. They were replaced by robust lifting rods carrying simple hand operated grabs and working through simple 'stuffing box' type gas tight glands in the top of the flasks.

WORK AFTER HIGH POWER OPERATION

Effects of the Use of Vented Fuel

10. The DFR driver fuel elements which are vented are filled with sodium prior to delivery to the reactor, and particular attention is paid to the elimination of voids in the sodium bond between the fuel surface and the inner surface of the cladding. When the fuel is loaded into the reactor, the sodium is displaced by reactor NaK coolant. About 5% of the total coolant flow sweeps between the fuel and the cladding and, as a result, fission products released from the fuel give an on-power radioactivity of about 1 Ci/litre in the gas blanket and 600 uCi/g in the coolant. Typical gamma scans of the coolant and gas blanket are shown in Tables I and II.

TABLE I

Analysis of DFR Sodium/Potassium Alloy by Gamma Spectrometry

Energy (MeV)	Measured Half Life	Probable Isotope	uCi/g NaK		
			Sample 1 (1966)	Sample 2 (1969)	Sample 3 (1972)
0.28	47 days	Hg-203	2.1	6.8	6
0.364	8 days	I-131	32	400	530
0.66	Long	Cs-137	63	100	178
0.80	Long	Cs-134	3.1	Not measured	4
1.06	18 days	Rb-86	3.8	86	Not measured
1.25	Long	Na-22	1.2	0.9	5
1.6	13 days	La-140	3.7	4.0	67
2.76	16 hours	Ns-24	37,000	Not measured	17,000

TABLE II

Typical Analysis of Blanket Gas Sample at Full Power

Isotope	^{41}Ar	^{88}Kr	^{133}Xe	^{135}Xe
Activity (dpm/l)	7.3×10^{9}	4.2×10^{10}	1.8×10^{12}	5.3×10^{11}

11. The high radioactive contamination of the blanket gas makes it essential to maintain a high standard of leak tightness in the gas blanket equipment. The maximum permissible leak which is tolerable from the most active part of the complex system is 1 cc/min. This represents a leak of 5×10^{-9}/min and would lead to an activity level in the containment building of 2×10^{6} dpm/m^{3} which is 1 mpc. A minor contamination hazard from ^{88}Rb, the solid 18 minute half life daughter of ^{88}Kr usually follows a gas blanket leak and it may be necessary to specify clothing changes or to impose restrictions on personnel access to the sphere. Such restrictions are rarely necessary and normally it is possible to keep the air activity down to about 100th of the mpc figure.

12. Maintenance from the point of view of gas blanket leak tightness is complicated by the fact that at each reactor shut down about eighty gas blanket joints must be broken to enable the shields to be rotated for fuel handling. However, it should be stressed that no complicated techniques have been found necessary. Meticulous attention to simple conventional engineering methods has been found to be adequate. In leak hunting, the radioactivity in the gas is used as a tracer and a very useful detection instrument has been found in the tritium monitor developed at Harwell for use on heavy water reactors.

Removal of the Core Centre Hexagon Block

13. This operation which comprised in effect the completion of the core tube nest change, was the first active modification task and it was carried out in 1963 after a total of three months of high power operation. The first mixed oxide sub-assembly was available for irradiation and it was therefore necessary to discharge the centre hexagonal block (fig 3) from the core tube nest so that it could be replaced by the sub-assembly and two rhombus section blocks each carrying six metallic fuel driver elements. The work was accomplished using the standard charge plug flask with no modification other than the addition of a few cms of shielding and with the now highly active primary NaK coolant at its normal level (1.3 m above the top of the tube nest). The charge plug flask comprised a simple shielded tube with a gas tight stuffing box type of gland at its upper end through which passed a solid lifting rod. When the normal charge plug had been removed and parked in an active storage column using the flask a special hollow plug was placed in the hole. This plug had three lower location points which entered three of the driver charge channels surrounding the hexagon block. With the plug in position and clamped down to make a cover gas seal, a built in central grab was pushed down through it to engage in the channels of the hexagon block which was then raised and secured within the plug. The whole assembly was then removed using the charge plug flask.

14. After disposal of the hexagon block. the special hollow plug was decontaminated and rebuilt with the sub-assembly support stool and three dummy steel sub-assemblies on its internal grab. The plug was then replaced in the charge hole using the flask which was again removed as soon as the plug top had made a satisfactory cover gas seal. The stool and dummy sub-assemblies were then lowered into position and released and the special handling plug was removed. The dummy sub-assemblies were then exchanged for the fuelled assembly and rhombus block using the sub-assembly charge machine. In this very early operation therefore, the pattern was set for future operations, ie the maximum possible use was made of standard reactor equipment - in this case the normal charge plug flask - and all equipment was kept as simple as possible.

Control Rod Drive Maintenance

15. Since the plant became highly active in 1962 it has never been necessary to discharge a screw and horizontal arm mechanism (see paras 5 and 8), but three top hats and seven carriers have been changed. A typical top hat discharge and replacement was undertaken during a planned reactor shut down in August 1969 (fig 5). Just prior to this a control rod could not be raised (to add reactivity) and an electrical fault had developed in the electro-magnet winding of another control rod. These faults like the previous control rod faults on DFR were 'fail safe'. They invariably involved difficulty in raising the rods to add reactivity. No fault has occurred which prevented the lowering of a rod, either by motor drive or during a trip.

16. The clutch and magnet windings were lifted out from both mechanisms and the suspected faulty stainless steel top hat was removed. The screw mechanism below the NaK surface was free and the top hat was removed from the reactor top to the

workshop for further investigation so that fuel handling could proceed. Up to this point the work had involved a few men working for short periods in diffused gamma beams up to 10 r/h.

17. The beta gamma activity from the top hat with its mechanism was about 20 r/h on contact. A significant part of this came from the splined drive shaft which was cut off and put into active storage. This, together with steam cleaning to eliminate NaK and particulate contamination reduced the radiation to about 8 r/h gamma activity. The interior ball bearings of the assembly were changed on an open work bench with temporary lead shielding erected round the mechanism. The reconditioned assembly was then reinstalled in the reactor.

18. This work and the rest of the programmed shut down work was completed with the normal maintenance work force of about 27 men. The total radiation dose received by the team during the period of this work was 27.5 r and therefore no difficulty was experienced in keeping individual doses within the statutory limit of 3 r in any quarter and 5 r in the year.

Control Rod Carrier Changing

19. Four control rod carriers have been changed. Studies indicated that four of the twelve original control rods were not required for safety purposes and could be released to make space available for the irradiation of instrumented experiments. The top hats, screw mechanisms and horizontal arms were left in the primary tank in the lowered position while the movable carriers were lifted out and replaced by fixed ones which were supported in position by the fixed core structure. The penetrations through the reactor top shield which originally housed the control rod position indicator equipment then became available for the instrument and electrical connections to experiments in the centre channel of the carriers.

20. The technique for handling carriers is extremely simple - the double rotating shield system enables the normal 230mm diameter charge hole to be located directly above any point in the core including the carriers. The carriers are engaged below the surface of the NaK and gripped in the centre channel by a simple grab on the end of a solid lifting rod which passes through a rubbing gland in the top plate of the shielded tubular handling flask.

21. This work with simple maintenance equipment showed the ease with which control rod carriers and instrumented experiments in fixed carriers could be handled. This was exploited by permitting previously prohibited extended experiments which might swell and jam in the reactor to be carried out in control rod positions. Occasionally it has been necessary to remove an experiment complete with carrier for post irradiation examination. Recently one fixed and one moving carrier have been changed to provide irradiation channels for more ceramic fuelled experimental sub-assemblies.

Discharge of Sub-Assembly Support Stool

22. In 1968, during the long reactor shut down to repair the primary circuit leak, and on this occasion taking advantage of the fact that the primary coolant had been dumped, the sub-assembly support stool which had by this time received a neutron fluence of 5×10^{22} was removed and despatched to the examination cells. It was examined non-destructively marked up with reference points for future examination and reinstalled using the simple flasks and grabs described earlier.

23. In 1972 it was decided that the reactor centre should be modified yet again, this time to accommodate ceramic fuel sub-assemblies of the same rhombus section but having longer fuel pins. This involved final discharge of the original stool - at a fluence of 10^{23} - and its replacement by a new shorter stool.

Maintenance of Fuel Handling Equipment

24. The highly active coolant and gas blanket inevitably creates problems in the operation and maintenance of the fuel handling equipment. However, it has not been necessary to introduce sophisticated techniques to reduce these to manageable proportions.

25. At the beginning of a shut down, the gas blanket is depressurised and purged with clean argon to minimise radiation doses to the maintenance team stripping the reactor top.

26. The charge hole through the main shield is fitted with a liner tube which extends down through the NaK surface to isolate it from the rest of the blanket gas. The activity in the relatively small volume of gas trapped in this liner tube which mixes freely with the charge machine atmosphere when the shielded loading ports are open, can be reduced to virtually zero by simple purging.

27. A major moving component of the charge machine is the rack tube which carries the driving chains and sprockets used to raise, lower and operate the grabs (fig 6). Originally the lower end of the rack tube was intended to dip into the NaK in the liner tube and it was found that this caused severe NaK contamination inside the the machine. There were difficulties in keeping an inert atmosphere in the flask during some maintenance tasks and the NaK contamination on the internal mechanisms became oxidised causing jamming and leading to a major strip down of the machine for an otherwise comparatively minor maintenance job. This situation was difficult enough but it was completely unacceptable to allow it to continue after high power operation because the highly active NaK would have made it necessary to carry out maintenance remotely.

28. The problem was overcome by a modified operating procedure, ie by pressurising the liner tube so that the NaK level inside it was lowered. The relatively smooth surfaced grab of the charge machine then became the only directly contaminated component of charge/discharge equipment. The lower portion of the charge machine test station which is situated inside the containment building was converted into a simple unshielded glove box so that running maintenance, eg cleaning, adjustment and changing of grabs during discharge operations could be accomplished quickly without losing the machine's inert atmosphere (fig 7). As fission product activity levels built up in the coolant, the glove box began to serve the additional purpose of preventing the spread of radioactive contamination. The box is usually cleaned out after each complete discharge operation and it has never been necessary to add shielding since the accumulated contamination inside the box after a normal discharge operation rarely exceeds a few mr/h.

29. A more recently adopted technique has reduced maintenance problems even further. The charge machine grab is normally examined cursorily at least twice during each discharge operation for element identification purposes and if NaK deposits are seen to be building up the grab is first lowered into a cylinder containing an organic solvent (tributyl cellusolve) and then into a second container filled with methanol. This simple remote cleaning operation often eliminates the need for longer operations in the glove box.

DAMAGED ELEMENT RECOVERY INCIDENTS

Broken Top End Fittings - March 1960

30. All DFR driver fuel elements are supported in the core by shoulders on their stainless steel top end fittings which cannot pass through the hole in the top core plate. The bottom end fittings pass through the lower tube plate with large clearance (7 mm) and are supported radially by six equispaced locating projections on the bottom fitting which have only 0.6 mm clearance. During core

discharge operations in March 1960 it was discovered that the top end fittings of two elements had become separated from the outer niobium cans as a result of brittle fracture of the top niobium welds and the elements themselves had fallen through the core into the bottom of the primary tank. Recovery was relatively easy because the plant was almost inactive at the time and the type A core tube nest was being replaced by the type B. A relatively large hole was therefore available leading to the bottom of the vessel and it was possible to dump all the primary NaK. This incident lead to the decision to fit a retaining plate to the under side of the bottom tube plate of the type B core. This new plate had channel holes of smaller diameter than the locating projections on the elements bottom end fittings to ensure that in future, similarly broken elements could fall only about 50mm and recovery would be relatively easier. The retaining plate has proved its worth on two occasions.

Bottom End Fitting Recovery - December 1968

31. In December 1968 a discharged element was found to be without its bottom end fitting which was eventually located resting in its correct channel supported by its locating projections on the retaining plate. A simple hook device was fitted to the bottom of a specially modified stainless steel dummy element and lowered by the charge machine into the channel. The hook engaged on a cross wire in the end piece and enabled it to be removed with no difficulty. All operations were carried out using the charge machine and with the primary NaK at its normal level.

Whole Element Recovery - October 1970 (figs 8 - 13)

32. During a discharge operation in October 1970 a Mk IIIA element top end fitting was found resting on top of control rod carrier No 10 which was in the lowered position. In a relatively simple operation it was removed and identified as belonging to an element in a short tube channel in the fixed core. Careful probing with a dummy stainless steel element on the charge machine grab established that the remainder of the element was resting in its correct channel supported radially by the short tube and vertically by its locating projections in the retaining plate. As a first step in checking for further damage and to provide support for possible debris, all six elements surrounding the broken one were discharged and replaced by stainless steel dummies one at a time. Probing with a 8mm diameter bar on the end of a dummy element on the charge machine grab proved that it was possible to pass the bar through the whole length of the element's inner tube and to make contact with the cross wire in the bottom end fitting. Two unsuccessful attempts were then made to pick up the element with hook and bayonet devices on the end of 8 mm diameter rods, but they resulted only in deformation of the cross wire.

33. A guide tube, terminating at its upper end with a breeder element top end fitting, was then lowered into the channel by the charge machine. The lower end of the tube came to rest about 50mm from the top of the broken element while the upper end was above the NaK surface in the charge hole. The charge machine was then removed and a shielded gland plate with viewing windows was installed in its place. A hand tool terminating in an expanding collet type grab was then lowered by hand through the guide tube and the element to the bottom end fitting past the damaged cross wire. The grab was expanded so that it gripped the end fitting and an attempt was made to lift by hand with a chain block and spring balance attached to the tool to assist with and measure the pull. Resistance was encountered when the jagged end of the element started to enter the hole in the core top plate and the pull applied was about 90 kg. A few upward blows with the open palms of the operator on the bar at the top of the tool were sufficient to get the element to enter the hole and from then on it was free. The whole assembly was lifted until the element was clear of the core and then the shields were rotated to enable it

to be lowered into a convenient parking hole, ie the centre channel of a nearby fixed control rod group. At this point the upper part of the hand tool was disconnected and removed leaving the charge machine to complete the discharge operation by engaging on the guide tube's breeder element type top end fitting. The whole operation was completed with the primary NaK at its normal level and with a minimum of special equipment.

MAJOR REPAIR JOBS

Outer Breeder Modifications

34. In 1965 during a sample discharge of outer breeder elements, several were found to be jammed and could not be discharged with the normal charge machine (fig 14). There was also evidence that some objects were lying on, or protruding from, the top of the breeder and interfering with top shield rotation. The NaK level was first lowered locally by pressurising an extended liner tube in the charge hole and the objects were identified as breeder element top end pieces. The overall primary NaK level was then lowered to uncover the top breeder plate and several element top end pieces were seen completely broken off and lying on top of the neighbouring elements.

35. It was established that the jammed elements were concentrated in the innermost pitches of the outer breeder and eventually the reason for the jamming was found to be uranium swelling under high temperature thermal cycling conditions. Approximately 200 elements were discharged, chiefly around the extremities of the affected zone, using the charge machines whose normal pull is about 25 kg greater than a breeder element's weight. Then a further 200 were discharged using simple 'heavy gear' illustrated in figs 16 and 17. This equipment comprised a top plate hold down tube through which a simple expanding collett grab was passed. The upper end of the grab and hold down tube passed through a rubbing gland seal mounted in a plate bolted immediately above the reactor top valve, and the grab could be lifted by hand operated chain blocks hanging from the main crane hook. A spring balance load indicator was normally fitted between the grab rod and crane hook so that the load applied to the element could be determined and limited if necessary. The gland plate through which the lifting rod passed included a lead glass window for direct viewing of engagement of the grab.

36. The normal technique was to exert a pull on an element not exceeding one tonne and if it (or part of it) came free it was lifted into the hole in the rotating shield which was then moved to a parking position where the element was deposited temporarily until a shielded flask, mounted over the second charge hole in the shield could be rotated over it for final removal. This two-charge-hole method of handling was never envisaged in the original design and it assisted in bringing a breakdown recovery job almost into the range of a production run. A very useful and simple aid in all this work was a quarter scale perspex model of the double rotating shield system mounted over a similarly scale plan of the core and breeder.

