I Windscale 8/24/70
II-C Saclay 3/15/60
II-C Mol 12/30/65

A REVIEW OF CRITICALITY INCIDENTS WITHIN THE EUROPEAN COMMUNITY

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1 INTRODUCTION

The recent criticality incident at the RA.2 facility in Argentina has served to heighten interest in the subject of criticality incidents in general. The purpose of this paper is to review criticality incident experience within the current boundaries of the European Community shown in Figure 1. As far as the author is aware there is no European register of such incidents and the self imposed geographical constraint makes the task more manageable within the time available. However, it should be remarked that two further incidents, which are not described in this paper, are known to have occurred within Europe taken as a whole; namely, the incidents in the Soviet Union in 1954 and in Yugoslavia in 1958 (1).

Four criticality incidents are known to have occurred since the inception of the nuclear industry in the member states shown in Figure 1. These are the criticality incidents at Saclay, France in 1960; at Mol, Belgium in 1965; at Windscale Works, England in 1970; at Cadarache, France in 1971. With the exception of the incident in a chemical plant at Windscale, all incidents occurred in critical facilities supporting reactor operations. The first three incidents will be described in some detail whereas the more recent French incident will simply be mentioned because of its similarity to the earlier one.

2 THE CRITICALITY INCIDENT IN THE ALIZE ASSEMBLY: SACLAY: 15 MARCH 1960

2.1 Experimental Assembly

The experimental assembly comprised 5257 aluminium clad sintered uranium oxide rods arranged on a 11.1 mm pitch in a 73 x 73 array contained within a 2m diameter cylindrical tank. Each rod had a diameter of 6.395 mm and a height of 1080 mm; the enrichment was 1.5% 235 U. The total uranium oxide inventory was 2.2 tons. Moderator and reflector were light water. The critical approach parameter was the water height in the tank.

The whole assembly was installed in a 9 m deep pit, closed during reactor operation by two concrete flags at ground level.

The safety and control devices were made with cadmium plates inserted in place of 6 groups of 12 uranium oxide rods; their positions are shown in Figure 2. These plates automatically dropped into the core on an excess power signal from one of two independent control loops. ALIZE could also be made subcritical by a fast water dump facility initiated on a period lower than 10s, as indicated by the power measurement instrumentation, or a period lower than 1s as measured directly by a period meter. It should be noted that water filling could only commence if at least two cadmium plates had been withdrawn.

2.2 Description of the Incident

The planned experiment required the irradiation of manganese foils on a long stable period in order to measure the radial buckling.

Many identical experiments had already been performed; the critical water height and appropriate water heights for irradiation were well known. A reactivity excess of 50 pcm, equivalent to 7.7 cents, had to be produced and shutdown would have taken place when a power level of 10 watts was achieved.

For no apparent reason, the operator began the critical approach without having completely removed safety plate number 4 (Figure 2). The counting rates, which were abnormally low compared to those predicted, led him to believe that some neutron absorber had been left in the core. Nevertheless, he continued the critical approach. A second indication that all was not as intended occurred when the critical height was calculated via an extrapolation based on measured counting rates. This yielded the result 902.5 mm which was greater than the known value of 846.9 mm. Despite this indication, water filling was continued.

At a water height of 885.1 mm, the safety rods automatically shut down the reactor. The operator's behaviour was consistent with a response to a spurious reactor trip. He decreased the sensitivity of the measuring instrumentation, intending to return it to its former value later. He then removed safety rod #1 completely and raised safety rod #4 to the mid-core height position. He resumed water filling without, however, having returned the measuring instrumentation to its former sensitivity. At a water height of 906 mm the reactor became critical and the period meter gave an on-scale reading. The operator treated the latter as an instrument fault and set the instrument to zero.

The actual reactor status was by this time being indicated by temperature and power recorders and, once again, by the period meter. Although the reactor was supercritical, the safety rods failed to fall automatically, probably because the power level was increasing too rapidly for the measuring instrumentation to respond. The operator finally realised what was happening and shut down the reactor manually by dumping the water in the tank. The excess reactivity was later evaluated as 950 pcm with an initial slope of 32 pcm/s. The total number of fissions was 3.3×10^{18} and the dose received by the operator was 2 to 3 rem. There was no material damage, no cladding rupture and no contamination.

2.3 Conclusion

The incident can be attributed to a long series of human errors, ie the criticality approach was started in error with plate #4 still within the core; failure to realise the significance of various instrument readings; desensitising the power measurement instrumentation which may have contributed to the failure of the automatic systems; resetting the period meter.

It should be noted that a similar incident occurred in the AZUR reactor at Cadarache in 1971. Again, the incident was due to a long series of human errors, leading this time to an operator exposure of 34 rem.

3 THE CRITICALITY INCIDENT IN THE VENUS ASSEMBLY: MOL: 30 DECEMBER 1965 (2, 3 and 4)

3.1 Experimental Assembly

The VENUS reactor (Vulcain Experimental NUclear Study) was, at the time of the incident, a nuclear model of the VULCAIN reactor and was used to determine its characteristics. The cylindrical reactor vessel was made of stainless steel and was 1.73 m high and 1.6 m in diameter. The vessel contained fuel assemblies and neutron absorbing rods, both passive and capable of remote insertion. The core was immersed in a mixture of light and heavy water, (Figure 4). The whole assembly was housed in a concrete chamber.

Each fuel assembly comprised a hexagonal array of 37 stainless steel tubes filled with uranium oxide pellets enriched to 7% ^{235}U. The pellet diameter was 7.4 mm and each pin had an active length of 1 m. The outer envelope was a hexagonal box pierced by water circulation holes. One feature, which became important with regard to the doses received during the accident, was the presence of a stainless steel plug at the top of each tube, and six stainless steel locating grids which held the pins in each assembly. The core contained 73 fuel assemblies and had a total inventory of 1.2 tonnes uranium.

There were eighteen neutron absorbing rods which took three forms. The eight safety rods were suspended on cables from a metal structure over the reactor and inside the concrete chamber. When an emergency shutdown signal was given, the electromagnetic clutches automatically freed the safety rods which fell into the core. The two power control rods were moved by an "endless screw" device which did not allow free motion. Operation of the safety and control rods was done remotely from the control room. Controlled insertion of safety and control rods was normally achieved by means of electric motors. There were also eight manually inserted rods.

3.2 Description of the Incident

The experimental programme in progress on 30 December 1965 was intended to determine the reactivity worth of the neutron absorbing rods by observing the correlation between the movement of the moderator level and the movement of groups of absorbing rods, with the reactor remaining critical. The level of the moderator could be varied between a minimum value corresponding to criticality with all rods withdrawn ie with 240 mm of fuel immersed, and the maximum level corresponding to 300 mm above the top of the fuel. On 30 December 1965 the moderator contained 70/30 parts of light to heavy water by volume. The work in progress was to investigate a configuration of (18 - x) absorber rods completely inserted and x rods partially or completely withdrawn, to allow the attainment of criticality at the maximum level.

The previous experiment was done under the following conditions; seven safety rods and seven manual rods inserted completely, one control rod (R_2) and one manual rod completely withdrawn, and a further control rod (R_1) partially withdrawn (Figure 4). Criticality was attained twice under these conditions, the latter being at 12.45 pm on the day of the incident while the chamber was unoccupied and closed in accordance with the reactor operating rules. Two further rules should be noted; control rod removal was required to take place while there was no water in the reactor vessel; otherwise, three additional safety rods were required to be inserted before rod manipulation. The second rule could not be satisfied with the above configuration and, therefore, the moderator should have been drained. Exceptionally, it was not.

