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Report

CULHAM CONCEPTUAL TOKAMAK MARK II DESIGN STUDY OF THE LAYOUT OF A TWIN-REACTOR FUSION POWER STATION

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DESIGN STUDY OF THE LAYOUT OF A TWIN-REACTOR FUSION POWER STATION

by

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ABSTRACT

This report describes the building layout and outline design for the nuclear complex of a fusion reactor power station incorporating two Culham Conceptual Tokamak Reactors Mk.II. The design incorporates equipment for steam generation, process services for the fusion reactors and all facilities for routine and non-routine servicing of the nuclear complex. The layout is based upon helium cooled reactors having a wall loading of 5 MW/m^2 but discussion of boiling and pressurised water coolants and 10 MW/m^2 wall loading is included. The dimensions of the reactor hall are determined by the overall reactor dimensions including neutral beam injectors plus space for maintenance machine access; the size of the process plant rooms are principally dependent on wall loading while the size of remote servicing facilities is virtually independent of any reactor operating constraint providing component lives are maintained. The design includes provision of temporary facilities for on site construction of the major reactor components and shows that these facilities may be used for disassembly of the reactors either for major repair and/or decommissioning.

Preliminary estimates are included, which indicate the cost benefits to be obtained from incorporating two reactors in one nuclear complex and from increased wall loading.

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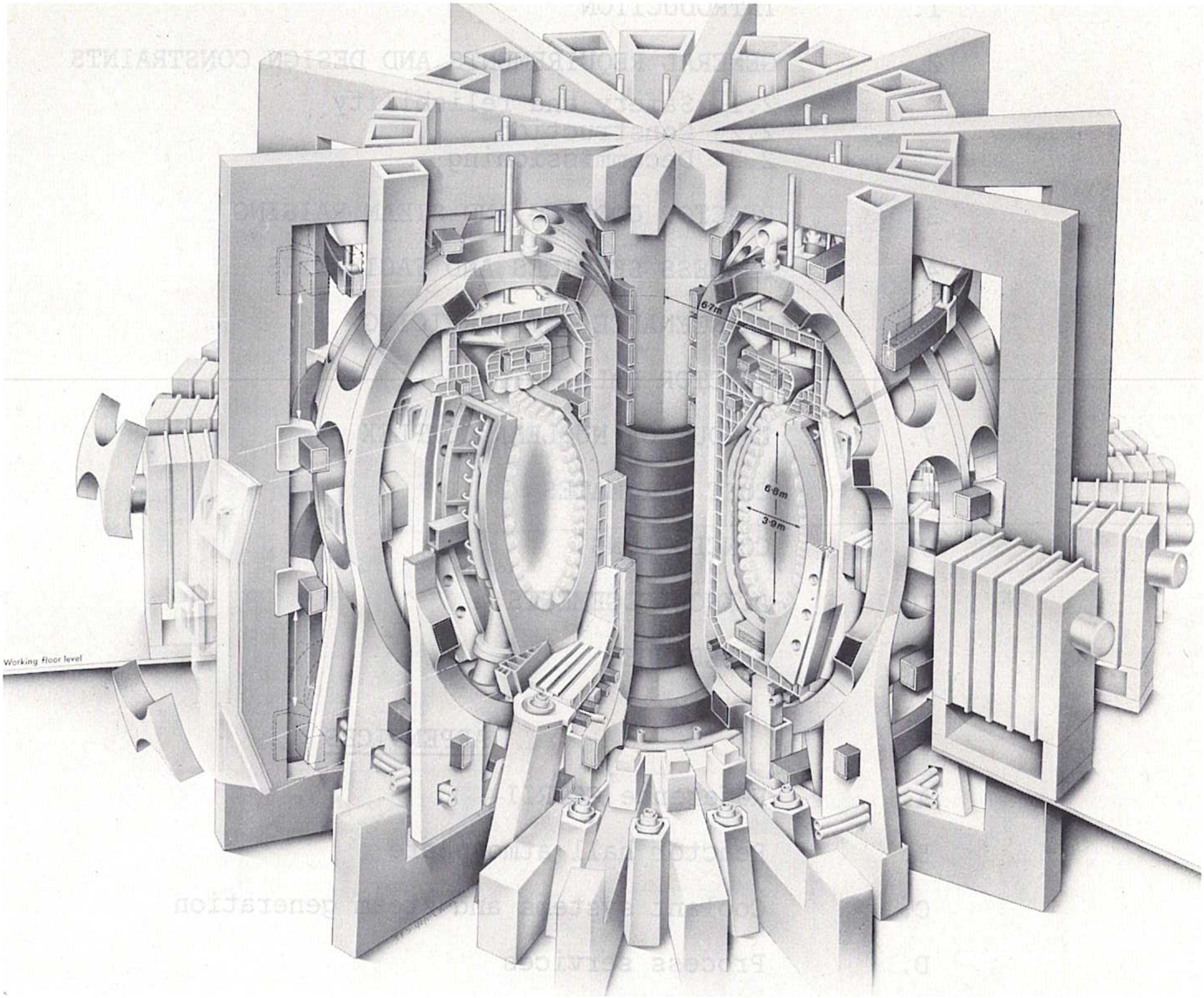

Fig.1 Artist's impression of Culham Conceptual Tokamak Reactor Mk.IIB.

1. INTRODUCTION

Design studies of commercial fusion power reactors usually adopt the deuterium-tritium fuel cycle since the reaction rate of a 50:50 D-T mixture is higher than other fusion fuels; thus it is the easiest fuel to burn and gives the highest fusion power density. However, each D-T fusion reaction produces a 14 MeV neutron and at the wall loadings required for economic fusion power generation the neutron irradiation of the reactor structure facing the plasma will cause high levels of activation of that structure and limit its service life to a few years. The design philosophy of the Culham Conceptual Tokamak Reactor Mk.II (CCTRII), Fig. 1, overcomes these problems by adopting a practical assembly/disassembly configuration and a modular blanket design of large segments, Fig. 2, which can be replaced by remote operated servicing machines, Fig. 3 and 4[1-4].

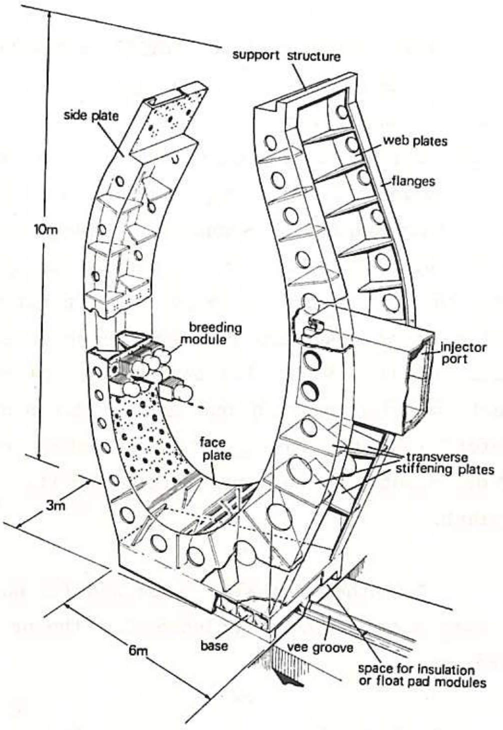

Fig.2 Support structure of interchangeable blanket segment showing mounting of blanket cells, alignment system and injector port.

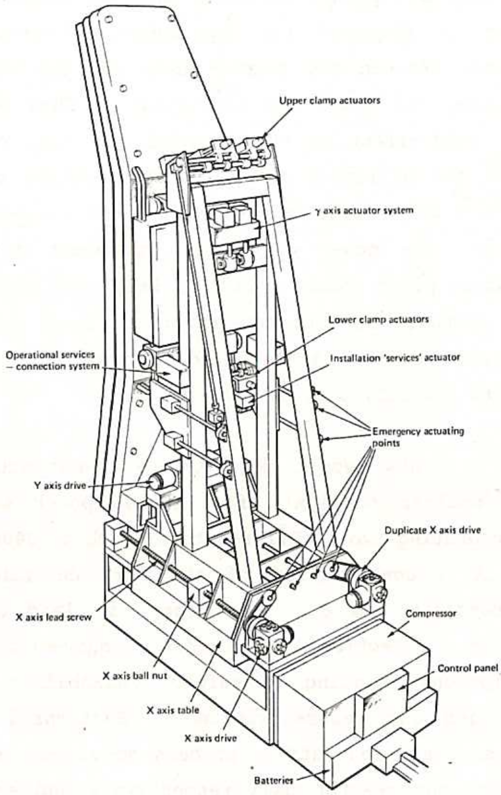

Fig.4 Door manipulator/transporter showing principal systems and emergency activation points.

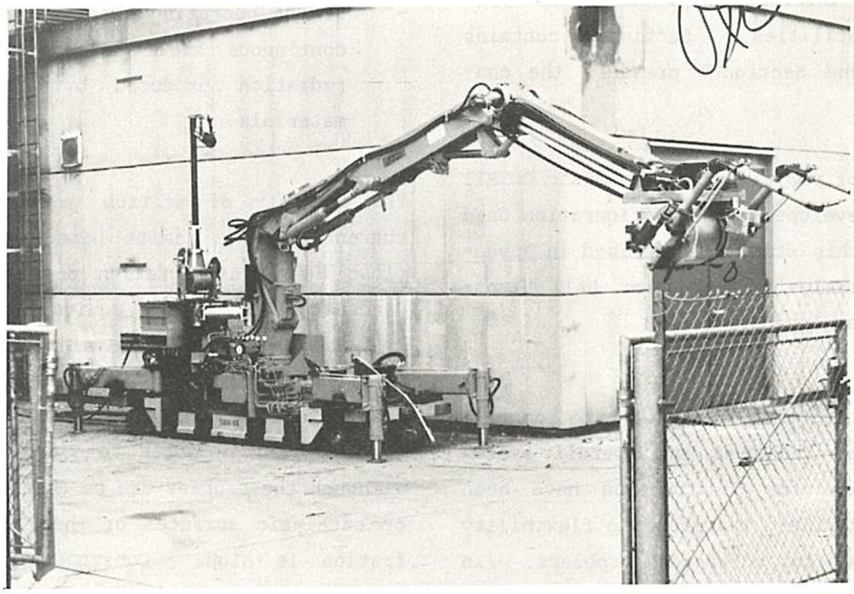

Fig.3 MANTIS in extended position showing MASCOT manipulator, viewing system and lights (by courtesy of CERN, Geneva).

The design of building complex to house a fusion reactor and its associated sub-systems and support facilities will have a significant effect on the general reactor operation and servicing and on the total capital cost of the power station. The walls and roof of the fusion reactor hall form the outer biological shield and tritium containment barrier. The support facilities include shielded and unshielded workshops, personnel facilities, control rooms and equipment rooms - some of which must also incorporate efficient tritium containment. Access is required for equipment and servicing machines between the reactor hall and the various workshops and servicing facilities. This has an overriding effect on the location and size of all the active buildings and places constraints on the location of coolant and service lines between the reactor, the power conversion equipment and the auxiliary plant rooms. It is likely that considerable economic benefit can accrue if there is more than one reactor in the building complex, enabling support facilities to be shared.

This report describes a layout study of the 'nuclear complex' of a fusion power station incorporating two CCTRII reactors, each of 3400 MW_t, and is a continuation of the work described in References 5 and 6. The report is laid out as follows. Section 2 discusses requirements and assumptions relating to safety, reliability, construction and decommissioning. Sections 3 to 6 discuss steam generation, process services, servicing and the reactor hall respectively and each is supported by an appendix containing more detailed discussion. Section 7 describes the overall layout and discusses the interactions between the previously defined facilities. Section 8 contains details of costs and Section 9 presents the conclusions.

A number of variations on the basic CCTRII concept have been developed; the configuration used as a reference in this study is described in Appendix A. A brief analysis of reactor hall atmospheres is included as Appendix B.

It is assumed that this power station will be one of a series and that the overall system design and programme for construction have been proven prior to ordering; therefore no flexibility is included to cater for unforeseen problems. In this study many assumptions have had to be made; these are referred to in the text. Non-nuclear areas have not been examined although their design will interact with the design of the nuclear complex and could have a significant bearing on the conclusions. It must be emphasised that no design optimisation of the power station has been performed and consequently its configuration would be expected to change as the design developed.

2. GENERAL REQUIREMENTS AND DESIGN CONSTRAINTS

2.1 Safety and reliability

The tritium fuel for CCTRII is produced by neutron irradiation of lithium in blanket cells surrounding the plasma. All reactor internal surfaces will be contaminated by tritium and the primary coolant circuit may also be expected to contain radiologically significant quantities of tritium which have leaked or permeated from the blanket cells. A tritium recovery and purification facility is an essential part of the power station complex and this will also be subject to leakage, permeation and outgassing problems. It can be seen therefore that the total tritium inventory will be well distributed around the reactor and its ancillary plant.

Carruthers et al[7] examined fusion reactor power stations and concluded that the principal hazards are:

- to the general public: a sudden large release of tritium the probability and severity of which is dependent upon whether or not a lithium fire is involved;
- to the operating staff: a sudden release or a continuous small release of tritium and the radiation produced by activated structural materials.

The toxicity of tritium gas is relatively high, current ICRP[8] limits being set at $2x10^{10}$ Bq/m^3 (1 Bq ≡ 1 disintegration per second) Derived Air Concentration, and the equivalent figure for HTO or T_2O is $8x10^5$ Bq/m^3. Tritium mixes and diffuses very rapidly in air, it quickly permeates through most materials and is adsorbed. It exchanges with the hydrogen in water to yield HTO fairly slowly, although the process can be accelerated by hot metal or catalytic surfaces or where the tritium concentration is high. Consequently, all the tritium process systems will require double or even triple containment systems to control the spread of releases due to leakage or permeation.

Other special requirements are:

(a) Afterheat must be removed to prevent overheating of the structure and excessive outgassing. Therefore afterheat removal must be reliable and powered from a guaranteed supply.

(b) Tritium removal equipment for all contained atmospheres in dryboxes and buildings.

(c) All processes and contained atmospheres must be monitored by a supervisory control system which will shut down the process line, isolate individual process elements and initiate clean up procedures in the event of preset limits for tritium concentration being exceeded.

(d) Oxygen detectors inside all tritium containments.

(e) Guaranteed power supplies for all isolating valves, tritium clean up plants and the supervisory control system.

(f) Equipment to remove tritium from the reactor coolant.

(g) Process plant should be modularised, i.e. small units run in parallel, to minimise the size of any individual leakage and to allow isolation of faulty units.

(h) Zoned process plant so that high tritium concentration plant is segregated from low tritium concentration plant.

(i) Buildings made as small as practical to minimise gas volumes to be cleaned up and surface areas to be de-tritiated.

(j) All gaseous, liquid and solid wastes discharged from the power station must be de-tritiated to acceptable standards prior to release to the environment.

The ultimate consequence of any accident is release of tritium and possibly activated reactor hall atmosphere; and hazard to the public from either must be controlled to acceptable levels. The limitation of such accidents and consequent releases will require the highest standards of station and safety equipment design and operation and Sherwood[9] suggests that, based upon the value of human life and risk of death, it is worth spending up to \$20 to contain one tritium curie. In addition there are two economic incentives viz:

- tritium recovery must be maximised as it is required for refuelling;
- fusion is a very high capital cost energy system and the integrated cost penalty incurred by reactor non-availability could well be greater than the cost of achieving high plant reliability.

The reactor shielding will be designed to reduce radiation levels to about 4000 R/hour which is an acceptable dose rate to the magnet insulation. The dose rate at the centre of a single segment after irradiation will be $\cong 10^6$ R/hour. Thus the reactor hall walls and roof must provide an attenuation of 10^{-10} and 10^{-8} respectively to ensure that an allowable dose, 10^{-4} R/hour to the manned areas outside the building, is achieved.

2.2 Construction

The CCTRII concept involves the use of large heavy components e.g. field coils and 250 tonne blanket segments which may be constructed in site facilities, or transported to site as complete assemblies. Blanket segment replacement as well as replacement of failed nuclear and non-nuclear components will continue through the reactor life.

It is possible that conventional road/rail transport facilities and/or air freighting systems suitable for such large loads may be available in 20-50 years time but their availability cannot be relied upon. Coastal locations are likely because of cooling water requirements in which case barge transport is a possibility though this would require costly port facilities to avoid routine landing over open beaches.

In general, UK fission reactor designs needing a large proportion of on-site precision assembly have resulted in construction problems, however this may be unavoidable in building a fusion reactor. On the other hand the handling, test and inspection machines required for remote servicing will be available for reactor assembly, see Appendix F7.

2.3 Decommissioning

The nuclear complex must be designed for decommissioning, including tritium recovery where economical, and storage of activated and tritiated components. The remaining structures have to be either decontaminated and razed or entombed.

3. REACTOR COOLING AND STEAM RAISING

The parameters for the helium cooled blanket cells, given in Appendix A, were based on the use of a high thermal efficiency steam cycle (around 40%) but it is by no means certain that they would be achieved in practice because of the high temperatures required in the blanket structure.

The use of water coolant has the potential advantage of higher heat transfer coefficients and therefore smaller heat transfer surfaces within the blanket cells. However, this is accompanied by much lower coolant temperatures than for helium, resulting in thermal efficiencies of the order of 30%. This lower efficiency might be counteracted by the lower temperatures permitting higher blanket thermal wall loadings. High temperatures and efficiencies could be achieved using a superheated steam coolant, but the heat transfer and other characteristics would be significantly poorer than for helium.

The most suitable location for the steam generators, in a helium cooled system, is in an annular trench running outside the reactor envelope because:

- horizontal access to the reactor by the remote servicing machines is unimpeded;
- the required high temperature gas ducting length is minimised thus economising on expensive materials;
- the helium coolant will become contaminated with tritium and the ducting should be located within the reactor hall to avoid additional containment costs;
- general purpose maintenance equipment will be available to service the steam generators;
- this location frees the reactor hall periphery for other plant e.g. cryogenic and electrical plant which should also be located as near the reactor as possible.

However, the configuration complicates the civil works by the need for a deep trench between the reactor foundation and the foundations for the walls.

An illustration of a helium cooled reactor coolant circuit is shown in Fig. 5 and a plan view of the reactor/steam generator system is given in Fig. 6. An examination of cooling/steam generation systems, covering helium, boiling water and pressurised water is given in Appendix C. No attempt is made to recommend a coolant system but it is shown that each can be accommodated within the proposed building configuration and generate a suitable steam supply.

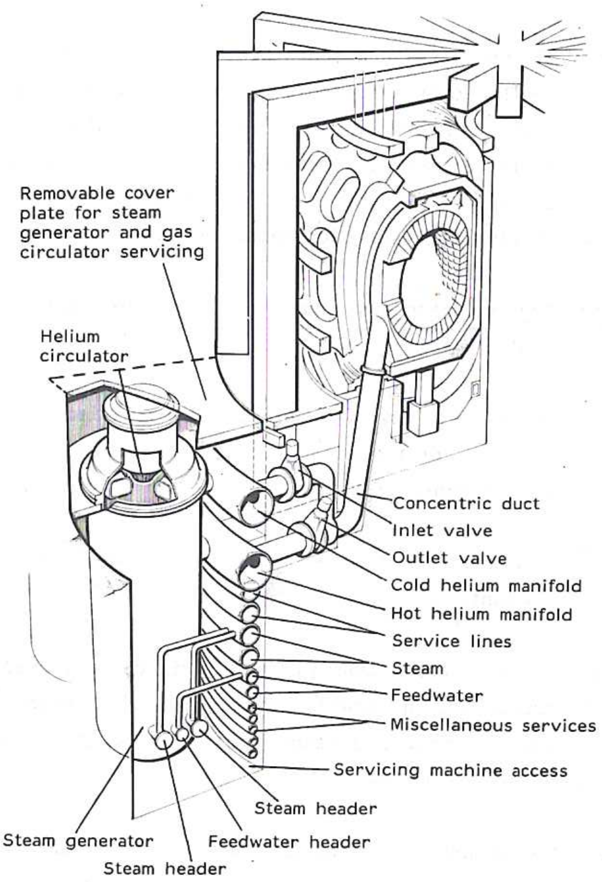

Fig.5 Configuration of coolant circuit and steam generators.

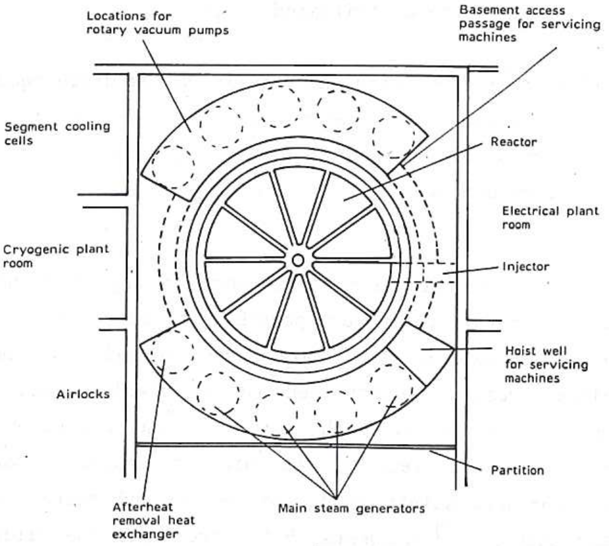

Fig.6 Plan view of reactor hall.

4. PROCESS SERVICES AND FACILITIES

Each reactor must be provided with:

- fuel gases (D,T) in the required quantities and conditions;
- means to transfer energy into and out of the superconducting coils;
- electrical power for injectors, divertors etc.;
- shield cooling water;
- cooling for auxiliary equipment;
- cryogenic liquids for superconducting coils and cryopumps;
- blanket/shield operational and shut down cooling;
- means to transfer all gaseous exhausts from the reactor system;
- gas for pneumatic actuators/sensors.

Provision must also be made for tritium recovery from the reactor exhaust, primary coolant circuit and building atmospheres.