37. There still remained about 200 elements which could not be removed by a one te pull. These were mostly centred in the innermost pitches of the affected zone and were by this time surrounded by empty channels. It was decided that part of the 38 mm thick top plate should be removed and this was accomplished by cutting through the 3 mm thick ligament between adjacent empty holes using the tool illustrated in fig 18. The cut plates were removed through the two 23 mm diameter charge holes through which all the removal and rectification work was carried out. The elements underneath the cut segments were then lifted out relatively easily (figs 19 and 20).

38. In one $60^{o}C$ sector of the outer breeder the whole of the top plate was accidentally loosened from its screwed and dowelled supports during these operations. This allowed one end of the plate to spring upwards a maximum distance of 80 mm leaving about 200 healthy elements underneath it free to fall over sideways. These elements were pushed back towards their correct channels and extension pieces were fitted in their top ends to hold them there in the now tilted top plate. It was not possible to force the plate down to its original level so it was left tilted and a number of struts and stay bars were fitted between it and the bottom breeder header to prevent any further movement. Similar fittings were installed in the other sectors (fig 21).

39. No attempt was made to replace the 600 swollen and jammed elements which were removed during the operation which lasted altogether about four months. All of the work on the outer breeder was carried out by the normal operation and maintenance teams with support from the site's design and workshops organisation who produced all the special equipment required. By careful planning of the operation no spread of radioactive contamination occurred and no one received a radiation dose in excess of the permissible 3 r in a quarter.

Primary Circuit Leak

40. In May 1967 while the reactor was operating at full power an alarm indicated that a leak of the highly active primary coolant into the leak jacket had occurred (fig 22). As soon as the reactor was shut down the leak appeared to stop. All parts of the extremely complicated primary circuit external to the heat exchangers are double jacketted for leak detection purposes and the leak jacket system is divided into 25 different sections each of which is fitted with a conduction type leak detector probe. The section indicating the leak was the most complicated of the 25 and it included the primary vessel itself with its 49 stub-connections.

41. The initial leak was small and could not be re-produced at shut down temperatures. Gamma scans of NaK from the leak drain tank indicated that the metal was quite 'old' having been held up for some time in the complicated jacket. It was thought at first that the defect could be somewhere between the shut down and operating liquid metal levels and this was why the leak ceased on shut down. After a few minor modifications to the leak jacket external pipework, the reactor was started up again in July 1967. The leak re-appeared at full power and in the course of 12 days operation the rate of loss of primary NaK rose from 50 to 150 litres/day. At this point the rate increased sharply towards 250 litres/day and the reactor was shut down.

42. To direct the work of leak location and repair a system of high level working parties was organised with members drawn from other parts of the UKAEA and assistance was obtained from certain specialised sections of private industry. Each working party was charged with a particular task, eg circuit decontamination, leak location, repairs, etc. In the local workshops, work started immediately on the building of a full scale model in wood and steel of a 90^{o} sector of the reactor vessel together with inlet and outlet stubs and supporting steel work. An early assessment indicated that the worst possible place for the leak was on the vessel wall at a bottom (outlet)stub and design work began immediately on a remotely operated machine capable of cutting out and rewelding a complete double jacketted stub together with a section of the vessel wall.

43. Meanwhile all the reactor core elements were discharged and efforts were made to establish whether or not the leak could be opened (and therefore located) at shut down. 10 grams of gold was added to the 50 te of primary circuit NaK and the circuit temperature was raised to $250^{o}C$ by pump heat. Samples of NaK draining down into the collecting vessel in the leak jacket were sent for 30 minutes irradiation in the Dounreay Materials Testing Reactor and the presence of gold was confirmed by gamma scan.

44. Helium was added to the primary cover gas and the leak jacket pipework system was then altered to facilitate gas sampling. Samples of leak jacket gas were isolated and analysed by mass spectrometry as the NaK level in the primary vessel was lowered. Helium appeared in samples when the NaK level reached the bottom (outlet) vessel stubs. This was five months after the first indication of the leak and three months after the decision to shut down and repair it.

45. The primary NaK was now dumped completely and an entry was made through the biological shield into the primary circuit vault. With helium in the primary circuit, gas samples were taken from the leak jacket while in turn the 24 primary heat exchangers were displaced by hand in both directions and then oscillated. The helium concentration in samples increased when 10A circuit heat exchanger was treated in this way.

46. To locate the leak precisely, the leak jacket pressure was maintained at about 48 kN/m^2 while the lower portion of the primary vessel was slowly filled with NaK. Piezo-electric accelerometers were attached to all 24 vessel outlet stubs. The noise of gas bubbles entering the NaK near the outlet stub of circuit 10A was clearly detected. Finally by using an auto correlator and the accelerometers clamped to the 10A circuit and the two adjacent ones, the time difference between the arrival of signals at the accelerometers was measured. These tests showed that the leak was not in the vessel wall but in the 10A circuit pipework at a distance of about 45 cm from the vessel wall where there was known to be a construction weld (fig 23).

47. These results, seven months after the first leak signal and five months after the reactor shut down, enabled the vital decision on repairs to be taken, ie all work would be carried out inside the reactor vault where the radiation field from the distributed pipework source varied from 0.5 r/h at the outer edge to 5 r/h in the immediate vicinity of the outlet pipes where they emerged through the vessel graphite shield. It had already been decided that the circuit would not be decontaminated and the inert cover gas atmosphere would be maintained.

48. Two more entrances were made through the biological shield into the primary circuit vault. These, together with the first one were selected from four access points, last used during construction of the reactor, which had been filled with blocks rather than cast concrete. One opening was designated as the personnel access and Health Physics control point and a clothing change barrier was erected outside it. The other two openings were reserved as cable and flexible pipe routes and emergency exits. At first there were no problems other than radiation and temporary floors were erected in the working areas and attempts were made to erect local shielding. These attempts were soon abandoned, however, partly because it eventually became necessary to work in several widely separated areas inside the vault.

49. The first task involved the removal of a 3 m length of 100mm primary circuit and its associated leak jacket and by pass connections. Twelve pipe cuts were necessary and most of these were carried out under argon using the PVC argon-filled 'glove bag' technique which had become fairly well established during several years experience on liquid metal circuits. Closed circuit television and a video tape recorder were used so that key personnel and teams waiting to relieve the workers in the radiation area could keep in close tough with the work from outside the shielding. Each glove bag was 'tailor made' for a particular cut using a PVC welding machine and similar equipment and in most cases a tray was built into the bag to catch NaK droplets and hold tools, pipe plugs etc. As each pipe was cut the open ends were sealed with expanding rubber plugs to prevent ingress of air into the primary circuit before the bag was removed. Annular plugs were required for the pipework of the leak jacket which had collected the NaK from the actual leak.

50. As soon as the first primary pipe was cut, radioactive contamination was added to the gamma radiation hazard, the most abundant contaminant being the gamma emitting fission product ^{137}Cs contained in NaK droplets and plated out on the inner surfaces of the primary pipework. However, the 'normal precautions against ingress of air to the circuits were invariably successful in containing the contamination.

51. When the 3 m section of pipe was removed the actual leak was found in it at a crack in a weld near the thermocouple block and a tee by pass connection. Detailed examination of the failure showed that,

i. There had been some misalignment between the pipe and the block spigot during the original welding

ii. The weld had tended to run off the line of the joint and there was some lack of penetration where there had been a double start.

iii. There was some evidence of thermal stress because the adjacent by pass connection supplied an appreciable flow of coolant into the main stream at a temperature 100°C below the main stream temperature.

52. Internal examination of the faulty vessel stub after removal of the cut pipe revealed that the site weld which was originally thought to be cracked after the bubble noise correlation tests, was actually sound but sufficiently suspect to justify the work of cutting it out. The complete repair programme was,

i. A further 1.8 m section of 100mm primary pipe inside the graphite neutron shield had to be cut out internally by remote means (fig 23 and 24).

ii. A new 1.8 m section of 100mm primary pipe had to be remotely welded into position.

iii. Outside the neutron shield but still inside the vault a new double jacketted 3 m section of pipe had to be welded into position between the new outlet pipe stub and the heat exchanger.

iv. The by pass connection responsible for the thermal stress had to be cut out on the faulty circuit, and, to eliminate similar leaks in the future, on six other circuits.

53. A glove bag was not considered good enough for handling the various tools to be used for cutting out and replacing the 1.8 m section of stub pipe, and a more robust perspex and steel glove box was built and sealed to the end of leak jacket of the stub pipe at the outside of the graphite shield. It was most important that the cut should be made without imparting any appreciable load to the tube wall which might lead to its deformation and thereby cause difficulties during re-welding. The tool finally chosen after development and trials on the model was a glass fibre re-inforced aluminium oxide cutting wheel driven by an air turbine at 30,000 rpm (figs 25 & 26) Argon was substituted for air to obviate the necessity of piping the exhaust back from the motor and out to atmosphere through the glove box. An essential part of the tool was a centralising spider which was screwed to the front of the cutter assembly and was pushed on beyond the cut and then left fixed in position so that in subsequent operations - eg facing of the cut end and re-welding, the same centre datum point could be picked up every time. The pipe was cut and removed on 4 February 1968 and the suspect weld was cut out and subjected to a detailed metallurgical examination.

Several sections of pipe were cut off and used on the reactor model in realistic tests designed to reproduce the problems likely to be encountered in remotely welding a new pipe to an active NaK contaminated stub.

54. The stub end was faced up with the original cutting tool and then three hand operated tools were used through the glove box to measure the stub's bore exactly, take a gutta percha impression of the prepared end and thoroughly clean the metal surface by abrasives and swabbing with toluene. The swabs were monitored to assess the level of contamination remaining on the prepared surface and cleaning was continued until it was considered that the active NaK residues would not have a detrimental effect on the new weld.

55. The fitting of the replacement pipe was also complicated by the fact that, at the joint it was necessary to change direction by 2^{o}. By 6 April after very comprehensive external tests and rehearsal procedures, a new section of 100 mm primary pipe was fitted into position and successfully secured by an internal fusion butt weld using a specially designed automatic welding machine (fig 27).

56. To examine the weld, a considerable amount of development work was done on gamma radiography equipment but by the time inspection was required, a 83 mm diameter 100 kV, X-ray unit was available. Test runs were carried out on the model with background radiation being reproduced by sections of active pipe. Local shielding was inserted in the annulus between the primary pipe and its leak jacket and very satisfactory X-radiographs were taken.

57. All the work so far described was carried out remotely (at about 2 m distance) through a glove box to maintain the reactor circuit's inert atmosphere held at a pressure 1.4 kN/m^2 for these operations.

58. While this work on the defective pipe was going on, nearly all the by pass circuit modification work had been completed. This had involved,

i. Cutting off and capping the double jacketted connections similar to the one near the fault, on six of the other twenty-three primary circuits in the vault.

ii. Modifying and re-routing the pipework elsewhere on these by pass circuits.

59. All pipe cuts were made in glove bags similar to the one illustrated in fig 28 and altogether 148 welds were completed, 40% of these on primary circuit pipes, the remainder being associated with leak jacket and drain connections, where, after the primary pipe had been sealed off, there was no further need to maintain the inert atmosphere.

60. After a few initial failures because of contamination of the back of the weld by active NaK droplets which had run down the pipe during handling, a simple modification to the technique was adopted. As soon as the sealing plugs were removed from the prepared pipe ends sodium plugs were hammered in and the glove bag removed, the butted prespared pipe ends backed up by the sodium plugs providing an acceptable reactor gas seal. The joint was then tack welded and finally completed using an automatic orbital welding machine and after successful radiography the sodium plugs were melted by the local application of heat.

61. The total work force employed in the reactor vault numbered 346, made up as follows,

Skilled craftsmen and mates	202
'Other staff'	144
	346

Access conditions in the work areas (see Fig 29) made it almost impossible for more than two or three men to work at a time. This fact combined with the radiation levels lead to the need for this total. 'Other staff' included some general workers, clerical, administrative and supervisory staff who assisted in such work as removal of lagging, laying of walkways, etc. It became general practice to concentrate essential repair work on day shift when there would be a preponderance of craftsmen working. Afternoon and night shifts were normally devoted to cleaning up, glove bag building and purging in general preparation for the next morning's work. Normally, men spend one day on the job working to a body dosimeter limit of 1 r and were not called upon again until all available men of their skill on site had been used. Most men were thus employed on about three occasions and very few exceeded the limit of 3 r per quarter.

62. The following table summarises the radiation doses received over the whole perio between the first opening and the final re-sealing of the reactor vault. Total rads received, 12 November 1967 - 24 April 1968 .. 446.

Dose Range	Numbers
2r	180
2 - 5r	140
5 - 8r	19
8 - 10r	7
	346

CONCLUSIONS

63. In the thirteen years which have elapsed since the DFR first went critical its operation and maintenance have made valuable contributions to NSS experience and technology albeit in an as yet highly specialised field - that of the liquid metal cooled fast reactor. Undoubtedly this experience will assume increasing significance during the next few years as larger fast reactor stations led by the prototypes are brought on-line throughout the world. First among the lessons to be noted is the importance of far sighted design in easing maintenance, component changing and repair problems. It may well be worthwhile to accept initial economic penalties as insurance premiums to protect investments later. The DFR illustrates these points in particular although most of its own component changes have been aimed at increasing its usefulness as a fuel and materials test reactor.

64. A further significant facet of DFR's experience is the handling of problems posed by repair and maintenance of components contaminated by a coolant which is opaque and both chemically active and highly radioactive. It has been shown that in these circumstances, simplicity of approach combined with well-tried and proved conventional engineering techniques provides the answer and indicates firm guidelines for the next generation of fast reactors.