At 12.47 pm the team leader, who had been with the reactor engineer in the control room, left the installation for lunch. He was replaced by a reactor operator; the engineer began to shut down the reactor by inserting a safety rod and both control rods. However, the engineer interrupted the sequence almost immediately to explain to the operator coming on duty the sequence of operations to be followed.

The sequence was to be:

i Insert safety rod S_2 (accomplished).

ii Insert control rods R_1 and R_2 completely (interrupted - only partially complete).

iii Insert a manual rod in position IO.

iv Withdraw a manual rod from position G330.

v Withdraw safety rods S_4 and S_5.

After the explanation, the engineer instructed the operator to continue with step (ii) above and then began to enter in the log book details of steps (iii) and (iv). The engineer gave written instructions to the technician who would make the core changes and returned to the control room. The technician then entered the reactor chamber and began the job without waiting for authorisation from the control room, which was connected to the chamber by intercom. At that moment control rod R_1 had been inserted but R_2 had only just entered the fuel region. The technician then carried out the two steps in his written instructions in the reverse order to that specified, ie he began to withdraw the manual rod from position G330 before inserting the manual rod in position IO.

When the technician started to withdraw the rod from G330 the reactor was subcritical by an amount equivalent to safety rod S_2 and control rod R_1. If the correct sequence had been followed the reactor would have been subcritical by an amount equivalent to

S_2, R_1, R_2 and the manual rod in position IO. The technician raised the manual rod in position G330 such that the increase in reactivity due to its movement became larger than the total safety margin afforded by rods S_2 and R_1. A divergent chain reaction took place and the technician, who was bending over the core in order to carry out the operation, saw a glow within the reactor. He released the manual rod, which fell back into the reactor, and left the chamber very rapidly while audible and visual alarms signalled an abnormal occurrence. The chain reaction was stopped by the falling manual rod, the Doppler Effect and finally the automatic emptying of the reactor vessel. The intended and actual sequence of events is illustrated in Figure 5, which also shows that the full insertion of R_2 would not have avoided criticality.

Subsequent re-entry on 31 December 1965 confirmed the rod positions given above. No damage to the reactor was apparent. The reactor vessel by this time contained no water as it had been emptied by the automatic drainage system during the nuclear excursion.

No detectable contamination of reactor components or the immediate environment was observed. There was some deformation of the pins taken from the most highly irradiated part of the core. The total number of fissions was 4.3 10^{17}.

3.3 Aftermath

The position of the technician at the time of the incident is shown in Figure 6. The technician was flown to Paris for medical attention because his symptoms, including vomiting, and his dosimeters indicated a substantial dose had been received. His QFE had discharged and the film badge worn on his chest indicated 580 R $\beta\gamma$. Detailed reconstructions of the incident, for the purpose of making dosimetric measurements using phantoms, were made with the help of information supplied by the technician affected. The external doses measured are shown in Figure 7; their inhomogeneity should be noted. The technician survived but it proved necessary to amputate his left foot.

After the completion of the Vulcain programme in 1966, the internal parts of the reactor were modified for programmatic reasons. In order to allow the study of clean fuel lattices, and, in particular, to avoid pertubations due to the presence of safety rod guide tubes, a fast water dump was installed. The time response of this system is short with respect to the water filling velocity and associated reactivity addition rate. Several other modifications were made at the same time. A redundant circuit breaker activated by the door of the reactor shielded room was introduced in the scram line. In this way, opening the door of the reactor room automatically initiates a water dump and reactor shut down.

As the door remains open during manipulations, re-arrangements of core components can only begin when the reactor vessel is empty - thus reducing the risk of accidental criticality. The operator responsible for the manipulations of the reactor core was also made responsible for opening and closing the door, and for restarting the reactor. Precautions are however taken to avoid restarting the reactor, which takes 20 - 30 minutes, when people are still in the shielded room. An intense audible signal is emitted when the door is being closed; there is also the possibility of initiating the fast water dump etc, from inside the room itself.

Organisational changes also took place. Two staff members are now involved in decisions concerning the operation of the reactor. Each daily programme is approved by these two people, one of them being mainly concerned with the research and experimental aspects, the other with operations and safety.

3.4 Conclusion

The incident was due primarily to communication failure and the further human error of performing instructions in reverse order. The modifications to working practices have proved satisfactory. The reactor has continued to be used intensively ever since and safety has been maintained over nearly twenty years of further operation.

4 THE CRITICALITY INCIDENT IN THE PLUTONIUM RESIDUE RECOVERY PLANT: WINDSCALE WORKS: 24 AUGUST 1970 (5, 6)

4.1 Plant Description

The Plutonium Residue Recovery Plant was originally designed as the Plutonium Purification section of the original Irradiated Fuel Reprocessing Plant. In 1964 it was adapted to recover plutonium from both solid and liquid residues by the TBP/OK solvent extraction process. These residues included oxides, mixed Pu/U oxides, fluorides, nitrates, slag and oxalate mother liquors. Aqueous raffinates, solvent wash liquors and off-specification product were recycled from time to time. Although the recycling of solvent wash liquor was an extremely rare occurrence, it is important to realise that all such recycled liquors may have contained entrained or dissolved solvent.

The plant consists of two parallel process lines, North and South, housed in separate cells with 300 mm thick walls. Extraction from nitrate solution is carried out in 3 pulsed and one static column, all of which are geometrically safe. The extraction columns are preceded by dissolver units, conditioners and constant volume feeders (CVFs) as shown in Figure 8. It is possible to transfer the contents of either the North or South dissolver to any one of four conditioners, two in each cell designated by the letters "A" and "B". The purpose of the conditioners is the reduction and/or the oxidation of the plutonium as necessary into the tetravalent state. Residues in the liquid state are fed to the plant via a separate cabinet and routed to either Conditioner "A" - North or Conditioner "A" - South. The conditioner was also permitted to receive recycled aqueous liquors directly.

The vacuum lift system between each conditioner and the CVF 4 vessel is also shown in the Figure. To effect a lift a vacuum is created in the Transfer Vessel by an ejector connected to a vent pipe at the top. The bottom outlet from the transfer vessel passes down through a lute 7.5 m deep which acts as a seal whilst the vacuum is maintained. When the conditioner has emptied the vacuum automatically collapses, allowing the contents in the Transfer Vessel to drain through the lute into the CVF vessel.

4.2 Description of the Incident

After a plant washout in April 1970, the next plutonium recovery programme through the North Cell began on the 14 August, the South Cell unit remaining shut down. The material treated initially was plutonium nitrate liquors from the Works Laboratories which were fed to the North Cell unit via Conditioner "A". A change to oxide feed material containing trace metallic impurities was made on 20 August 1970 and by the 24 August, the day of the incident, a total of 37 batches had been transferred from the two dissolvers using both the "A" and the "B" Conditioners. Oxide batch 37 was in Conditioner "A" at the time of the incident and batch 36 was being transferred from Conditioner "B" to Transfer Vessel "B" en route to CVF 4. There was no positive evidence to show whether the vacuum in transfer vessel "B" had broken when the alarm sounded at 18.15.