The supply of these services will require the following process plants and it is proposed that they are grouped together as indicated:

Tritium extraction and purification plant room (TPR)

- fuel gas storage
- exhaust processing and tritium extraction
- coolant cleanup
- building atmosphere cleanup

Blanket cell servicing facility (BCSF)

- tritium recovery from blanket cells

Electrical plant room (EPR)

- TF and PF supply, control and protection
- electrical supply and distribution

Cryogenic plant room (CPR)

- gas liquefaction plant

Shield cooling water plant room (CWPR)

- shield cooling water

Appendix D considers the tritium plant room appropriate for helium cooled reactors and discusses the variation introduced by water cooling and increasing wall loading. It is concluded that little modification will be required for the change to water cooling although the building area in every case should be increased by ≅75% if the wall loading is doubled to 10 MW/m^2 assuming that the required number of process plant modules is proportional to the fusion power. The proposed layout (Fig. 7) provides for two TPRs, one associated with each reactor, which should be interconnected to improve overall reliability providing this does not cause significant operational or safety problems.

Equipment requirements for the other plant rooms defined above cannot be estimated at the present time and they are only discussed briefly in the appendix. The above comments, with respect to cross connections between pairs of plant room, generally apply to all plant rooms.

5. MAINTENANCE AND SERVICING

Maintenance and servicing can be divided into routine regular servicing and non-routine maintenance and repair which is carried out as required.

The following design constraints have been identified:

(a) The reactor maintenance facilities must provide all systems required for routine servicing and for 'high probability' repairs. These facilities and their operating systems must be designed on the basis of minimising reactor down time and must achieve high levels of reliability and availability.

(b) The general facilities and reactor design should make provision for the recovery from major component and structural failures which are credible but unlikely. Facilities for large scale, but unlikely, repairs need not be permanent providing the necessary buildings and equipment could be obtained and erected quickly when required. In extreme circumstances such facilities might be as large as the reactor hall.

(c) Servicing facilities and systems should be shared between the two reactors as defined by economic analyses.

(d) Each servicing control room should be sited to provide direct viewing of the associated reactor or workshop.

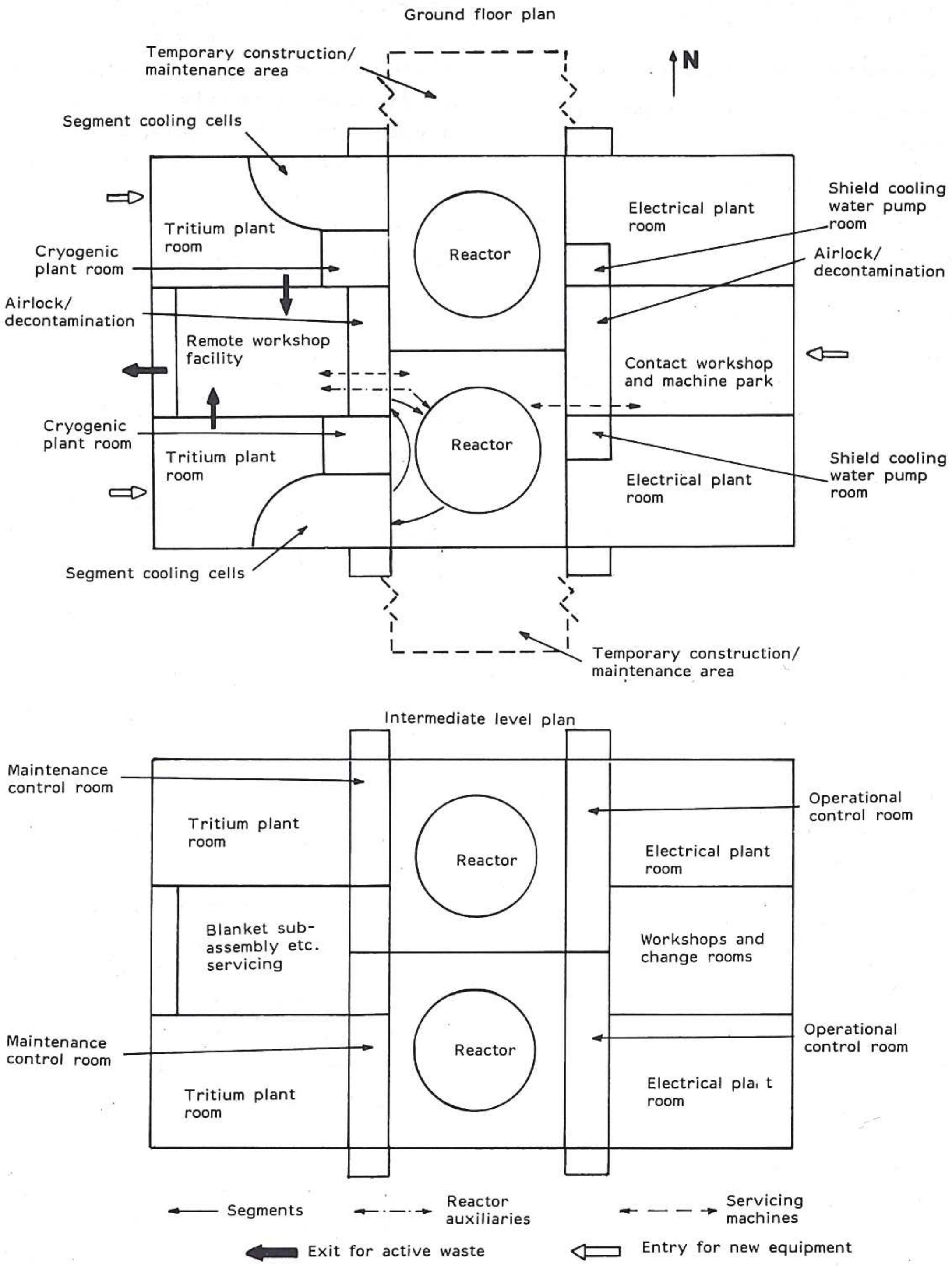

Fig.7 Simplified view of nuclear complex.

Appendix E examines the maintenance requirements of the fusion reactor systems in two areas:

- routine servicing operations such as segment changing, and
- non-routine servicing on the basis of a derived worst case scenario i.e. a toroidal field (TF) coil change.

Remote servicing machines are required for normal operation and a small number of additional machines will be imported for major repairs. The facilities required for the operation and maintenance of the remote servicing machines are derived and layouts are presented. The effects of alternative cooling systems and increased wall loadings are shown to have little effect on the layout of individual maintenance facilities provided that component lives are the same as those assumed for a 5 MW/m^2 helium cooled system.

The layout shown in Fig. 7 has been developed so as to provide space, at either end of the reactor hall, for a temporary building to be used during construction (Appendix F7). When construction is complete these buildings would be removed leaving the permanent foundations in place. In the event of a major reactor repair the adjacent temporary facility would be re-constructed, the reactor hall end wall removed, and the permanent crane rails extended to provide the additional storage areas required (Appendix E2).

6. REACTOR HALL

The building structure forms the outer radiation shield and is required to carry the loads arising from the sub-atmospheric internal pressure. It will be of massive construction and consequently its cost will form a significant part of the total capital cost of the plant. It is therefore essential that the dimensions and particularly the span should be as small as possible. The most significant influencing factors, apart from the plan dimensions of the reactor itself, are:

- the configuration of the steam raising equipment;
- the space required to withdraw equipment such as neutral beam injectors, divertors and refuellers etc. and the access required by the mobile servicing machines.

Appendix C2 indicates that eight steam generators installed under the reactor hall floor could be required for a 3400 MW_t reactor. Figure 6 shows them located in two groups of four so that the building span is minimised. Similar components are required for the PWR system but they are smaller than the equivalent helium cooled components and so fit within the dimensions of the helium cooled system, Appendix C4. The BWR system is, in general, more compact than the other systems, so that it too can be contained within the dimensions of the helium cooled system (Appendix C3).

Servicing and maintenance scenarios are examined in Appendix E. It is necessary to provide 'two-way' traffic around the reactor at ground level necessitating a radial passage ≅6 m wide outside the poloidal coil support structure. This will provide the clearance space to remove and replace floor mounted ancillary equipment such as injectors and divertors. The reactor hall will be provided with two high level cranes with integral manipulators running on common rails and two lightweight hoists with overhead manipulators running on a lower set of rails. The building height is defined by the clearance necessary to remove the ohmic heating coil and central PF coil support structure.

Appendix F contains brief discussion of construction, partition doors, internal finish, service ducts, integral maintenance facilities and airlock/decontamination facilities. Sizes of reactor hall are derived in Appendices D and E, i.e.:

- for two helium cooled reactors, 115 m long x 50 m span x 35 m height;
- for two boiling water and pressurised water cooled reactors, 100 m long x 50 m span x 35 m height.

If the wall loading is doubled so that the station output is increased to ≅4.8 GW_e the reactor hall span must be increased to 57 m to accommodate the eight additional helium heated steam generators. A 50 m wide hall is sufficient for the larger output water cooled reactors as the number of steam generators can be doubled within the existing layout.

Control requirements for plant operation and remote maintenance are completely different in terms of equipment, personnel and space requirements and the control facilities are therefore separated on opposite sides of the reactor hall, see Fig. 7. This arrangement is advantageous since it allows operator training and control systems maintenance to take place on non-employed facilities.

7. LAYOUT OF NUCLEAR COMPLEX

The overall design philosophy is defined below:

(a) The nuclear facilities are grouped together to form a single 'nuclear complex' to allow concentration of servicing facilities and short service lines.

(b) The nuclear complex is separate from the non-nuclear generation equipment.

(c) The nuclear complex as a whole and its individual facilities are laid out to provide one-way material flow i.e. entry for new equipment well separated from the exit for irradiated and contaminated waste.

(d) Active areas should be at sub-atmospheric pressure and the atmospheric circulation system arranged so that flows are directed through

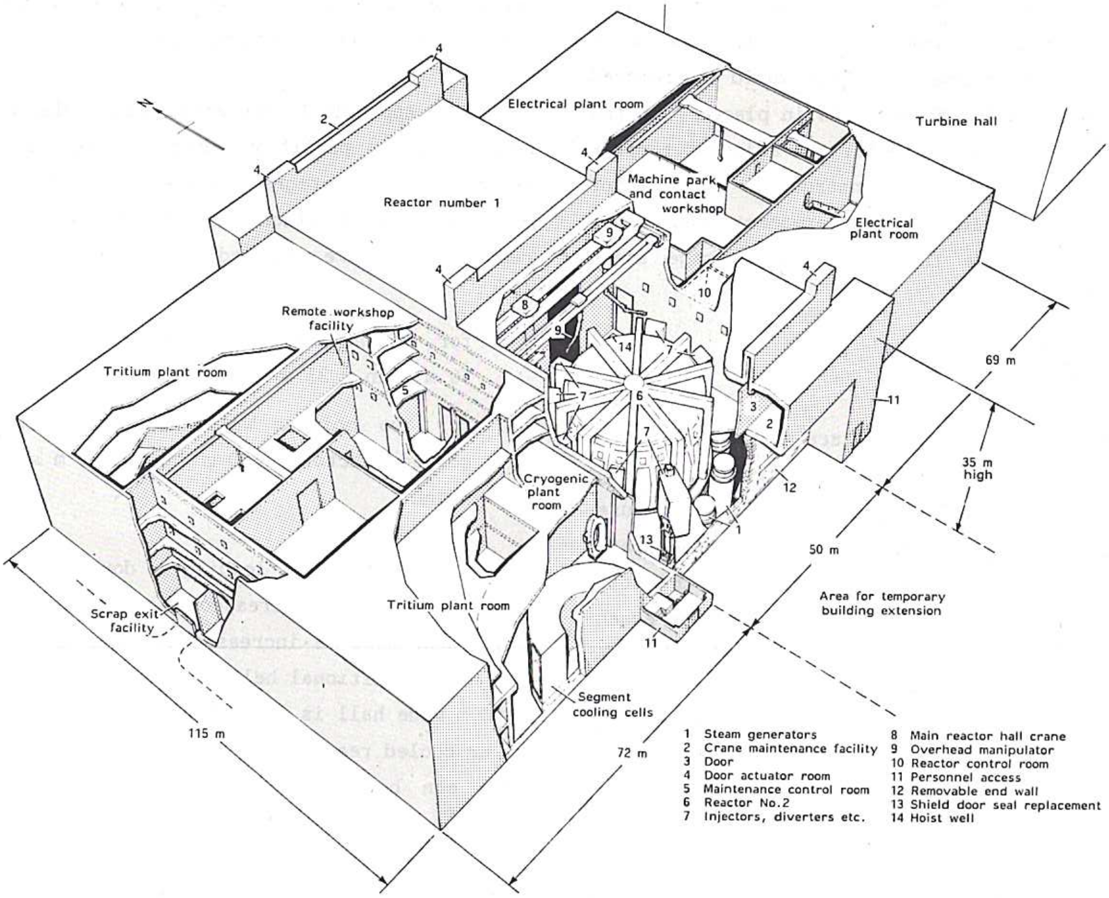

Fig.8 Layout of nuclear complex.

facilities of increasing radiological potential hazard.

(e) The nuclear complex should be laid out to allow reactor erection and temporary maintenance facilities to be located adjacent to the reactor hall.

Figure 7 is a simplified layout of the nuclear complex showing the relative positions of the principal features, machine movements, material flows and including an arbitrary north. The complex is arranged so that highly active facilities are grouped on the west side and mainly inactive facilities grouped on the east side i.e. closest to the remainder of the power station. The constructional/temporary maintenance facilities are shown at the north and south ends of the reactor hall. Access points are shown for those facilities which have been discussed in previous sections.

An artists impression of the complex is shown in Fig. 8.

8. COST ESTIMATES

Hollis and Evans'[10] cost estimate for a 1.2 GW_e CCTRII single reactor power station derived the total direct capital costs for the station as £910M (1977 values). Allowing for engineering management and services (35% of the direct capital cost), owners costs (15%), interest during construction (50%) and a notional contingency (14%) Hollis and Evans derived the gross capital cost of the 1.2 GW_e station as £2000M and the specific cost as £1667/kW_e (1977 values). Following this more detailed study of the nuclear island buildings and facilities, we have revised the estimated capital costs for a number of items (see Appendix G).

The total direct costs for both a twin and a single reactor station based on this study compare with the original Hollis and Evans estimate for a single reactor station as follows:

	Costs (1977 values)	
Station	Direct capital cost £ million	Station specific cost £/kW_e
2.4 GW_e twin reactor (this study)	1659.3	1450
1.2 GW_e single reactor (this study)	859.6	1507
1.2 GW_e single reactor (Hollis & Evans)	950.8	1667

For the comparison to be realistic the Hollis and

Evans estimate has been adjusted (see Table G1) to allow for increased heat exchanger costs and to cover requirements for spare blanket segments.

With the 2.4 GW_e twin reactor station, further economies should accrue from lower management and design costs due to replication of components giving specific costs 20-25% below the original Hollis and Evans estimate. A guide to the reduction of direct capital costs to be anticipated from increasing the wall loading to 10 MW/m^2 may be obtained by assuming:

(a) no change to the fusion reactor costs;

(b) doubling of all costs of heat transport from the reactor, heat exchangers and turbo-alternators, i.e. items 213, 214, 222 and 231 to 246 inclusive of Table G1.

With these assumptions the indicated direct costs of the 4.8 GW_e twin reactor station would be £2,141M (1977 values) - equivalent to a specific cost of £943/kW_e - 35% down on the 5 MW/m^2, 2.4 GW_e twin reactor station costs. This must be taken as a guide estimate only for it neglects any increased reactor costs to raise fusion power and the blanket rating as well as any possible reductions from replication.

9. CONCLUSIONS

9.1 A layout for the nuclear complex of a twin fusion reactor power station, assumed to be one of a series, has been developed which meets preliminary qualitative requirements relating to: long term operation, material flows, inter-facility access, steam generation, routine and non-routine servicing and safety. Although further analysis is required before its suitability, with respect to seismic criteria, and construction on a variety of ground conditions, can be provisionally demonstrated.

9.2 Various arrangements of reactor/steam generators were examined. The configuration selected has the steam generators located beneath the reactor hall floor, outside the reactor plan area. Reactor hall layouts have been developed for both helium and water cooled reactors with rated wall loadings of 5 MW/m^2. In both cases the required reactor hall span is 50 m defined by the overall dimensions of the reactor, and its auxiliaries (injectors etc.) plus the space required for remote servicing machine access. With water cooled reactors the reactor hall length is 100 m but this must be increased to 115 m to accommodate the large helium heated steam generators.

At 10 MW/m^2 wall loading the fusion power and the steam generation capacity will be doubled. For the water cooled reactor the same number of, slightly larger, units will be required and the reactor hall dimensions will remain at 50 m x 100 m. For the helium cooled system the number of steam generators is increased to 16 per reactor and the reactor hall dimensions will be 57 m x 115 m.

9.3 With the possible exception of the high temperature helium circulators and valves, all the cooling circuit components (whether for water or helium cooling) are current state-of-the-art units. Development of high capacity circulators could be avoided by using two circulators per helium steam generator.

9.4 No assessment of the relative merits of helium and water cooling was attempted: however, the following should be noted:

(a) The lower thermal efficiency of water cooled systems, compared to helium cooled systems, may be outweighed by the lower materials temperatures which result, and may therefore provide potential for increasing the wall loadings;

(b) The segment exchange programme for a water cooled system requires further development to provide methods of draining, filling, afterheat removal during transport, preheating before installation and outgassing;

(c) Overhead steam drums may be required for the boiling water cooled system to avoid downward flowing steam/water lines. Before adoption, this configuration would require careful evaluation of its effect on the overall CCTRII concept and its maintenance philosophy.

(d) In the boiling water coolant system high tritium concentrations may arise in the steam and condensate systems of the conventional power plant although careful design, materials selection and manufacturing techniques may limit the problem. In addition, the coolant will become activated, causing radiation problems around the conventional power plant. However, this problem occurs in current fission BWR systems and is overcome by the addition of local shielding and access restrictions.

9.5 Neglecting energy demand constraints of the electrical supply network the minimum cost segment exchange scenario is one segment changed every 5/6 weeks. The segment servicing elements of the remote workshop facility have been based upon twice this loading to provide redundancy. The remote workshop facility will also be required to give regular service to injectors, divertors, refuellers and vacuum pumps for which three work stations plus one spare are provided.

9.6 Types and numbers of servicing machines have been estimated and the reactor hall, remote workshop facility and airlocks specified to allow for their operation e.g. adequate clearance to allow two vehicles to pass and two routes to each reactor work site. Machines are removed from the reactor hall when not in use and the necessary machine park is provided with its associated contact maintenance workshop. The remote machines must be designed for regular and rapid decontamination.

9.7 The servicing philosophy outlined in Ref. 1 has been extended to cover steam generators and the remote workshop facility. Operations in the remote workshop facility were evaluated and it is shown that they are best executed by remotely operating mobile machines similar, in principle, to those proposed for the reactor hall. The requirements for steam generator servicing will probably be limited to gas circulator exchange and tube plugging both of which will be executed by dedicated remote machines.

9.8 The requirements for process service lines have been qualitatively examined and these can be located under the reactor hall floor. Using published data, the overall sizes and arrangements of the tritium processing and clean up plant rooms have been defined for each reactor. Notional areas have been allowed for the remaining service rooms - but these can be modified easily within the overall configuration if required.

9.9 Non-routine major maintenance tasks have been examined and the toroidal field coil change scenario identified as the worst credible case. This operation requires many facilities and large areas adjacent to the reactor hall which could not be justified on a permanent basis. It is shown that the provision of additional, temporary, facilities may offer an attractive solution particularly since similar facilities may be required during construction. Assuming that there are a number of similar fusion power stations, specialised maintenance equipment would be held in a central store for issue as required.

9.10 The temporary facilities can be re-erected at the end of reactor life and used for reactor decommissioning. These facilities may also be used as an aid to decommissioning the building structure.

9.11 A preliminary design is presented for the reactor hall structure, using reinforced concrete side walls and foundations and a flat, post tensioned, concrete roof. The foundation design assumes a ground bearing capacity of 69 tonnes/m^2. Further work is required to design the foundations suitable for sites requiring lower ground loadings.

9.12 It is estimated that the cost advantage to be gained by constructing a twin reactor power station (2.4 GW_e) as compared to two single reactor power stations (each of 1.2 GW_e) will be in the order of £60M when direct costs only are taken into account. This cost advantage is due principally to the utilization of shared services and will be doubled when indirect costs are included.

10. ACKNOWLEDGEMENTS

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10. Hollis, A.A. and Evans, L.S. An analysis of the estimated capital cost of a fusion reactor. Atomic Energy Research Establishment Report AERE-R9933.

REFERENCE CCTRII

CCTRIIB is selected as the reference reactor for this study, its principal parameters are given in Table A1 and some additional parameters in Table A2.

REFERENCE

A1. Spears, W.R. and Hancox, R. A pulsed tokamak reactor study. Culham Laboratory Report CLM-R-197 1979.

