CLM-R 205

CLM-R 205

CULHAM LIBRARY
REFERENCE ONLY

UKAEA

Report

DESIGN OF THE SHIELD DOOR AND TRANSPORTER FOR THE CULHAM CONCEPTUAL TOKAMAK REACTOR MARK II

CULHAM LABORATORY
LIBRARY
31 JUL 1981

J. A. S. GUTHRIE

CULHAM LABORATORY
Abingdon Oxfordshire

1980

C/18

Available from H. M. Stationery Office

£3.00

© - UNITED KINGDOM ATOMIC ENERGY AUTHORITY - 1980
Enquiries about copyright and reproduction should be addressed to the Librarian, UKAEA, Culham Laboratory, Abingdon, Oxon. OX14 3DB, England.

DESIGN OF THE SHIELD DOOR AND TRANSPORTER FOR THE CULHAM CONCEPTUAL TOKAMAK REACTOR MARK II

by

J.A.S. Guthrie

Associated Nuclear Services
123 High Street,
Epsom, Surrey,
KT19 8EB

ABSTRACT

In the Culham Conceptual Tokamak Reactor MKII (CCTRII) access to the interior for blanket maintenance is through large openings in the fixed shield structure. These are to be closed by removable shield doors when the reactor is operational. This report describes the design of the doors and the associated special-purpose remote operating transporter manipulator. Each door is a welded stainless steel box structure containing manganese iron and borated water shielding and carrying the outer, lead, gamma shield. The door periphery and frame are stepped to provide continuity of shielding and incorporate a pressurised elastomeric vacuum seal at the outer step where radiation levels are lowest. The design of the door manipulator transporter is based upon qualitative assessments of alternative systems and components against specific requirements. The manipulator comprises: the structure to support, lift and orientate the door, the principal motion and ancillary drives, local control, power supplies and backup systems. The self-contained, replaceable transporter utilises gas film bearing units and steerable electric traction motors. Control is by a combination of on-board and supervisory computers connected via a UHF link with provision for manual override. The times for door removal and replacement, including testing, are estimated to be 25 and 45 minutes respectively.

The study shows that the concept is generally within the present day state-of-the-art technology and suggests some further development studies e.g. pressurised elastomeric vacuum seals for use in radiation environments.

April 1980

ISBN 085311 089 1

CONTENTS

1. INTRODUCTION

2. SHIELD DOOR

2.1 Functional requirement
2.2 Design philosophy
2.3 Design
2.4 Manufacture
2.5 Reliability
2.6 Door frame
2.7 Estimated cost

3. TRANSPORTER/MANIPULATOR

3.1 Functional requirements
3.2 Design philosophy
3.3 Systems definition and evaluation
3.4 Vehicle parameters
3.5 Manipulator structure
3.6 Design of door manipulative system
3.7 Interfacing systems
3.8 Transporter services
3.9 Reliability assessment
3.10 Operating sequences and timings
3.11 Estimated costs