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4. KIRK J and WALKER J B - The DFR Primary Circuit Failure - Report of joint International Discussion Meeting of Active Working on Reactors -BNES London Oct. 1970

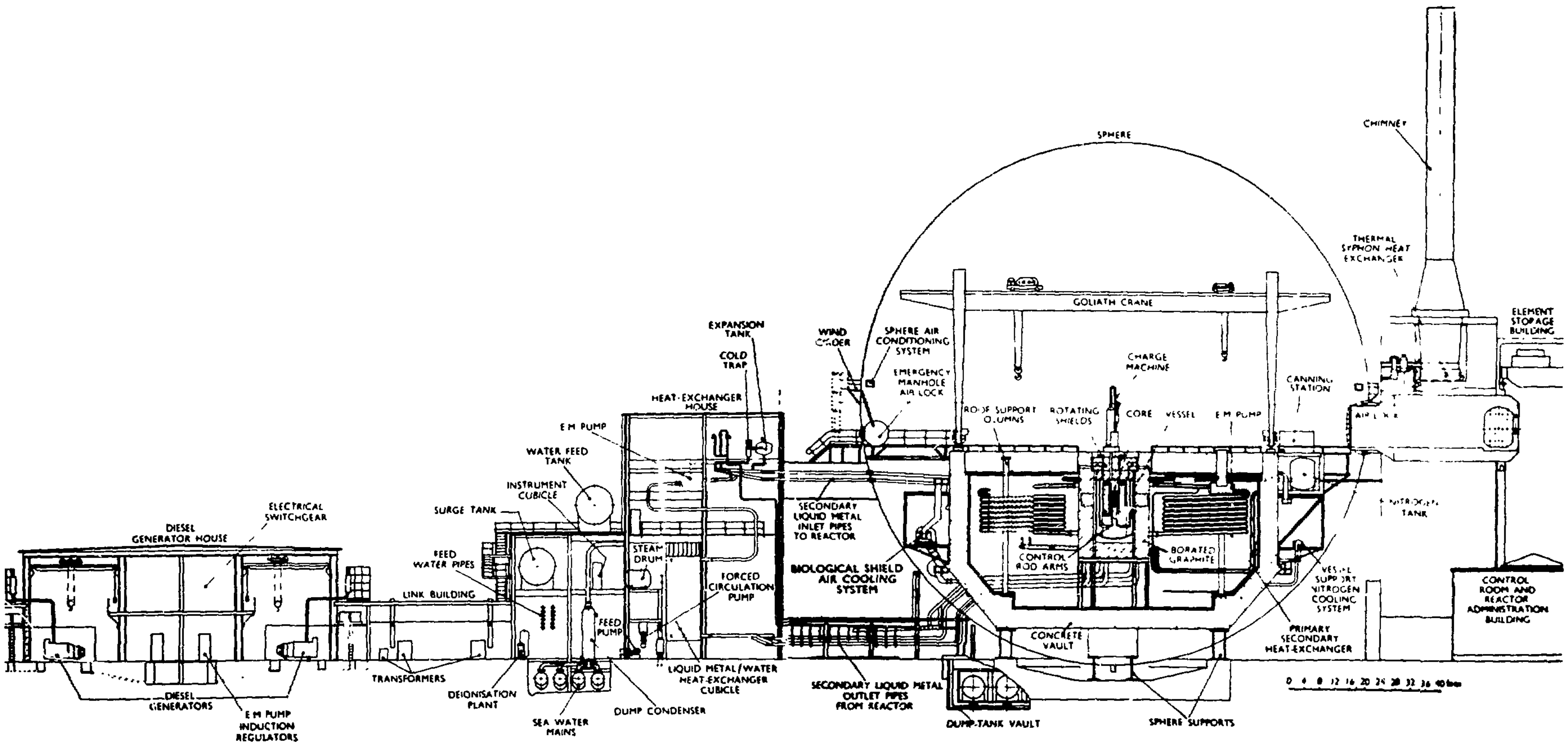


FIGURE 1 - General arrangement of reactor and ancillary plant

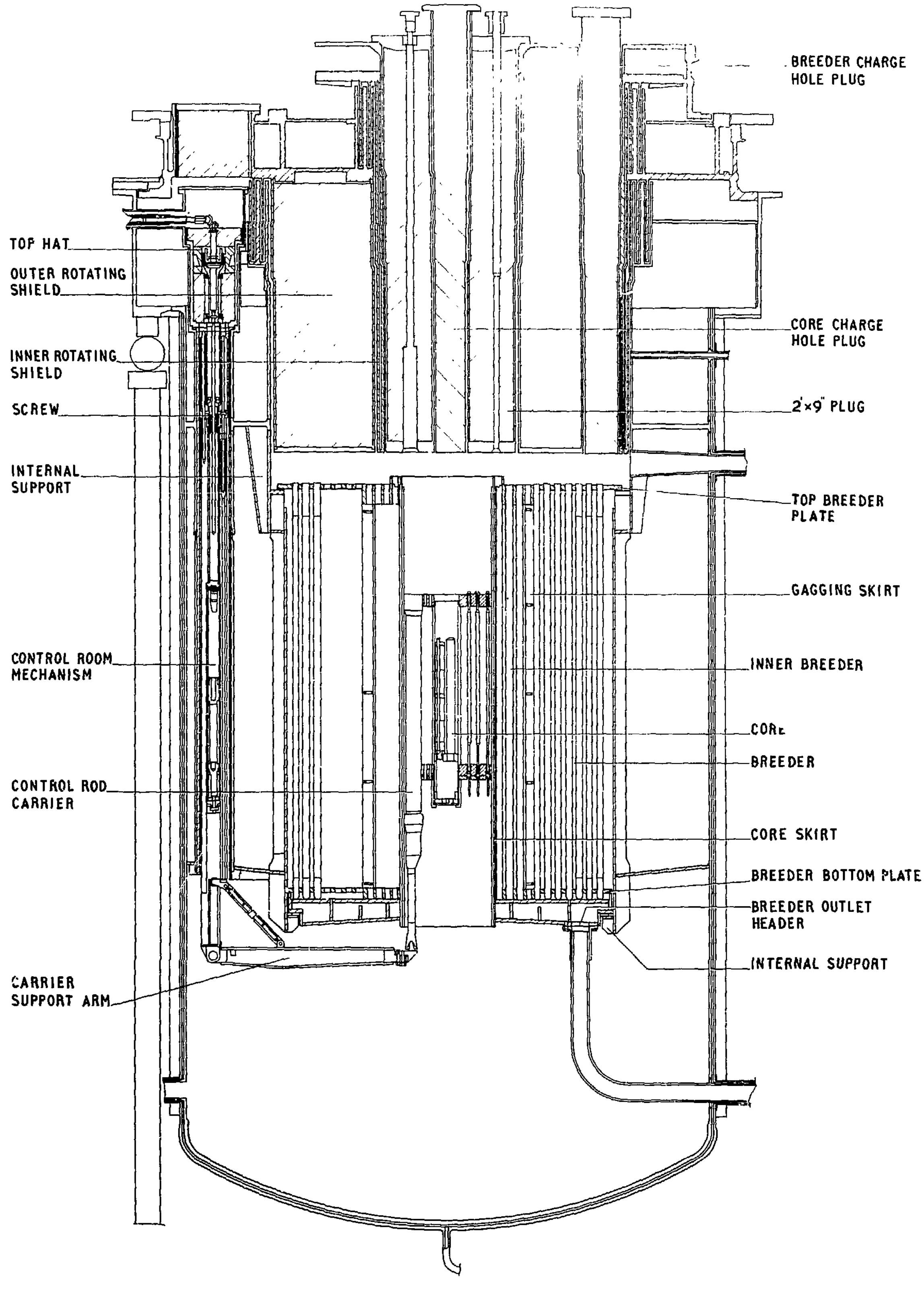


FIGURE 2 - Internal supports and control rod mechanism

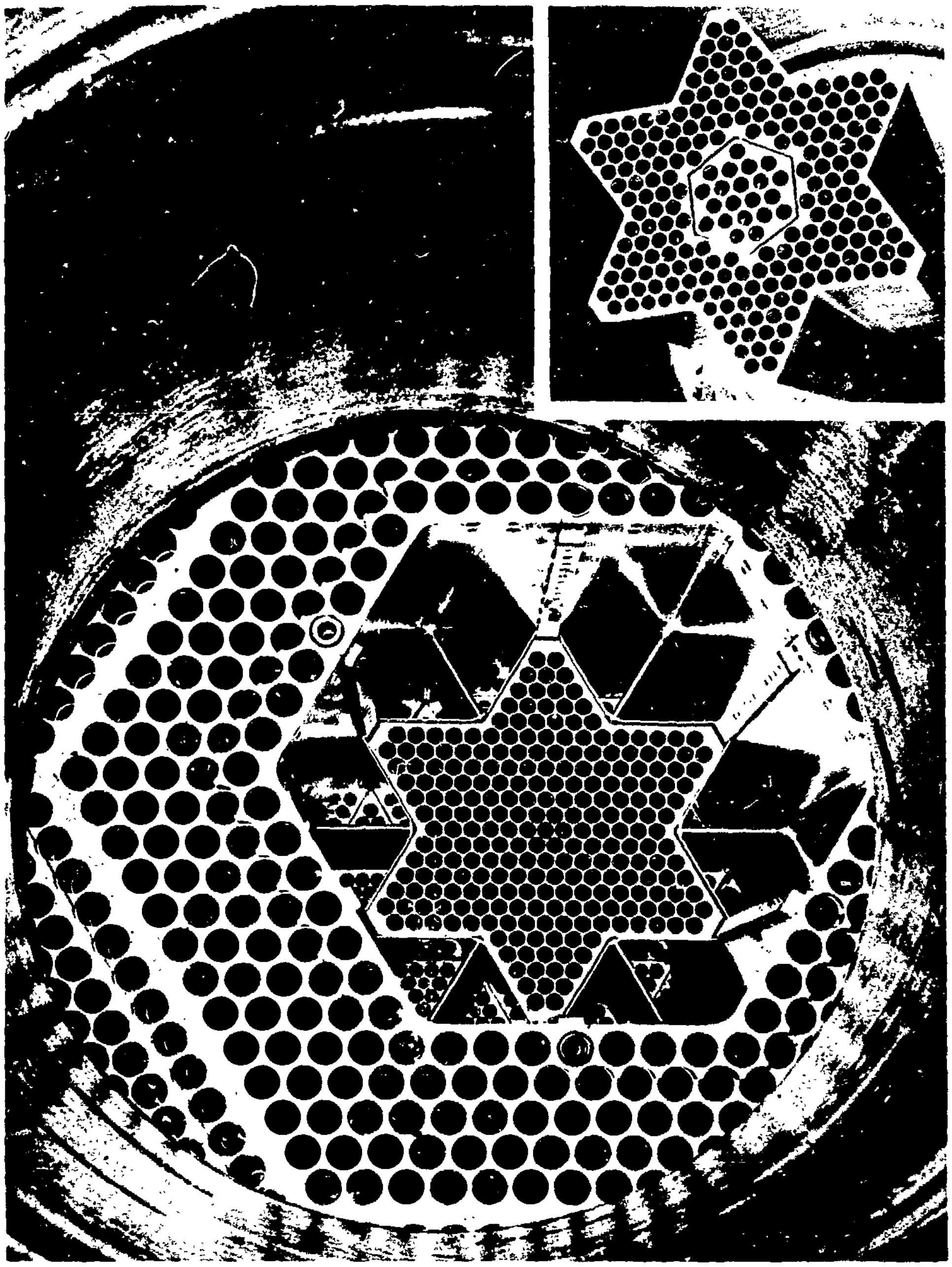
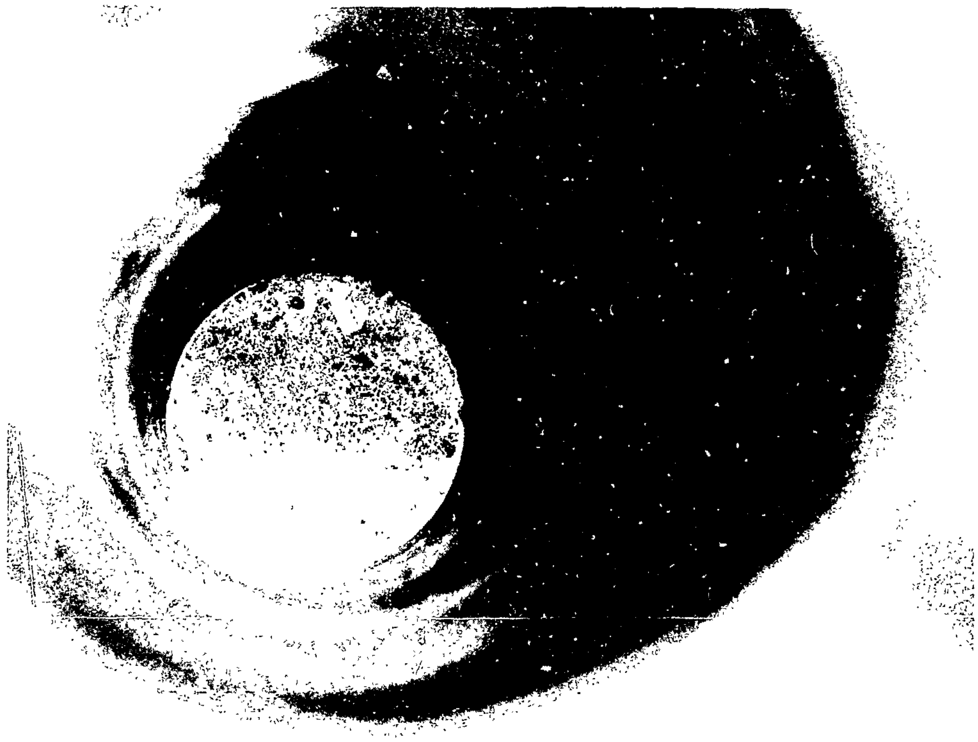