TABLE A1

PARAMETERS OF THE CULHAM CONCEPTUAL TOKAMAK Mk.II REACTOR DESIGNS

		Mk.IIA (Ref.1)	Mk.IIB (Ref.1)	Mk.IIC (Ref.A1)
Net electrical power	MW_e	2500	1200	600
Gross thermal power	MW_t	5830	3400	1830
Major radius	m	7.4	6.7	7.8
Minor radius (horizontal)	m	2.1	1.9	2.0
Aspect ratio		3.5	3.5	3.9
Ellipticity		1.75	1.75	1.68
First wall power loading	MW/m^2	6.7	4.5	2.2
Flux density on axis	T	4	4	3.9
Peak flux density	T	8	8	8.3
Plasma current	MA	11.7	10.2	11.0
Safety factor (at wall)	q	2.6	2.5	2.2
Plasma pressure ratio	β_p	1.9	1.9	2.5
Plasma pressure ratio	β_t	0.093	0.092	0.077
Central plasma density x 10^{20}	ions m^{-3}	3.5	3.2	5.0
Required energy confinement time	s	1.5	1.64	≅1

TABLE A2

ADDITIONAL PARAMETERS
(CCTRIIB WITH AIR CORED TRANSFORMER)

Deuterium requirement	8.16 kg/day
Tritium requirement	5.44 kg/day
Breeder	Li in closed cells
Coolant	He, 60 bar, inlet temperature 350°C, Outlet temperature 750°C, Mass flow 1660 kg/sec
Ohmic heating and poloidal field coils	
Energy content	7.4 GJ
Cryogenic requirements	30 kW at 4 K
Toroidal field coils	
Energy content	45 GJ
Cryogenic requirements	50 kW at 4 K
Neutral beam injectors	
Power requirement	200 MW pulsed
Supply voltage	various
Coolant requirement	not known
Cryogenic requirement	
Bundle divertors	
Power requirement	not known
Coolant requirement	
Cryogenic requirement	
Fixed shield cooling	3500 kg/sec water at 1 bar
Vacuum pumps	
Injector	cryo-condensation backed by turbo-molecular pump and Roots blower. Injector load ≅6 gm/day plus part of plasma chamber outgassing load
Divertor	cryo-condensation backed by turbo-molecular pump and Roots blower. Principally to extract the fusion exhaust ≅15 kg/day and part of plasma chamber outgassing load
Guard vacuum	turbo-molecular backed by Roots blower. To control outgassing and other gas loads in secondary vacuum space ≅0.2 torr litres sec^{-1}[4]
Environment	nitrogen at sub-atmospheric pressure - between 0.9 and 1 bar (see Appendix B)

REACTOR HALL ATMOSPHERE

Leonard and Perry (Ref. B1) examine the activation of containment atmospheres in fusion facilities based upon a reference design for the Tokamak Engineering Test Facility assuming an air filled reactor hall and conclude that the dominant reactions are:

^{14}N	$(n,{}^{3}H)$	^{12}C	(^{3}H half-life 12.6 yrs)
^{16}O	(n,p)	^{16}N	(^{16}N half-life 7.1 s)
^{14}N	(n,p)	^{14}C	(^{14}C half-life 5730 yrs)
^{14}N	$(n,2n)$	^{13}N	(^{13}N half-life 9.97 min)
^{40}Ar	$(n,2n)$	^{39}Ar	(^{39}Ar half-life 269 yrs)
^{40}Ar	(n,γ)	^{41}Ar	(^{41}Ar half-life 1.8 hrs)

The resulting saturation concentrations of short lived isotopes are many times the MPC values and the time required for the long lived isotopes to build up to MPC values are in the order of days so that a considerable potential radiological hazard exists.

The use of helium as a reactor hall atmosphere is potentially attractive but will be costly and will require expensive air-lock equipment. Nitrogen is a cheaper alternative, in terms of plant and gas inventory, and its use is therefore proposed for the reactor hall.

Tritium, produced from N-14, is not considered to be a significant problem since containment and purification will be present to cater for accidental tritium spillages. C-14 will be produced and using the radiation levels defined in Section 2.1, it is estimated that the total production from two reactors operating continuously for 30 years will be in the order of 10^{10} Bq/m^{3} of nitrogen atmosphere assuming no cleanup takes place. The principal radiological hazard will be accidental leakage but this level of activity is not considered to be a practical problem over the timescales involved.

The situation with respect to N-13 cannot be assessed as no limits are specified in ICRP. The significance of N-13 release requires detailed calculations using fundamental data, which are outside the scope of this report.

REFERENCE

B1. Leonard, B.R. and Perry, R.T. Activation of atmospheres in DT fusion facilities. ANS 4th Topical Meeting on the Technology of Controlled Nuclear Fusion, King of Prussia, 1980, preprint.

COOLANT SYSTEMS AND STEAM GENERATION

C1. INTRODUCTION

Three types of coolant system have been considered: helium gas, boiling water and pressurised water; plant configurations for each are discussed briefly in Section 3. In the design of the power conversion systems it is assumed that the reactor blanket is a steady state heat source. However, experimental Tokamaks are operated in a pulsed mode because the plasma current is driven inductively; and a Tokamak reactor may have to be operated similarly with 30 s or more between pulses so that an energy storage system will be required to give a constant steam supply to the turbine.

It has been assumed that ≅12% of the gross reactor output will be deposited in the divertors, and will be recovered in the main blanket coolant system.

Blanket cooling is also required following reactor shutdown to remove afterheat, ≅½% of the full reactor heat output. Control of blanket segment temperatures immediately after shutdown may help to achieve removal and fixation of tritium in the structure. Auxiliary heat exchangers and circulators are assumed necessary to achieve the required control of segment structure temperature as the main steam generators/circulators are too highly rated.

Blanket segments removed from the reactor for maintenance will require temporary cooling to remove afterheat while they are in transit to the cooled storage cells[2].

C2. HELIUM COOLED REACTOR

C2.1 General

The reference blanket cell design[2] adopted helium inlet and outlet temperatures which were selected to permit generation of steam at conditions (160 bar, 538°C) comparable to those used in modern conventional power plants and in the more advanced gas-cooled fission reactor plants.

The helium conditions specified correspond closely to those derived in comparatively recent design studies for high temperature gas-cooled reactor (HTGR) power plants both in the USA and in Germany. It was therefore decided to base the coolant system components for this layout study on data available from relevant HTGR designs.

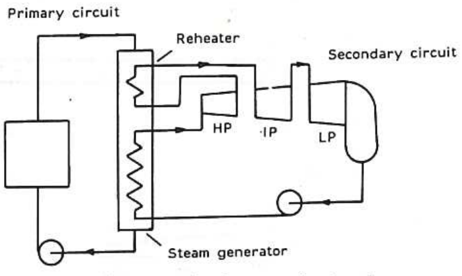
C2.2 Type of steam cycle

The use of the quoted steam conditions is generally considered to require a reheat steam cycle so that turbine blade erosion problems can be avoided. Two possible systems are possible:

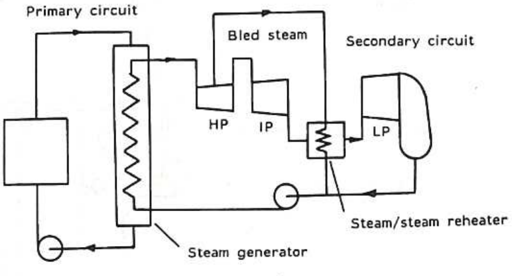
(a) 'gas reheat', in which the partially expanded steam is returned to the heat source to be reheated, Fig. C1(a); or

(b) 'steam reheat' in which the steam is reheated adjacent to the turbine using main or bled steam as a source of heat, Fig. C1(b).

The former system, which provides slightly higher thermal efficiency, is generally used in conventional plants and has also been used for some gas-cooled fission reactor plants. Comparative assess-



(a) Conventional steam reheat cycle.



(b) Steam/steam reheat cycle.

Fig.C1 Reheat cycles.

Note: Steam generator comprises an economiser, an evaporator and a superheater.

ments of the two systems for HTGR designs have generally shown little overall difference in total generation cost. However, it is considered that the use of steam reheat is desirable for nuclear plants as easing layout restraints and reducing steam generator complexity, hence improving inspectability and maintainability and it is therefore used in this layout.

The total circulator mechanical power input required for a 3400 MW_t reactor is likely to be of the order of 85 MW, supplied by either steam turbine or electric motor drives. Steam turbine drives can provide maximum cycle efficiency but they complicate the steam pipework, and create difficulties during start-up and part load operation. Electric drives overcome these disadvantages at the cost of a slight reduction in efficiency and are therefore chosen for this application, electrical power input being around 100 MW.

C2.3 Size of turbogenerator unit

The specified reactor heat output of 3400 MW_t corresponds to a turbogenerator gross output of around 1340 MW_e. This could be provided by two 670 MW_e machines similar to those currently standard in the UK, or by one 1340 MW_e machine. Within the likely timescale of this reactor, the larger size could well become a standard unit (sets approaching this size already exist in other countries). Whilst availability arguments might favour smaller machines it is unlikely that the choice would affect the layout of the reactor/steam generator system and the use of a single 1340 MW turbogenerator for each reactor has been assumed.

C2.4 Coolant circuit configuration (Fig. C2)

Large HTGR designs generally incorporate 4-8 coolant loops each containing a steam generator and a circulator unit. Because each loop is connected to the reactor inlet and outlet plena, it is usually possible to operate with one loop out of service. A brief survey of gas cooled reactor operating statistics indicates a coolant loop unavailability of about 1%.

The reference fusion reactor system (Appendix A) is rather different in that heat is generated in twenty separate segments instead of in one central core space. All segments must be equally cooled during operation and therefore a manifold system must be incorporated if the reactor is to continue operation with a steam generator/circulator unit out of service. The conceptual layout therefore includes hot and cold annular gas manifolds between the segments and the steam generators. Valves are necessary in the segment/manifold connections to allow a segment to be isolated for removal. Flow trimming control facilities are also likely to be necessary to closely control the distribution of flows to the reactor segments. It is anticipated that the flow to each segment would be controlled to maintain a constant helium outlet temperature. Valves will also be necessary at each end of the

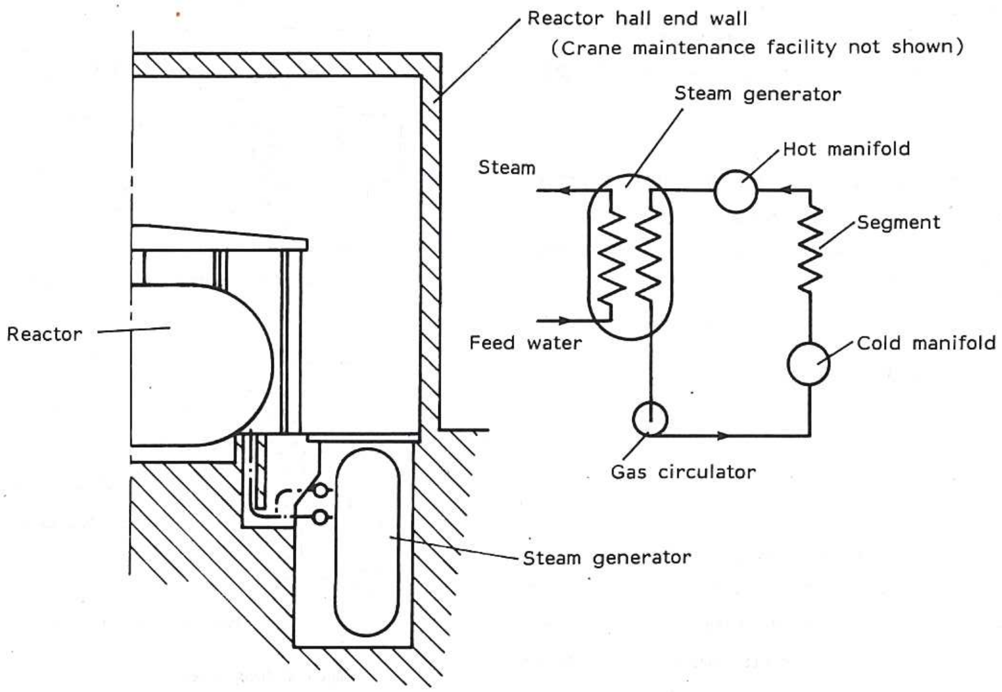


Fig.C2 Gas cooled reactor.

boiler/circulator loop so as to permit part load operation with one circulator or exchanger removed.

Because of the high helium outlet temperature (750°C), design of the high temperature part of the coolant circuit requires careful consideration. The CCTRIIB blanket segment uses concentric helium inlet/outlet ducts with thermal insulation on the inner, hot, duct so that pressure stresses are carried only by the cooler outer duct. To eliminate the need for special annular control and shutoff valves the low and high temperature manifolds are separated though the latter must still be controlled within an insulated low temperature pressurised shell as before.

C2.5 Steam generators

A number of published and unpublished documents relating to HTGR steam generator designs are available and a survey has been made of the steam generator configurations and main parameters (typically Ref. C1 and C2).

Without exception, the steam generators were designed to be installed in a cylindrical envelope, either a steel pressure vessel or a cylindrical cavity within a prestressed concrete reactor vessel. Most designs use helically wound heat transfer tubing and operate in a once-through mode. This heat transfer surface configuration is particularly well suited to a cylindrical envelope, the central core housing steam/feed connections, and cool outlet gas passes up the annular space around the tube bundle to cool the containing vessel. One design uses a serpentine arrangement of tubing in which horizontal straight tubes cross and re-cross the gas flow path between 180° bends at each end. The tube bundle is of square cross-section and the spaces around the bundle in the cylindrical outer vessel are used both for feed and steam connections and for cool gas return passages.

The rating of relevant HTGR steam generators is between 2-4 MW_t/m^3. The top end of this specific size range is generally associated with General Atomic designs which incorporate a complex gas flow path in order to allow upward water flow boiling in a counter-flow steam generator with a net upward gas flow. These designs also incorporate a gas reheater. For the CCTRII conceptual layout envisaged, the steam generators would be mounted in vertical steel vessels below the level of the reactor. Hot gas could therefore enter the top of the steam generator, pass down through the upward-water-flow heat transfer tubing, the cool gas returning up the annular space around the helical tube bundle. There is therefore no need for a complex gas flow path and a specific rating of 2.3 MW_t/m^3 is considered feasible.

Within limits, the height/diameter ratio of a helical heat exchanger can be adjusted by varying the helix angle and the tube pitch, without significantly changing the heat transfer characteristics.

Steam generator sizes were estimated on the basis of 8, 10 or 12 steam generators per reactor. With 8 steam generators the unit dimensions are ≅4 m diameter x 12 m high - suitable for road transport. Figure 5 shows the configuration of steam generators, manifolds and steam and feed pipework, all below the reactor hall floor level, maintaining uninterrupted above floor level access for reactor servicing.

C2.6 Gas circulators

The choice between steam driven and electrically driven gas circulators was discussed in Section C2.2 and it was concluded that electric drives should be adopted. Since gas flow control will be necessary for start-up and part-load operation, a choice has to be made between constant speed drives with flow control by mechanical means (e.g. guide vane control) and variable speed drives. Satisfactory operation of mechanical devices is difficult to achieve in a helium atmosphere and these are therefore best avoided. Variable speed drive by means of induction motors or synchronous motors with a variable frequency supply from static frequency changers is recommended.

Total circulator electrical power input is estimated to be about 100 MW_e, resulting in eight units of 12.5 MW_e each which is believed to be feasible with current technology.

The circulator units are located within the top end of each steam generator vessel, providing satisfactory access for maintenance purposes.

C2.7 Afterheat removal

Separate heat exchangers and circulators are provided for afterheat removal (Section C1) and duplicate systems are included to provide the necessary redundancy.

C2.8 Stored energy

The possibility of a pulsed reactor system is mentioned in Section C1. The power conversion system for such a reactor must have a large energy store to minimise power output and temperature variations due to pulsing. The helium coolant/steam generation system described above is poor in this respect as there is relatively little energy stored in either the primary or secondary coolants. The blanket cells themselves probably represent the most significant thermal energy store, but the temperature cycling associated with the use of this store poses major design problems.

C2.9 Blanket cell design and wall loading

Detailed discussion of blanket cell design is beyond the scope of this study. However, in order to achieve a mean helium outlet temperature of 750°C, very close control of helium flows in the many parallel coolant paths would be required to avoid excessive tube temperatures. It seems unlikely that there is scope for increasing wall loadings without reducing helium temperatures and incurring very high circulator powers.

C2.10 Costs

The specific cost for the steam generators, excluding any containment vessel, is estimated to be £27,000/MW_t (1977 - £) based upon a recent Select Committee Report[C3]. An allowance of 20% has been made for suitable vessels and support arrangements. Electric gas circulators with associated control equipment are be expected to cost around £300/kWe (1977). An additional overall allowance of 10% has been made for helium manifolds, ducts and valves, giving the following costs for one 3400 MW_t unit:

	£x10^6 (1977)
Steam generators (3400 MW_t)	92
Containing vessels etc.	18
Gas circulators (100 MW_e)	30
Manifolds, ducts and valves	14

C3. BOILING-WATER COOLED REACTOR

C3.1 General

The use of a direct coolant system, generating steam which can be used by a turbogenerator without the complication of intermediate heat exchangers, has obvious attractions. Because of the lower coolant and material temperatures an increase of blanket cell rating above 5 MW/m^2 might be more easily attained. However it should be noted that heat transfer will be two phase and less predictable than for alternatives.

C3.2 Steam generation system (Fig. C3)

The blanket cooling system will probably

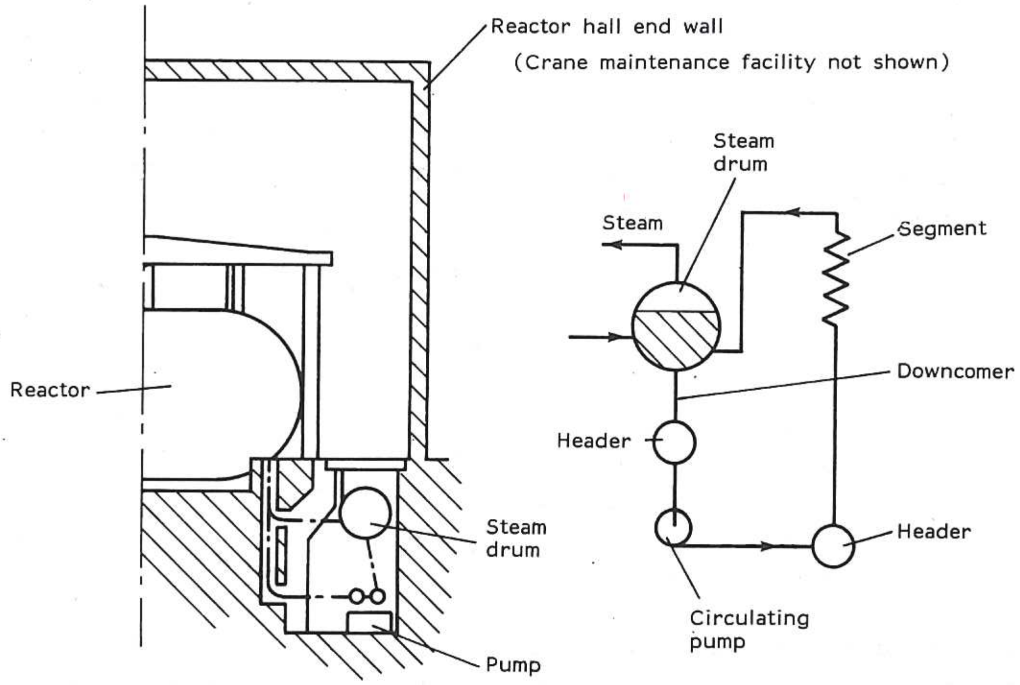


Fig.C3 Boiling water cooled reactor.

comprise a very large number of parallel cooling tubes. To attempt to balance the coolant flow through each tube to match the heat input would be difficult. If a once through system was used in which feed water was pumped into the coolant system and steam emerged, substantial variations in coolant tube conditions could occur: some tubes might be producing superheated steam and have very high tube temperatures, while others might produce a steam/water mixture and have comparatively low tube temperatures. In order to minimise temperature variations in the coolant system it is desirable to recirculate the water coolant via a steam drum. The mean steam quality (percentage steam by weight) at the coolant system outlet might be around 10% - the steam is separated in the steam drum and the water recirculated via a recirculation pump. Provided the flow/heat input variation between parallel coolant paths is not too great, tube temperature variations will be small. Excessive heat input to a tube, or low flow, could cause the critical heat flux to be exceeded with substantial rise in tube temperature.

This steam generation system is analogous to that used in the steam generating heavy water reactor (SGHWR) concept, and data relating to that reactor has been used to estimate component sizes for this study. The reference SGHWR design (Ref. C4) used a steam drum pressure of about 54 bar and a pressure of about 60 bar at the fuel channel inlets, comparable with the coolant pressure in the helium cooled CCTRII design. Although some improvement in steam cycle efficiency could be achieved by using higher pressures, the additional hardware cost would probably outweigh any benefit. This study has therefore been based on coolant conditions corresponding to the reference SGHWR design.

Typical main coolant system/steam cycle parameters are provided in Table C2 which shows that the cycle efficiency is lower than for a helium cycle operating at the conditions quoted in Table C1.

C3.3 Steam drums

The coolant flow leaving the reactor segments is a two-phase mixture of steam and water. This is separated in steam drums so that dry steam can be taken to the turbine and the water recirculated through the blanket elements. The effectiveness of separation depends to some extent on the drum internal fittings, but is largely dependent on the area of the water/steam interface. The use of two drums is convenient from a layout viewpoint and results in steam drums of a readily transportable size, 26 m long x 4 m diameter.

It is desirable to maintain a clear space around and above the CCTRII reactor for maintenance purposes so the steam drums should be located below the reactor level. This is contrary to normal practice: steam drums are usually placed above the heat source to maximise natural circulation effects, thus minimising pumping power. An alternative layout has been investigated with steam drums above the reactor and is discussed in Section C3.12.

C3.4 Circulating pumps

Circulating pumps are required to recirculate the coolant from the drums and through the reactor segments. The pumps must be located at a sufficient depth below the drums so that cavitation does not occur. This was not a particular constraint for an SGHWR, where the steam drums are located above the reactor, but could be more difficult to achieve for CCTRII if drums are located beneath the reactor level. This configuration would result in higher than normal circulating pump power, and could cause part-load problems due to the downward two-phase flow in parts of the coolant circuit. The reference SGHWR design used two steam drums, each with downcomers to four circulating pumps. The use of a similar configuration for the CCTRII design leads to pumps of around 3.75 MW_e each although this value is very dependent on the coolant pressure drop in the blanket. A vertical shaft, glanded, design is probably the most suitable.