4. INTEGRATION WITH THE CCTRIIB CONCEPT

4.1 Door support
4.2 Height of reactor hall floor

5. CONCLUSIONS

5.1 Shield door and frame
5.2 Transporter/manipulator
5.3 CCTRII servicing

6. ACKNOWLEDGEMENTS

7. REFERENCES

APPENDICES

A. Shield door design

B. Neutron streaming

C. Shield door cooling

D. Transport design

E. Schedule of operations and timings

F. Fixed shield support

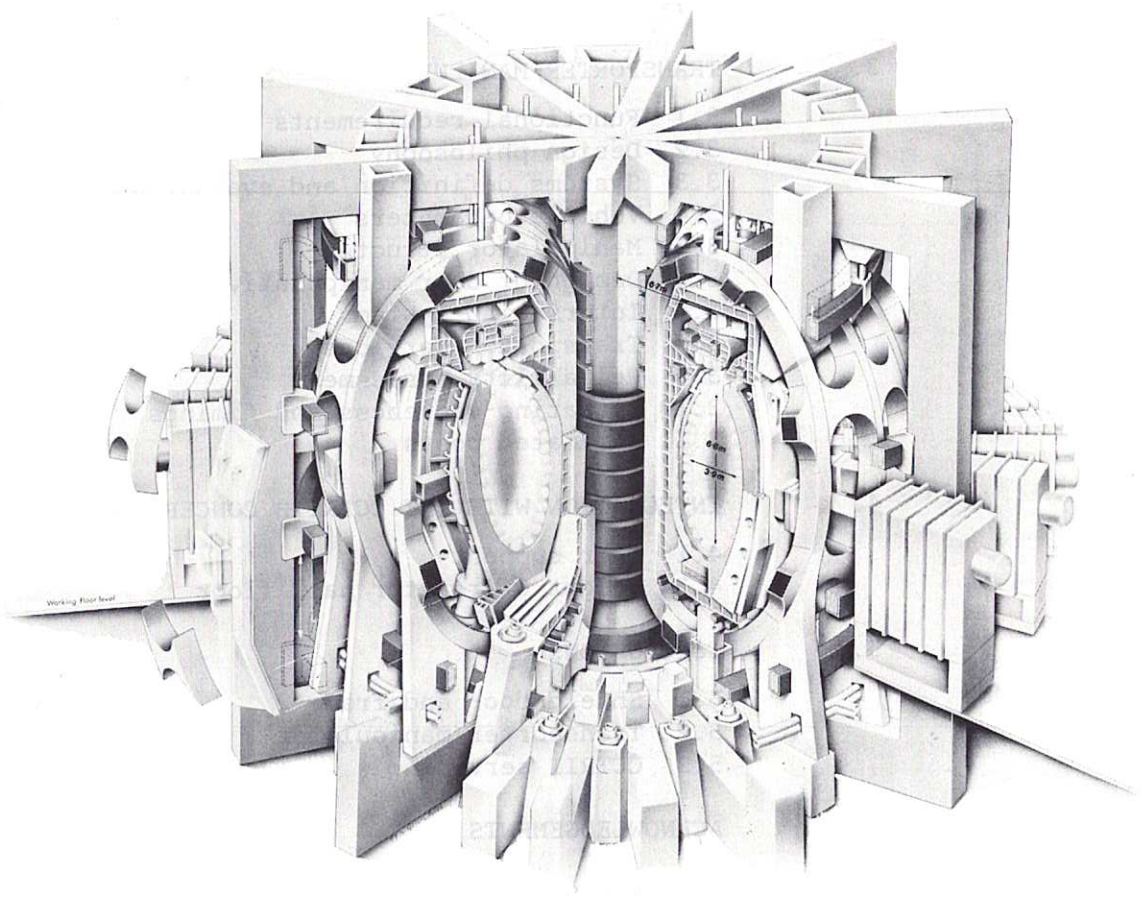


Fig.1 Artist's impression of Culham Conceptual Tokamak Reactor Mk.IIB.

1. INTRODUCTION

In comparison with other possible fusion reactor fuels, the combination of deuterium and tritium has the advantage of higher cross section and energy output. However, there are two less desirable consequences of this choice. First, the life of the structure surrounding the vacuum space will be limited by the economic requirement for high wall loadings, to a few years as a result of the damage caused by the high energy reaction-product neutrons. Second, the associated activation level in the structure will require that any exchange operation on the structure should use remote machines to eliminate radiation exposure to personnel.[1] It is obvious too that the reactor lifetime output should be maximised and therefore that the duration of all reactor shut-downs - or downtime - should be minimised.

The design of the Culham Conceptual Tokamak Reactor Mark II (CCTRII), Fig. 1, has been developed with these factors in mind.[2,3] In all Tokamak reactor concepts, the magnet windings are designed as discrete modular coils. In CCTRII, there are 20 toroidal field coils and the blanket and inner shield enclosing the toroidal reaction space is also divided into the same number of segments,[4] forming individual modules which can be replaced when necessary.

Access through the outer shield to execute the exchange operation is via openings in the shield between the toroidal field coils, so that the need to move these coils is eliminated. Each opening is closed by a 'shield door' so as to maintain the radiation shielding and the vacuum enclosure round the reaction space, Fig. 2. This report describes the design of the 200 tonne doors and the associated special purpose transporter/manipulator required for their remote replacement, Fig. 3.

Whilst attempting to examine all relevant aspects the study is only a preliminary scoping design, is not optimised, and incorporates simplifying assumptions (noted as relevant). The design generally uses available commercial equipment and state-of-the-art techniques and while future technological developments are unlikely to affect the structural design of either door or transporter it is certain that developments will be made in commercial equipment e.g. drives control systems etc., which would be incorporated in, and modify, any final design.

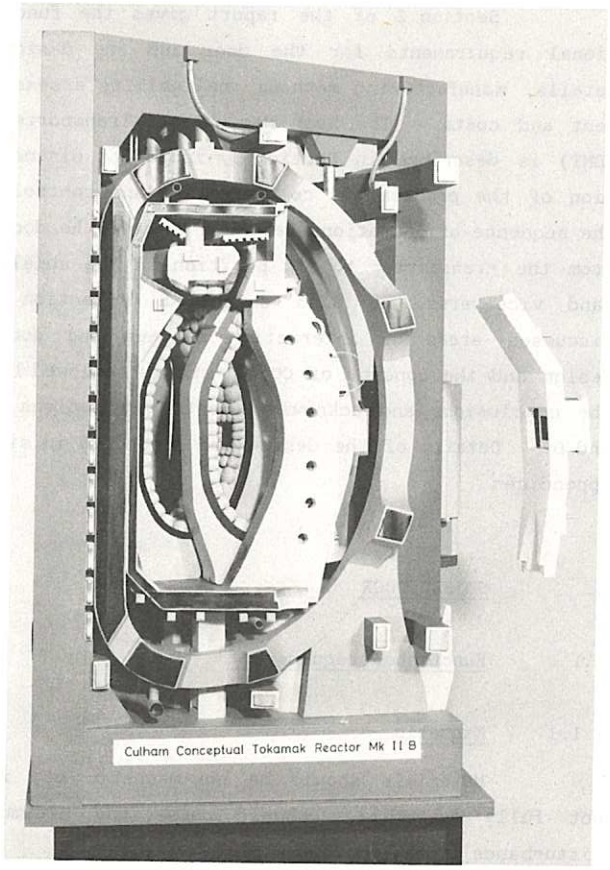


Fig.2 1/25 scale model of Culham Conceptual Tokamak Reactor Mk.IIB with door and segment partly withdrawn.