FIGURE 3 - Core tube nest modifications



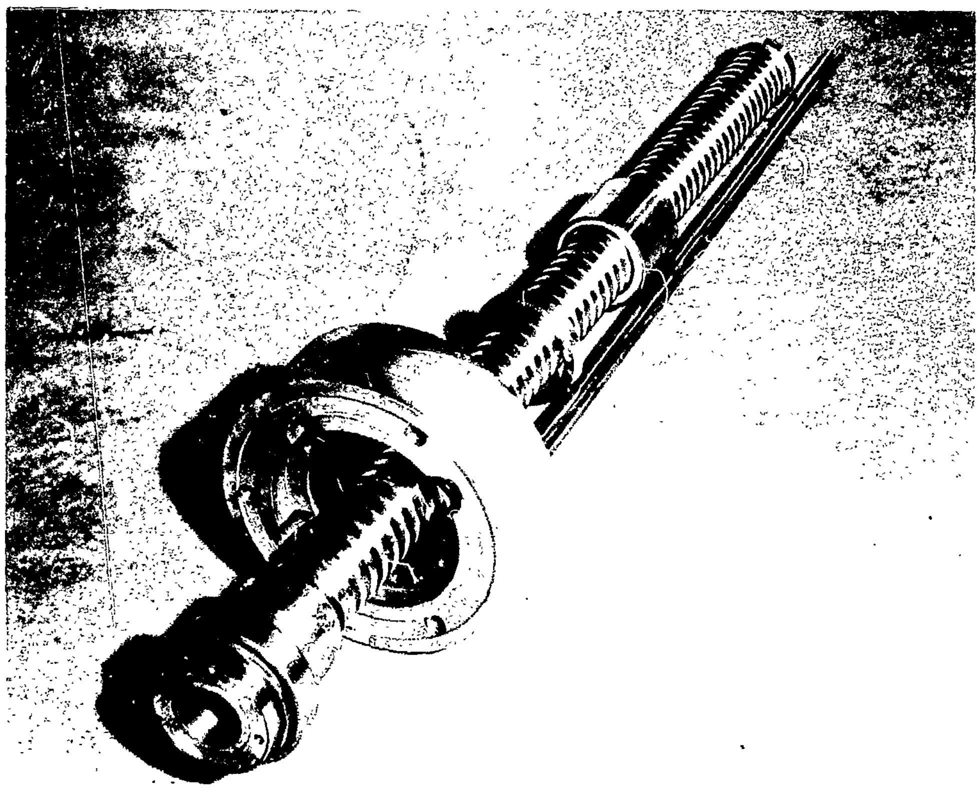


FIGURE 4 - Control rod mechanism screws and contaminated coolant surface

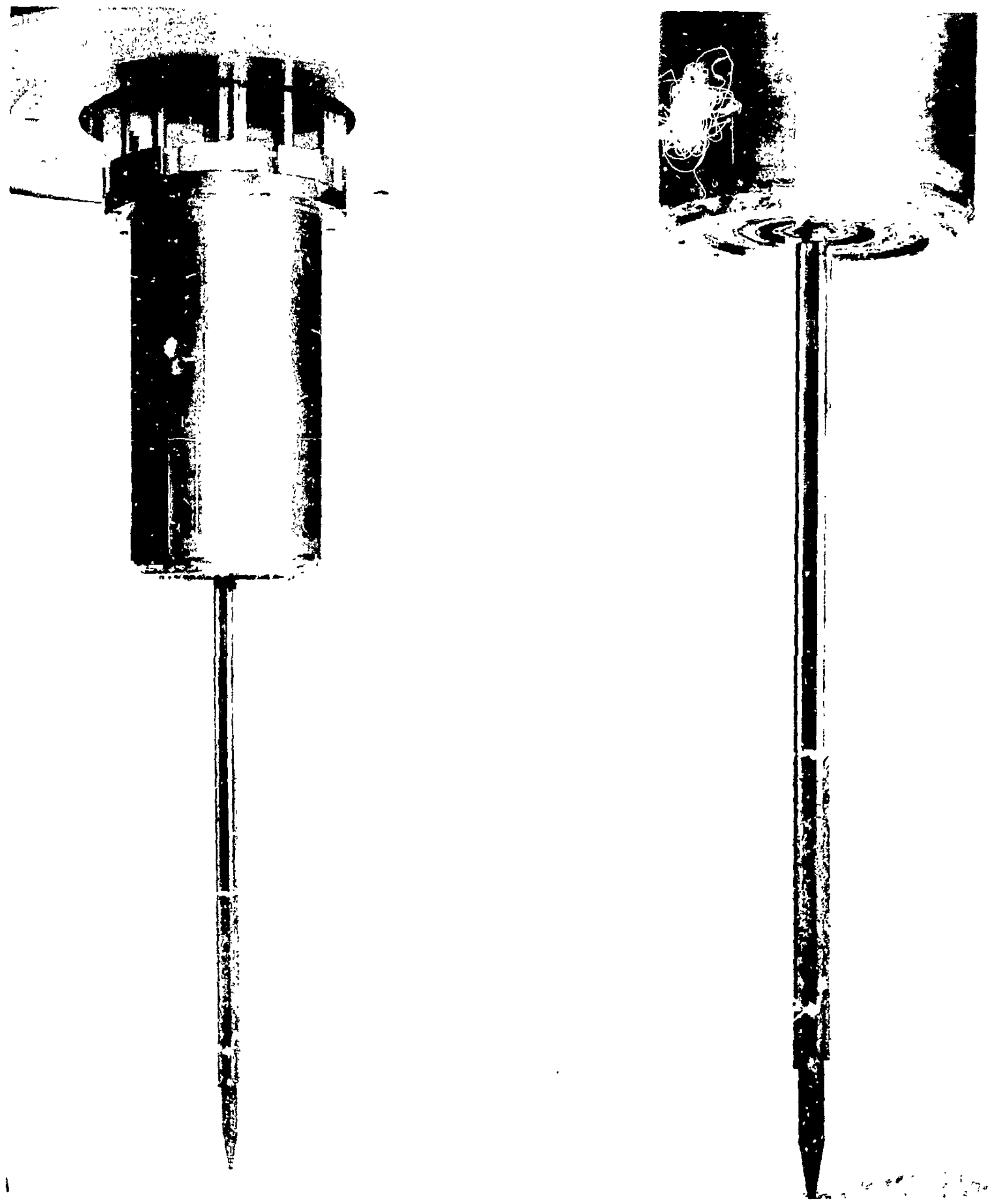


FIGURE 5 - Control rod mechanism top hat

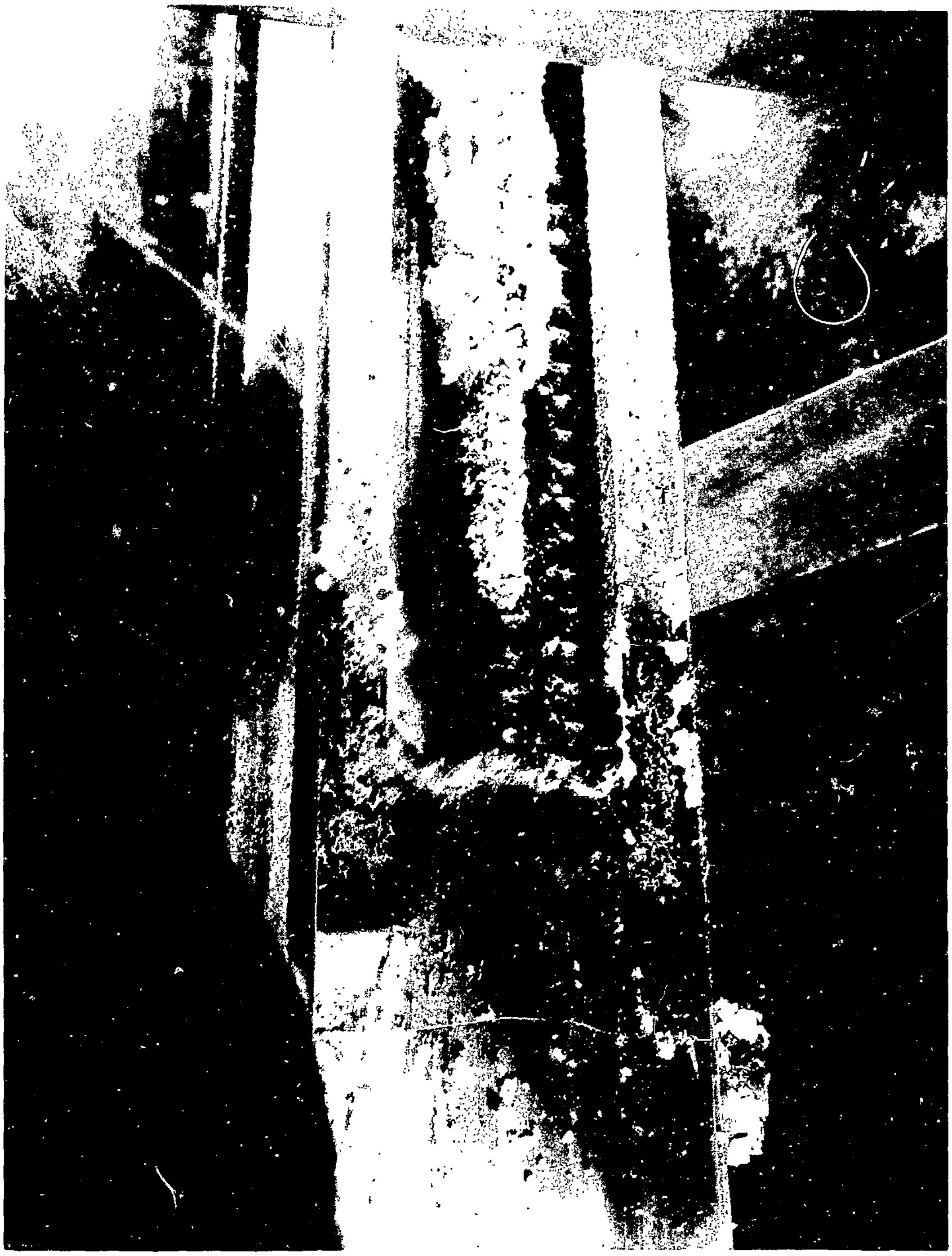
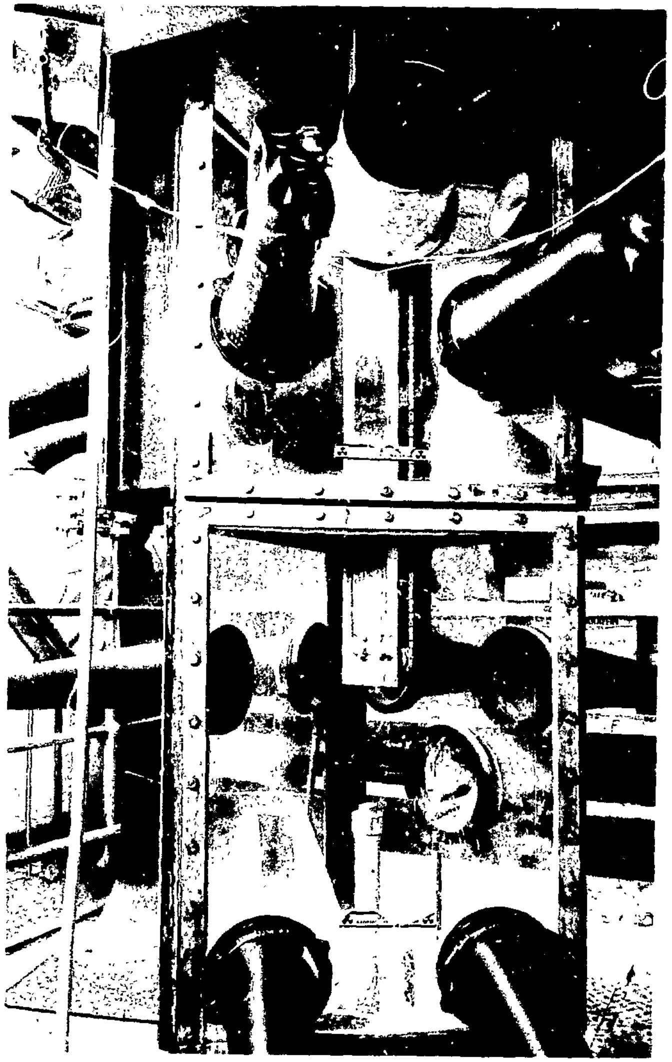


FIGURE 6 - Contaminated charge machine grab



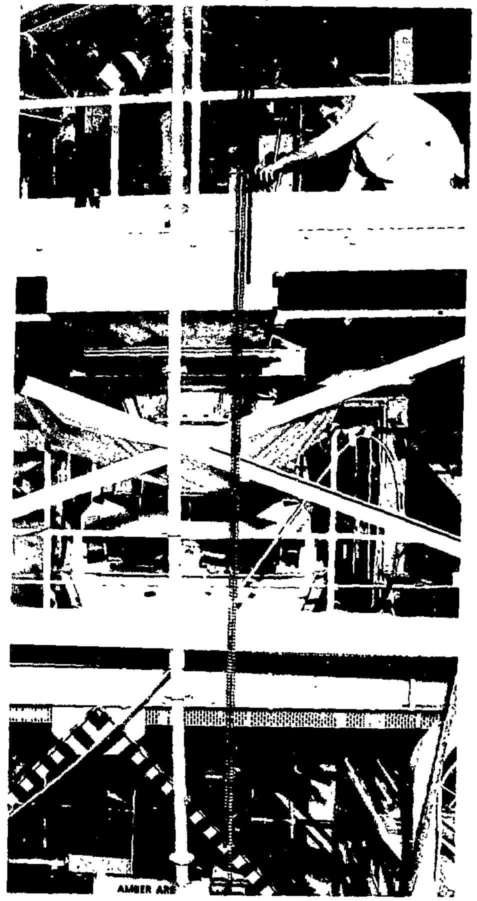
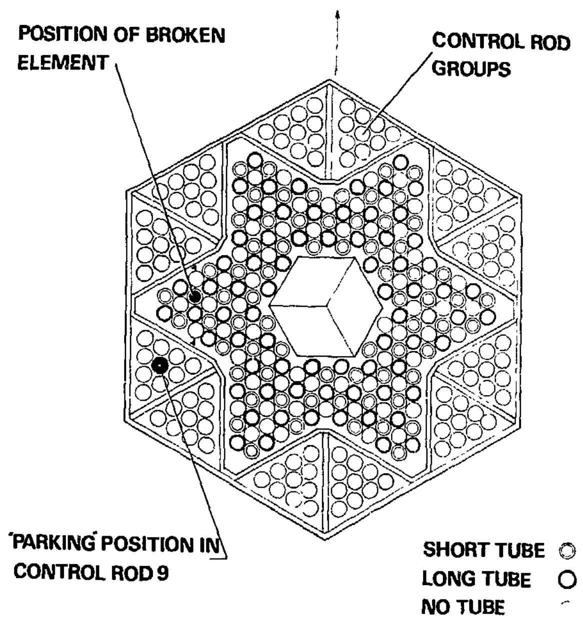


FIGURE 7 - Charge machine maintenance - glove box



PLAN OF CORE SHOWING POSITION OF DAMAGED ELEMENTS

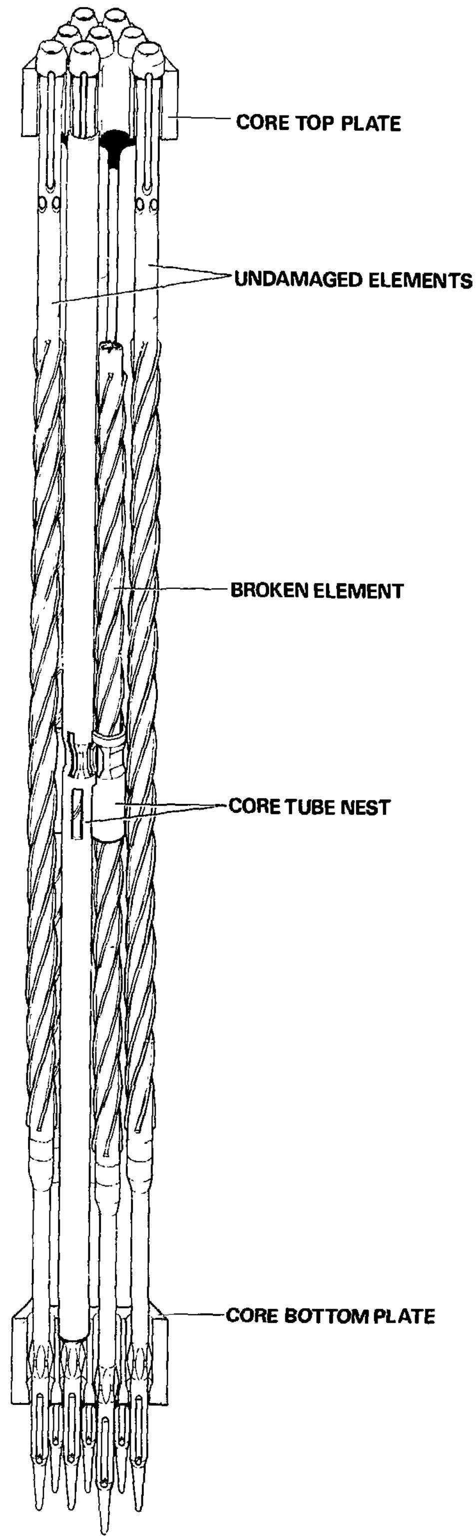


FIGURE 8 - Detail of broken element and surrounding channels

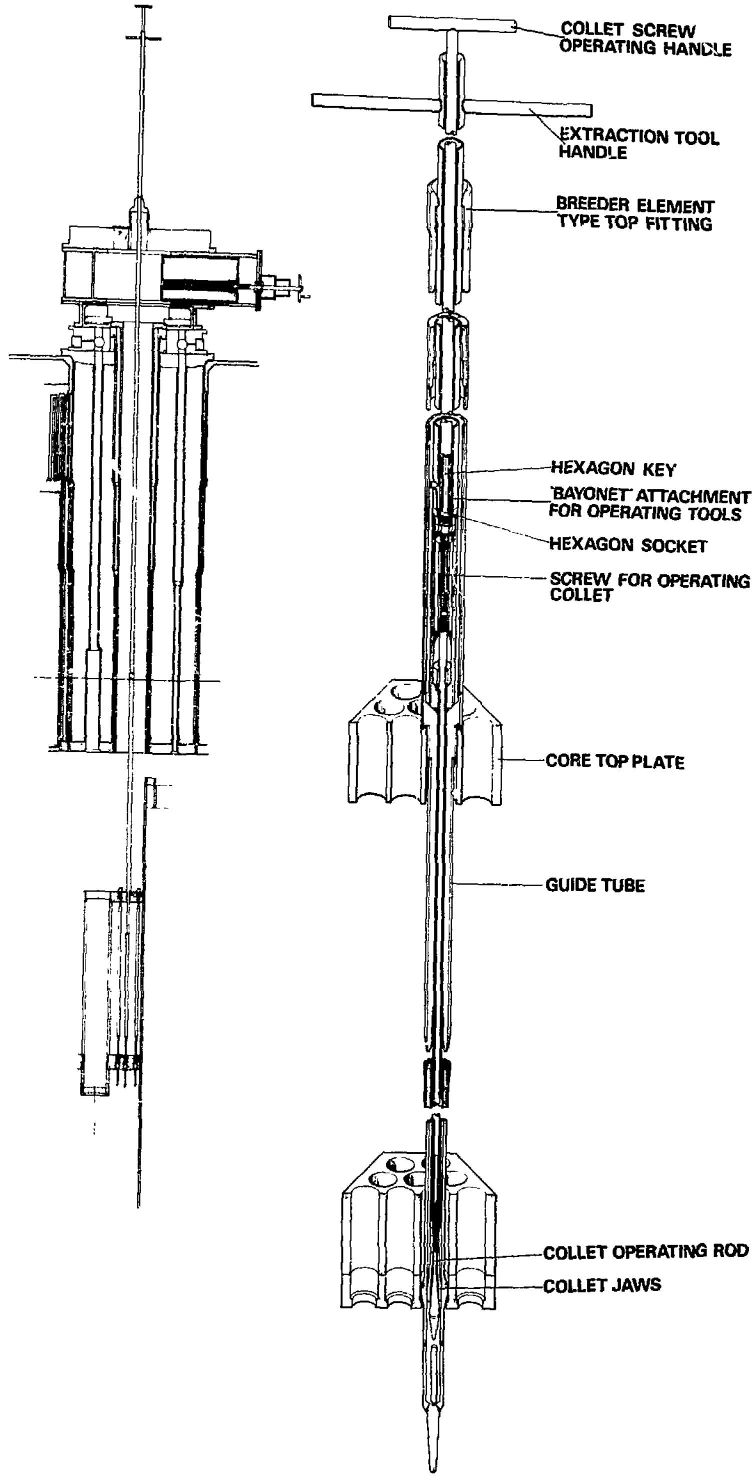


FIGURE 9 - Detail of guide tube and extraction tool recovery of DFR broken driver element