C3.5 Coolant pipework

The main coolant system pipework sizes have been based on SGHWR reference data, adjusted as necessary to suit the CCTRII reactor output. Each drum must be provided with sufficient downcomers to avoid excessive variations of the water level along the drum length, which can lead to steam being drawn into the downcomers. Eight/ten downcomers per drum would probably be appropriate and they would terminate in a pump inlet manifold at their lower ends. The segment inlet and outlet coolant duct sizes are smaller than for the helium cooled design, and there is no incentive to adopt a concentric design owing to the low coolant temperatures.

C3.6 Turbogenerator

Steam would be delivered at 52 bar, saturated, to the turbogenerator plant. Unit sizes of 1200-1300 MW are commonplace for BWR and PWR power plants using steam at similar conditions and include moisture extraction and steam reheating between cylinders to avoid excessive erosion of the low pressure blading.

C3.7 Effect of boiling water coolant on blanket design

Complete assessment of the affects of boiling water coolant on the blanket design are beyond the scope of this study. However preliminary estimates suggest that heat transfer surface areas could be reduced relative to helium, but the extent of this reduction would depend on the accuracy of flow distribution between parallel flow paths. An area reduction of 50% may be possible while still retaining a reasonable margin to 'dry-out'. Material temperatures for the heat transfer surface will be very modest (≅280°C) compared with the helium system (>750°C), and will be essentially constant during normal operation. Aspects of the design which require attention include:

- effect of coolant leakage into the blanket material;
- development of a viable blanket coolant circuit.

C3.8 Tritium

Tritium will be generated in the lithium in the blanket. It will diffuse and may leak through the walls of the heat exchange tubing into the water coolant, where it will become oxidised, forming tritiated water. This will be carried through the turbine into the condenser and thence into the condensate system. Very little tritium is likely to be extracted by a condenser off-gas system. Being a soft beta emitter, the tritium is unlikely to represent a radiological problem as long as it is contained in the pipework systems of the steam plant. However, leaks of steam and condensate are unavoidable and will impose an upper limit on allowable tritium concentration in the steam to the turbine. Tritium concentration in the coolant can be controlled in several ways:

- continual extraction of tritium from the blanket material minimising its tritium content;
- continual removal of tritiated water from the condensate system;
- use of special heat transfer tubing to reduce the tritium diffusion rate: Ref. C5 includes a proposal to use tubing comprising two concentric titanium tubes, each coated with nitride, with lead and zirconium layers between them - this construction is claimed to minimise tritium diffusion. Ref. C6 reports that tritium permeation through austenitic and ferritic steels is reduced when an oxide film is present.

The evaluation of the tritium problem for a direct coolant cycle of this type would require an assessment of likely steam and feed leakage rates, ventilation systems and allowable airborne concentrations, together with the factors mentioned above. This assessment is beyond the scope of this study. If exotic heat transfer tubing were to be necessary, economic considerations might favour use of the indirect (non-boiling) water coolant system described in Appendix C4.

C3.9 Afterheat removal

Maintenance of normal coolant recirculation flows after shutdown would probably be required to avoid formation of steam pockets in the coolant system, bearing in mind the use of downward flow paths from the reactor to the steam drums. After flood-through of the coolant system coolant flows may be reduced gradually so that temperature control is achieved by appropriate control of feedwater input to the drums, and water offtake to a heat sink system. Alternatively, heat could be removed as steam, and temperature control achieved by control of drum pressure.

The above system for afterheat removal will result in a fully flooded coolant system after shutdown. This may be unacceptable for longterm shutdown and for blanket segment removal. Unless the blanket cooling system can be designed to be self-draining (a major design restraint) it may be preferable to change over to a gaseous (e.g. helium) coolant system at shutdown in order to use afterheat to dry out the blanket coolant circuit.

C3.10 Stored energy

The total water inventory of the coolant system is likely to be substantial, ≅300-400 te and would represent a usefuel energy store if the fusion reactor is pulse operated. Neglecting the energy

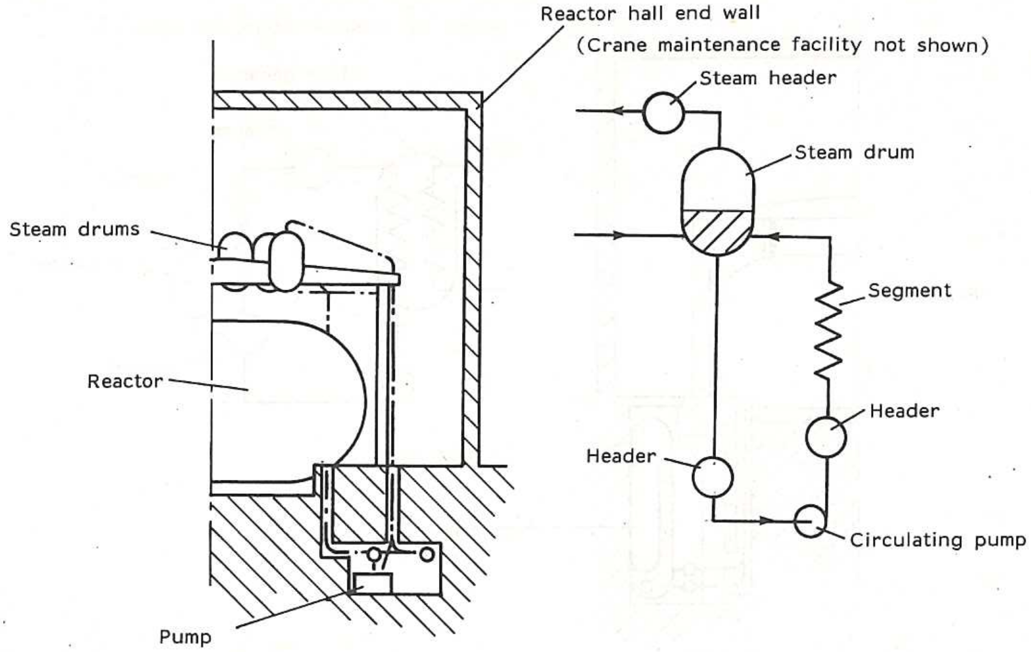


Fig.C4 Boiling water cooled reactor – alternative layout.

stored in the structure and blanket, and assuming feed to the drum is interrupted when there is no fusion reaction (i.e. zero heat input) steam pressure would fall by 25% in 15 seconds. Whilst this estimate is conservative because it neglects energy stored in the blanket it is probable that significant turbine output fluctuations would occur. Thermal cycling may also be a problem with pulsed operation.

C3.11 Coolant activation

The exposure of the water coolant to high neutron fluxes in the blanket cells may lead to the activation of any impurities in the water. These may then deposit out in the conventional plant causing a build-up of activity which may cause maintenance problems. This phenomenon is also encountered in BWR plants and satisfactory maintenance and/or preventative techniques have been evolved. An evaluation of the extent of the problem relative to BWR experience is beyond the scope of this study.

C3.12 Alternative layout with high level steam drums (Fig. C4)

As mentioned previously in Section C3.3 downward flow of the two-phase mixture to the steam drums may cause problems during part-load operation which could be avoided by locating the steam drums above the reactor. The resultant effect on reactor accessibility and on the reactor hall dimensions could be minimised by providing ten small vertical cylindrical drums, each serving two blanket segments and located between the top limbs of the "poloidal field coil structure" (Fig. C4).

C3.13 Costs

No attempt has been made to estimate capital costs for the water cooled reactor alternatives discussed in this report. It is clear that the elimination of the steam generators and the high coolant temperatures of the helium cooled system must result in a substantial reduction in capital cost for the water cooled system. However, control of tritium diffusion may require exotic and expensive blanket tubing. The capital cost saving is accompanied by a substantial reduction in overall thermal efficiency, so the specific capital cost (£/MW_e) might increase rather than decrease. Water cooling is unlikely to show significant cost advantages over helium cooling unless it permits an increase in blanket wall loading to say 10 MW/m^2 or more.

C4. PRESSURISED WATER COOLED REACTOR

C4.1 General

Some of the disadvantages associated with the boiling water cooled system can be eased by the use of a non-boiling water primary coolant which transfers heat to a secondary system in separate steam generators. This concept is analogous to the

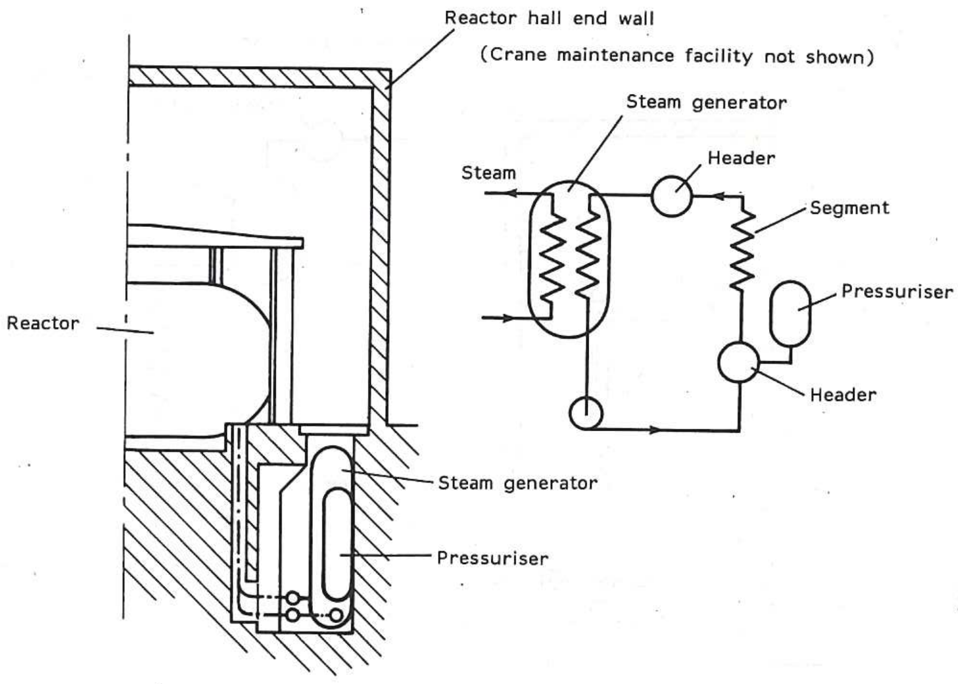


Fig.C5 Pressurised water cooled reactor.

cooling system used for pressurised water (fission) reactors (PWR).

In order to allow steam generation at reasonable conditions (62 bar saturated) the primary coolant must be pressurised to around 155 bar to suppress boiling within the blanket cells. Once again, the control of flows in individual flow paths is important, in this case to prevent local boiling of the primary coolant, but is eased relative to the boiling water coolant, since it is temperature rather than steam quality which is the critical parameter.

Table C3 gives typical parameters for a pressurised water coolant system associated with a CCTRII reactor. The data are based on existing PWR designs of similar reactor heat output. For layout purposes, component sizes have also been based on PWR practice. Since the main coolant system components can be virtually identical to those of existing PWRs, they can be regarded as proven, and no detailed discussion is necessary here.

C4.2 Primary coolant circuit (Fig. C5)

A typical PWR coolant circuit for 3400 MW_t incorporates four coolant loops each with a coolant pump and steam generator. The primary system pressure is controlled by a pressuriser vessel in which electric heaters or water sprays control the saturation temperature of the contents and hence the pressure. After leaving the reactor, water is circulated through the steam generators in which heat is transferred to the lower pressure secondary water coolant. The steam thus generated is separated and dried in the top end of the steam generator vessel.

For the CCTRII design, inlet and outlet primary coolant manifolds would be required to distribute the coolant to all the blanket segments. Each segment would be provided with valves to allow isolation for segment removal.

Each steam generator would be around 20.5 m high by 4.5/3.5 m diameter, while the pressuriser would be 16 m high by 2.4 m diameter. Coolant pump power will depend on the pressure drop in the blanket coolant system - for the comparable PWR plant pumps are 6500 kW each, and stand 8.7 m high by around 2.5 m diameter. The main coolant pipes are 0.74 m and 0.70 m internal diameter for the hot and cold legs respectively. These components can readily be accommodated in the annular trench provided for the steam generators of the helium cooled design. Thus a similar basic reactor layout can be retained.

C4.3 Turbogenerator

Steam conditions are similar to those for the boiling water coolant system, thus the comments in Section C3.6 apply.

C4.4 Effect of pressurised water cooling on blanket cooling circuit design

In order to maintain adequate primary/secondary temperature differentials in the steam generators, while still retaining a reasonable margin from the coolant boiling point, the coolant temperature rise in the reactor must be fairly small, typically from 288°C to 325°C. A high coolant flow rate is therefore required to remove the full reactor heat. In practice the primary circuit flow is about ten times the steam generation rate; it is therefore comparable with the recirculation rate for a boiling water cooled reactor with a mean output steam quality of 10%. Coolant pipe cross-sections are likely to be similar for both types of water cooling at least for the inlet system; the outlet system for the boiling cooling system may require increased flow areas due to steam voidage. Although the coolant temperatures are slightly higher for the non-boiling coolant, they are still very modest compared with the helium cooled design.

The higher coolant pressure (155 bar) will require heavier coolant pipe construction than for the boiling-coolant system, but the coolant system configuration may be simplified because steam voidage and buoyancy effects are eliminated.

C4.5 Tritium

By comparison with the boiling water cooled system, the tritium concentration in the steam plant system of a CCTRII reactor with pressurised water cooling should be low because of the use of intermediate heat exchangers. Tritium diffusion between primary and secondary coolants in the heat exchangers should be insignificant, but because of the higher primary system pressure, tube leaks in the heat exchangers would result in contamination of the secondary coolant. However, small leaks may be tolerable if the tritium concentration in the primary coolant is minimised by continuous tritium removal.

C4.6 Afterheat removal

In principle, controlled afterheat removal is possible using the normal coolant pumps and steam generators; natural circulation in the primary coolant will not occur due to the location of the reactor above the other coolant system components. However, ease of control and safety considerations require the provision of auxiliary coolant loops in parallel with the main pump/steam generator loops, with dedicated heat rejection systems and secure power supplies.

C4.7 Stored energy

The comments with respect to the boiling water cooled system (Section C3.10) generally apply to this system also.

C4.8 Costs

As mentioned in Section C3.13 capital cost estimates have not been made for the water cooled reactor alternatives. Capital costs for boiling water and pressurised water fission reactors are comparable, the extra complication of the PWR coolant circuit being balanced by other factors e.g. the need for shielding of the conventional plant of the BWR. Similar considerations probably apply to the water cooled CCTRII alternatives; the control of tritium is likely to be the most significant factor.

C5. REFERENCES

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C5. Dai-Kai Sze. Blanket and power conversion system of NUWMAK, 10th SOFT.

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TABLE C1

TYPICAL MAIN PARAMETERS FOR HELIUM COOLED CCTRII POWER PLANT

Reactor gross heat output	3400 MW_t
Heat to fixed shield	34 MW_t
Heat to blanket and divertors	3366 MW_t
Helium flow rate	1660 kg/s
Helium inlet pressure	60 bar
Helium loop pressure drop	2 bar
Helium inlet temperature	350 °C
Helium outlet temperature	750 °C
Total circulator power	100 MW_e
Total steam generator heat transfer	3440 MW_t
Feed temperature	220 °C
Steam temperature	538 °C
Steam pressure	160 bar
Steam generation	5052 te/h
Steam cycle efficiency	39 %
Gross electrical output	1340 MW_e

TABLE C2

TYPICAL MAIN PARAMETERS FOR BOILING WATER COOLED CCTRII POWER PLANT

Reactor gross heat output	3400 MW_t
Heat to fixed shield	34 MW_t
Heat to blanket and divertors	3366 MW_t
Water inlet temperature (segment)	269 °C
Water inlet pressure	60 bar
Water inlet flow (total)	16500 kg/s
Circulating pump power (estimated)	30 MW_e (total)
Steam quality leaving reactor	10 % wt (mean)
Feed temperature (to drum)	180 °C
Steam generation	1680 kg/s (6040 te/h)
Steam conditions at TSV	52 bar (saturated)
Steam cycle gross efficiency	33 %
Gross electrical output	1120 MW_e

TABLE C3

TYPICAL MAIN PARAMETERS FOR PRESSURISED WATER COOLED CCTRII POWER PLANT

Reactor gross heat output	3400 MW_t
Heat to fixed shield	34 MW_t
Heat to blanket and divertors	3366 MW_t
Water inlet temperature (segment)	288 °C
Water inlet pressure	155 bar
Water inlet flow (total)	16400 kg/s
Coolant pump power (estimated)	4 x 6.5 MW_e
Water outlet temperature	325 °C
Feed temperature to steam generators	227°C
Steam generation	1883 kg/s (6780 te/h)
Steam condition from steam generators	62 bar (saturated)
Steam cycle gross efficiency	34.5 %
Gross electrical output	1170 MW_e

PROCESS SERVICES

D1. GENERAL

Section 4 defines the required process services and indicates the allocation of equipment to plant rooms. This appendix deals with each plant room separately below.

D2. TRITIUM EXTRACTION AND PURIFICATION PLANT ROOM (TPR)

The most complete sources of information about tritium purification and handling, relevant to fusion reactors, are the reports and papers which discuss the Tritium Systems Test Assembly (TSTA) (typically Ref. D1-D3) and the tritium facility for the Engineering Test Facility (ETF) (Ref. D4). The following discussion is based upon these data, extrapolated to cover a helium cooled CCTRII.

The tritium plant room contains:

(a) Fuel cleanup plant (FCU) - to remove impurities such as argon, tritiated water and tritiated hydrocarbons from the reactor exhaust streams and to recover tritium from the tritiated waste streams. Typically the process would utilise disposable hot metal beds or regenerable cryogenic adsorption beds plus catalytic oxidation.

(b) Coolant cleanup plant (CCU) - A major design requirement for the first wall, blanket and shield is that tritium leakage into the coolant should be minimised. The CCU will therefore be required to treat large amounts of coolant to remove small quantities of tritium. For the purpose of this study it is assumed that the method outlined for the ACU (c, below) will be suitable.

(c) Atmosphere cleanup plant (ACU) - This plant will remove tritium, and airborne contamination, from the reactor hall, remote workshops and plant room atmospheres. Typically the unit would utilise particulate filters and precious metal catalytic recombination to convert all hydrogen isotope to water which is collected in molecular sieve drying towers.

(d) Isotope separation unit (ISU) - to produce streams of tritium and deuterium from the mixed output of the fuel cleanup plant. A module containing a cascade of five distillation columns is required.

(e) Tritium waste treatment plant (TWT) - to remove tritium from all gaseous effluents to permit their discharge to the environment. Such effluents arise from dry boxes, secondary enclosures and exhausts from the fuel cleanup and isotope separation units. The process involves catalytic conversion of all hydrogen isotopes to water which is processed in the tritiated water recovery plant.

(f) Tritiated water recovery plant (TWR) - This plant will remove tritium from all potentially tritiated water streams. This process will be achieved by a combined electrolysis-catalytic exchange plant.

(g) Tritium and deuterium storage - It is assumed that the blanket cell servicing facility (BCSF) will deliver a constant supply of freshly produced, but contaminated, tritium which will be purified in the TPR and then supplied to the reactor. Assuming also that the tritium demand is balanced by the supply there is no requirement to maintain a substantial quantity in an on-site store except to cover a process plant failure. The tritium inventory should be minimised because:

- at current prices, ≅£5M per kg, stored tritium will represent a considerable capital investment e.g. one days supply for one reactor would be valued at ≅£27.5×10^6;
- tritium decays with a half life of about 12.5 years so that, excluding leakage, ≅80% of the stored quantity, if it is assumed constant, will require replacing over the reactor life;
- the potential radiological hazard should be minimised.

As the process plant is modularised with several parallel circuits there is little likeli-

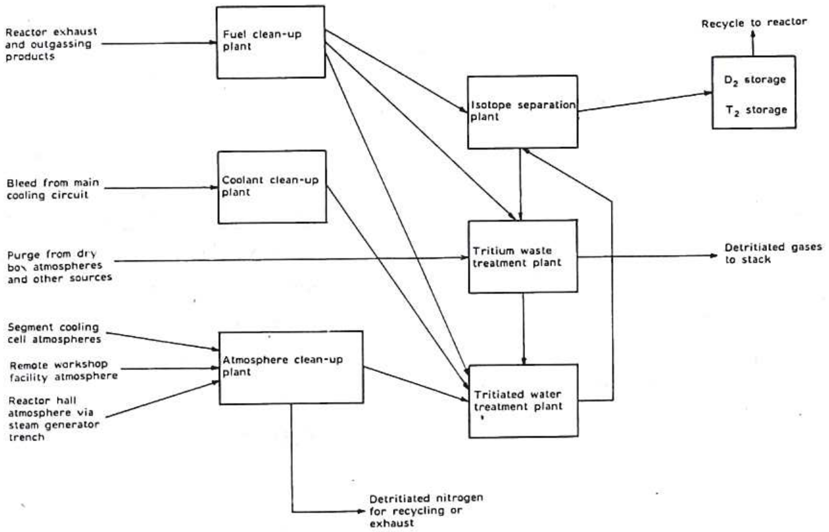


Fig.D1 Tritium purification plant.

hood of a major break in tritium supply and a 24 hour reserve (≅5500 gm) is therefore proposed. It should be noted that additional tritium may be imported from the reserves of other power stations should the on-site reserve be inadequate.

It is assumed that tritium will be stored as bottled gas within a suitable vault structure.

(h) Transfer pumps - A detailed assessment of installed tritium purification plant is outside the scope of this study and no attempt is made to define or size the pumps and blowers required to transfer process fluids and effluents around the plant. It is assumed that rotating machinery including helium compressors will require an area of 25-35% of the total plant area.