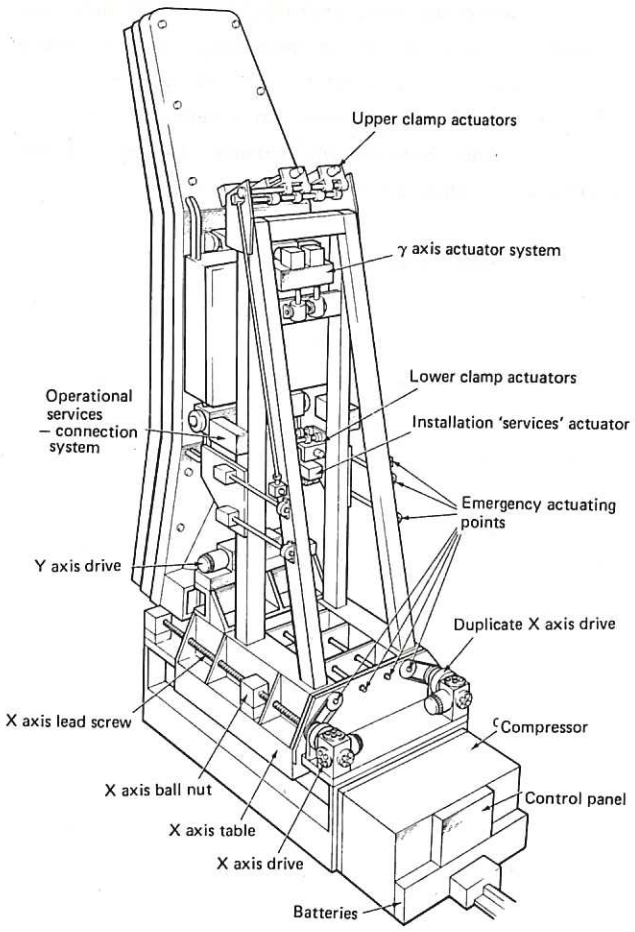


Fig.3 Door manipulator/transporter showing principal systems and emergency actuation points.

Section 2 of the report gives the functional requirements for the door and the design details, manufacturing methods, reliability assessment and costs. The Door Manipulator/Transporter (DMT) is described in Section 3, including discussion of the problems of communication and control. The sequence of operations required to move the door from the transporter to its position in the shield (and vice-versa) is also described. Section 4 discusses areas of interaction between the door design and the concept of CCTRII and is followed by the conclusions and acknowledgements in Sections 5 and 6. Details of the design are described in six appendices.

2. SHIELD DOOR

2.1 Functional requirement[5]

2.1.1 Magnetic

Materials should be non-magnetic or, if not fully austenitic, should cause the minimum disturbance to the applied magnetic field.

2.1.2 Shielding

Assuming that organic insulating material is used in the coils it is necessary that the total integrated dose is limited to 10^9 rad over 30 years, i.e. the shield must provide an attenuation of 10^{-3} to 10^{-4}. The attenuation through the door/frame interface gap should be of the same order.

2.1.3 Temperature

The maximum coolant temperature should be less than 100°C in order to maintain an unpressurised cooling system. However the door structure must be capable of withstanding approximately 150°C for outgassing.

2.1.4 Vacuum

The fixed shield, which includes the access doors, will form the primary vacuum enclosure and its base pressure will be in the order of 10^{-6} torr.

2.1.5 Pressure

The operational pressure difference across the door is likely to be 0.9 bar acting inwards. However a possible fault condition is failure of the coolant circuit in a breeding cell which could produce a net pressure difference of about 1 bar acting outwards (see Appendix A1).

2.1.6 Seismic and inertia loadings

It is probable that future UK fission reactors will be required to withstand earthquake loadings equivalent to an 0.25 g horizontal acceleration and the equipment must be designed so as to be capable of being safely shut down after such a loading. In the absence of specific criteria for fusion reactors the 0.25 g acceleration limit has been used in this design study.

2.1.7 Dimensions

The door dimensions are defined by the geometry of the segment and an optimisation (minimum size) of the fixed shield and coil system. The nominal dimensions used in this study are shown in Fig. 4.

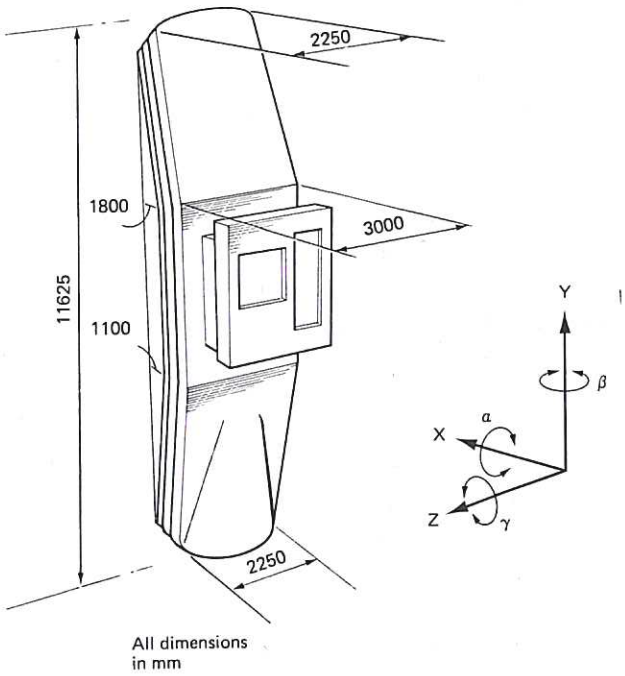


Fig.4 Door dimensions and axes of motion. Seal length = 2(11625 + 2250) ≃ 30 m.

2.1.8 Penetrations

The principal penetrations through the door are the injector and vacuum ports. Other penetrations (e.g. for diagnostic equipment, instrumentation etc.) will be required but their sizes and required locations are not yet known. Ideally the door design should not impose constraints on the locations of these penetrations.

2.1.9 Interchangeability

The door and frame should be designed so that cumulative manufacturing tolerances permit any door to fit any frame.