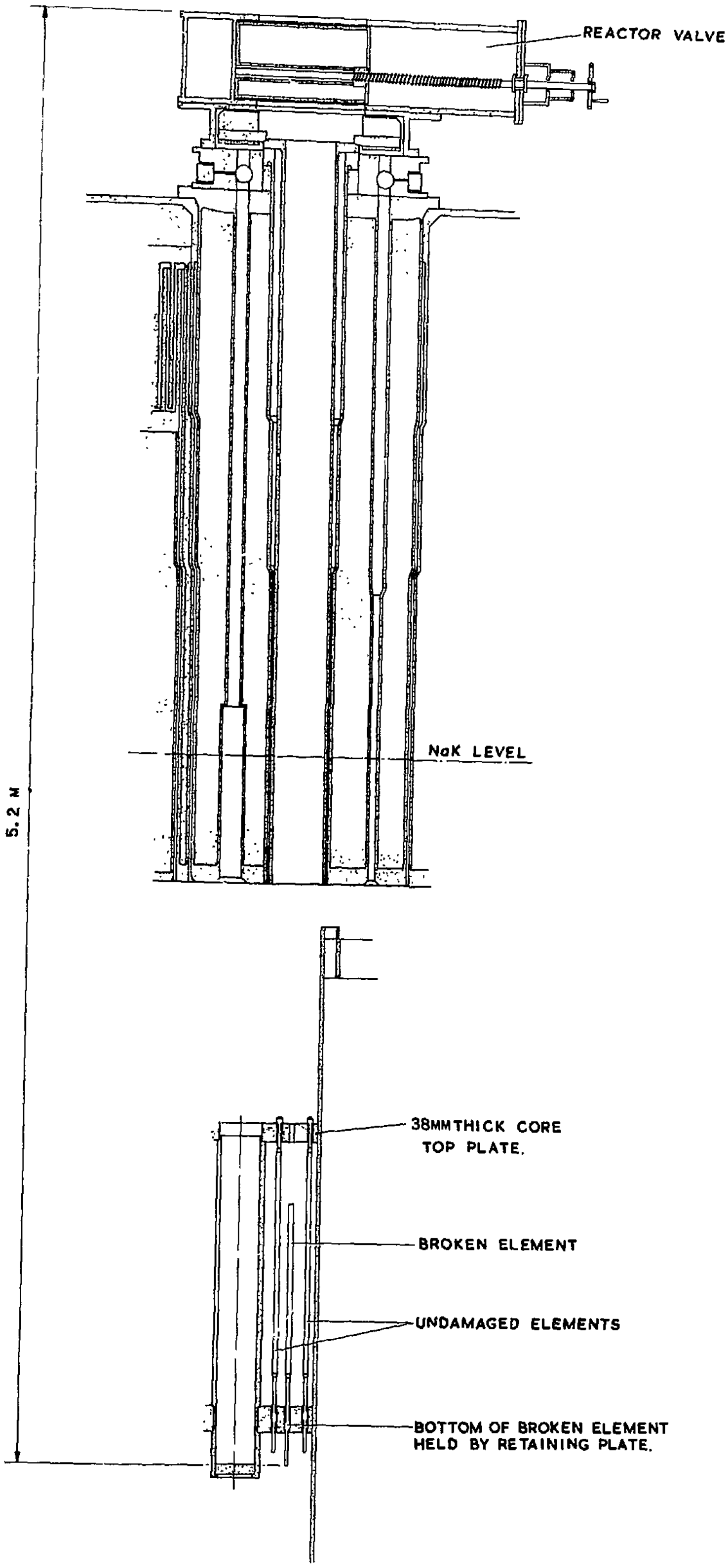


FIGURE 10 - Broken DFR driver element after removal of head

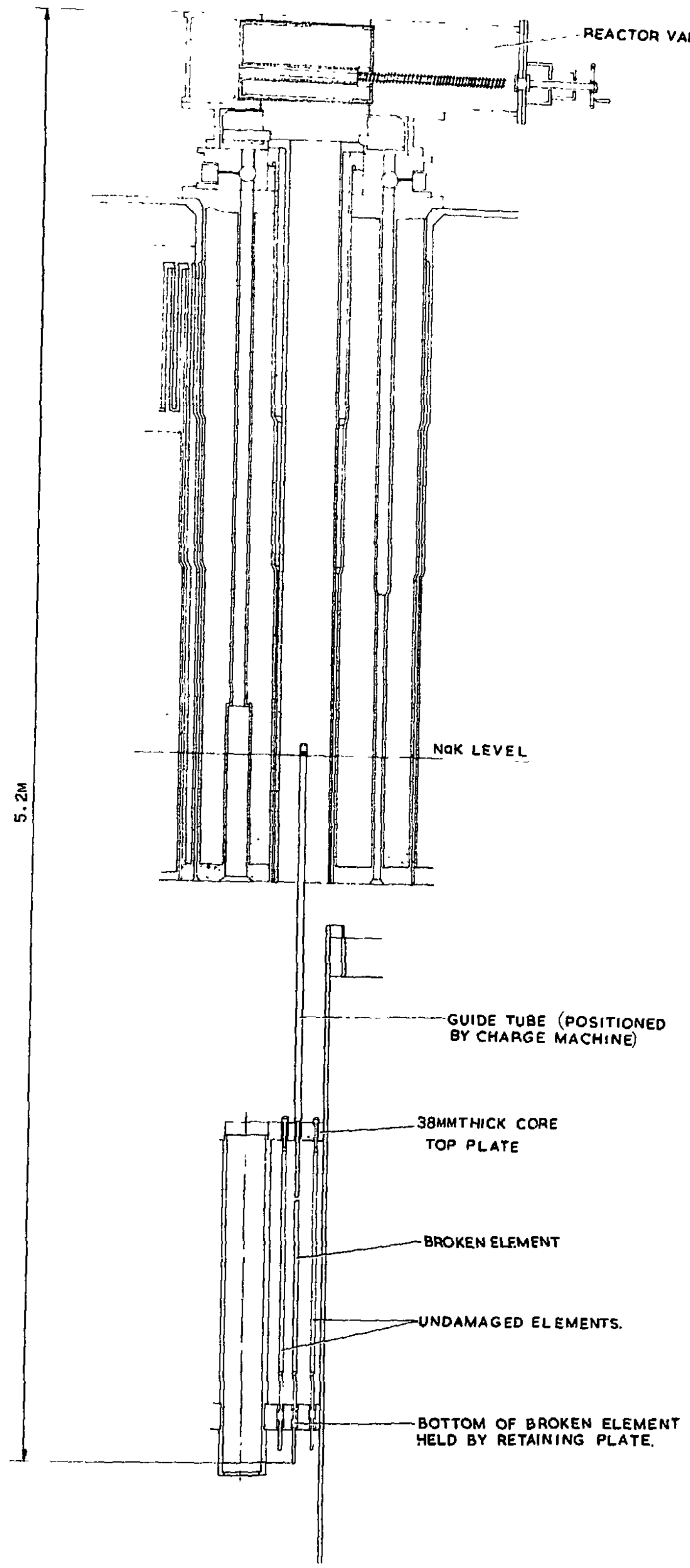


FIGURE 11 - Guide tube - over broken element

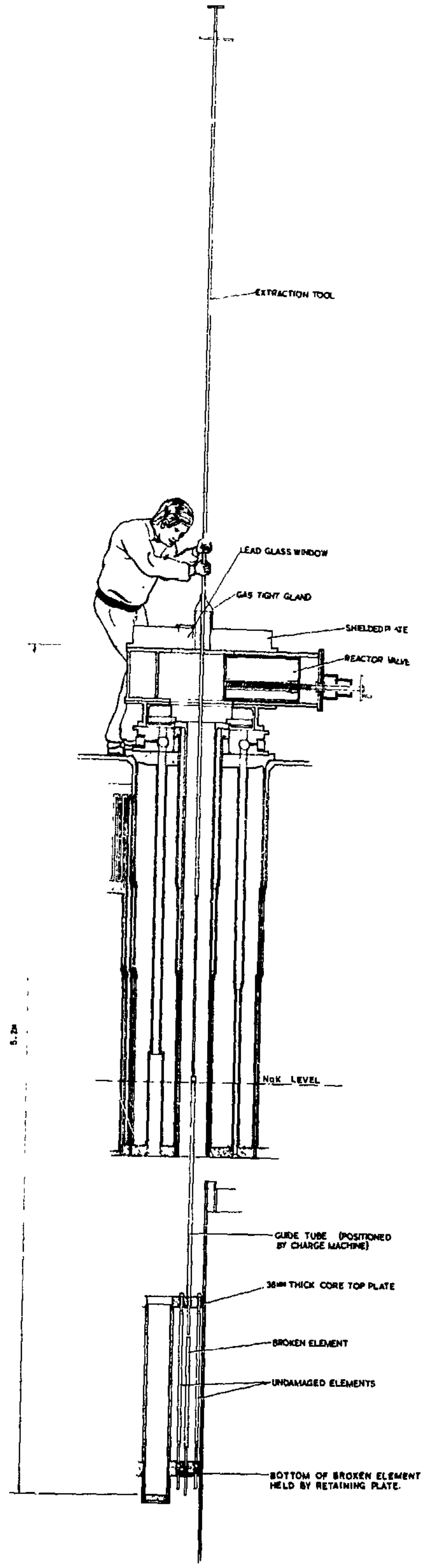


FIGURE 12 - Extraction tool being lowered by hand into guide tube

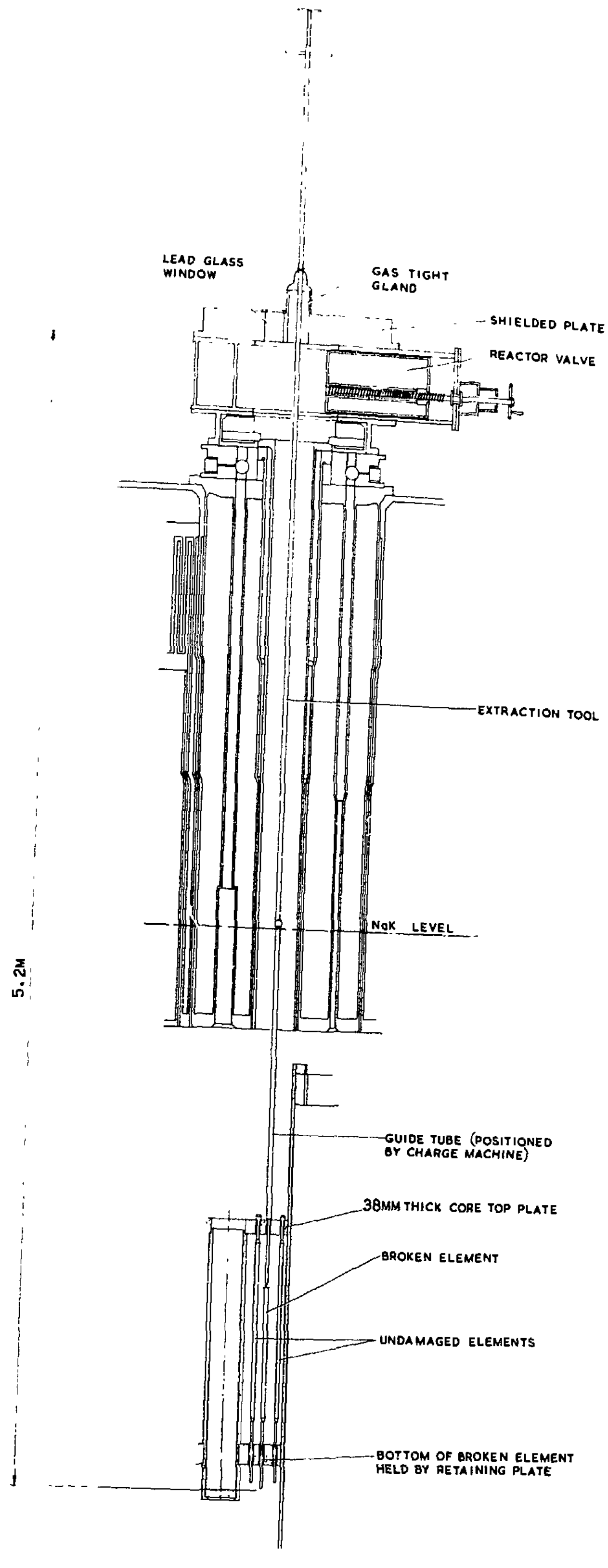
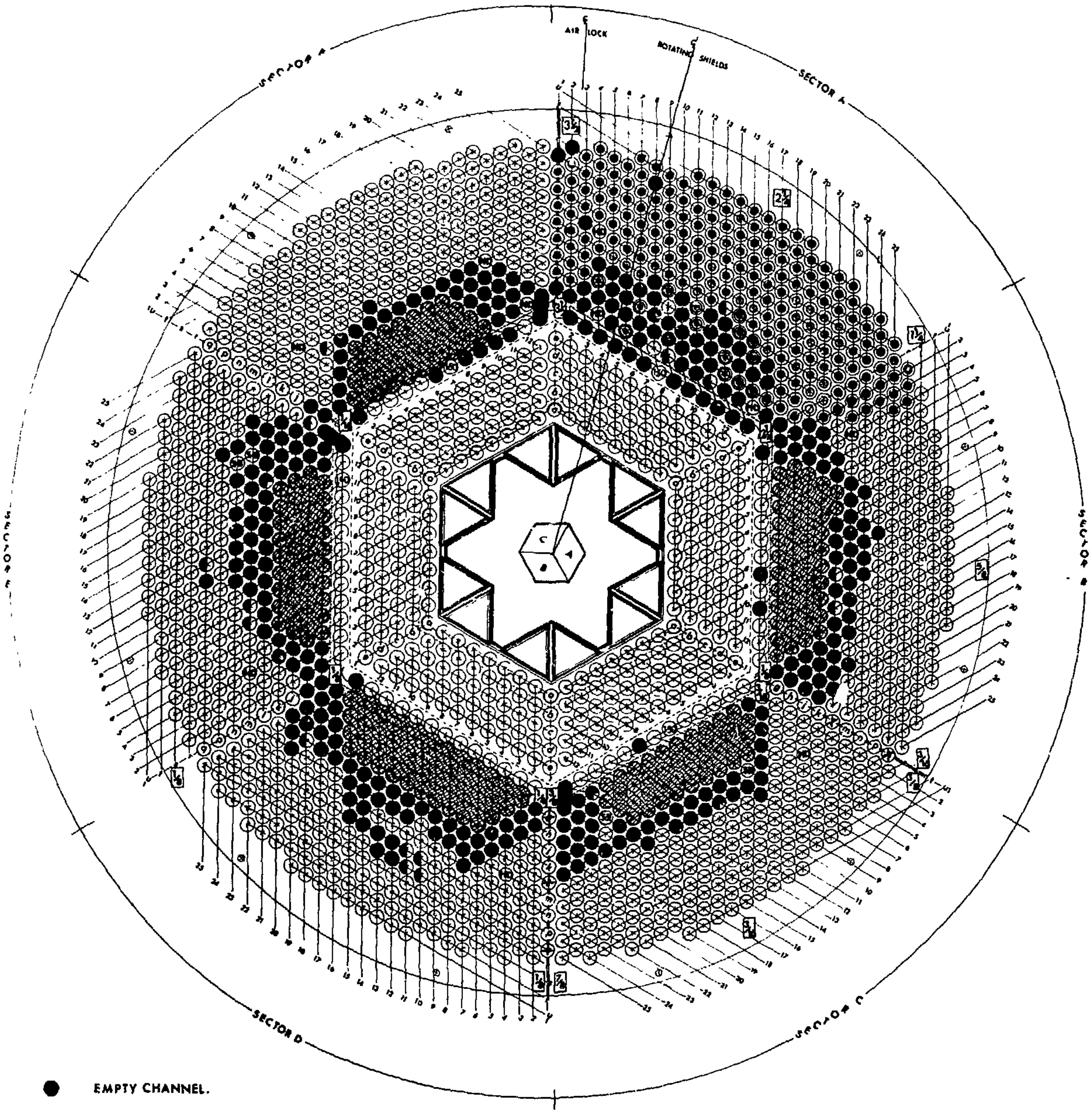


FIGURE 13 - Extraction tool engaging upon broken element



- EMPTY CHANNEL.
- EMPTY HOLE-TOP PLATE ONLY.
- HEADLESS OR DAMAGED ELEMENT.
- ELEMENT WITH PEG.
- ELEMENT WITH PEG IN WRONG TOP PLATE HOLE.
- PART OF ELEMENT DISCHARGED.
- STAY BARS.
- HOLD DOWN BARS.
- TOGGLE BOLTS.
- Ni ELEMENT.
- HEIGHT OF OUTER PLATE ABOVE INNER PLATE DATUM.
- LINK BARS.
- SECTION OF TO PLATE REMOVED.