The two men working in the building evacuated promptly and re-entry surveys commenced at 18.25. Abnormal radiation levels upto 300 mR/h γ were detected in the main control area on the third floor of the building - Figure 9 - and 40 mR/h γ at the vessel ventilation extract filter on the second floor. Subsequent monitoring indicated these levels to be decaying rapidly, indicating the presence of short lived fission products. Gamma ray measurements were made inside the North Cell using a detector on a boom passed through a ventilation louvre in the cell wall on the 3rd floor. Indications of short lived fission products were obtained from measurements in contact with the transfer vessel between Conditioner "B" and the CVF. The liquor in this transfer vessel at the time of the incident would, it was thought, have subsequently passed into the CVF carrying with it any fission products. The contents of the CVF, about 30 - 40 litres, were therefore siphoned into geometrically favourable vessels outside the cell. Analysis gave the expected plutonium concentration of 6 g/litre together with a normal acidity level. The presence of short lived fission products indicated that the liquor had been associated with a criticality excursion while in the Transfer Vessel "B".

It was not possible at this stage to see any reason why plutonium should have accumulated in Transfer Vessel "B". The form of the material was not known although the evidence from radiation measurements indicated several kilogrammes could be involved. Investigations were made into the contents of vessels on the South Side, which had been shut down for some considerable time. Solid plutonium bearing solids were found in some of the vessels of interest; 12 litres of solvent at 1.5 g/litre plutonium were drained from the lute between Transfer Vessel "B" and CVF 4 on the South Side.

In the light of these discoveries, investigation switched back to the North Side. Gamma radiographs of Transfer Vessels "A" and "B" indicated the presence of liquor in both vessels. The entry point to the CVF is 300 mm below the base of the Transfer Vessel which should have been empty except during a transfer. A hole was bored in the cell roof and the vent pipe to Transfer Vessel "B" was cut in order to insert an endoscope and miniature lamp. Visual confirmation of the presence of liquor was obtained. A conductivity probe inserted in the vent pipe indicated that the depth of the liquor was about 21.6 cm, which was equivalent to about 40 litres. Incidentally, the relatively low deflection of the conductivity probe gave the first indication that the solution was not aqueous. The liquor was transferred by suction into a series of $2^{1/2}$ litre bottles. Approximately 40 litres of liquor were removed from the vessel and analysis showed it to be TBP/OK with a concentration of dissolved plutonium of 55 g/litre. Its degraded state indicated that it was almost certainly in the Transfer System before the latest campaign began and probably for several years before that; the washout procedure would not have removed it. Subsequently, 7 litres of solvent with a concentration of 45 g Pu/litre were removed from Transfer Vessel "A".

The evidence indicates that at the time of the criticality incident Transfer Vessel "B" contained 40 litres of solvent with 55 g/litre of dissolved plutonium and about 50 litres of 7M HNO_3 with 6 or 7 g/litre plutonium in solution. The probable incident size was 10^{15} fissions indicating a geometric shut down mechanism.

4.4 Aftermath

The subsequent analysis of personal dose meters, whole body monitor and ^{24}Na measurements indicated process worker doses of 1 and 2 rads. The fast neutron component was insignificant.

There was a small (approximately 5mCi) release of gaseous and particulate fission products to atmosphere but the effects of this release were not detectable at ground level.

Otherwise, most interest following the incident centred on how solvent came to be in Transfer Vessel "B" and on the configurations which would cause a criticality. Trials conducted on a specially constructed inactive rig demonstrated that trace quantities of solvent which might have been present with the aqueous feed liquor could have separated while the lift was in progress and then have floated on the aqueous liquor in the Transfer Vessel. When the vacuum broke only the aqueous layer beneath drained via the lute to the CVF; the solvent remained hydraulically trapped in the Transfer Vessel. The practice of washing out the plant periodically with acid would not have displaced the solvent from the lute but may have reduced its plutonium concentration.

The source of the solvent has never been positively identified. The solvent in Transfer Vessel "B" is unlikely to have been introduced directly in residue liquor feeds as Conditioner "A" was designated for this purpose. The Board of Enquiry concluded that it was most likely to have been an accumulation which built up via the recycling of liquors.

A straight forward mechanism can be postulated for the build-up of plutonium once solvent is trapped in the Transfer Vessel. Successive batches of conditioned plutonium nitrate at approximately 7 g/litre would come into contact with the solvent layer each time a transfer took place. Calculations indicated that as few as 18 oxide batches needed to pass through the Transfer Vessel in order to achieve a plutonium concentration of 55 g/litre in a 40 litre solvent layer.

Monte Carlo calculations, performed by J H Chalmers, indicated that the solvent layer itself was subcritical. This, together with the low fission yield, suggested geometric causes for the occurrence and shut down of the incident. Using the inactive rig, changes in liquor geometry in the model Transfer Vessel were observed; the following four distinct stages are illustrated in Figure 10.

i Filling: A streamlined jet falling freely from the filling pipe broke into a mildly turbulent mixture of coarse emulsion, ie a mixture of the solvent and aqueous phases, while passing through the solvent and caused an agitated region of depression of the interface immediately below the point of impact. From this region an irregular "emulsion band" spread over the whole interface. This stage took an average of 4 minutes.

ii Inrush: The point of impact of the falling jet was observed to move slowly across the surface, from an initial position near the centre of the vessel towards the vessel wall opposite the inlet pipe, as the filling stage progressed. Its position just prior to the final inrush, however, varied considerably, due to variations in ejector performance etc, and in about 50% of cases observed the jet had progressed beyond the surface itself to impact mainly on the wall. The final inrush, lasting about 2 seconds, always impacted upon the upper wall and lower top dome of the vessel. Wave motion of the solvent layer occurred and its surface was momentarily broken by many falling droplets. The emulsion layer did not change significantly during the inrush phase, being apparently maintained by the general downwards flow of aqueous liquor.

iii Separation: The instant of inrush termination could be determined within less than a second. It was followed by rapid separation of phases, lasting typically 5 - 10 seconds.

iv Draining: The vacuum was broken at the end of the inrush stage; draining began immediately, while separation was taking place. Initially this was at a high rate of 1 litre/second declining to 0.1 litre/second after 10 seconds.

Further Monte Carlo calculations suggested the following mechanism for criticality. While an aqueous jet continued to penetrate the solvent layer, as was the case during the filling and inrush stages, the contents of the Transfer Vessel were subcritical. When the penetration ceased, at the end of "inrush" the three phase system of solvent, emulsion and aqueous became critical. Within a few seconds the emulsion layer disappeared and the completely separated phases became subcritical, increasingly so as the contribution from the aqueous phase reduced with drainage.

4.4 Conclusion

Operations in the Plutonium Residue Recovery Plant were reviewed following the incident, specific attention being devoted to solvent "traps" and the detection of accumulations of plutonium. Drainage points were fitted to lutes to allow their periodic emptying; no significant quantities of solvent have since been found. Facilities were provided to allow neutron monitoring of vessels with unfavourable geometry. The plant has operated safely since; it is due to close at the end of 1985.

5 DISCUSSION

The Saclay incident illustrates the capacity of the human mind for retaining an initial interpretation of events even when the evidence against is increasing to the point of being overwhelming. This mental inertia, for which the terms "mindset" and "concreting" have been coined, has been of considerable importance in other incidents.

The criticality incident at Mol was similar to the recent Argentinian incident without, happily, having such severe consequences. The facilities concerned were both research reactors; the incidents occurred during core configuration changes; operating procedures were not followed in either case - in particular the water moderator had not been drained. There is also a suggestion of intensive work in both cases - the Mol core configuration was being changed at 12.47pm on 30 December while the RA.2 configuration underwent changes towards the end of a Friday afternoon shift.