2.2 Design philosophy

To minimise reactor down time it is necessary that:

(a) the doors are interchangeable;

(b) all active mechanisms, associated with the door, are reliable and capable of rapid engagement;

(c) active mechanisms must remain operative between servicing operations;

(d) all active systems (on the door), e.g. cooling, vacuum, instrumentation etc., must be tested prior to withdrawal of the servicing plant and at intervals during their operating cycle.

The following preliminary design criteria, to be confirmed by cost/reliability analysis, were therefore established:

- the active elements of any mechanism should be located on the most accessible item e.g. the vacuum seals should be located in the door;
- where possible duplicate systems should be provided which are designed and operated so as to minimise common mode failures;
- any mechanisms should be capable of operation by the back-up, general purpose, robot manipulator. A current robot system of the type which will be required is MANTIS developed at CERN[6] (Fig. 5).

2.3 Design

2.3.1 General

The shield door is an internally braced welded box structure fabricated from stainless steel plate (Fig. 6 and 7). The internal partitions are

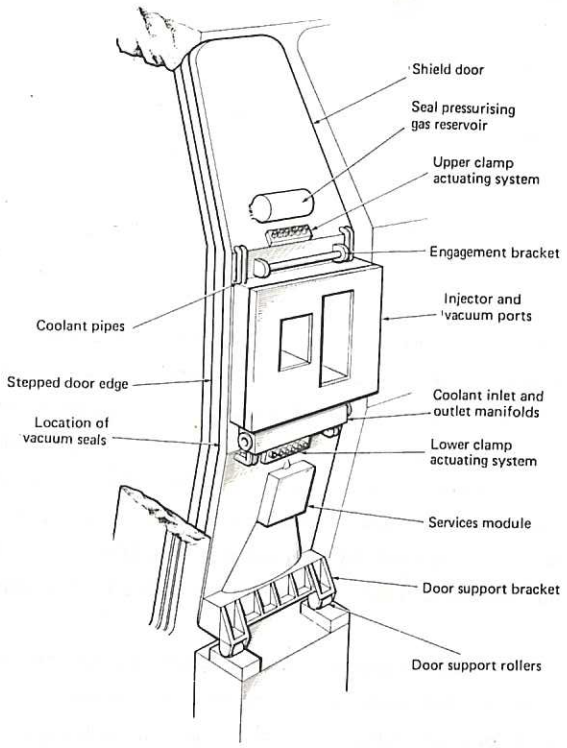


Fig.6 Shield door showing method of mounting and principal systems.

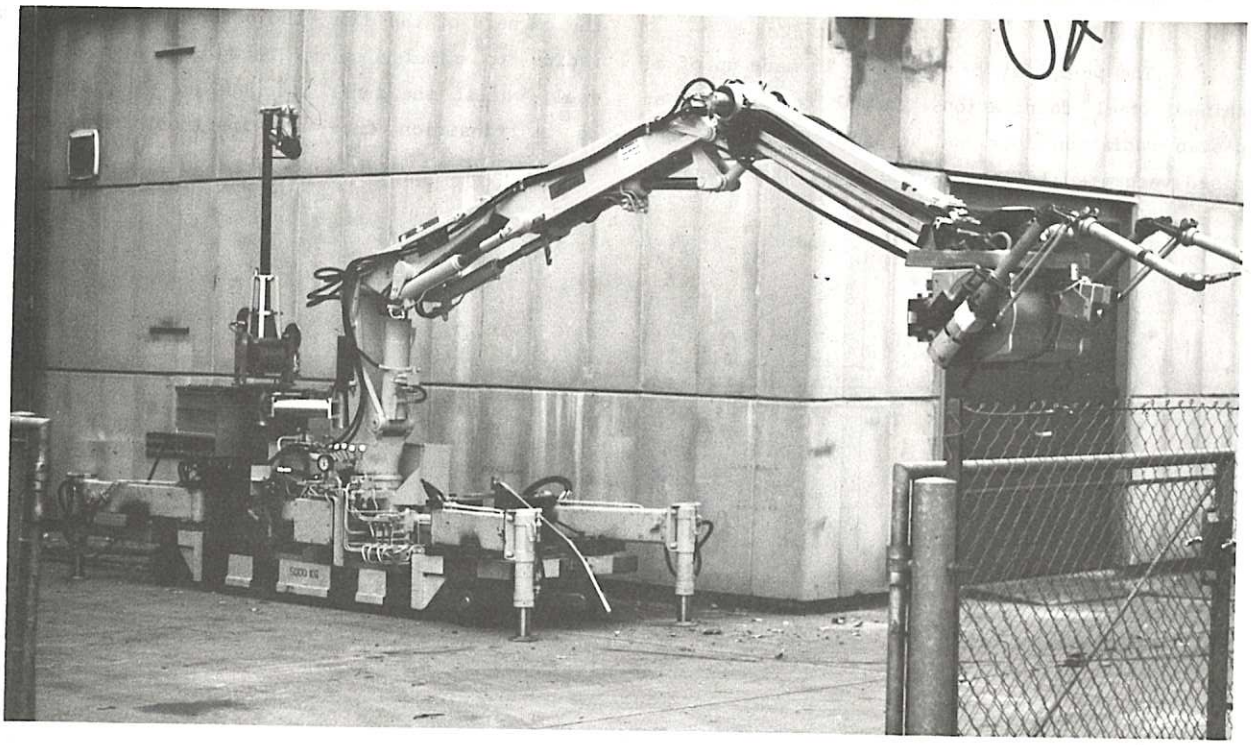


Fig.5 Mantis in extended position (by courtesy of CERN, Geneva).