FIGURE 14 - Plan of outer breeder

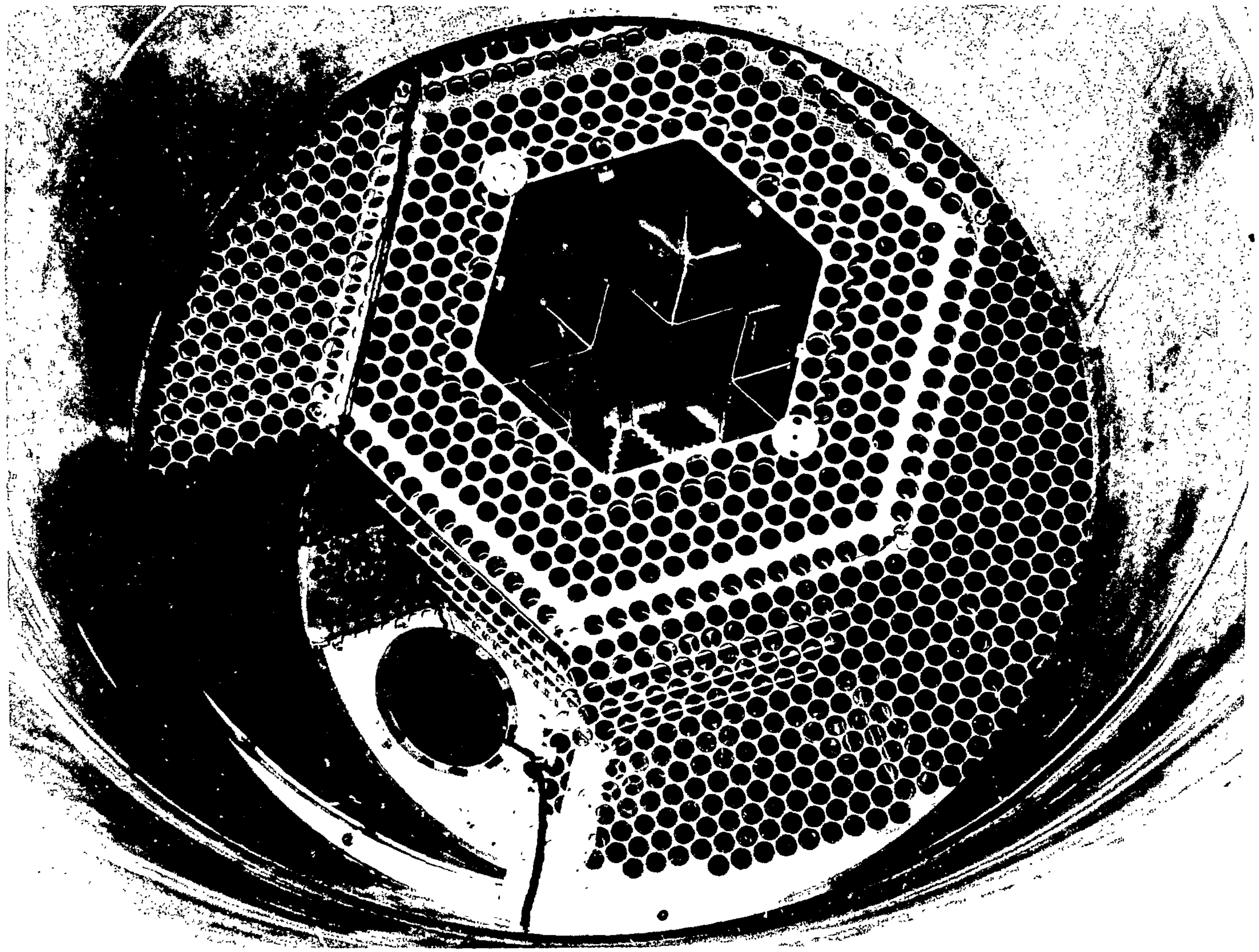


FIGURE 15 - View of outer breeder during construction

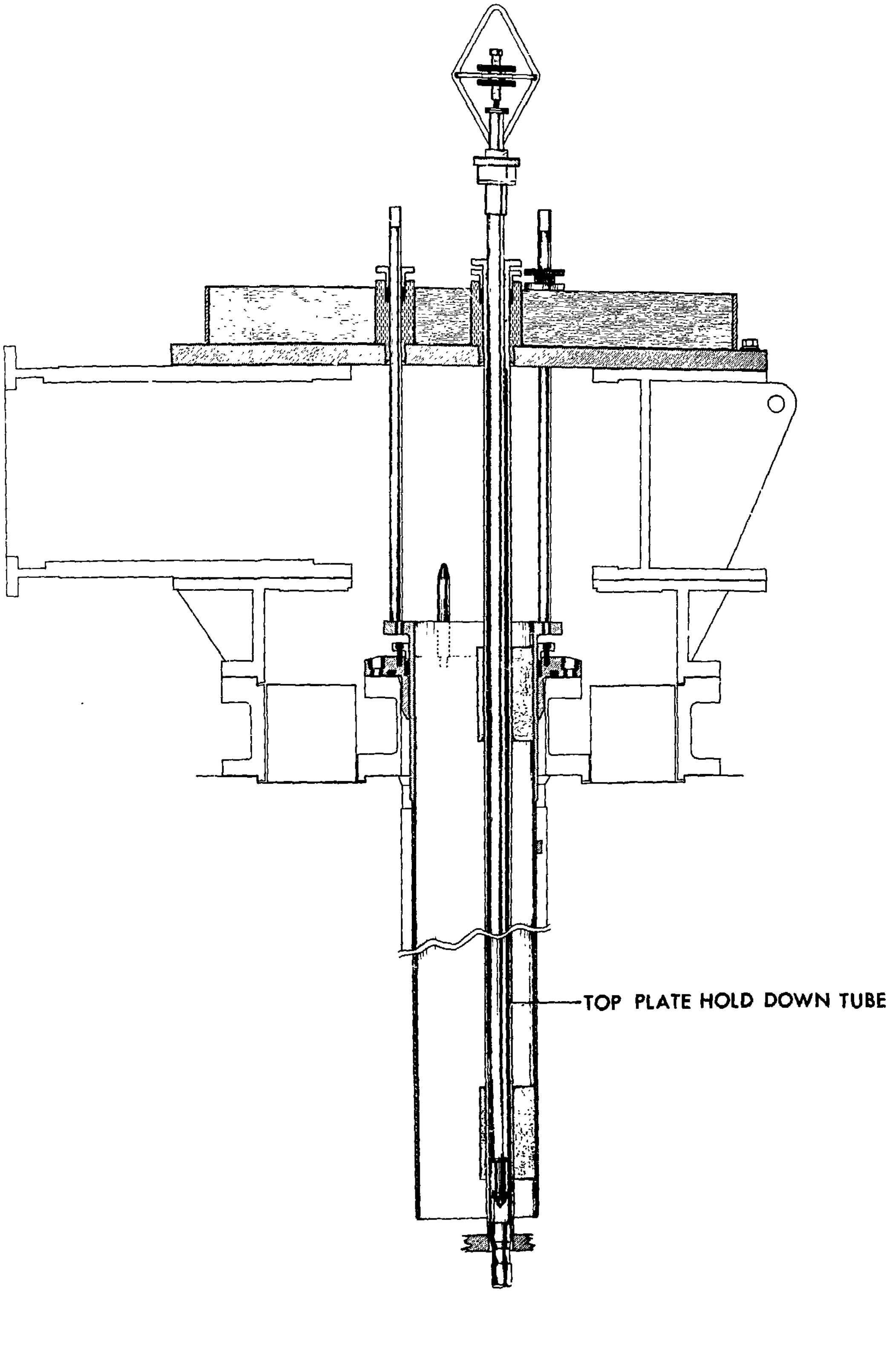


FIGURE 16 - Heavy discharge gear

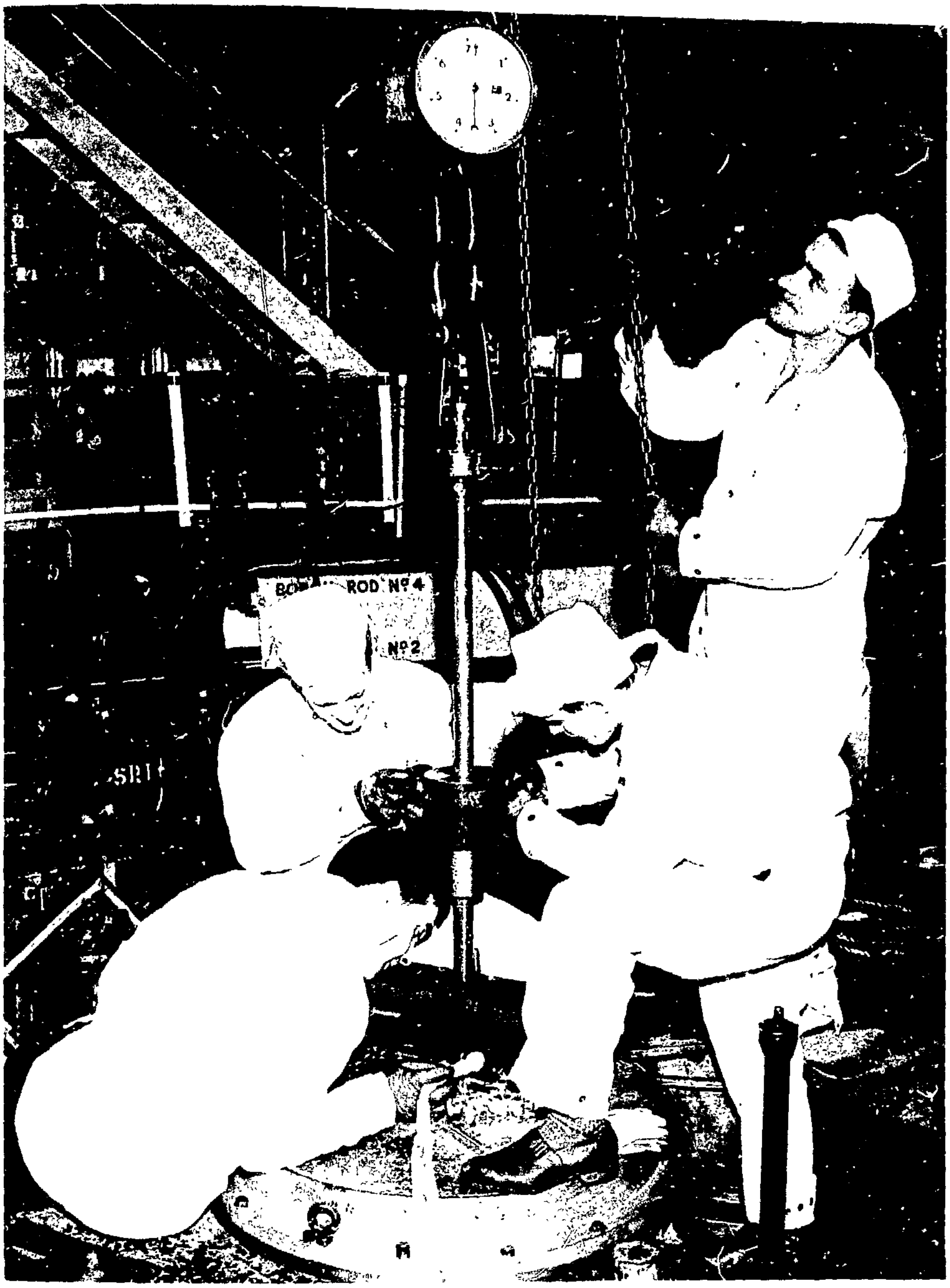


FIGURE 17 - Heavy discharge gear in operation

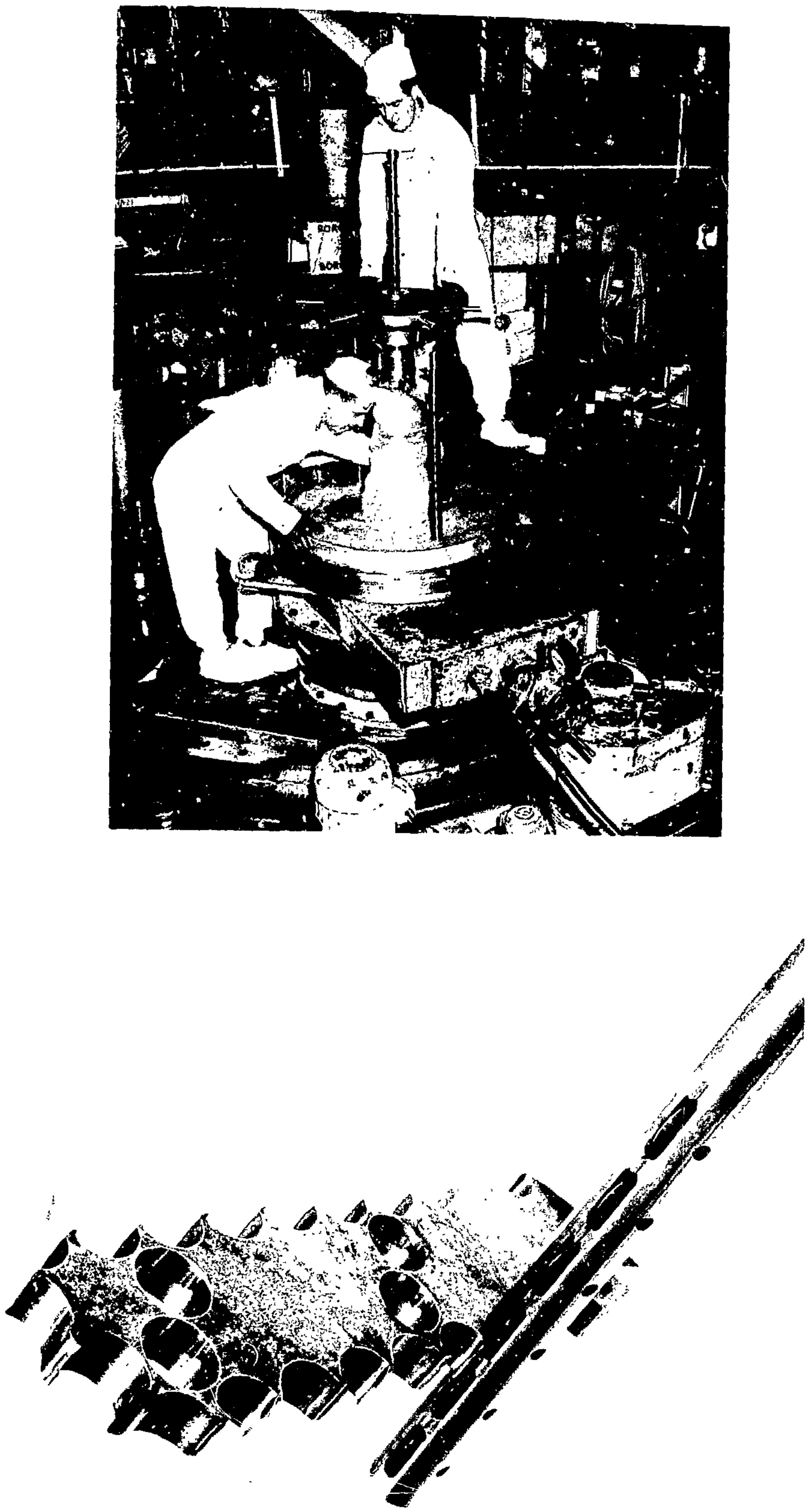


FIGURE 18 - Breeder plate cutting equipment

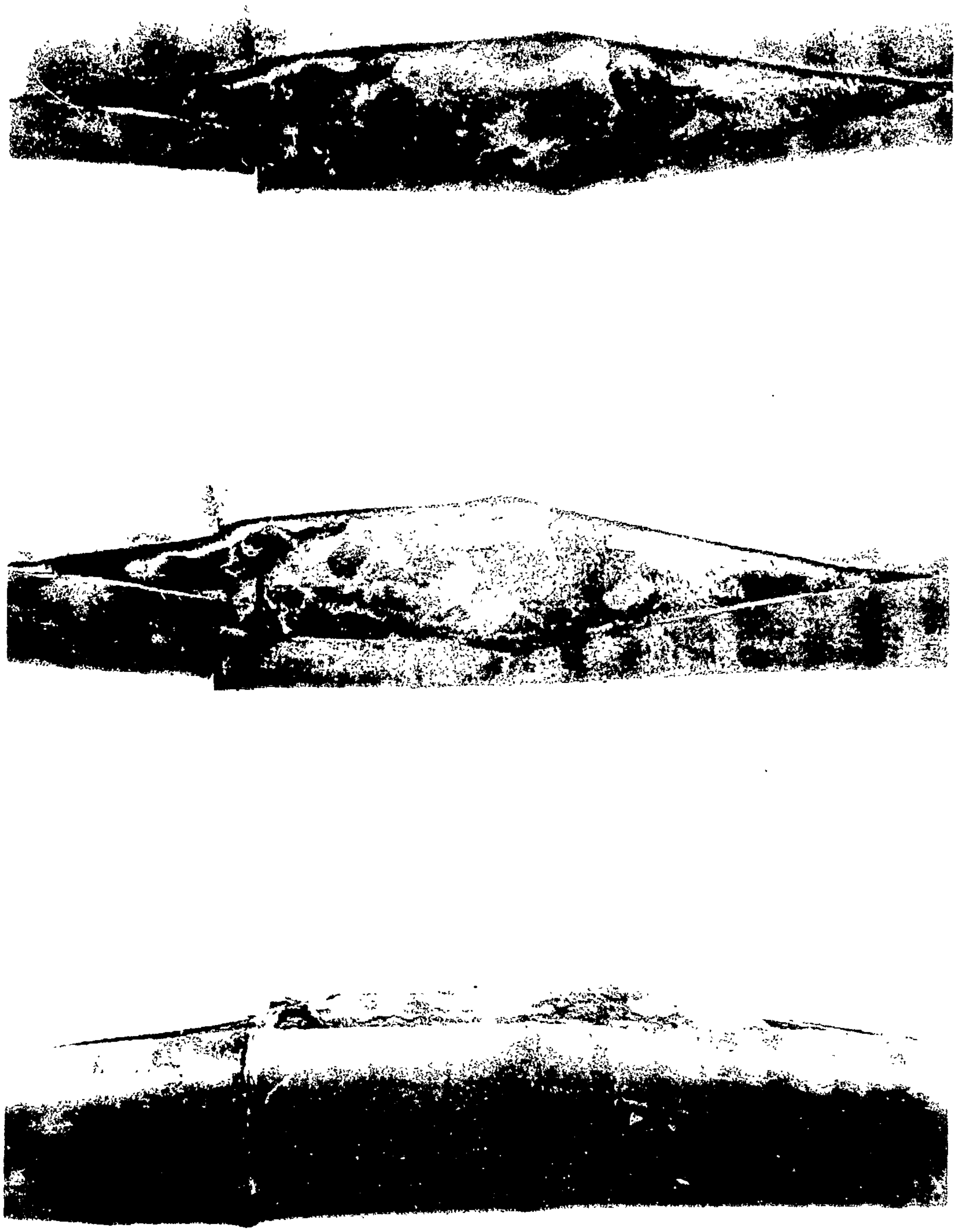
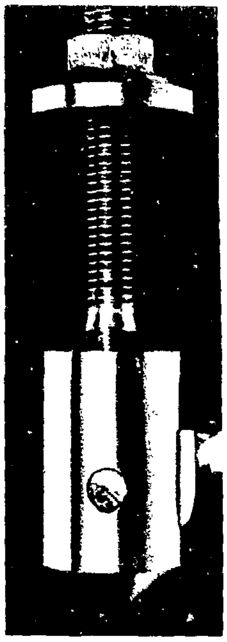


FIGURE 19 - Swollen breeder element

FIGURE 20 - Swollen breeder element during discharge



TOGGLE BOLT

LINK BAR