Communications appear to have been a factor in the Mol incident. Although written instructions were given, and found in the reactor room after the incident, they were misinterpreted and two operations were performed in reverse order.

The incident at Windscale Works happened because solvent build-up of the type which occurred was not anticipated. There was no evidence from 15 years of plant operation to suggest that it could have taken place. The incident underlines the importance of having sound chemical, chemical engineering, and operational data on which to base a criticality safety assessment.

6 ACKNOWLEDGEMENTS

I would like to acknowledge the considerable assistance given in connection with the incidents at Saclay and Mol by Monsieur J C Puit of CEA, France, and Monsieur J Debrue of CEN/SCK, Belgium. Thanks are also due to those who provided me with first hand accounts of the incident at Windscale Works, in particular B Bailey, J T Daniels, G Chatburn, W Guest and H Stocks; also to Mr G Storey and Dr C Magrabi for providing translations of the Mol papers from the original French text. Any errors or misinterpretations of information supplied are, of course, my own.

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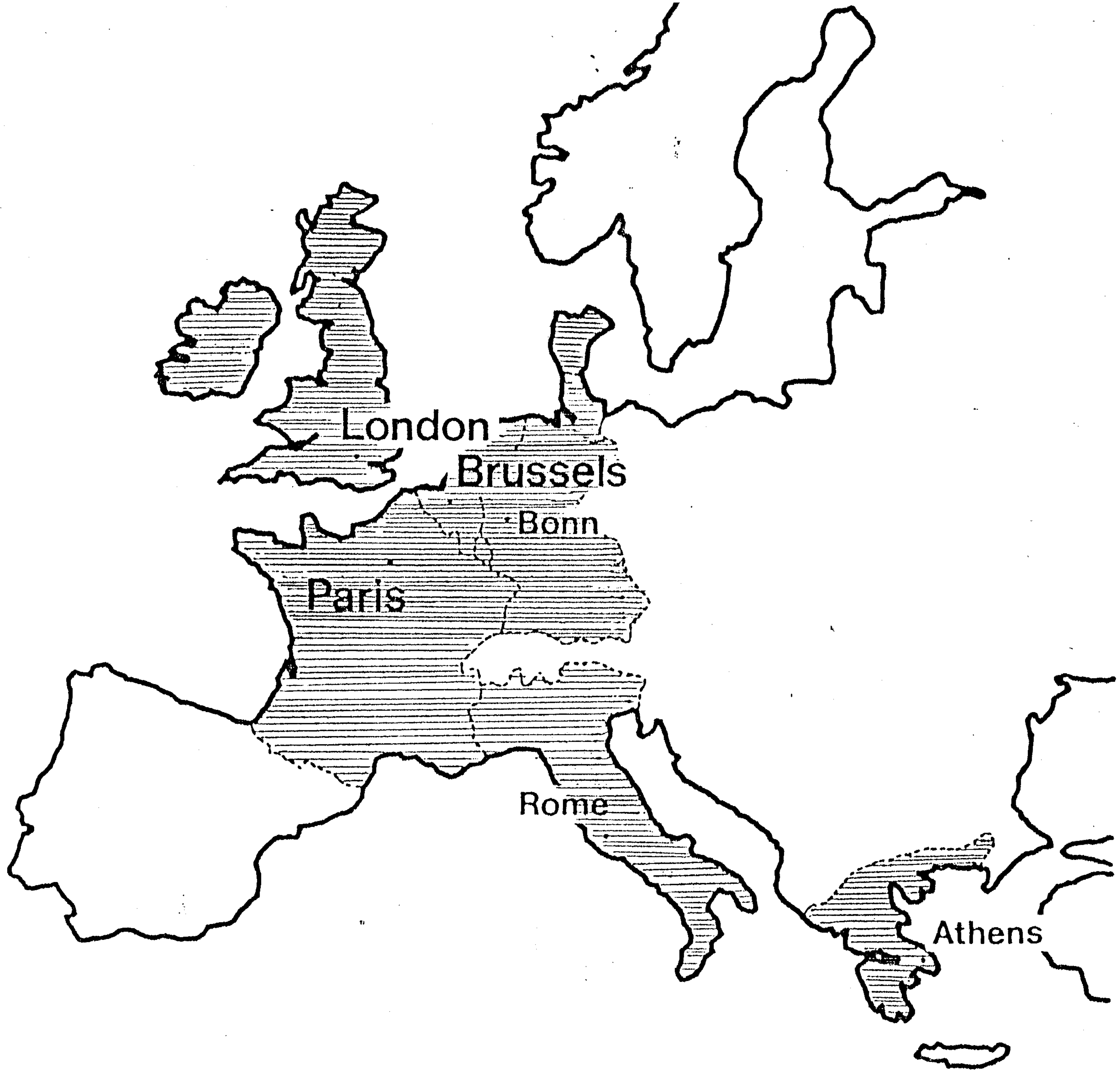
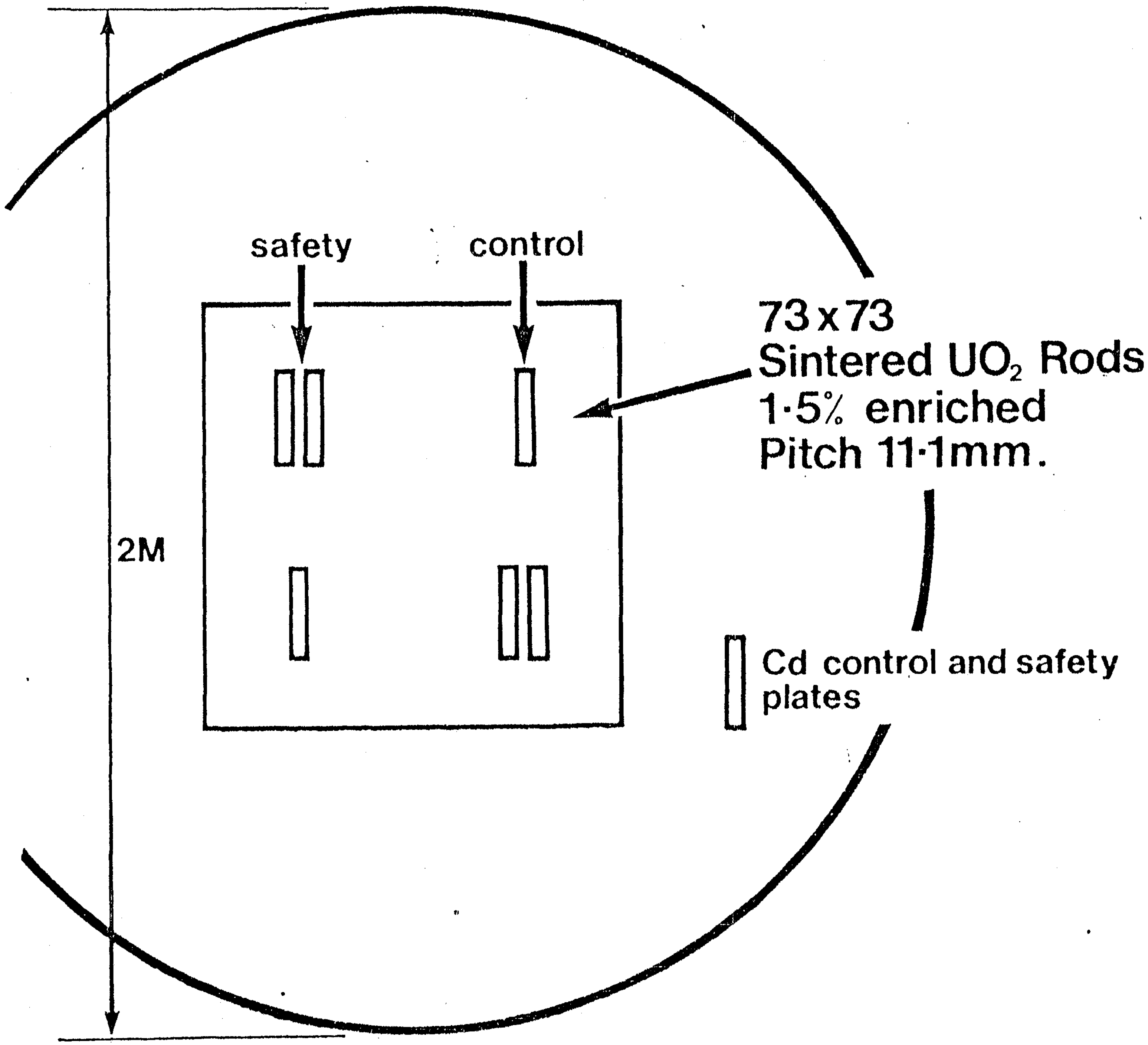
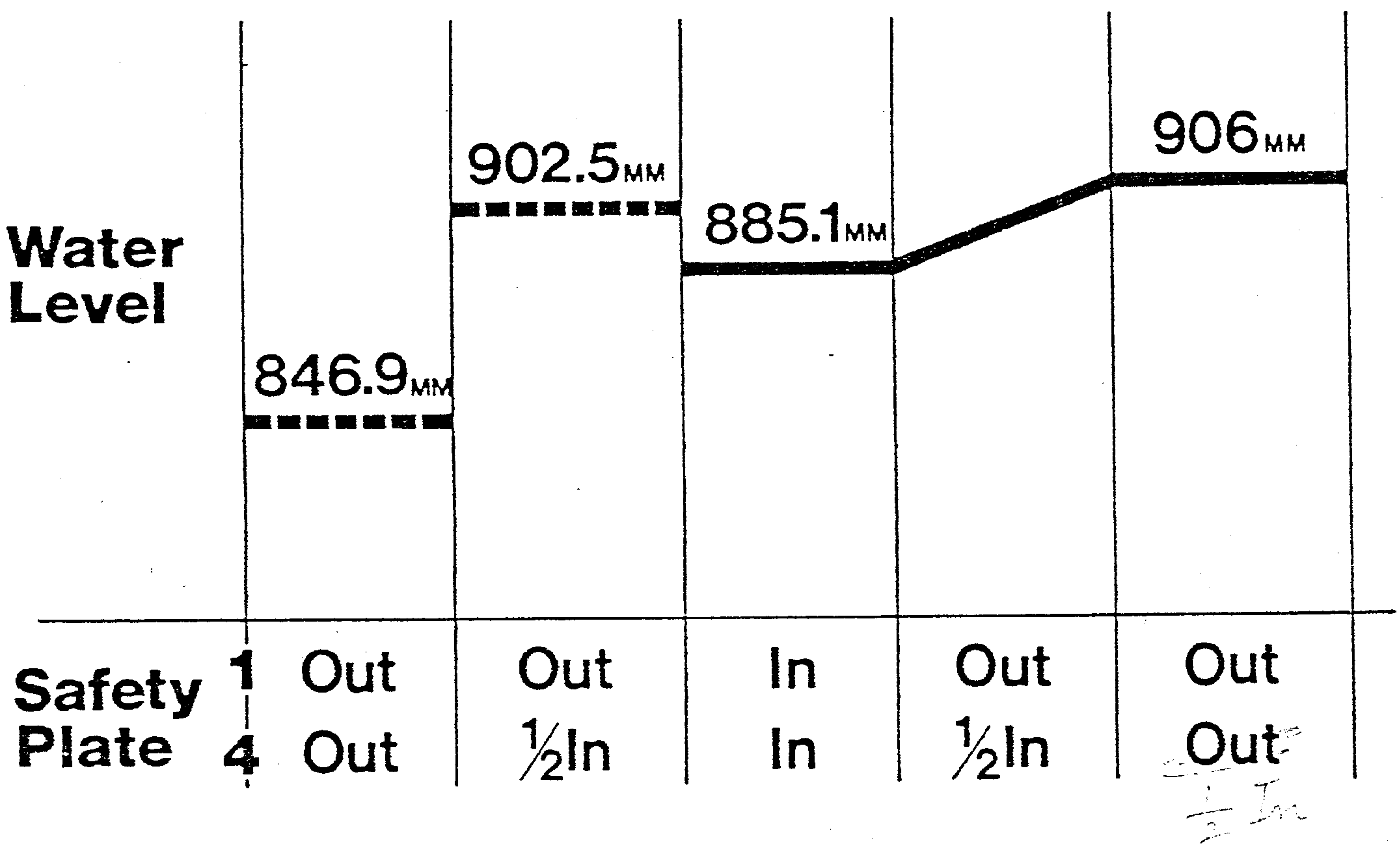
8 FIGURES