The FCU and ISU form part of the main fuel cycle while other units are less strongly coupled to reactor operations. The plant functions, excluding pumps and blowers, are connected as shown in Fig. D1 and Table D1 provides the derivation of plant sizes in the TPR using appropriate scale factors to adjust the sizes quoted for the ETF plant. For improved system reliability and to facilitate maintenance it is advantageous if all TPR units are modularised by

Process facility	Quoted size of facility for E.T.F. (Ref.D4) m	Multiplication factor Value and basis	No. of units required for single CCTRII reactor 5 MW/m^2 wall loading	No. of units required for single CCTRII reactor 10 MW/m^2 wall loading	Comment
FUEL CLEAN UP (FCU)	6 x 2 x 2	$\frac{3400\ \text{MW}}{1130\ \text{MW}} \simeq 3$ Exhaust quantity proportional to fusion power.	4	8	Includes 30% over capacity to allow for maintenance.
HELIUM COOLANT CLEAN UP PLANT (CCU)	-	Assuming total loop inventory to be cleaned in 24 hours, flow rate = 10 atmosphere clean up units.	15	30	Includes 50% over capacity to cover continuous operation.
ATMOSPHERE CLEAN UP PLANT (ACU)	10 units, ea. 8 x 8 x 5	X2 Based upon treatment of atmosphere in remote workshop ($10^5 m^3$) plus one reactor hall ($10^5 m^3$) or one tritium plant room ($10^5 m^3$) in 24 hours.	24 (total for whole plant)	24 (total for whole plant)	20% over capacity included to allow for maintenance.
ISOTOPE SEPARATION (ISU)	3 x 3 x 12	X3 Quantity of gas to be treated is proportional to fusion power.	4	8	Includes 30% over capacity to allow for maintenance.
TRITIUM WASTE TREATMENT PLANT	5 x 5 x 5	X4 Generally based upon ratio of fusion powers but increased to cover waste generated by coolant clean up plant.	5	10	Includes 25% over capacity to allow for maintenance.
TRITIATED WATER RECOVERY PLANT (TWR)	6 x 9 x 3 3 x 4 x 3	X4 As for tritium waste treatment plant.	5	10	Includes 25% over capacity to allow for maintenance.
T_2 + D_2 STORAGE	6 x 3		1	2	Based upon standard gas cylinders in concrete vault.

Table D1
Tritium Plant Room

paralleling small units and we have based the module size on equivalent ETF units and used scaling faults to determine the number of modules.

Several levels of containment are required for the tritiated process streams, typically:

1st level: the container or pipework carrying the tritiated fluid and the associated isolating valves;

2nd level: each process system will be contained in a sealed box which has a continually purged and monitored inert atmosphere. This level will probably not be required for fluid transfers at room temperature and low pressure where transfer lines are not liable to accidental damage;

3rd level: the building fabric and ventilation system.

There will be little gamma activity present in the TPR and contact maintenance, by suited operators, should be possible except perhaps in the event of a large tritium release requiring immediate corrective action. In this case a general purpose manipulator will be imported from the reactor hall or from the remote workshops area.

The TSTA is designed for manually supervised computer control and this arrangement will be suitable provided there is adequate communication with the upstream and downstream control functions of the tritium processing loop.

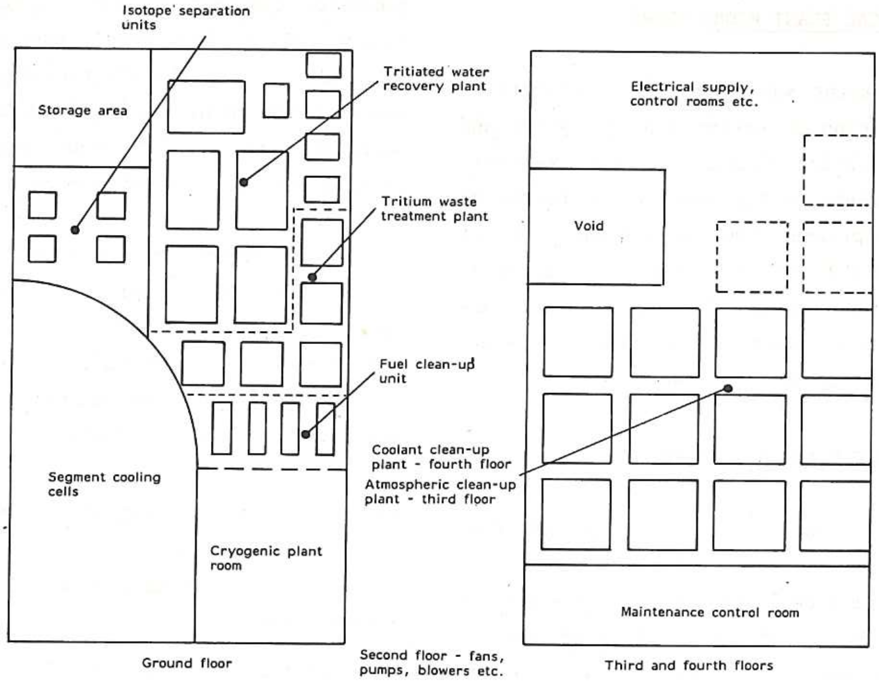
The overall layout, Section 7, provides convenient locations for two TPR's, one associated with each reactor. As the plant is modularised it is acceptable to divide the total requirement more or less equally between these facilities providing that adequate cross connections between functions are installed. It is desirable to zone the process plant by grouping high tritium inventory processes together, and this is achieved using separate floors as below - see also Fig. D2.

Ground floor - tritium recovery and extraction plant
First floor - transfer pumps
Second floor - coolant cleanup
Third floor - atmosphere cleanup

With reference to water cooled reactors the following points should be noted:

i. It is probable that tritium contained in hign temperature helium will be more likely to escape from the coolant circuit than tritium contained in either of the water cooled circuits. It is assumed therefore that 5-10% of the water inventory should be de-tritiated per day as opposed to 100% of the helium inventory.

ii. Two coolant treatment plants will be required:
- a de-tritiation plant assumed to be simi-



Ground floor
Second floor - fans, pumps, blowers etc.
Third and fourth floors

Fig.D2 Layout of tritium plant room.

lar to that outlined above in (f). Scaling up the pilot plant defined in Ref. D5, to provide a 5% inventory detritiation per day, gives a plant having dimensions 10 m x 20 m for each reactor;

- a water chemistry treatment plant whose function will be to maintain the coolant in the desired chemical state. It is not expected that this plant will be very large and it is assumed that it can be accommodated without requiring the TPR size to be increased.

iii. The length of reactor hall required for water cooled reactors is less than that for helium cooled reactors, see Section 6, and the widths available for the TPRs are correspondingly less. This is not significant as plant layouts can be readily modified and the TPR lengthened without a significant cost increase.

iv. Table D1 includes an assessment of the plant required to service a reactor with 10 MW/m^2 wall loading and shows that an increase in area of approximately 75% will be required.

The TPR's will not require shield walls as there will be no γ-activity present except in the case of the water cooled systems where CCU and chemical treatment plants will handle activated water and corrosion products. The TPR should be lined with aluminium cladding similar to that for the reactor hall, see Appendix F3.

D3. ELECTRICAL PLANT ROOMS (EPR)

Each reactor will require an electrical plant room containing an energy storage system and the power distribution boards for the reactors. The size requirements of the reactor EPR cannot be estimated at the present time as systems have not yet been defined for CCTRII. The areas shown in Fig. 7 have been arbitrarily chosen. All EPRs are inactive and their construction will therefore follow normal practice for such facilities.

D4. CRYOGENIC PLANT ROOM (CPR)

Cryogenic requirements cannot be specified at the present time and the CPR has not been sized. Each reactor CPR will be located in the relevant TPR as shown in Fig. D2 and it should be noted that the size of facility can be adjusted or increased to accommodate the cryogenic plant requirements.

D5. SHIELD COOLING WATER PLANT ROOM (CWPR)

One percent of the fusion power, i.e. 34 MW, will be released in the fixed shield and will be removed by about 3500 kg/s of cooling water. It is assumed that the heat from this water will ultimately be rejected to the main station cooling system and that this plant room will contain only pumps and flow controls.

Assuming there is a low probability of the system becoming contaminated with tritium the CWPR has been located adjacent to other clean areas and it conforms to conventional construction practice.

D6. OPERATIONAL CONTROL ROOM (OCR)

The functions of the OCRs are to control the operation of the reactor, its associated turbogenerators and all directly connected ancillary equipment. It is probable that the reactor will require many more data linkages than the turbine hall or electrical plant room and, since it is desirable from reliability considerations that the total linkage length should be as short as possible, the OCR should be located as close as possible to the reactor. It is belived that the safety argument for separating the OCR from the reactor, which is used for fission reactors, is not applicable in the case of a fusion powered system since there appears to be a low probability of any catastrophic accident.

Each reactor/electrical plant room/turbogenerator combination will require an OCR and this is located, at high level, overlooking the reactor hall adjacent to the electrical plant room. Much computer equipment will be required but it is not profitable to predict space requirements because precise control functions have not yet been specified and development over the long lead time, >20 years, cannot be predicted. It is envisaged that control and communications links will be run in underground service ducts with cross connections as required. Each OCR will contain the facilities necessary to provide emergency control for the other reactor/turbogenerator combination.

D7. NITROGEN CIRCULATION SYSTEM (Fig. D3)

The functions of the nitrogen circulation system are to:

- maintain sub-atmospheric pressures in the active facilities;

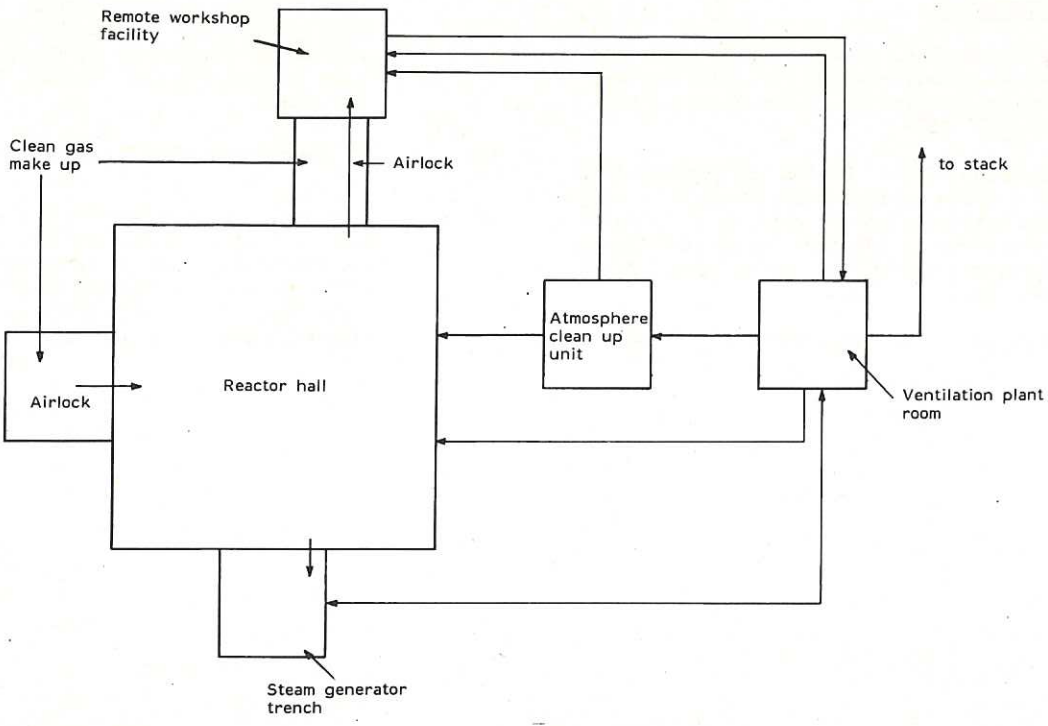


Fig.D3 Nitrogen purification system.

- maintain the reactor and auxiliary plant surfaces at the design temperature;
- remove airborne particle contamination from the reactor hall;
- remove tritium and gaseous impurities from the reactor hall.

There are five types of facility as defined by the actual or potential radiological hazard, viz:

(a) high radiation levels plus potential for large tritium release i.e. the reactor hall, steam generator trench and irradiated segment cooling store;

(b) high radiation levels plus potential for high levels of airborne particulate, contamination and large tritium release, i.e. the remote workshops;

(c) low radiation levels plus potential for large tritium release, i.e. the tritium plant room;

(d) low radiation, contamination and tritium levels, i.e. the contact workshop and machine park;

(e) non-active areas.

These areas must be maintained at differential pressures to ensure that all gas flows are towards the most active areas.

Previous discussion of this topic (Section D2) dealt only with tritium removal and implied a system capable of treating $2x10^5$ m^3 per day i.e. ≅40% of the total contained volume. It is probable that a greater number of atmospheric changes per hour will be required to ensure the adequate removal of contamination and heat but as the necessary calculations of heat and gas loads cannot be carried out at the present time the following example is used as an illustration.

Current active facilities specify about 10 air changes per hour and if this figure is applied to the reactor hall and Remote Workshop Facility approximately $3x10^6$ m^3/hour of ventilation capacity will be required. This requirement can be met by ten (currently available) fans each of which is contained within a 4 m x 4 m x 6 m envelope. The second floor of the TPR is allocated to fans, pumps, blowers etc. and this area should be sufficient for this equipment.

D8. STEAM GENERATOR SERVICES

Services required by the steam generators are primarily electrical power, instrumentation and water treatment. Electrical power and instrumentation will be supplied via the service ducts. Water treatment will be carried out in facilities in, or adjacent to, the turbine hall except in the case of a boiling water cooled system for which the water treatment plant should be located in the TPR.

D9. REFERENCES

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D4. ETF Newsletter, ORNL, p.2, 1980.

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MAINTENANCE AND SERVICING

E1. ROUTINE SERVICING

The CCTRII reactor will require a wide range of routine servicing operations or small repairs to be carried out at frequent intervals. The principal requirements are discussed below.

(a) First wall and blanket

While the life of the structure surrounding the fusion plasma will be limited by radiation damage, it should not be less than two years if reactor availability is to be maintained at economic levels. Assuming this segment life, a range of segment replacement scenarios are possible, i.e.:

i. changing 20 segments, during a long shutdown every two years;

ii. changing 1 segment, during a weekend shutdown, every five or six weeks;

iii. any intermediate case, e.g. 10 segments changed during a long shutdown each year.

Assuming that there is no demand constraint, the minimum cost option is case (ii) since the segment inventory and shielded and unshielded storage area requirements are lowest.

The minimum segment inventory for the station will be 64 made up as follows:

In the reactors	40
In afterheat removal cells	20
Available for immediate installation including unscheduled requirements and stored in the Remote Workshop Facility (RWF)	3
Being refurbished in the RWF	1

In addition a number of new segments will be held in the new components store. This inventory will enable an adequate flow to be maintained during normal operation but it must be carefully controlled during the first two year period to match the RWF capacity.

The operations sequence for a helium cooled segment change is given in Fig. E1. After removal from the reactor the segments will be placed in cooling cells for about one year to allow afterheat to decay to an acceptable level for subsequent processing.

The reference helium cooled blanket segment carries separately cooled cells which contain a non-combustible lithium compound. Cell removal and replacement will take place in the RWF and will require services to manipulate and unbolt cells in a variety of positions and the blanket cell servicing facility (BCSF) will require machinery to dismantle the cells, extract any tritium and irradiated lithium compound, re-pack and re-assemble the cells (Ref. E1) while carrying out necessary inspection and test procedures. The segment servicing programme is shown in Fig. E2.

The power station contains two reactors so that the throughput of segments through the RWF will be approximately one every 2½ weeks. The blanket cell throughput will be 200 or more cells each 2½ week period.

The operations required to change a water cooled segment will be similar to those for a gas cooled segment except that a drainage operation is introduced on removal and a filling/venting operation introduced on replacement. These two operations have not been examined in detail but preliminary inspection suggests that they do not affect the overall layout provided that the use of water coolant does not reduce segment life to less than two years.

(b) Neutral beam injectors

The ion sources of positive ion neutral beam injectors are expected to have an operating life of 10^5-10^6 seconds (Ref. E2) which is equivalent to 11-110 weeks of reactor operating time (20 second injection, 1000 second burn, 75% availability). The remainder of the system e.g. beam dumps, bending magnets etc. is expected to have a life of the same order as that of the segment ≧2 years. Each injector will require shielding and complex service

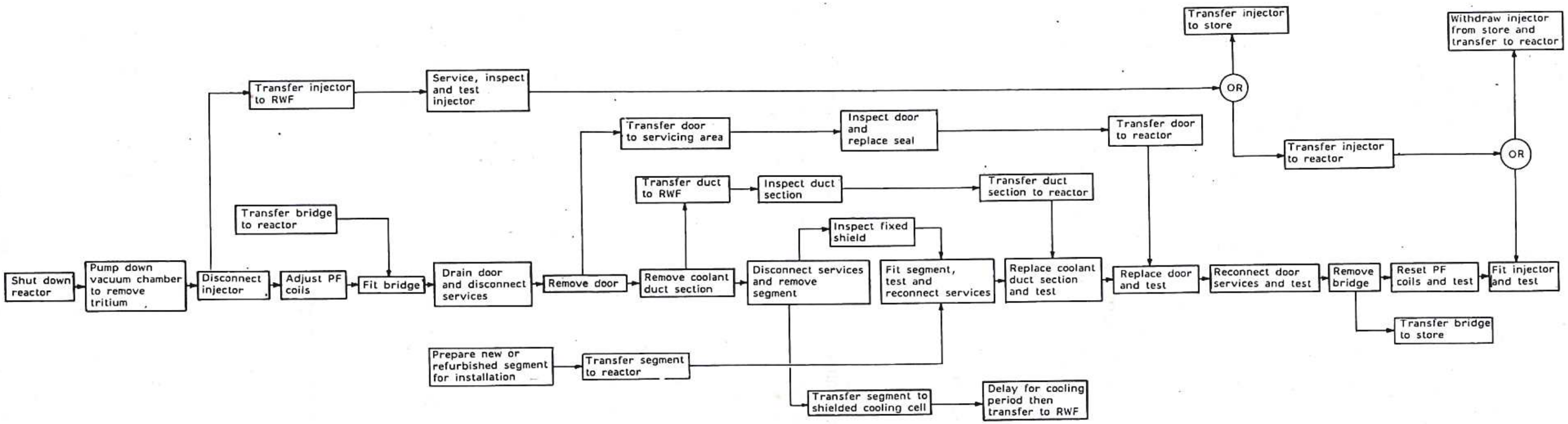


Fig.E1 Helium cooled segment exchange programme.

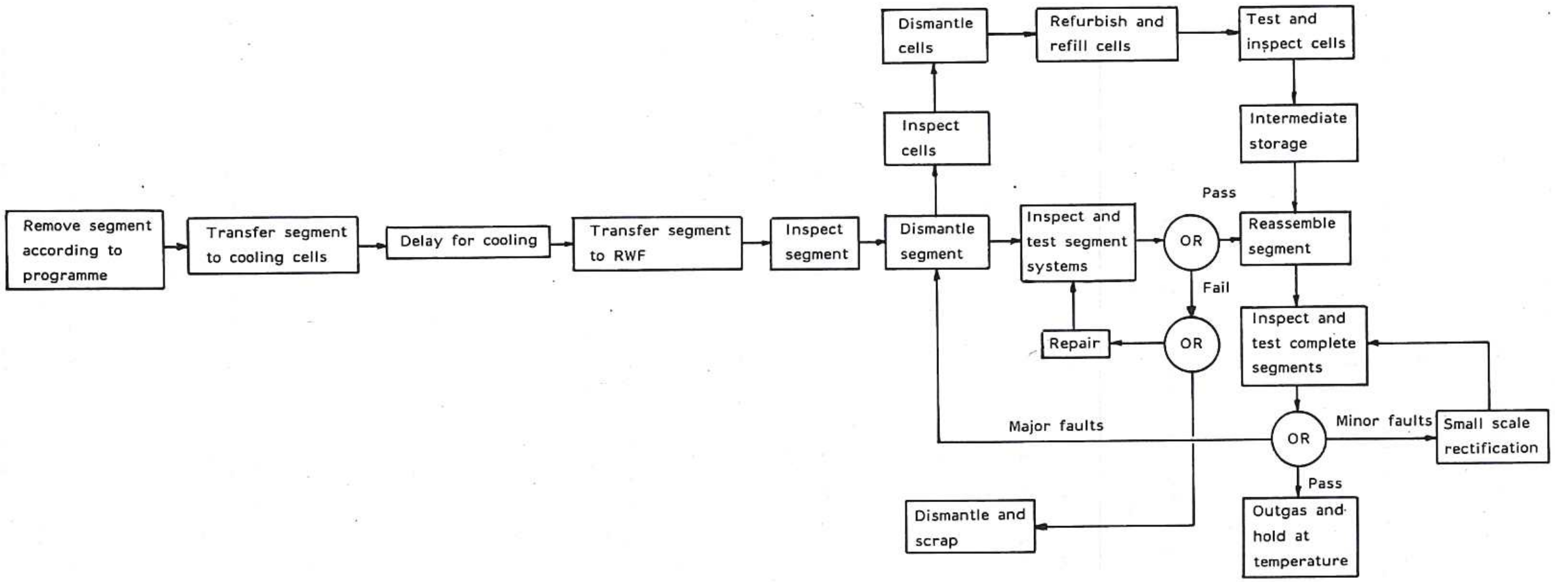


Fig.E2 Segment servicing programme.

connections so that it is desirable to perform in situ source changing. Since spare, on line, injector capacity would almost certainly be provided it is also desirable to change sources while the reactor is on load. This objective might be achieved by a special purpose machine using fluidic control systems and constructed from electrically non-conducting material.

The injectors will be transferred to the RWF for maintenance and, based upon predicted life, throughput considerations are not important. The reference unit, similar to the injector proposed for JET is designed with all internal components mounted on a central core which can be replaced as necessary. Injector servicing therefore breaks down into two separate phases i.e.:

i. opening the vacuum containment, removing the central core and replacing it with a refurbished unit and reassembling the vacuum vessel;

ii. dismantling the extracted central core and servicing its component parts.