ELEMENT PEG
(Sector A)

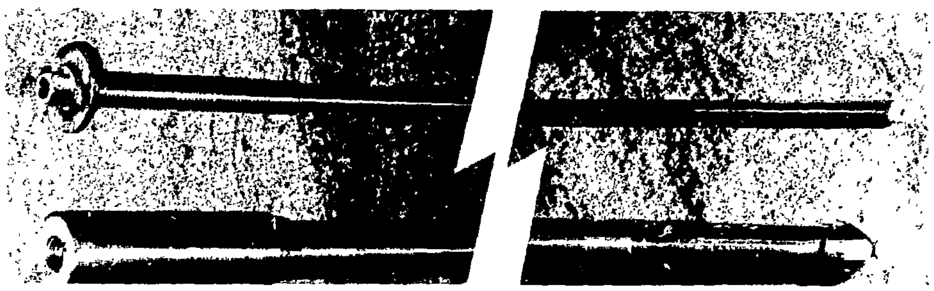


PLATE HOLD DOWN BAR WITH BOTTOM COLLET OPERATING SHAFT

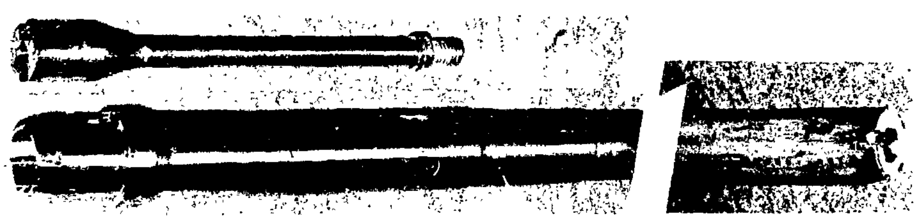


PLATE HOLD UP BAR WITH UPPER COLLET OPERATING STUB

FIGURE 21 - Cut plate and element securing devices

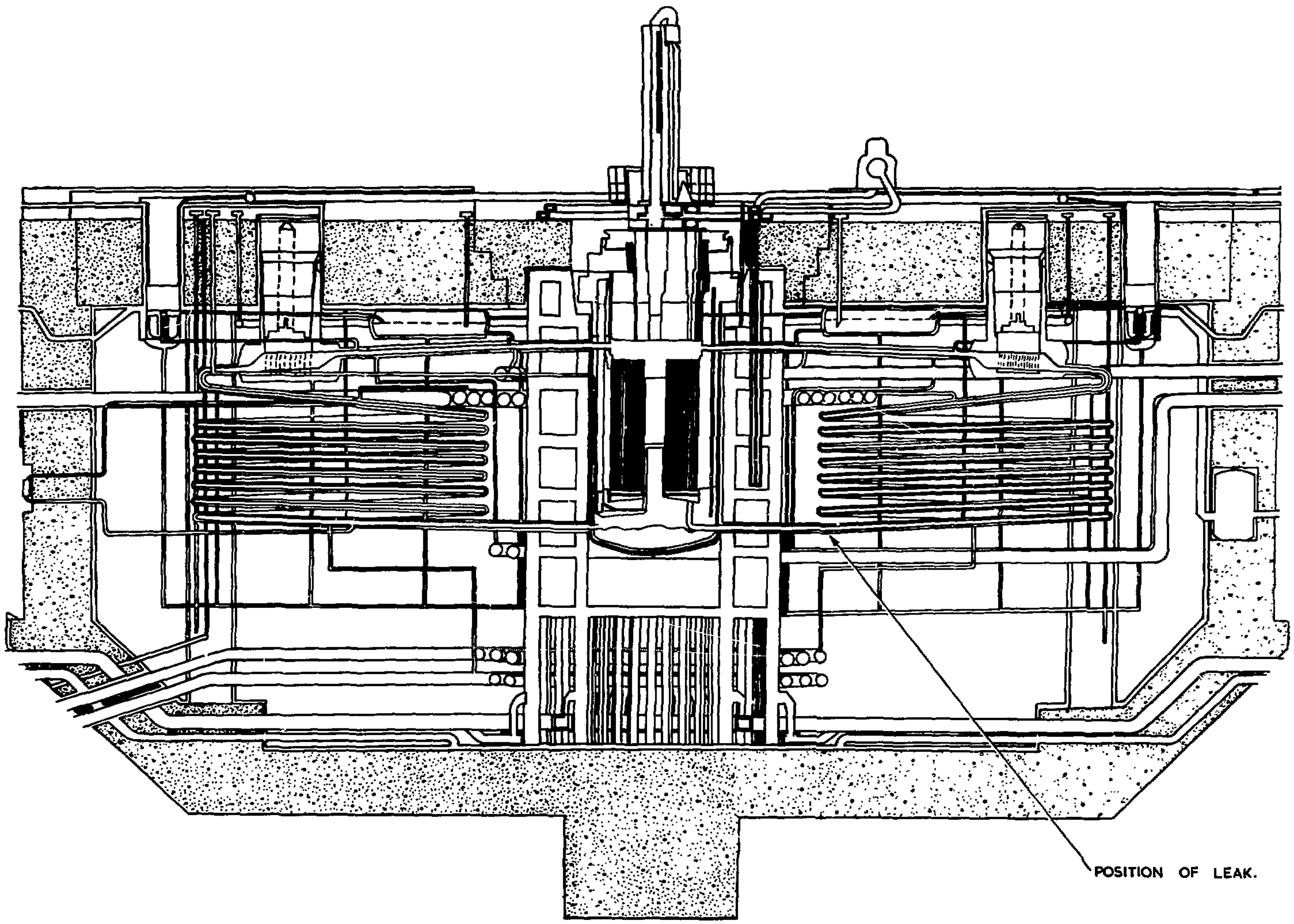


FIGURE 22 - Reactor vault showing position of leak

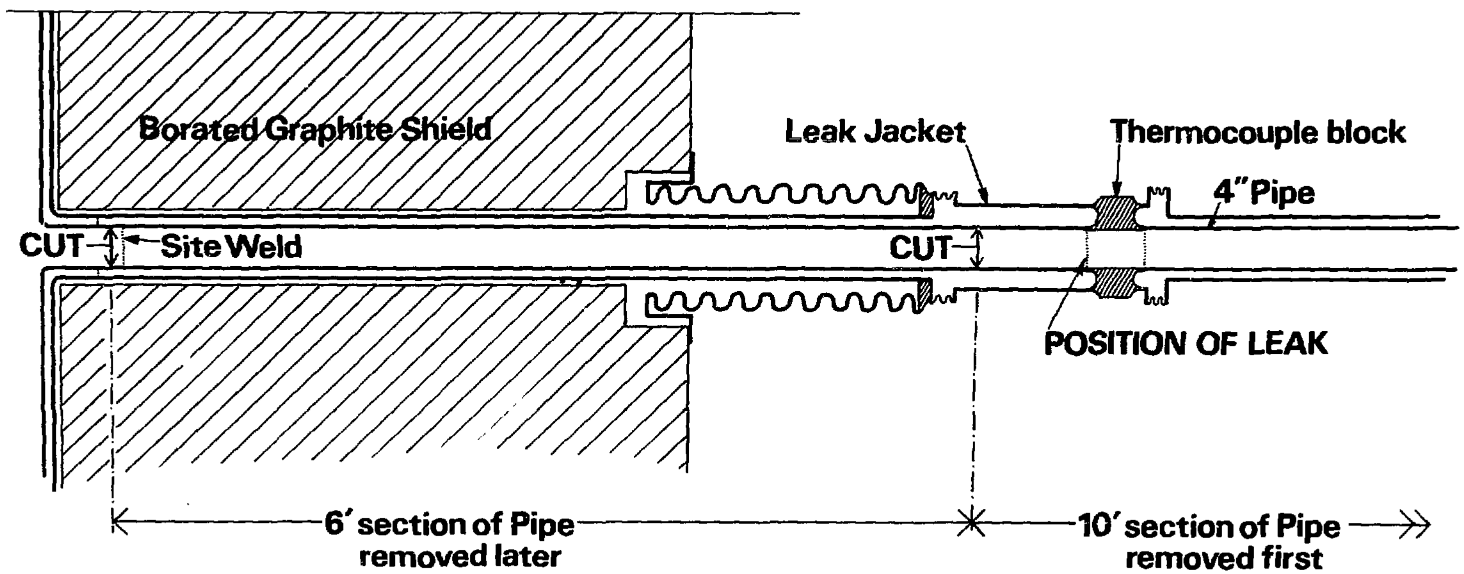


FIGURE 23 - Section of pipe that had to be removed

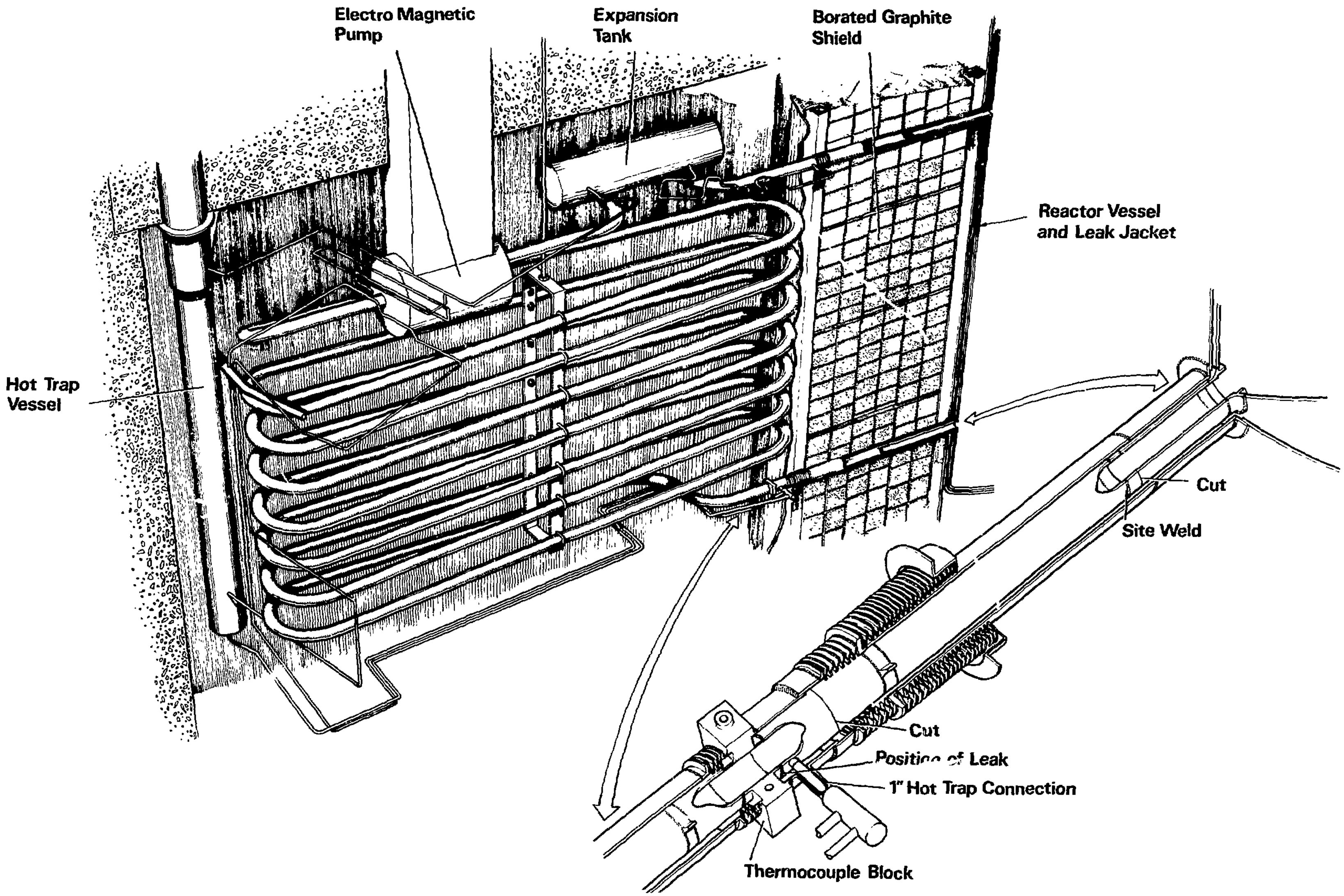


FIGURE 24 - General arrangement of heat exchanger and hot trap circuit showing position of leak