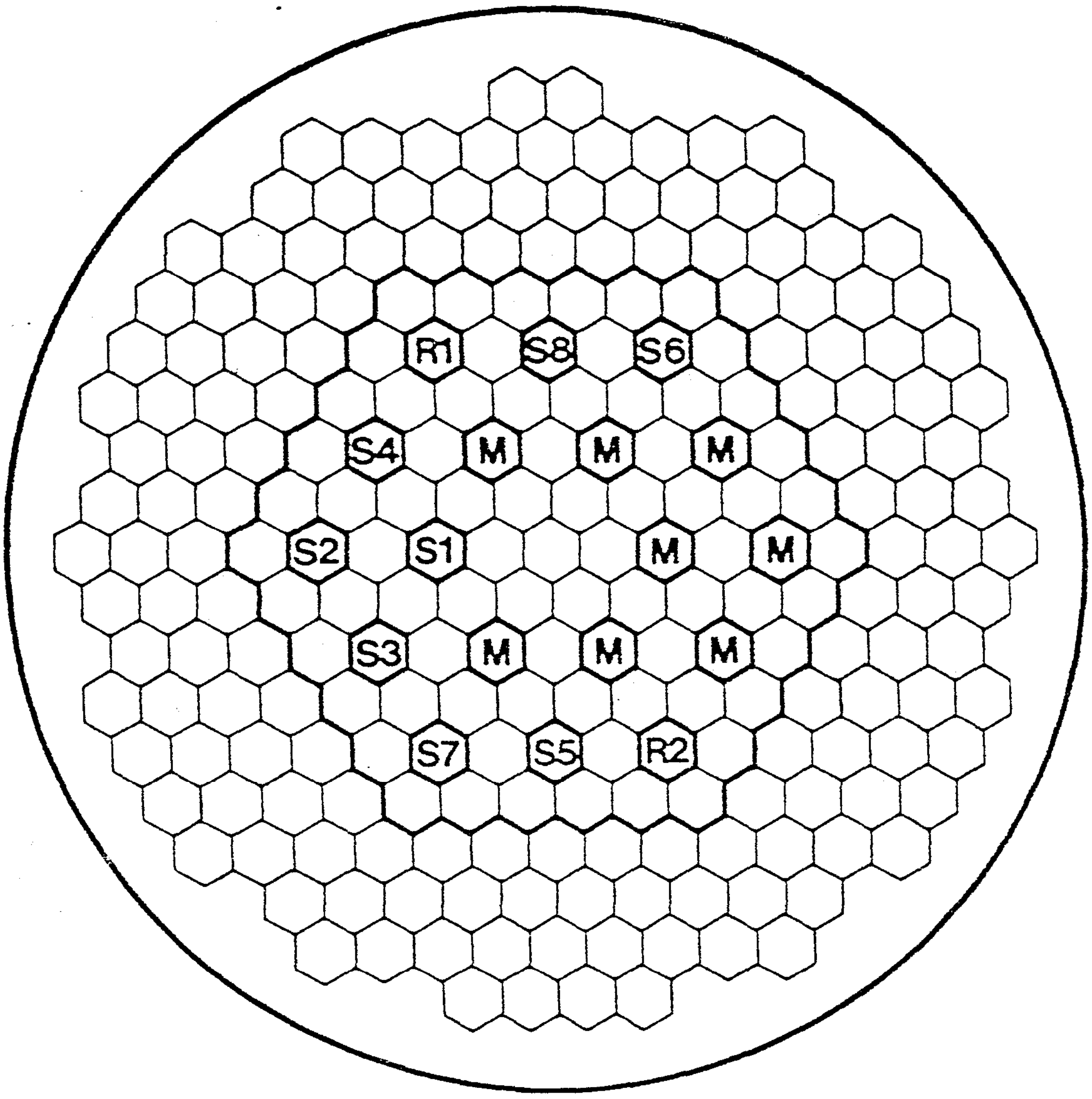
1 The European Community.