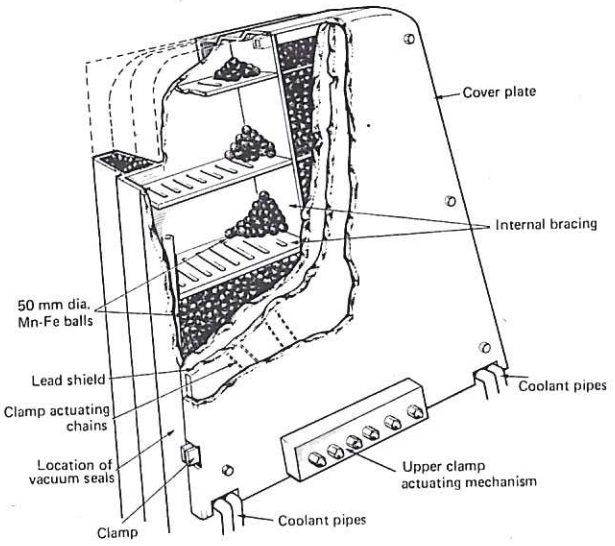


Fig.7 Construction of shield door internal structure and filling.

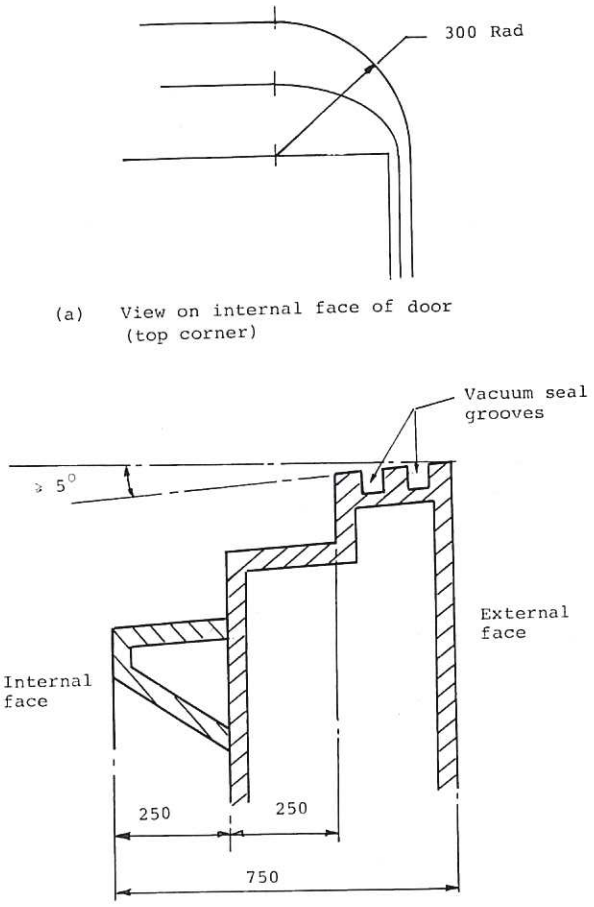


Fig.8 Schematic diagram of door interface (all dimensions in mm).

arranged to form a number of virtually closed compartments, the horizontal diaphragms being slotted to allow the free vertical passage of cooling water, and the internal voids are filled with 50 mm diameter manganese steel spheres. The door structure is arranged to span horizontally i.e. the applied loads are carried by horizontal stiffners to the stiff vertical ribs of the fixed shield structure.

The injector and vacuum ports in the centre of the door are a welded extension of the shield box structure. There is in principle no difficulty in including further small penetrations e.g. for special instrumentation.

The periphery of the door is made up of a machined steel fabrication, formed to provide a two-step radiation lock and housings for two pressurised vacuum seals (Fig. 8 and 9). Where necessary this arrangement will be locally modified, for example, to accept position error detectors. At the corners of the door, the outer step has a 300 mm radius to avoid a sharp bend in the pressurised seal, whilst the inner step has an elliptical form as a transition from the innermost right-angled corner (Fig. 8a).

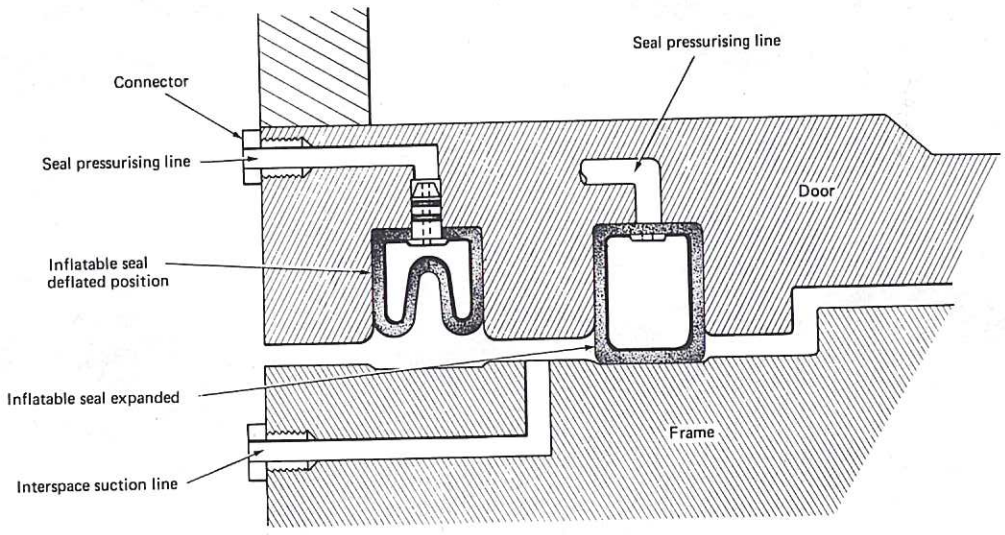


Fig.9 Layout of vacuum seals and pressurising and test ports.