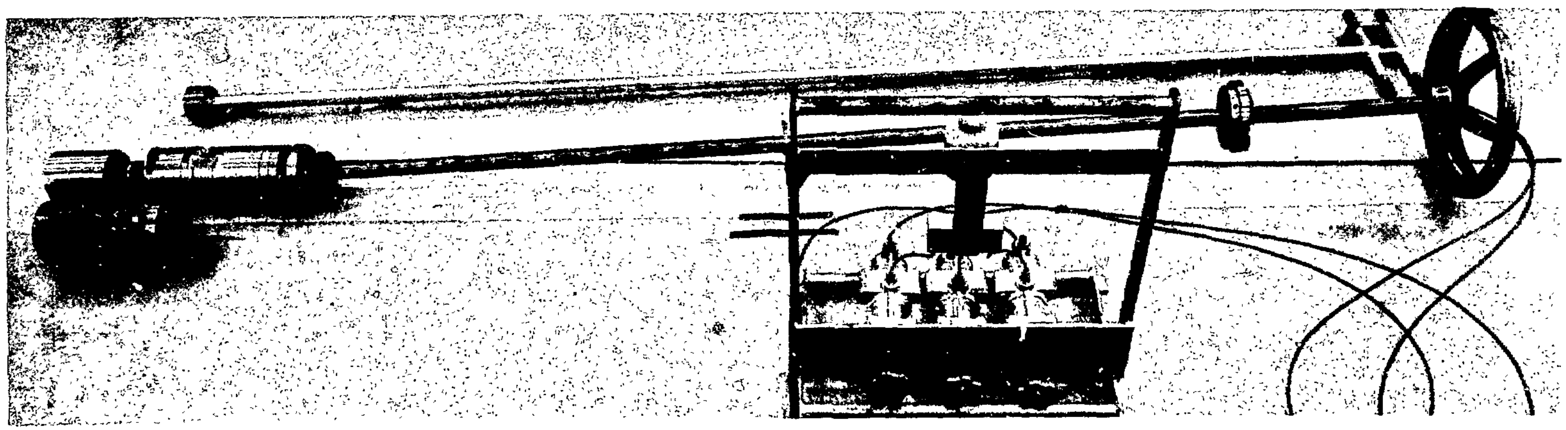


FIGURE 25 - Internal pipe cutter

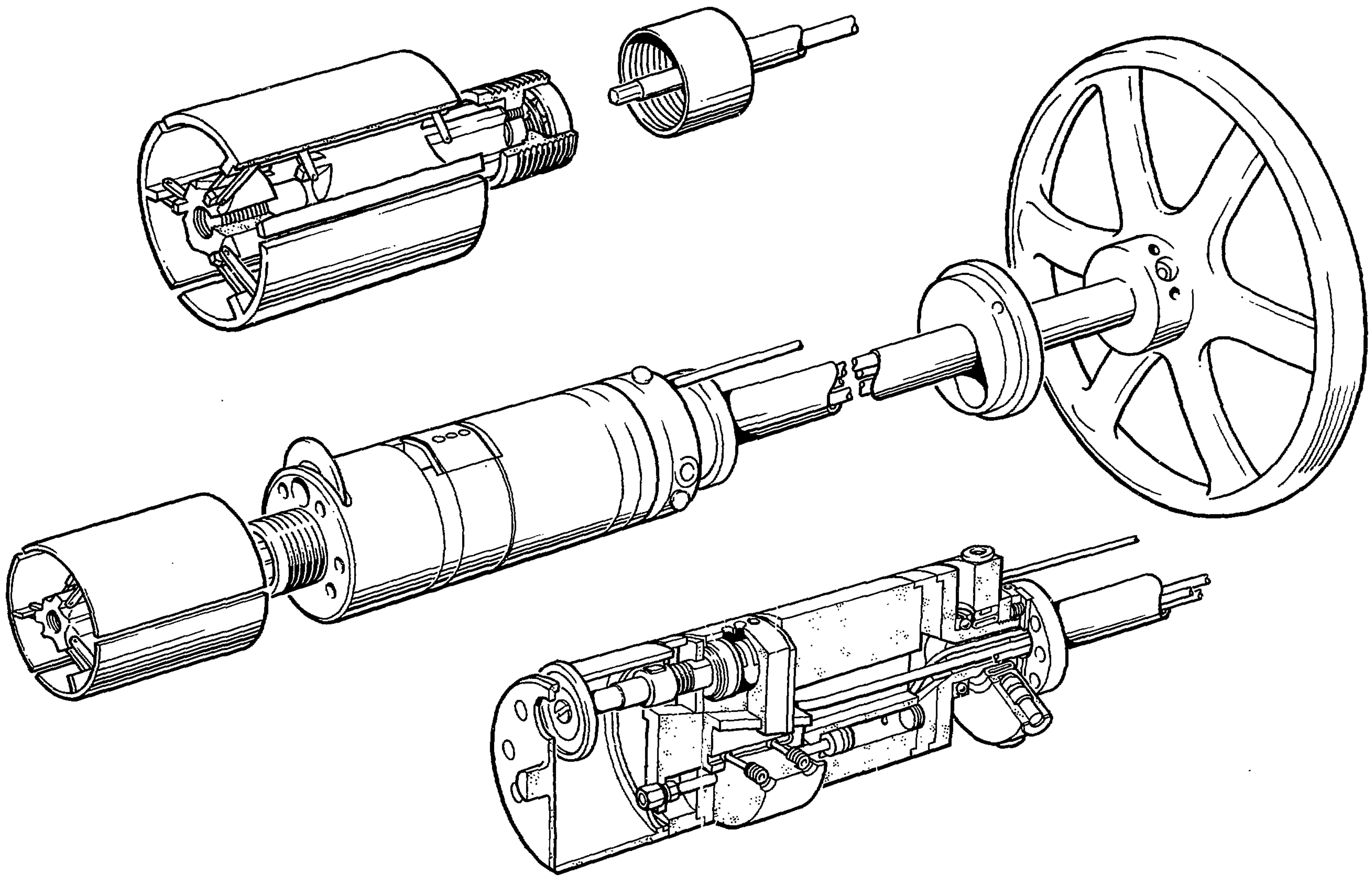


FIGURE 26 - Internal cutting and facing head

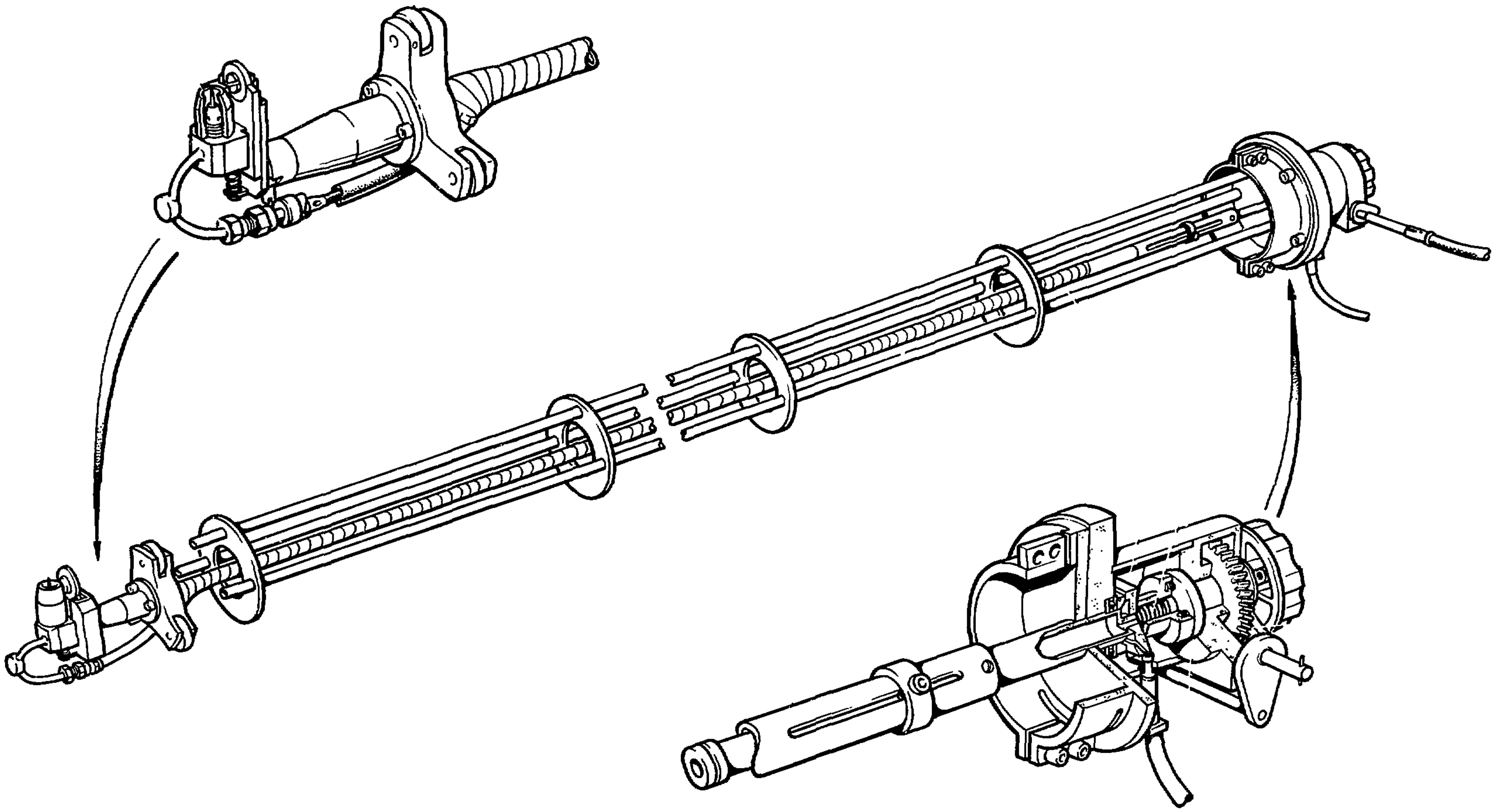


FIGURE 27 - Internal welding equipment

FIGURE 28 - Glove bag for smaller pipe repairs

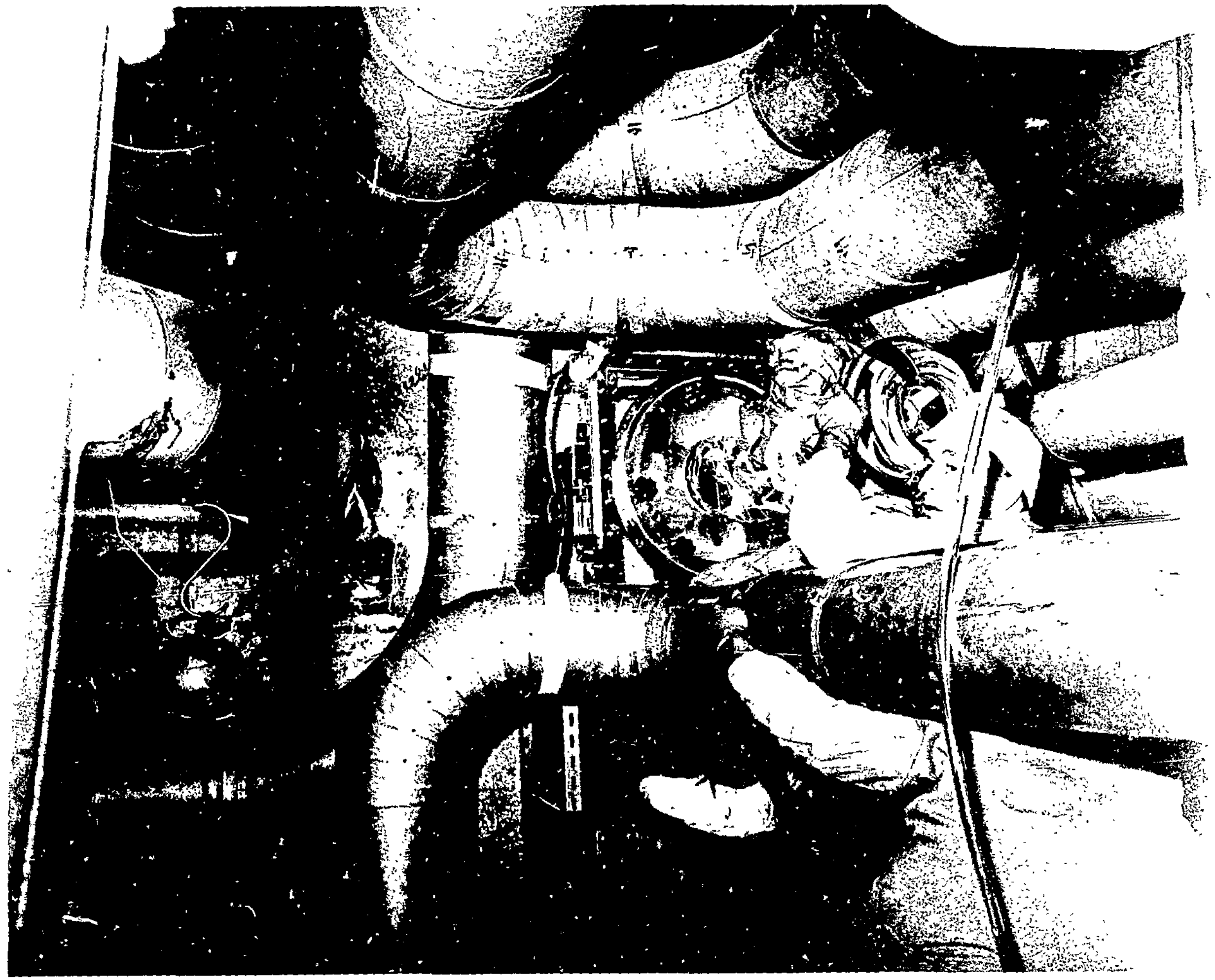


FIGURE 29 - Typical working conditions in the reactor vault