2 The ALIZE reactor (schematic).



3 Reactor states during the accident sequence.



S **Safety Rods**

R **Regulating Rods**

M **Manually Positioned Rods**

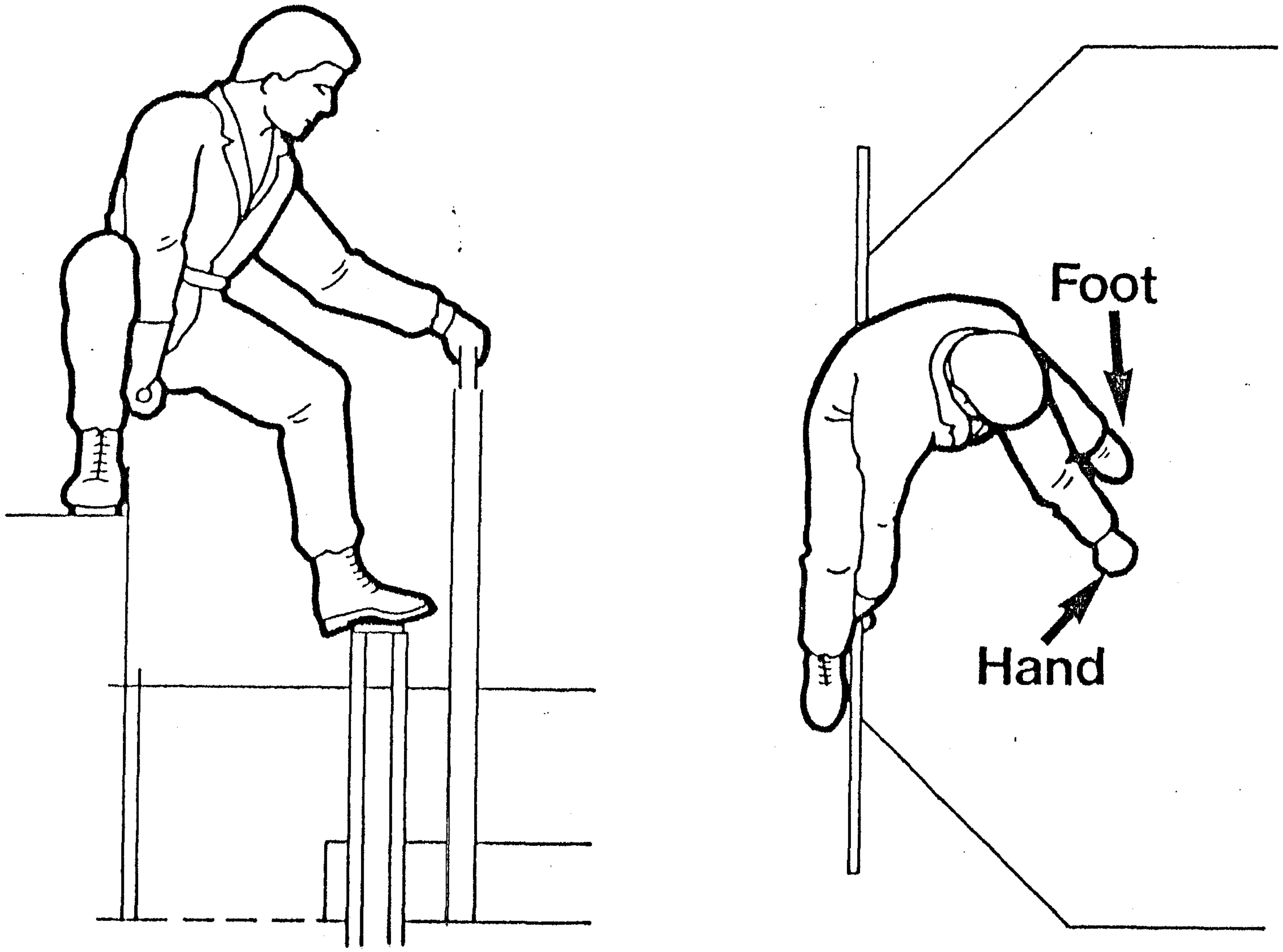
4 The VENUS reactor (schematic).

Instructions	As Instructed		IO Step Omitted		R_2 Step Omitted		Actual	
S_2 + R_1 Inserted	0.993	Y	0.993	Y	0.993	Y	0.993	Y
R_2 Inserted	0.986	Y	0.986	Y	0.993	N	0.993	N
IO Inserted	0.980	Y	0.986	N	0.986	Y	0.993	N
G330 Removed	0.990	Y	1.013	Y	0.996	Y	1.019	N