The external surface of the door, at the base, is fitted with a fabricated bracket which carries two 300 mm diameter rollers (see Appendix A.5). The rollers seat on the fixed structure, see Fig. 6 and Section 4.1, and carry the weight of the door when it is mounted in the reactor. A projection welded to the door bracket is engaged by the transporter to lift the door when it is being moved (Section 3.7.3), so that the door weight is always carried on the bracket eliminating differential deflections during weight transfer.

2.3.2 Materials

Austenitic stainless steels are commonly used materials for nuclear applications since they have attractive corrosion, mechanical, nuclear and electrical properties and are capable of being fabricated into large complex structures. A typical specification is type 316 stainless steel which has been selected for other structural elements inside the toroidal field coils.[4] The most efficient shielding process for high energy neutrons requires inelastic scattering in medium Z materials (to reduce energy levels to about 1 MeV), elastic scattering in low Z materials (to thermalize the 1 MeV neutrons) and finally absorption of these thermalised neutrons. A suitable arrangement of materials is a homogeneous mixture of iron, water and boron which, in the shield door, is approximated by manganese steel balls and borated water. Manganese steel has been selected on the grounds that this material provides a low cost, non-magnetic source of iron (a medium Z material). The cooling water must be treated to prevent corrosion of the Mn-Fe spheres.

The neutron absorption process produces γ-rays, as does decay of the activation product of manganese, and this gamma flux is attenuated by a layer of lead attached to the outer surface of the door, see Fig. 7.

2.3.3 Structural design

The structural design is outlined in Appendix A2-A4. This analysis concludes that a structure, as illustrated, made from 45 mm thick (type 316) stainless steel will be adequate for the design loads namely the weight of the contents and the over-pressurisation and seismic forces.

The normal and emergency reactions are transferred to the structure via the clamping system described in Section 2.3.4.

The weight of the door and contents is ≅200,000 kg and its centre of gravity is 300 mm inboard of the roller centre line when mounted on the reactor. The overall dimensions of the door are given in Fig. 4 which also defines the axes of motion required for removal/replacement.

2.3.4 Attachment

The normal operational forces acting upon the door are:

- the forces necessary to balance the door (since its centre of gravity is offset 300 mm towards the internal face);
- the forces necessary to counteract the effect of the, inwardly acting, pressure differential of about 0.9 bar.

Abnormal conditions will apply in the event of: an internal pressurisation (0.9 bar differential acting outward) or seismic accelerations (where the force may act in any direction).

Threaded bolt and clamping systems were considered for this requirement, clamps being finally selected because:

- the alignment tolerances in the Y- and Z-directions are less critical than for bolts;
- no projections, beyond the door boundaries, are required when the door is being moved i.e. the maximum possible clearance between the door and TF coils is obtained;
- the clamp brackets (Fig. 10) mounted on the door frame are less susceptible to damage and simpler than for bolts;
- it is easier to provide offset actuation for clamps;
- the mating elements are visible so that fault diagnosis will be easier.

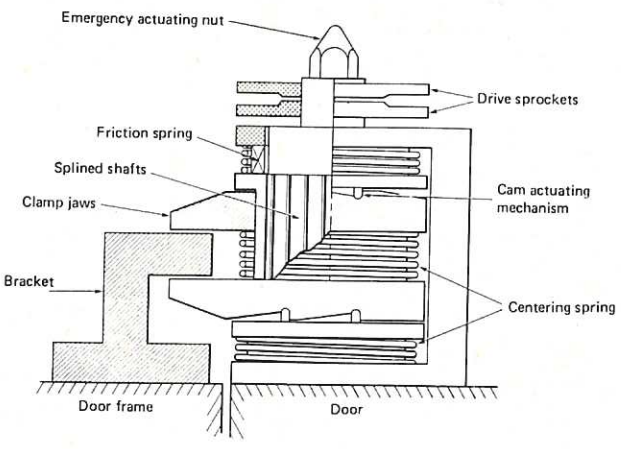


Fig.10 Door clamp.

It will not be possible to manufacture the door to the dimensional accuracy required to enable it to seat on a number of distributed bearing surfaces and the structure is too stiff to be pulled into position using reasonable applied forces. A self centering, caliper, type of clamp is proposed which restrains door movement in the positive and negative X-direction, see Fig. 10 and Appendix A6. The development of a satisfactory clamp is critical to this shield door concept.

2.3.5 Neutron streaming

The door/frame interface gap should have the same shield performance as the door itself i.e. a neutron flux attenuation of 10^{-3} to 10^{-4}.

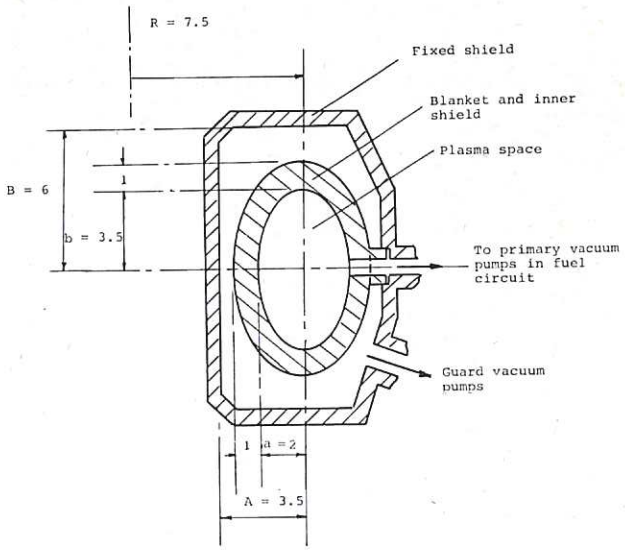
Appendix B shows that the total interface length should be 750 mm with two 20 mm steps. It is therefore necessary to locally increase the interface length to 750 mm, see Fig. 7 and 8.