The first phase will require cutting and welding equipment to open and close the casing and lifting equipment, to remove the core. The second phase component servicing will require fairly delicate and accurate manipulative equipment and tools.

(c) Divertors

Divertors will be required to reduce the charged particle flux on the first wall to a relatively low level. At the present time it is believed that semi-portable bundle divertors, incorporating gas targets, will be used. The probable maintenance cycle for this equipment is not known but it is assumed that they will be given minor maintenance on site and only transferred to the RWF for major repair.

(d) Miscellaneous

The reactor/steam generator system uses a number of components which operate in parallel e.g. gas circulators and guard vacuum pumps which, while they may not require routine servicing, will require maintenance. The numbers of these components are such that a regular throughput of units can be expected and standard servicing facilities will therfore be required.

It is logical that all such ancillary equipment should be constructed on a modular basis and the servicing requirement is broken down in a similar manner to the neutral beam injectors i.e. dismantling using remote cutting and/or dismantling machinery and module repair by remote equipment or in conventional caves.

The layout shown in Fig. 6 shows an injector and indicates the space which is required for its withdrawal. This space ≅6 m is sufficient to provide for two way traffic round the reactor hall which will in fact be required to allow the scenario given in Fig. E1 to be achieved.

With reference to the steam generators the most probable failure modes will be tube leaks and gas circulator failure. The cooling system configuration, Fig. 5, allows steam and feed headers to be accessible from the floor of the trench (for tube plugging) and gas circulators to be exchanged through hatchways in the reactor hall floor. Valve servicing will also be carried out through flow hatchways.

E2. NON-ROUTINE REPAIR

A wide range of non-routine maintenance operations will of course be required, ranging from simple component replacement to major programmes which require a reactor to be shut down for many months. The most significant of these operations are examined in Table E1. Inspection suggests that the worst case reference scenario, in terms of reactor down time, will be a toroidal field (TF) coil change. Potentially more troublesome faults are identified but the provision of installed spare capacity, careful design and materials selection and good quality assurance practice should reduce the likelihood of failure during the reactor life to an acceptable level.

The required programme for a TF coil change is detailed in:

- a block diagram (Fig. E3) which shows the programme from fault realisation, through repair, to startup and shows those tasks which may be performed in parallel. The relationship between series and parallel paths is based upon a qualitative assessment of plant utilisation and access to the work area;

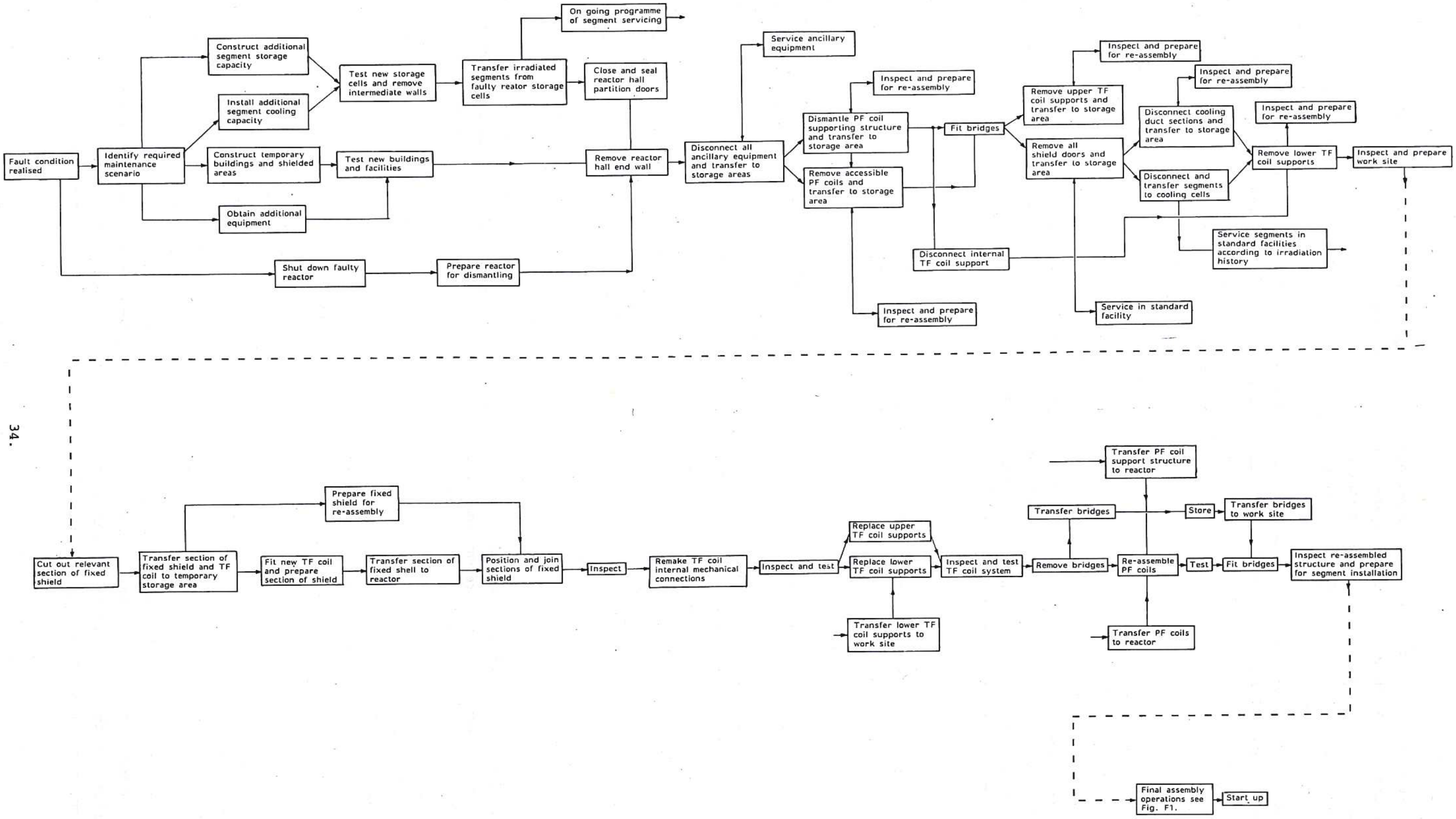


Fig.E3 TF coil change programme.

Condition	Operations	Comments
Coolant duct failure.	Cut out section of reactor hall floor. Cut out faulty duct section and replace.	Not probable as duct well shielded from neutron flux.
Poloidal field coil failure.	Cut out faulty coil, position and connect installed spare.	Impossible to replace lower PF coils economically.
Toroidal field coil.	Cut out section of reactor, exchange TF coil and replace.	Selected as reference case. See discussion in body of appendix.
Helium circuit valve failure.	Cut out failed valve and replace.	Should be achievable with existing facilities. Changing lower valve, (see Figure 5) will be the most time consuming.
Failed steam generator/ evaporator/heater.	Cut, or break, connections to failed component, remove through top of trench and replace.	Some spare capacity will be installed but will be insufficient to cater for complete unit failure.

Table E1
Major Non-Routine Repair Operations

- an operational listing (Table E2) which gives details of requirements for remote machines, special facilities and additional storage areas together with an assessment of traffic density in the reactor hall.

The preparatory work contained in the proposed programme requires that all removable reactor components are, in fact, removed from the reactor so as to maximise internal and external access and minimise the loads carried by the fixed shield. This requirement includes removal of the ohmic heating coil and central PF coil support structure and it is assumed that these will be removed in sections, the longest being 10 m. This requirement effectively sets the height of the roof at 35 m.

The temporary storage area is required to hold components taken from the reactor, in shielded storage areas if necessary, and provide space for maintenance and repair operations. A layout for the area is shown in Fig. E4 using the areas defined in Table E2.

Comparison of Table E2 with the machine inventory given in Table E3 shows that the following additional equipment will be required during a TF coil change:

- miscellaneous storage fixtures to be used for poloidal field coils, shield doors etc.;
- a remote operating overhead travelling crane and manipulator to operate principally in the temporary storage area and mounted on rails which are extensions of the reactor hall rails;
- assembly fixtures;
- a general purpose manipulator to operate, independently, inside the central core of the reactor;
- a machine to remove and replace concrete wall blocks (see Appendix F1).

E3. SEGMENT COOLING CELLS

The assumed segment exchange scenario (Appendix E1) requires that one irradiated segment be removed from the reactor every five or six weeks and that the segments require a period of one year in store to allow sufficient afterheat decay for dismantling. The power station must be provided with cooled storage for 18-20 irradiated segments located adjacent to and opening into the reactor hall. It is assumed practicable to utilise the normal segment coolant ducts and coolant to remove afterheat, estimated to be 0.5 to 1% of the fusion power.

The most compact storage layout, Fig. E5, which is capable of expansion, duplicates that of half the reactor i.e. 10 cells located in a semicircle. As the layout is similar to the reactor, similar segment handling equipment, procedures and cooling systems will be used.

E4. REMOTE WORKSHOP FACILITY (RWF) (Fig. E6)

Two basic types of facility for servicing large modules such as segments and injectors can be envisaged i.e.:

Operation	Operating plant dedicated to TF coil change ops.		Special facilities required	Reactor hall. number of op. machines		Temporary storage area		Remarks	
	Machine	Number employed		Floor	Over/ head	Storage area m^2	Accum. total m^2	Operational	Storage
Construct additional segment storage capacity	-	-	-	1*	-	-	-	Non-active operation, external access.	-
Install additional cooling capacity at each segment storage facility	-	-	-	1*	-	-	-	Non-active operation, external access.	-
Construct temporary storage/workshop facilities, inc. areas and special facilitites	-	-	-	1*	-	-	-	Non-active operation, external access.	-
Test new segment cooling cells and remove intermediate walls	GPM	1	Machine to remove concrete blocks.	1*	-	-	-	Non-active then active operation. GPM required for clean up operations. Waste removed via flasking out facility.	New segment storage areas active on completion of this operation.
Test/inspect temporary facilities.	-	-	-	1*	.-	-	-	Non-active operation, external access.	-
Transfer irradiated segments from shutdown reactor storage cells to operating reactor storage cells.	SC GPM DS	2+ 1 2	-	6+ *	-	-	-	As many segment carriers as possible should be used to minimise duration.	
Close and seal reactor hall partition doors	GPM OHM	2 2	-	4*	2	-	-	Partition door design assumed to be such as to allow operations to be executed by designated machines. Machine totals include 1 GPM and OHM in adjacent reactor hall.	-
Remove section of reactor hall end wall.	GPM EOTC OHM	2 1 1	Machine to remove concrete blocks.	2	2	-	-	Essentially an active operation. May require use of GPMs and EOTCs to execute clean up operations. Waste removed via temp. facility.	Temporary storage area is now "active".
Disconnect all injectors, refuellers, divertors and guard vacuum pumps and transfer to temporary stressed storage area.	TU GPM	4+ 2	-	7+ *	-	$\boxed{464}$	$\boxed{464}$	As many transporter units as possible, compatible with access, to be used to minimise duration. Units to be serviced in the permanent facility, in rotation, during period of reactor shut down.	Assumes that all units require storage in temp. shielded facility. Areas calculated on basis of 16 units.
Dismantle poloidal coil supporting structure and transfer to temp. storage facility.	EOTC OHM GPM	1 1 2	EOTC in temp. facility. Special lifting beams.	3*	2	463	463 $\boxed{464}$	These operations to take place at the same time - individual elements are inter-linked.	Assumes top structure central column and all external columns removed and stacked for storage All verticals removed to maximise access.
Disconnect and remove poloidal field coils and transfer to temp. facility.	EOTC OHM GPM	1 1 2	EOTC in temp. facility. Storage fixture.			1225	1688 $\boxed{464}$		Storage fixture is assumed to be of similar configuration to the reactor but compressed vertically. Max.coil dia. 30 m, fixture assumed to be 35 m square.
Fit bridges.	EOTC GPM	1 2	EOTC in temp. facility. 18 bridges.	3*	1	0	1688 $\boxed{464}$	This operation may be run in parallel with previous operations.	Two bridges are normally stored in the reactor hall. Eighteen additional bridges are therefore required.
Break internal TF coil support.	EOTC OHM	1 1	Special purpose manipulator to be located and operated in the central core.		2	0	1688 $\boxed{464}$	It is assumed that this operation can be executed by the designated machinery. This operation is in parallel with other operations and it is assumed that the EOTC and OHM can be made available when required.	

Table E2
TF Coil Change Operations

Operation	Operating plant dedicated to TF coil change ops.		Special facilities required	Reactor hall. number of op. machines.		Temporary storage area		Remarks	
	Machine	Number employed		Floor	Over/ head	Storage area m^2	Accum. total m^2	Operational	Storage
Disconnect, remove and transfer upper toroidal field coil supports to temporary facility.	EOTC OHM	1 1	EOTC in temp. facility. Storage fixtures	5*	2	12	1700 $\boxed{464}$	Units to be serviced in the permanent facility, in rotation, during the period of reactor shut down.	There are two units, each say 3 m x 1 m Assume these are stacked on a storage fixture of area 3.5 x 3.5
Remove all shield doors and transfer to temp. facility.	DM GPM	2 2	EOTC in temp. facility. 20 storage fixtures.			480	2180 $\boxed{464}$	Two systems operating in parallel to minimise duration. Service as convenient during shut down period.	20 storage fixtures to allow doors to stand vertically required, nominal 4 m x 6 m area.
Disconnect, remove and transfer all coolant duct sections to temp. storage area.	DS GPM	2 1	EOTC in temp. facility.	7	2	80	2260 $\boxed{464}$	Two systems operating in parallel to minimise duration. Inspect as convenient during shut down period.	Duct sections may contain absorbed tritium and should be stored within some form of containment, eg. bagged.
Remove all segments and transfer to cooling cells.	SC GPM	2 2				0	2260 $\boxed{464}$	Two systems operating in parallel to minimise duration. Service according to irradiation history and as convenient during shut down period.	Note one GPM operating in segment storage area.
Remove lower T.F. coil supports.	GPM MC EOTC	1 1 1	Special purpose manipulator located in central coil	3*	1	12	2272 $\boxed{464}$	Assumes that outer unit removed from trench and inner unit removed via central core.	Stored on same fixture as upper T.F. coil supports
Inspect and prepare work site.	GPM IM	2 2	Special purpose inspection systems.	5*	0	0	2272 $\boxed{464}$		
Cut out relevant section of reactor structure.	EOTC OHM GPM IM	1 1 2 2	Special purpose manipulator located in central coil	5*	2	0	2272 $\boxed{464}$	The materials for the fixed shield have not yet been specified, possible choices being steel or concrete. If steel, section of fixed shield will be cut out and transferred to the temporary storage area. This will require the provision of a storage fixture of about 7.0 m x 11 m plan area. If concrete, section of structure may be cut up prior to removal and a precast section fitted or alternatively, a new section cast in situ. Machine and storage requirements estimated on the basis of steel structure.	
Transfer section of reactor structure to temporary facility.	EOTC OH manip. GPM	1 1 2	EOTC in temporary facility. Storage fixture Special purpose manipulator located in central coil.	3*	2	77	2349 $\boxed{464}$		

Notes:

(1) Storage areas in the temporary storage area are:

UNSHIELDED - DEFINED 2260

SHIELDED - DEFINED $\boxed{464}$

(2) Storage areas do <u>not</u> include allowances for access or working.

(3) Machine totals relate to shut down reactor only, unless otherwise stated.

Key:

GPM	General purpose robot manipulator.
SC	Segment carrier.
EOTC	Remote overhead travelling crane.
TU	Transporter unit.
OHM	Crane mounted overhead manipulator.
DM	Door transporter/manipulator.
DS	Duct servicing machine.
MC	Mobile crane.
IM	Internal manipulator.
*	Includes one GPM engaged on "house keeping" duties, or unspecified inspections, etc.

Table E2 – Continued

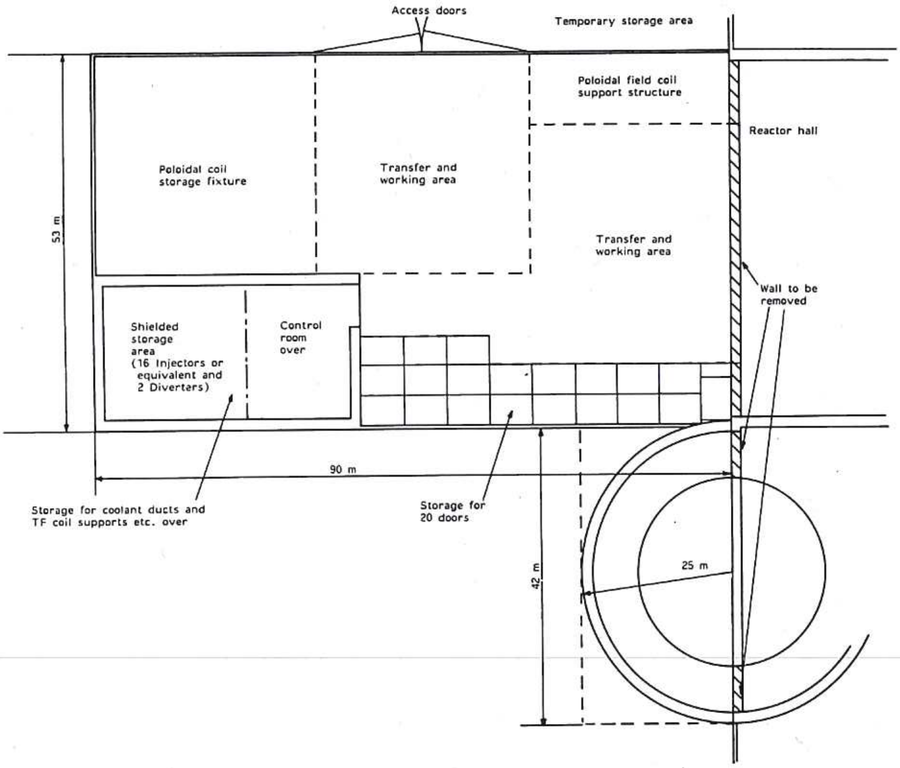


Fig.E4 Layout of temporary storage area.

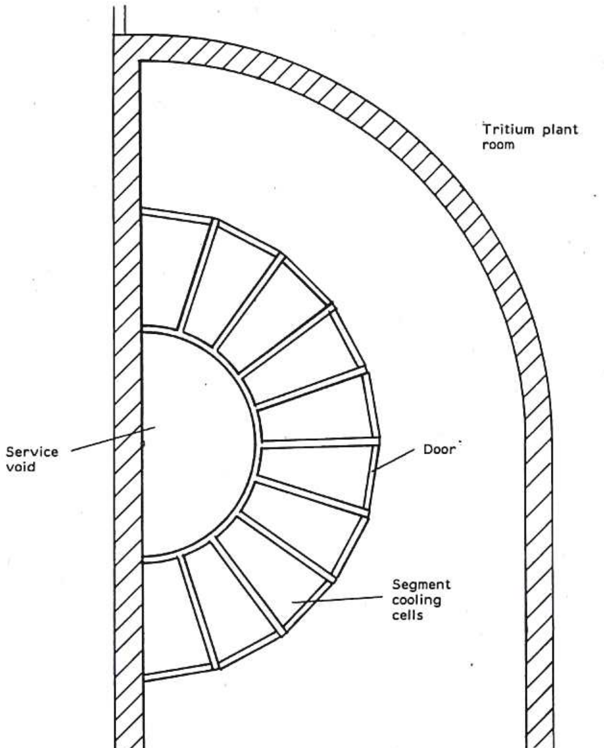


Fig.E5 Layout of segment cooling cells.

Machine	Code	Reactor hall	Remote workshop	Machine park	Maintenance bay	Total	Remarks
Segment carrier	SC	1 (a)	1	1 (e)	1 (R)	4	The unit in the machine park is on standby against failure of machine in the reactor hall or remote work shop or unscheduled shut down of second reactor. Standby unit may be required at short notice.
Duct servicing machine	DS	1 (a)	-	1	1 (R)	3	A unit on immediate standby is required in case of an operational unit failure during a duct change or if a new duct is to be fitted.
Door manipulator	DM	1 (a)	-	1	1 (R)	3	A unit on immediate standby is required in case of an operational unit failure during a door change, or if a new door is to be fitted or to cover an unscheduled shut down of the other reactor.
Internal manipulator	IM	1 (a)	-	1 (R)		2	An immediate standby unit is not required as there is time to bring a unit in maintenance up to operational status. Maintenance periods can be integrated with reactor maintenance cycle.
Segment dismantling/ assembly machine	SD	-	2	1 (e)	1 (R)	4	Two operating units are required to cover the possibility of a segment having to be reworked. Two operational units and one standby unit are required in order to minimise component inventories.
Universal welding machines	UW	-	2	1 (e)	1 (R)	4	These units are assumed to be required for injector and divertor maintenance on a regular basis and for segment repair on an irregular basis. Two duty units and one immediate standby unit are required in order to minimise component inventories.
Injector/diverter servicing machines	IS	-	1	1 (e)	1 (R)	3	A unit is required on immediate standby to minimise injector/ divertor inventories.
Heavy duty cutting machine	CM	-	-	1 (e)	(R)	1	This machine is required for scrap concentration and for general purpose metal cutting when thick sections are involved. Will normally operate in remote workshop.
Circulator servicing machines	BS	-		2	1 (R)	3	Two units are required on immediate standby to cover the case of both reactors being shut down due to circulator failures.
General purpose mobile crane	MC	-	-	1	(R)	1	
General purpose manipulators	GPM	3	2	2	(R)	7	One unit is in each reactor hall, two on duty in remote workshop performing miscellaneous small servicing tasks, two units in maintenance/standby park and one performing miscellaneous inspection tasks in remote workshops or reactor hall or steam generator trench. Immediate standby in machine park is not required as emergencies can be covered by other operating machine
Transporter units	TU	3 + 5(a)(d) + 2(b)	6 + 2(b) + 3(c)	1	2 + 2(f)	26	Assume duty machines fitted with TUs. Immediate standby covered by other operational machine. However, to cover case of limited access, one standby unit is provided.