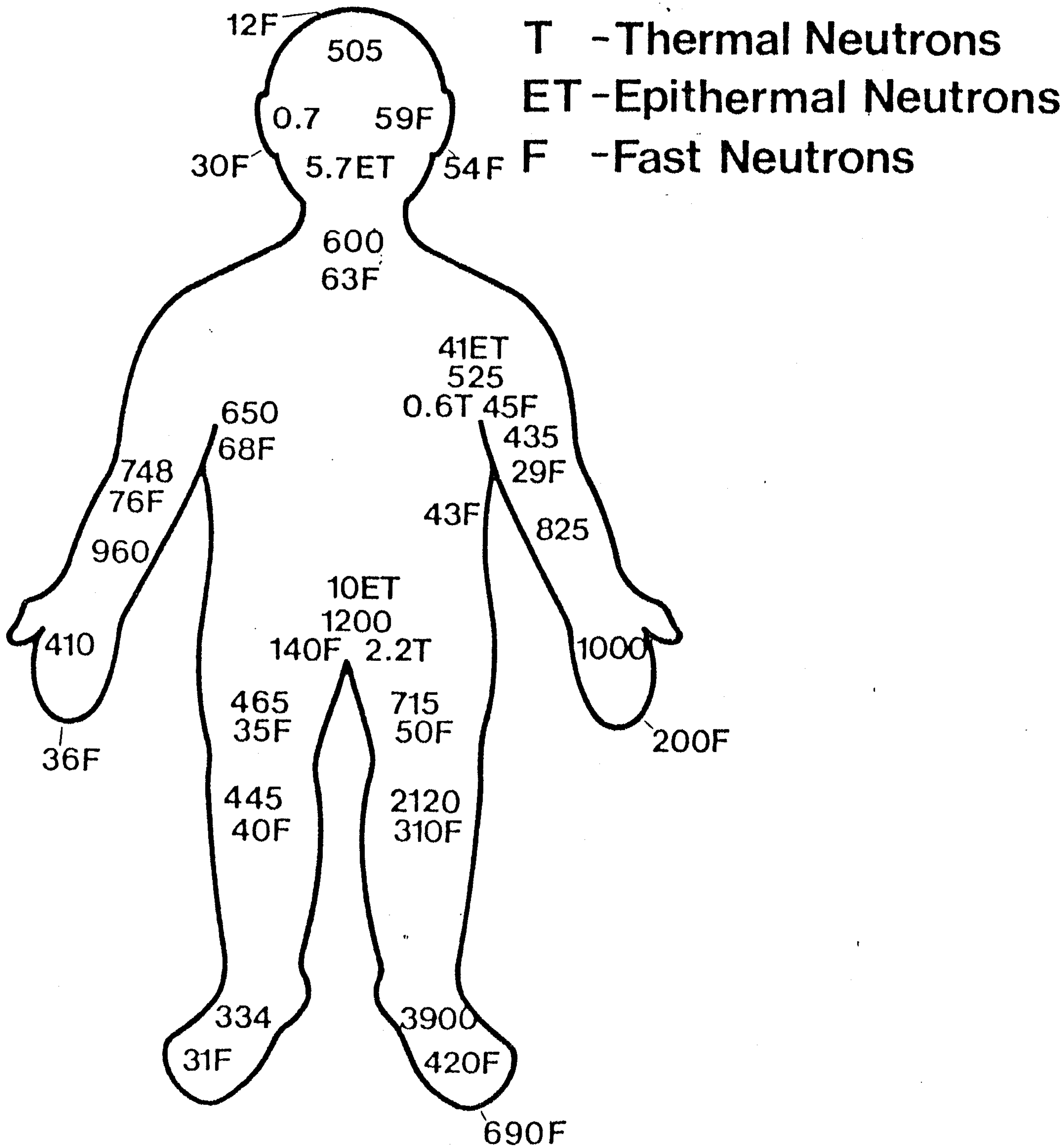
FIGURE 5

REACTOR K-EFFECTIVE DURING POSSIBLE MANIPULATION SEQUENCES

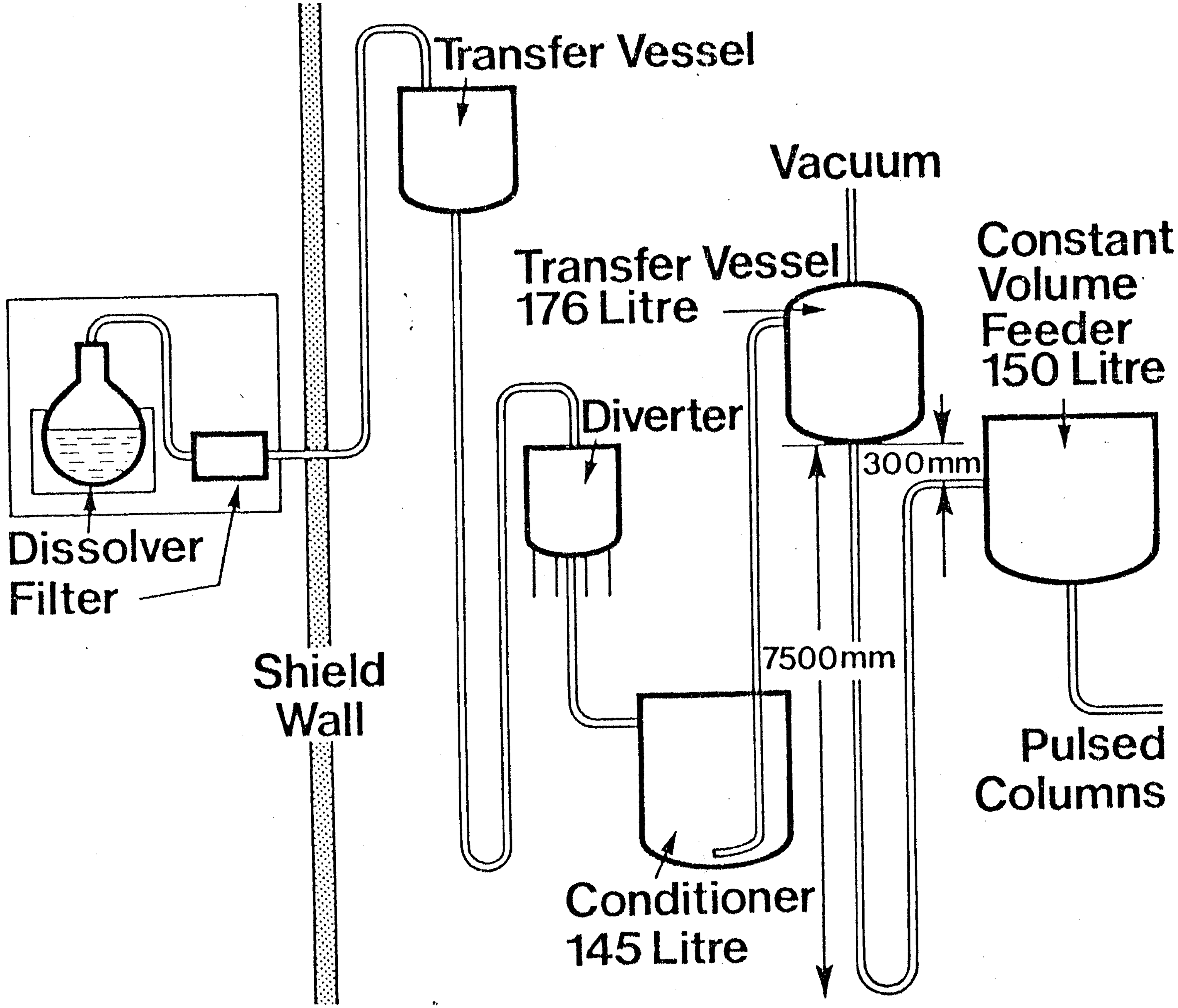
Y indicates the step was carried out
N indicates its omission