2.3.6 Vacuum sealing

The provision of adequate vacuum seals is vital for a number of separate systems on the reactor and as a consequence the development and testing of seal materials and geometries should form the content of a separate ongoing programme.

Conceptually, the vacuum system of CCTRIIB is a 'double pumped' system with a separate 'guard' pumping system connected to the space between the blanket/shield segment and the fixed outer shield, as illustrated in Fig. 11. The purpose of the guard system is to evacuate outgassing impurities from the outer fixed shield and adjacent structure separately from the primary fuel vacuum system thus eliminating the need for extreme temperature baking and outgassing/clean up treatment for the fixed shield structure etc. The number and disposition of the guard system ducts has not been decided - clearly there could be at least one per segment and possibly more, depending on pump down times, outgassing rates etc.

A number of seal concepts have been considered including: flanges with soft sealing gaskets, thin welded metal seals, and inflatable gaskets. The first two techniques have the disadvantages of long assembly/disassembly time and/or the requirement for very close manufacturing tolerances (which would be difficult to achieve on such a large structure) and the inflatable seal is therefore selected. The proposed seal is a pressurised tube seal, conceptually the Membramatic Seal as marketed



(All dimensions in metres)

Fig.11 Schematic layout of vacuum space.

by Le Joint Francais. It comprises a reinforced radiation resistant elastomer such as VITON, or a development of VITON or ethylene co-polymer formed into a tube and pressurised with helium. It is to be assembled in a double seal arrangement (see Fig. 8) with provision to evacuate the interspace for seal checking and to minimise leakage of tritium into the reactor hall.

The principal disadvantage of this seal concept is the question of hardening of the elastomer, under irradiation. The radiation level at the outer surface of the door will probably be defined by electrical equipment insulation requirements, i.e. for instrumentation, control and/or magnet windings. Assuming the radiation flux in the outer shield region is $\gtrsim 10^9$ rads in 30 years, then the seal elastomer life requirement is $\cong 10^8$ rad over 3 years or $\cong$4000 rad/hr. Since the seal is pressurised, changes of hardness and elasticity are perhaps not so important as increased permeation of the pressurising helium and adhesion of the seal to the outer frame towards the end of the irradiation dose. Table 1 gives the properties of a range of seal materials. If satisfactory pressurised seal cannot be developed a weld-sealed joint could be used and its aforementioned disadvantages accepted.

The Membramatic Seals would be held in position by lengthwise tension (seal tube free length < groove length) plus a slight dovetail in the groove if necessary. Seal pressurising gas (helium) will be supplied from a rechargeable reservoir mounted on the door (see Fig. 6). This form of seal will easily take up the door gap tolerances of between 10-4 mm and will pass round the 300 mm

TABLE 1

ELASTOMERS TO BE CONSIDERED FOR THE SHIELD DOOR VACUUM SEALS

Elastomer	Made in inflatable form by:	Previous use in nuclear industry	Test data at 10^8 rads gamma					Gas (b) permeability	Remarks
			Temp. °C	% Change			Leak (a) rate t.l.s^{-1}		
				Comp. set.	Hardness	Weight			
Silicone (reinforced) (c)	Dunlop Ltd	PFR cave doors DERE Dounreay	150	100	26.9	-2.6	0.14	2800	High leak rate but tests were carried out at high temp. Cheap seal worth testing
Ethylene Propylene (c) (reinforced)	Le Joint Francais	French nuclear industry	66	79	16.3	-0.1	0.062		Probably first choice Ref. 14
Nitrile (c)	Le Joint Francais	French nuclear industry	66	75	23.5	-0.1	0.007	20	Low leak rate recommended (Ref. 14)
Viton		French nuclear industry							Flourine gas evolved with irradiation
Urathane	Du Pont rubber supplied to Le Joint Francais	French nuclear industry						25	
Vamac	Le Joint Francais	French nuclear industry							Copolymer of ethylene and methyl acrylate

Notes: (a) Leak rate for 20 doors assuming single seal.
(b) Gas permeability (x 10^9) in cm^2 x sec^{-1} x atmos^{-1} Nitrogen at NTP.
(c) Properties for "O" ring seals.

radius corners of the door. The contact surfaces on the door and frame will require a surface finish of ≅1 μm and it is proposed to recess the frame in the contact area, by a few mm, as a measure of protection. Use of this seal should contribute to minimising reactor downtime because only seal inflation and vacuum testing are on the 'critical path', seal assembly in the door grooves being done while the segment is being exchanged.

An indication of the vacuum pumping requirements can be obtained from Table 2 which shows the estimated gas inputs to the 'guard' vacuum system after initial assembly. The outgassing and permeation rates given for the Membramatic Seal assume VITON elastomer at a temperature of 50°C and seem to be reasonable in comparison to the other gas loads, cooling duct leaks etc.