Table E3
Servicing Machine Inventory

Notes

(R) Service in rotation but normally arranged so that machines are available during scheduled reactor shut downs.

(a) These machines are only in the reactor hall when a segment exchange is taking place, normally parked on standby.

(b) Transporter units on location but being recharged.

(c) Transporter units on duty as mobile pallets.

(d) Including one unit for segment/diverter/vac. pump transfers.

(e) Parked in remote workshop machine park.

(f) Two transporter units on duty doing routine transfers in maintenance/parking facility.

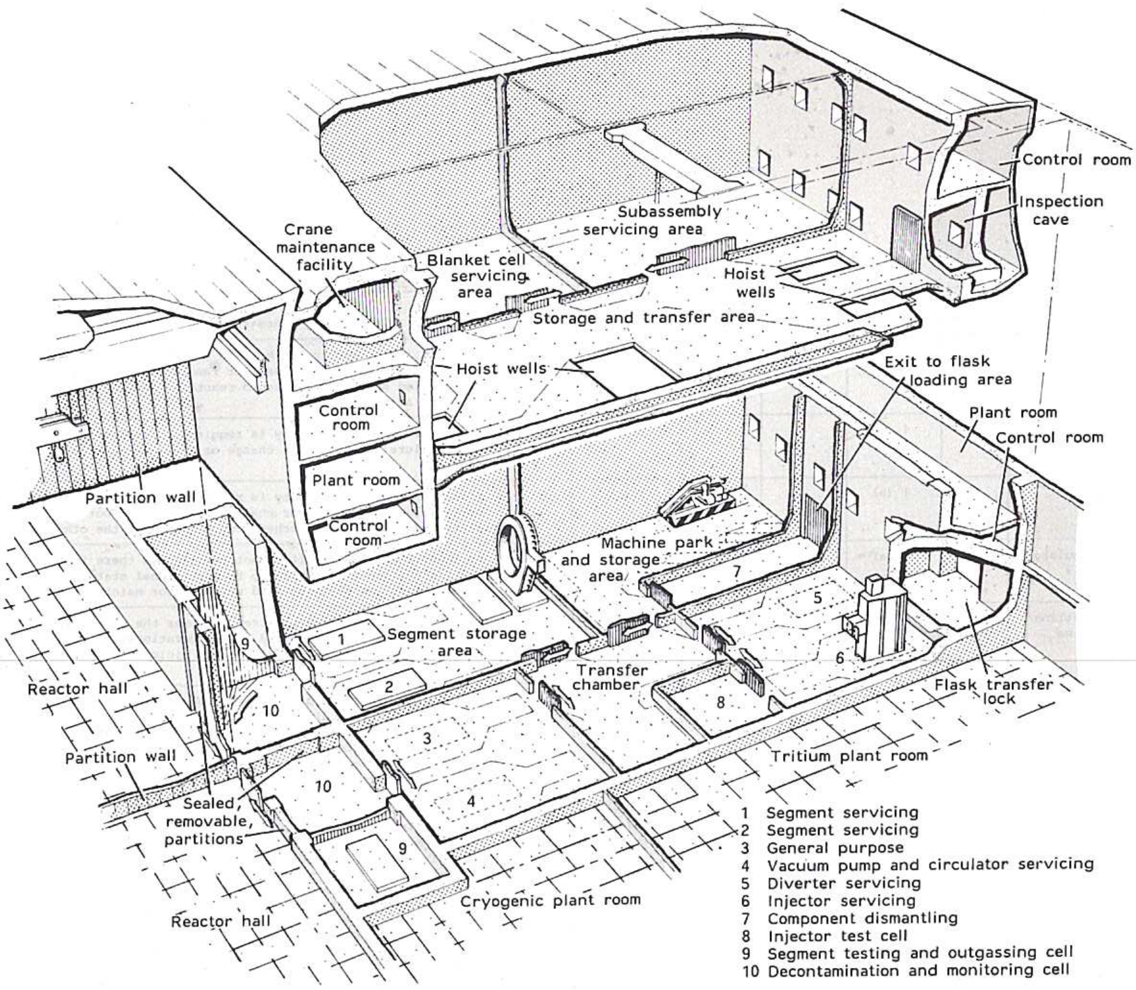


Fig.E6 Remote workshop facility.

(a) a system in which the modules are traversed past a series of fixed work stations, or

(b) a system in which the module remains stationary and is serviced by interchangeable special purpose mobile machines.

The latter system is preferred because:

i. Preliminary inspection suggests that it will require ≅100 m² less area.

ii. Machine maintenance will be easier because the servicing machines are free ranging and they can transfer to the contact workshop when required.

iii. Less cranage is required because all maintenance lifts will be executed in the contact workshop.

iv. Control rooms with direct viewing can be sited close to the work station.

The RWF is designed with two floors:

- the ground floor containing facilities for dismantling large units; and
- an upper floor containing machines for refilling and refurbishing blanket cells and facilities required for repairing failed sub-assemblies e.g. central cores removed from injectors.

Equipment transfers between floors are achieved by the installed crane.

The ground floor facilities comprise six component work stations, each of which is:

- fitted with a suitable plinth or mounting fixture;
- adjacent to a dedicated control room; and
- accessible to free ranging servicing machines.

The work stations are:

- two segment parking stations (No.1 and 2) each provided with a plinth of the same height as the fixed shield floor. One station will normally be in use, the other immediately ready for use;

- one pump/blower servicing station (No.4);
- one divertor servicing station (No.5);
- one injector servicing station (No.6);
- one general purpose work station (No.3) which can, with the provision of suitable fixtures, accept any component.

Additional features include: an injector test cell, component and mobile machine parking areas, scrap concentration and monitoring facility, segment outgassing cells, a hoist well and air-lock/decontamination cells.

The upper floor contains the blanket cell servicing facility (BCSF), subassembly servicing bays and a conventional shielded cave.

Internal partition walls are provided to limit the spread of contamination and tritium; critical permanent features such as air locks are duplicated for improved reliability. An allowance of free space has been included for component storage e.g. blanket cells, and as a contingency to cover as yet unidentified small maintenance tasks.

In the absence of data on the activation of divertors and injectors the walls are the same thickness as those of the reactor hall and are clad with aluminium to limit tritium permeation.

E5. REMOTE SERVICING MACHINES

The active area servicing concept requires that all mobile plant should be manually maintained in a contact workshop. As machines will be subjected to particulate and tritium contamination their design must allow decontamination and monitoring and should of course minimise the potential for contamination.

Each machine will be enclosed by removable cover plates and the resulting voids will be pressurised with an inert gas. Prior to leaving the work site each machine would deposit its peripherals for separate decontamination or disposal. This concept offers the following advantages:

(a) The pressurised void can be monitored continually for leakage and the machine withdrawn from service should this become significant. Prior to entering the manned areas the void can be sampled for tritium content. Thus the sensitive (and expensive) components ought not to become contaminated with tritium.

(b) The cover plates can be discarded, with little cost penalty, should they become contaminated.

(c) The preliminary decontamination process can be rigorous since only cover plates are involved.

The following general assumptions have been used in inventory estimates:

i. It is desirable to minimise reactor servicing times and so keep component inventories as small as possible and minimise the requirements for active storage.

ii. The manipulative and traversing elements of all servicing machines are separated so that interchangeable transporter units can mate with, and transfer, all servicing machines. The same design of transporter unit is used to move components such as injectors and divertors and is used for routine load carrying. The transporter units are self contained and utilise pneumatic lifting pads.

iii. Inventories are based upon routine servicing and minor maintenance operations only. Non-routine, low probability maintenance may require additional machines to be imported.

iv. A high degree of automation will be available in the machine servicing facility e.g. automatic checkout and diagnostic equipment.

The reactor hall will be provided with two, remotely operating, overhead travelling cranes whose crabs will cover the entire reactor hall area. Each crane crab will carry a heavy duty manipulator in addition to the hoists. A second set of rails will be fitted under the main crane rails to carry separate overhead manipulators.

The inventory of ground based servicing machines, together with the basis for estimation, is given in Table E3.

E6. MACHINE PARK AND CONTACT WORKSHOPS (Fig. E7)

The ground floor of this facility contains the airlock access to the reactor hall and the remote servicing machine park and maintenance workshop. The upper floor comprises change rooms, small component workshops and the ventilation plant.

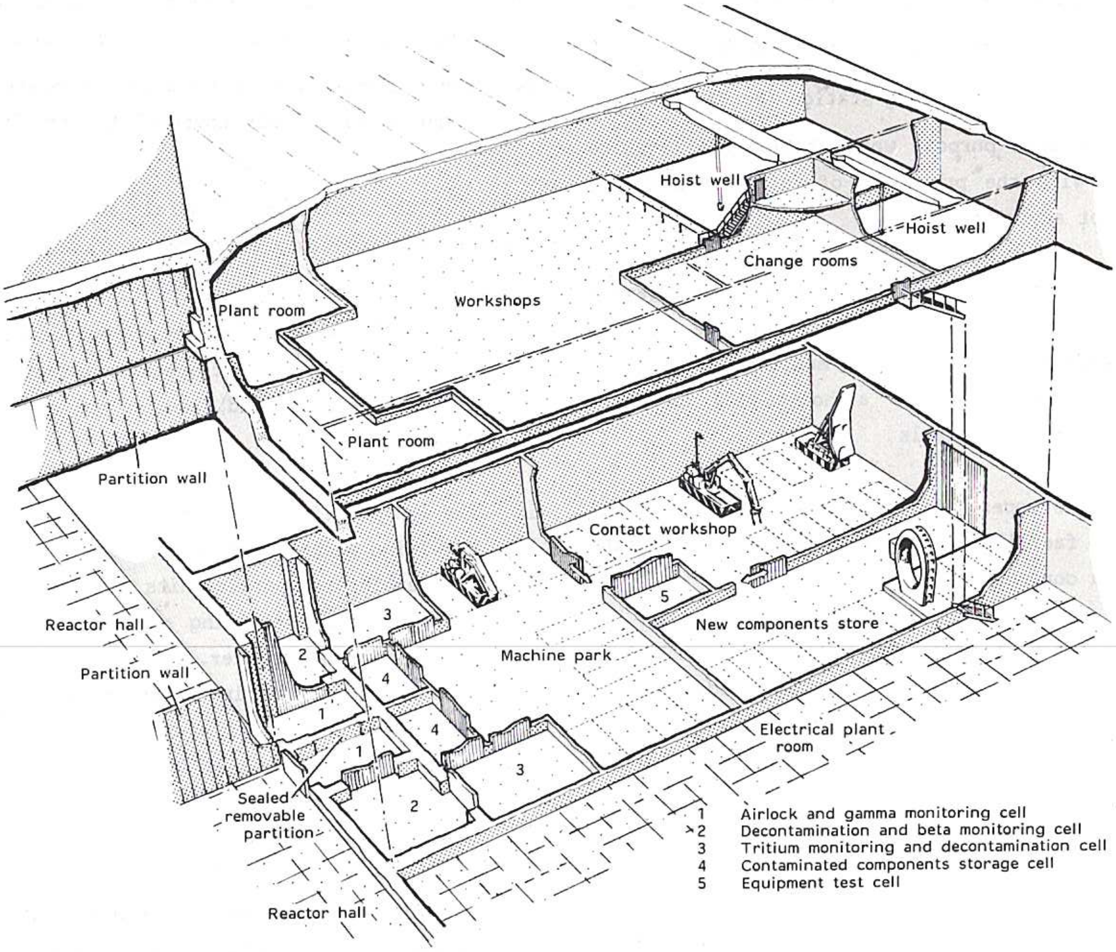


Fig.E7 Machine park and contact workshop.

The operating philosophy requires that currently non-employed but available machines, apart from those on immediate standby in the RWF or reactor hall, should be held in a powered up state with on board control systems energised and linked with the central control system. These machines will be located in the parking area and, as their operational status will be continually monitored, they will be immediately available for transfer into the active areas. Machines requiring maintenance will be transferred into the contact workshop.

The contact workshop is divided into bays so that:

- inspection, functional testing and fault diagnosis will take place in the primary assessment bay;
- routine servicing or minor repair will take place in the routine servicing bay; and
- major servicing will take place in the main workshop areas.

The areas provided are based upon the machine inventory defined in Table E3.

E7. REFERENCES

E1. Mitchell, J.T.D. Private communication, February 1980.

E2. Mitchell, J.T.D. Private communication, November 1980.

APPENDIX F

DETAILS OF REACTOR HALL

F1. CONSTRUCTION

F1.1 Walls and roof

Arched and flat roofs were assessed and a flat roof selected on the following grounds:

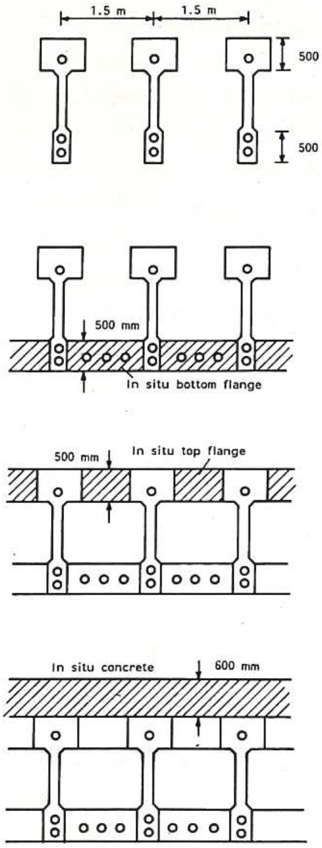
(a) An arch is inherently more expensive than a flat slab where a minimum thickness is specified because of: increased materials usage, more difficult construction techniques and more complex wall design (to carry the horizontal loads imposed by the roof).

(b) An arched roof would require extensive temporary falsework during construction, increasing the overall construction cost.

(c) Horizontal loads, due to seismic forces would be more severe for an arch than for a slab.

In this application it is necessary that the roof should be self supporting during all stages of its construction. A cellular, post tensioned slab is used comprising pre-cast, pre-tensioned, concrete I-beams and in situ cast infill panels as illustrated in Fig. F1. The imposed loadings used to derive this design are:

External pressure	10 kN/m^2
Allowance for cladding	5 kN/m^2
Allowance for finishes	1 kN/m^2
Allowance for additional loading	1.5 kN/m^2



1. Precast 2 m deep I beams and apply partial pre-stress Note. Beams may be constructed on site or manufactured in shorter lengths in a factory and then joined on site. Erect pre-cast beams on supporting walls

2. Using permanent shuttering cast the bottom flange of the slab incorporating additional tendons. Increase pre-stress in I beam tendons and apply pre-stress to new tendons

3. Using either permanent or temporary shuttering cast top flange. Increase pre-stress in all tendons

4. Cast remaining thickness of top flange to give total thickness of 1.6 m

Fig.F1 Roof construction sequence.

It should be noted that incremental post tensioning will present constructional difficulties and high levels of technical competence and supervision will therefore be required.

The interfaces between the walls and roof have not been examined and detailed analysis will be required to ensure that the design will meet seismic criteria. The magnitude of the horizontal seismic loading will define the need for additional buttresses to support side walls. The 115 m long side walls, including any buttresses, will be constructed conventionally from reinforced concrete.

This roof design will be suitable, with some modification, for spans slightly in excess of 50 m. The roof cost will be approximately proportional to span up to 60 m after which a different design may be required with a corresponding step change in costs.

It is envisaged that the end walls should be constructed from interlocking concrete blocks so that they can be removed for a major repair. The detailed design of the blocks will require careful study and tests to ensure structural and containment integrity under all specified conditions including seismic shock.

F1.2 Foundations

The reactor hall foundations have a complex geometry, illustrated in Fig. F2. The design is based upon ground having a load bearing capacity of 69 tonnes/m^2. A detailed design will require much additional information e.g. of site conditions and load distributions during all constructional and operational phases, means for de-coupling reactor and building foundations, temperature effects and seismic effects.

F1.3 Material quantities

The required material quantities are given in Table F1.

TABLE F1

MATERIAL QUANTITIES

	Concrete m^3	Reinforcement tonnes
Reactor hall foundations	65,000	150
Reactor hall superstructure	73,000	1,000
Remote workshop facility, foundations and superstructure	53,000	500
Tritium plant rooms, electrical plant rooms, contact workshop and machine park, foundations and superstructure	57,000	1,150

F2. PARTITION DOORS

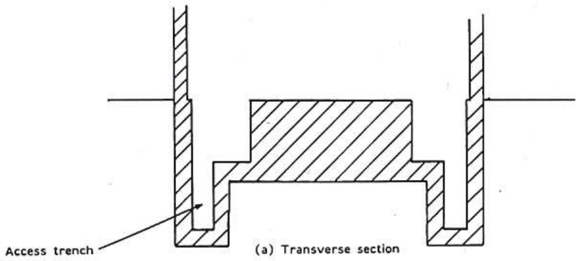
The reactor hall incorporates a set of partition doors set midway between the two reactors. They will be normally closed and their principal functions will be:

(a) To prevent tritium, accidentally released from one reactor or an in-transit segment, from contaminating the whole reactor hall.

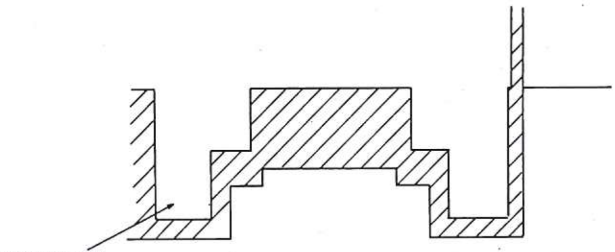
(b) To allow major non-routine maintenance (typically according to the procedures described in Appendix E2) without affecting operation of the other reactor.

(c) To minimise radiation levels on magnet coils; the reactor fixed shield is designed to limit the radiation level seen by the magnet coils to ≅4000 Rad/hour. The dose rate between two adjacent reactors would be approximately 8000 Rad/hour if no shielding is provided i.e. double the magnet design limit.

(d) To minimise the radiation levels on servicing machines traversing the reactor hall.



(a) Transverse section



(b) Longitudinal section

Fig.F2 Layout of foundations.

(e) To protect each reactor and its ancillary systems from damage from missiles caused by a malfunction in the other reactor.

(f) To reduce the radiation levels from an operating reactor so as to allow the construction and operation of a temporary facility adjacent to the other reactor.

It is necessary therefore, that the doors should be massive and act as a ventilation barrier.

The proposed design, Fig. F3, comprises a horizontal sliding door of the same height as the lower crane rails to provide approximately 6 m wide access at the centre and a vertically sliding door which will be raised to allow the crane/manipulator to pass. The horizontal element will be carried by a pneumatic film system and restrained by the adjacent structures and the vertical element lifted by winches mounted on the roof. Their thickness will be defined by requirement (f) above.

F3. INTERNAL FINISH

The internal surfaces of the reactor hall walls and roof are clad in aluminium sheet, selected because of low tritium permeation. The aluminium sheet will be attached to vertical rolled sections fixed to the concrete structure and welded to form a continuous lining. A gap will be required between the cladding and concrete to facilitate construction and inspection: in operation this gap would be purged with nitrogen at reactor hall pressure and

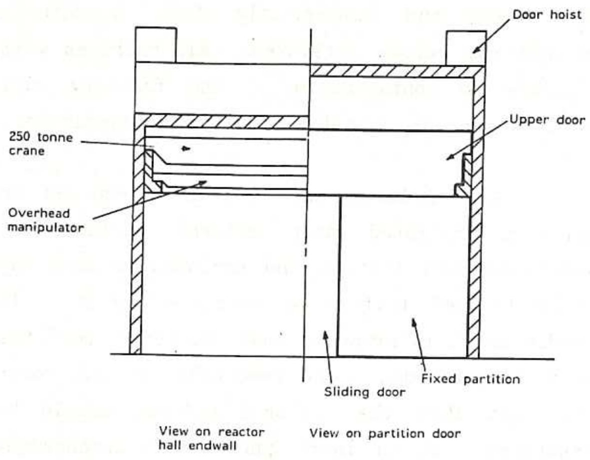


Fig.F3 Arrangement of cranes and partition doors.

regularly sampled for tritium.

The floor will comprise steel plates formed into a membrane which is laid directly onto the concrete floor with the necessary expansion joints. Removable bridge sections will be provided over the steam generator trench.

F4. SERVICE DUCTS

Services will run from each reactor to its associated turbine hall, electrical plant room, tritium plant room etc. It is necessary that each type of service should be segregated, and in certain cases duplicated, to ensure adequate reliability and maintainability. The services will be run in underground service ducts and the following minimum will be required for each reactor:

- a steam and condensate return duct;
- a duct for electrical power cables;
- a duct for tritium and tritiated process fluids;
- shield cooling water duct; and
- a control cable duct.

The ducts will each be provided with sealed bulkheads corresponding to the main containment barriers and will be sized to provide access for remote servicing and test machines. Ducts which are open to contaminated or potentially contaminated atmosphere must be continually purged with clean gas and sampled, particularly for tritium.

From Fig. 5 and 6 it can be seen that there will be space available under the reactor hall floor between the steam generators. This space can be used for smaller items e.g. rotary vacuum pumps associated with injectors and divertors.

F5. REACTOR HALL CRANE MAINTENANCE FACILITIES (Fig. F4)

It is envisaged that each overhead crane and overhead manipulator will have a built in maintenance capability in that the crab, main drive and onboard control modules can be lowered onto the reactor hall floor using onboard emergency actuators or actuators on another high level machine. A minimum of in-situ maintenance will therefore be required and it is probable that it can be completed by remote machine or by manually operated through-the-wall tools located in the crane maintenance facilities.