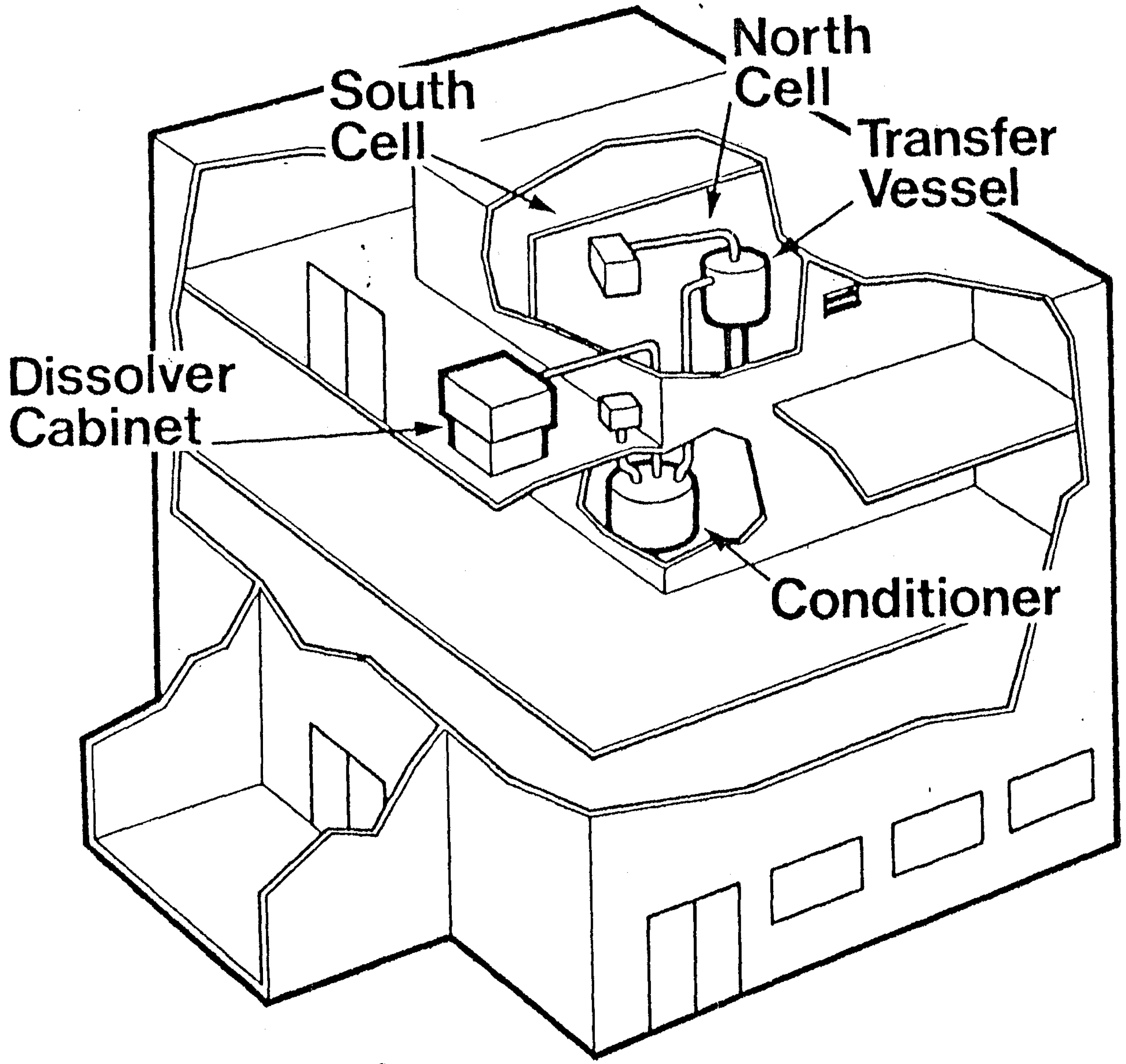
6 The position of the Technician (schematic).



External doses.



The Windscale Plutonium Residue Recovery Plant (schematic).



Plutonium Residue Recovery Plant - cut-away diagram.

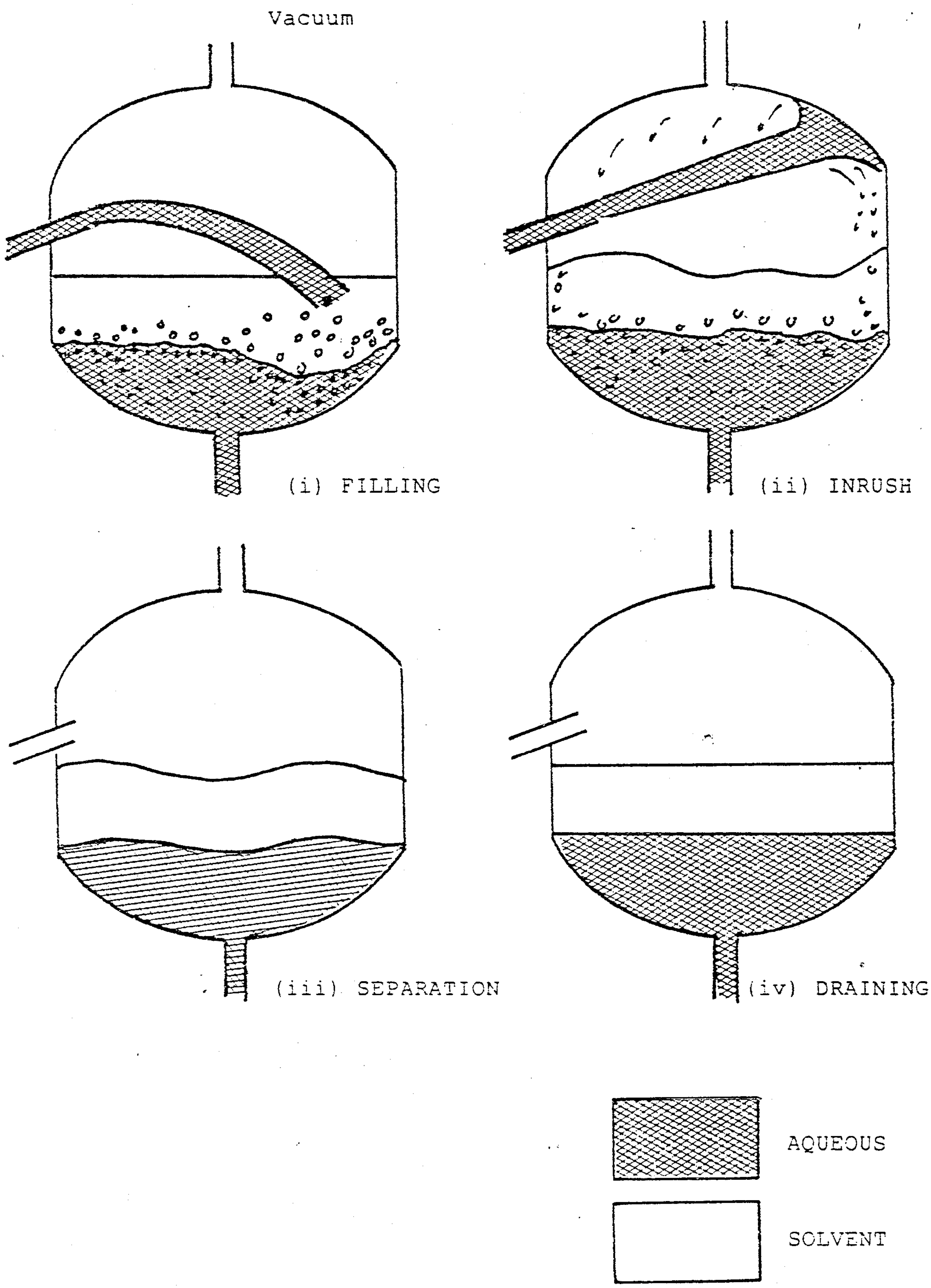


FIGURE 10: LIQUOR GEOMETRIES IN THE MODEL TRANSFER VESSEL