Two crane maintenance facilities are provided at high level, one at either end of the reactor hall, which can be isolated from the reactor hall by vertically sliding doors. It is not necessary that these doors are shield doors, as radiation sensitive onboard components can be locally shielded and manual access is unlikely to be required.

F6. AIRLOCKS AND DECONTAMINATION FACILITIES

F6.1 Introduction

There are five types of facility defined in Appendix D7 and these must be segregated to ensure plant and personnel safety, proper atmosphere control and to limit the spread of tritium. Intermediate access points must therefore maintain shielding and containment integrity and adequate decontamination equipment must be provided. The following inter-facility access points are required:

i. reactor hall - remote workshop;

ii. reactor hall - machine park/contact workshop;

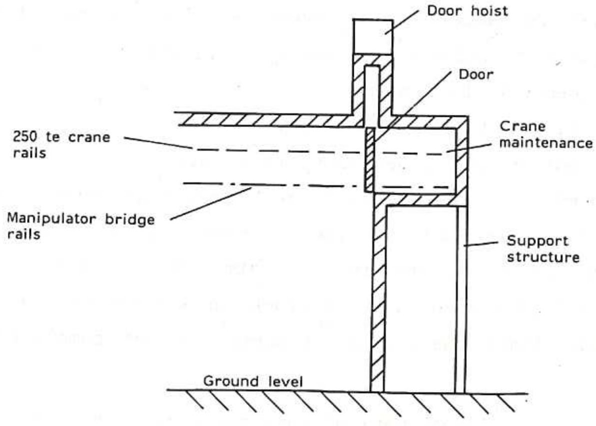


Fig.F4 Crane maintenance facility.

iii. contact workshop - non-active areas;

iv. remote workshop - non-active areas;

v. tritium plant room - non-active areas;

vi. remote workshop - tritium plant room (emergency access only).

The access facility between the reactor hall and machine park/contact workshop will be the most critical on the basis of radiological hazard and frequency of usage and this facility is used as an example described below.

F6.2 Reactor hall - machine park access point

The function of the decontamination system is to allow routine and unscheduled machine and component transfers to and from the reactor hall while:

- preventing contamination of the reactor hall atmosphere by external gases or impurities;
- preventing the potentially contaminated reactor hall atmosphere from reaching the manned areas or the environment;
- maintaining shield integrity;
- preventing the transfer of radiation sources or contaminated plant to the manned areas by a combination of monitoring and rigorous decontamination procedures.

Atmosphere exchange can be achieved by sequential pumping/purging operations but this process will be expensive in terms of plant capital and maintenance costs for plant duplicated to provide adequate reliability. As the reactor hall is to be filled with nitrogen and since liquid nitrogen is inexpensive the following alternative process is proposed. For outward transfers the airlock is pressurised with nitrogen from an evaporator, and vented into the reactor hall or the ACU intake so that contamination is prevented from leaving the system containment. The pressurising and venting sequence to be continued until the airborne activity level has fallen to the desired level. For inward transfers it is necessary to ensure that no oxygen enters the reactor hall so the nitrogen purge gas will be vented into a local treatment plant prior to exhausting to the external atmosphere. Once the level of oxygen in the airlock has reached an acceptable limit the machine transfer can be completed.

Remote manipulators and other machines may be required to work in close proximity to an operating reactor and consequently their structural materials may become activated; all machines will be liable to contamination. The facility must therefore include suitable monitoring facilities.

All machines may have been exposed to tritium or tritiated water, external surfaces may contain absorbed tritium and enclosed volumes may contain trapped tritium or tritiated water. In Appendix E5 it is proposed that the remote machines should be provided with removable sealed cover plates and that the enclosed volumes should be pressurised with an inert gas. This arrangement will allow:

- a rigorous decontamination process to be adopted;
- cover plates which are still contaminated after the initial treatment to be removed prior to machines being admitted to the manned areas. These covers can be reprocessed within the access facility or scrapped;
- internal volumes can be sampled for tritium.

The tritium decontamination process will be required at frequent intervals and should be executed rapidly for economic reasons.

The facility is laid out as shown in Fig. E7. Two parallel systems are provided to ensure availability. An interconnecting door for emergency use is located between the two innermost chambers (1) to ensure adequate access if one reactor hall is tritium contaminated. Each system comprises:

- an atmosphere exchange and gamma-monitoring chamber (1);
- a particulate decontamination and beta-monitoring cell (2) using steam and/or water decontamination;
- a tritium monitoring and decontamination cell (3 - each chamber will include provision for cover plate removal);
- a small parts tritium decontamination cell (4).

The main shield doors will be approximately 10 m high x 3 m wide x 750 mm thick (if steel). Their weight will probably be too great to be carried by the building structure so they will be traversed using removable, pneumatic film transporters and are only attached to the building for restraint purposes. Reference 4 describes pneumatic seals for use on the reactor shield doors and a similar arrangement will be suitable for these doors providing adequate arrangements are made for maintenance.

F7. ON-SITE CONSTRUCTION

Assuming that on-site construction of reactor components is required (Section 2.2) facilities for stainless steel fabrication and coil winding must be provided as well as conventional facilities such as concrete casting yards. The location of conventional facilities is not critical, apart from the need to minimise on-site transport costs, and they can be sited anywhere near the work site. However it is desirable to use as many of the permanent facilities as possible so the fabrication and coil winding shops should be located at opposite ends of the reactor hall where installed cranes (extended as necessary) can be used and there is easy access for large components. Each facility is discussed separately below.

(a) Fabrication shop

The principal reactor components to be fabricated are: blanket segments, sections of fixed shield and shield doors all of which will be too large for conventional road transport. These components will be constructed from pre-fabricated subassemblies or from plate. For the purposes of this study it is assumed that:

- the shield doors are delivered in the form of subassemblies;
- segments are constructed from subassemblies;
- fixed shield sections are constructed from pre-cut plate;
- components will require machining prior to and during assembly;
- shield doors will require filling with FeMn spheres;
- comprehensive in-process and final inspections will be required.

Several thousand blanket cells will be required and it is assumed that these will be delivered as components and assembled in the permanent cell servicing facility. Similarly the blanket segments can be fitted out with blanket cells inspected and tested in the remote workshop. Apart from the obvious economic advantages to the above procedure there is an associated technical advantage viz. an extended period of inactive commissioning of all the remote workshop facilities.

The layout of the fabrication shop is shown in Fig. F5.

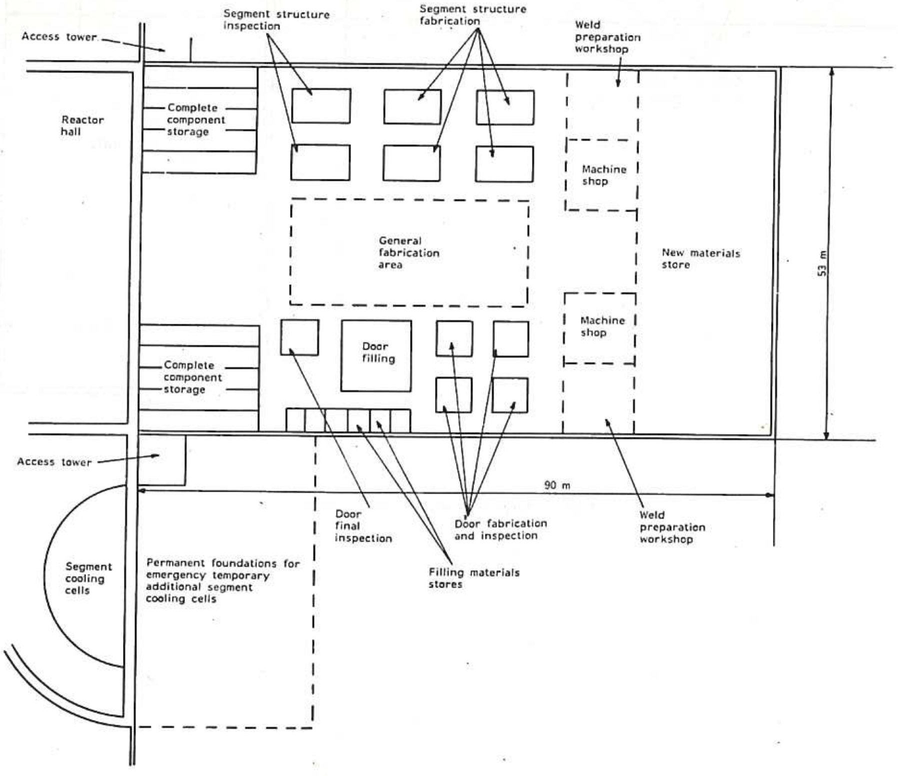


Fig.F5 Layout of fabrication shop.

(b) Coil winding shop

Coils which will probably require on-site winding and assembly are the TF coils and the larger PF coils (diameter ≧15 m). The required facilities are shown in Fig. F6. The dimensions shown represent the minimum requirement and practical considerations may require the length to be increased.

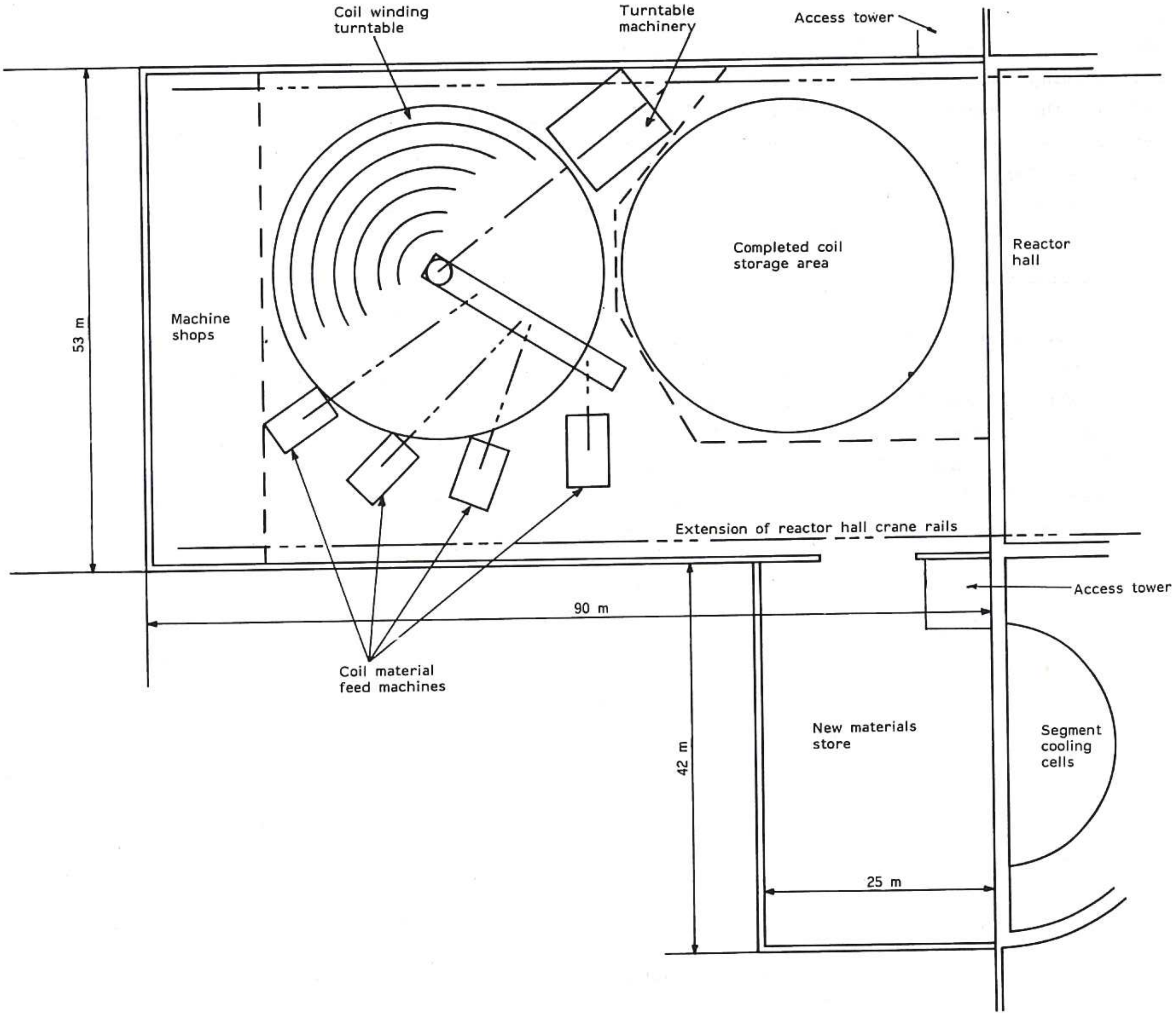


Fig.F6 Layout of coil winding shop.

DIRECT CAPITAL COST ANALYSIS

The IAEA account numbers which relate to construction capital costs are reproduced in Table G1 with direct capital cost figures for three power stations i.e.:

(a) 1.2 GW_e single reactor power station based on CCTRII with a Li metal blanket.

(b) 1.2 GW_e single reactor power station based upon CCTRII with a solid Li compound blanket for the one reactor as defined in this study.

(c) 2.4 GW_e twin reactor power station as defined in this study.

So that they shall be directly comparable all costs are given in the same values as the original Hollis and Evans study[10] - namely mid 1977.

The costs are derived as follows:

- the costs derived by Hollis and Evans are reproduced for (a). The total cost is modified, as noted in the table, to facilitate comparison;
- the costs for the nuclear complex - excluding the reactors - for the twin reactor power station are estimated on the outline design contained in this report. Costs for the reactors and conventional systems are extrapolated from the costs quoted in Ref. 10;
- the costs for (b) are taken from Ref. 10 or extrapolated from the cost data for (c) making allowances for the lack of common facilities.

The total direct capital costs for the original and modified single reactor power stations are £950.8M and £859.6M respectively (1977 values). This difference, of £91.2M, is due to:

- the change of breeder i.e. dump tanks and associated circuitry are not required;

Account No.	Item	Cost of single reactor power station (Ref.10) £M	Revised cost of single reactor power station £M	Cost for twin reactor power station £M	Remarks
	211 SITE IMPROVEMENTS AND FACILITIES				
211.1	General yard improvements.	4.5	3.0	5.0	Scaled from Ref. 10 on basis of building areas for the whole station.
	212 REACTOR BUILDINGS				
212.1	Basic building structure.	25.0	30.0	52.4	Includes basements and foundations for heat exchangers
212.2	Building services	9.0	2.5	5.0	Scaled from Ref.10 on basis of building volumes.
	213 TURBINE BUILDINGS				
213.1	Turbine hall.	20.0	20.0	40.0	
213.2	Water treatment, etc.	0.5	0.5	1.0	
213.3	Oil store.	0.1	0.1	0.1	
213.4	Fitting and machine shop.	2.0	2.0	3.0	
213.5	Heating and ventilation.	1.0	1.0	2.0	
	214 INTAKE AND DISCHARGE STRUCTURES				
214.1	Intake structure.	9.7	9.7	15.0	
214.2	Discharge structure.				
214.3	Unpressurised intake and discharge				

Table G1
Direct Capital Cost Breakdown

Table G1 – Continued

- the modified design requires buildings with smaller volumes so that the costs of services are less although construction costs are expected to be higher;
- the requirement for fixed blanket/injector servicing equipment is reduced in the modified design;
- the costs of mobile machines are less for the modified design and are based upon fairly detailed estimates of machine requirements and previous cost estimates.[4]

The direct capital costs for two single reactor stations and one twin reactor station are £1719.2M and £1659.3M respectively (1977 values). This economy is realised as a result of the twin reactor station utilising shared facilities such as remote workshops, access locks and servicing machines.

Account No.	Item	Cost of single reactor power station (Ref.10) £M	Revised cost of single reactor power station £M	Cost for twin reactor power station £M	Remarks
	215 REACTOR AUXILLARIES BUILDINGS				
215.1	Blanket/injector maint. building	7.5	13.5	13.5	
215.2	Blanket assembly, workshops, control room	21.0	10.0	10.0	
215.3	Li process building	0.5	-	-	Not required since breeder is assumed to be solid.
215.4	Cryogenic plant room	0.8	-	-	Cost included under tritium plant room (see below).
215.5	Heat exchange building	0.5	-	-	Not required - heat exchanges located in reactor hall.
215.6	Gases storage building	0.5	-	-	Cost included under tritium plant room (see below).
	216 RADIOACTIVE WASTE BUILDINGS				
216.1	Effluent treatment building	2.5	-	-	Cost included under tritium plant room (see below).
216.2	Radioactive waste building	0.3	-	-	Cost included under tritium plant room (see below).
	218 MISCELLANEOUS				
218.1	Control room building	*	-	-	Not required since the control rooms are integral with the reactor halls.
218.2	Diesel generator building	1.0	1.0	1.5	
218.3	Admin. and welfare building	2.5	2.5	4.0	
218.4	Services building and laundry	0.5	0.5	0.75	
218.5	Ventillation plant room	0.4	0.4	0.6	
218.6	Helium storage building	0.5	-	-	Cost included under tritium plant room (see below).
	219 STACKS				
219.1	Exhaust ventillation stacks	0.4	0.4	0.6	
	221 REACTOR EQUIPMENT				
221.5	PRIMARY TOROIDAL STRUCTURE				
221.51	Removable blanket structure	60.7	90.0	180.0	Number of segments increased to 30/reactor to allow for aftercooling
221.52	Toroidal field coils	60.0	60.0	120.0	
221.53	Poloidal field coils	52.0	52.0	104.0	
221.54	Fixed shield structure and doors	40.7	40.7	81.4	
221.55	Transformer core	68.0	68.0	136.0	
221.56	Support structure	0.8	0.8	1.6	
221.6	PRIMARY REACTOR EQUIPMENT				
221.61	Li circulation and storage	9.5	-	-	Assumes solid Li compound in blanket
221.62	Fixed shield cooling	3.5	3.5	7.0	
221.63	Cryogenics	11.0	11.0	22.0	
221.64	Vacuum equipment	6.0	6.0	12.0	
221.65	Injectors/refuellers	80.0	80.0	160.0	
221.66	Fuel system and storage	2.0	-	-	Cost included under tritium purification and treatment plant.
221.7	REACTOR ANCILLARY EQUIPMENT				
221.71	Shield doors for storage position	2.0	2.0	4.0	
221.72	Rail tracks	0.5	-	-	Not required.
221.73	Cranes within reactor hall	1.1	1.0	2.0	Includes overhead manipulators.
221.74	Cooling circuits in storage bays	0.5	0.5	1.0	
221.75	Cooling circuits for containment structure	1.0	1.0	2.0	
221.76	Installed closed circuit TV	1.5	1.5	3.0	
221.77	Containment vacuum and tritium system	1.0	-	-	

Table G1 – Continued

Account No.	Item	Cost of single reactor power station (Ref.10) £M	Revised cost of single reactor power station £M	Cost for twin reactor power station £M	Remarks
221.8	BLANKET AND INJECTOR HANDLING SYSTEMS				
221.81	Installed cell equipment and controls	50.0	12.0	20.0	Includes blanket cell servicing line, test cells and scrap handling facility.
221.82	Trolleys	50.0	10.0	15.0	Extrapolated from cost data in Ref.4 (∿ £625K/machine)
221.83	α, β, γ cell line.	0.5	-	-	Included in remote workshop facility.
221.84	Rail tracks and turntables	2.0	-	-	Not required.
221.85	Cranes	1.8	0.8	0.8	
221.86	Closed circuit TV	1.5	1.0	1.0	Scaled on reduced building volumes.
221.87	Services	2.5	2.5	2.5	
	222 MAIN HEAT TRANSFER AND TRANSPORT SYSTEMS				
222.11	Helium circulators	30.0	32.0	64.0	Revised estimate based upon Ref.C3
222.12	Helium ducts and fittings	15.0	14.0	28.0	
222.13	Heat exchangers	44.0	55.0	110.0	Revised estimate based upon Ref.C3
222.14	Auxillary circuits	1.9	1.9	3.8	
	224 RADIOACTIVE WASTE TREATMENT AND DISPOSAL				
224.1	Liquid waste processing equipment	1.0	-	-	Included in tritium process plant (see below)
224.2	Gaseous waste processing equipment	1.2	-	-	Included in tritium process plant (see below)
	226 OTHER REACTOR PLANT EQUIPMENT				
226.1	Inert gas systems	0.5	0.5	1.0	
226.3	Coolant receipt, storage, make-up	0.5	0.5	1.0	
226.5	Fluid leak detection	5.0	5.0	7.5	
227	Instrumentation and control	31.0	31.0	62.0	
231	Turbo generators	55.0	55.0	110.0	
232	Heat rejection systems	4.9	4.9	9.8	
233	Condensing systems				
234	Feed heating system	3.9	3.9	7.8	
235	Other turbine plant and equipment	10.4	10.4	20.8	
236	Instrumentation and control (T/G)	3.0	3.0	6.0	
241-6	Electrical plant and equipment	30.0	30.0	60.0	
247	Power supplies to field coils	40.0	40.0	80.0	
251	Transportation and lifting equipment	5.3	5.3	10.6	
252	Air and water service systems	4.4	4.4	6.5	
254	Furnishings and fixtures	2.0	2.0	2.0	
*	Tritium plant room	*	9.4	18.8	
*	Tritium recovery & purification plant	*	10.0	20.0	
		909.8	859.6	1659.3	
	Cost adjustment, see Notes 4 and 5:	+ 41.0			
	TOTALS:	950.8	859.6	1659.3	

Table G1 – Continued

Notes:
1. The comments column refers to the modified single and twin reactor power station costs.
2. Items marked * are not included in Ref. 10.
3. Items underlined are new estimates based on this study - other figures are scaled as indicated.
4. For purposes of comparison with the new estimate the total derived by Hollis & Evans should be increased by £30M to include for spare blanket segments (Account No. 221.51).
5. The costs of the steam generators quoted by Hollis & Evans are increased by £11M to agree with recently published data (Ref. C3) and with estimates obtained from UK manufacturers.

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