TABLE 2

CCTRII - OUTGASSING AND OTHER GAS LOADS IN SECONDARY VACUUM SPACE

Item	Dimension details (See Figure 11)	Unit outgassing rate	Ref.	Impurity gas load torr litres s^{-1}
Blanket segment outgassing from back surfaces	Area 2πR. π (a+b+2) x 2 (to include duct surface etc.)	<10^{-9} torr litres s^{-1}cm^{-2} for stainless steel at 500°C	12	0.02
Fixed shield inner surface outgassing	Area 2πR. π (A+B) x 2 (to include ribs etc.)	<10^{-10} torr litres s^{-1}cm^{-2} for stainless steel at 150°C	12	0.003
Desorption by energetic particles	Depends on energetic particles flux in secondary vacuum space between blanket segment and fixed shield		-	?
Helium cooling duct joint leaks	Two joints per segment duct - twenty segments	10 times test figure for Greyloc couplings - Table 1 of Reference	11	0.02
Segment helium cooling ducting	The ducting is in a low radiation flux level behind the segment shield and will be designed and tested to high standards		-	?
Door seal Elastomer outgassing	No. of seals 20 x Exposed area cm^2 30x100 (long) x 2 (wide) (See Figures 4 and 9)	<2 x 10^{-8} torr litres s^{-1}cm^{-2} VITON @ 50°C	13	0.042
Door seal Pressurising gas permeation	As for elastomer outgassing but 4 mm thickness	≃ 5 x 10^{-7} N_2 @ 50°C torr litres s^{-1} mm thick/cm^{-2} bar	13	0.042

Note: An additional gas load will arise due to leakage of gas from the main plasma space between the segments into the secondary vacuum system. This will cause the pressure (and total gas load) on the 'guard' vacuum pumps to rise and fall but will not alter the impurity gas loads.

2.3.7 Interface angle

As described in subsequent sections the door is rotated into position using the foot roller as a hinge. In order to facilitate this operation the angle of the interface at the top and bottom is set at >5° to the normal to the door outer surface. The sides are normal to the outer surface, see Fig. 8.

2.3.8 Cooling

The shield door receives energy inputs by neutron and γ absorption and by thermal radiation from the inner shield. Preliminary analysis (Appendix C) indicates that the thermal inputs will be in the order of 800 kW and 60 kW respectively. It is therefore necessary to cool the shield.

The shield configuration, 50 mm diameter manganese steel pebbles forming a packed bed through which water flows, exhibits a high overall heat transfer area and a high apparent transverse thermal conductivity. Preliminary analysis (Appendix C) shows that if coolant at 35°C is supplied at 90 kg/s the door maximum temperature will be <50°C.

An assessment of decay heating (Appendix C7) concludes that shutdown cooling will not be required since the ΔT required for after heat removal by natural convection $\leq$ the ΔT which occurs after removal.

The sensitivity of the door to coolant failure was examined (Appendix C6) and it is concluded that:

- in the event of a coolant pump failure and assuming no back-up, the system will not become pressurised in less than 12 minutes;
- in the event of a catastrophic failure of the coolant system, involving complete loss of water in one section of the door, the reactor must be shut down and brought up to ambient pressure or alternative cooling provided, within approximately 45 minutes otherwise the door will expand and would jam in the frame assuming the minimum clearance of 10 mm (Appendix D9).

2.3.9 Services

Services required by the door fall into two categories viz:

- operational services - which are only in use when the reactor is operational e.g. cooling water, instrumentation, seal pressurising gas and vacuum.
- Installation services - which are in use only for operations associated with installation and removal of the door e.g. instrumentation and mechanical actuators.

The transporter will be required to make and break the operational services connections and will wait until these services have been tested before continuing with its planned sequence of operations. Installation services require connections between the transporter and the door.

Following the principles outlined in Section 2.2, the active elements of the operational services connectors are located on the door and arranged to extend or retract in the transverse direction to avoid limiting access within the reactor envelope (Fig. 6) and engage fixed connectors located between the structure and the toroidal coils, see Fig. 12.

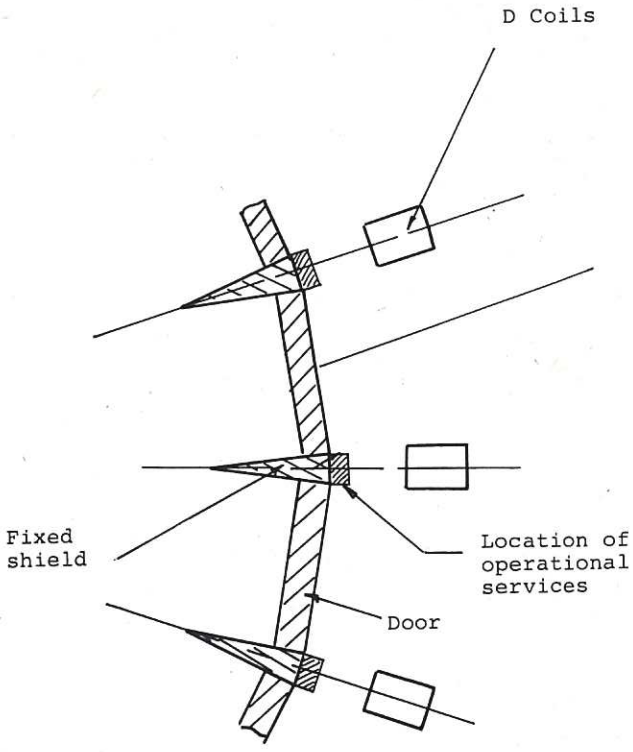


Fig.12 Location of operational services connections.

Door mounted installation services, Fig. 6, are all passive and located with their axes of engagement parallel to the X-axis. Active elements are located on the transporter as described in Section 3.7.4.

2.4 Manufacture

2.4.1 Techniques

Discussions with manufacturers and research organisations indicate that arc and electron beam welding are both suitable techniques for door manufacture. Use of these techniques, for a similar application, is briefly reported by Briaris and Stanbridge.[4]

Diffusion bonding is gradually gaining acceptance as a viable industrial process especially for large joint areas.[7] It involves pressing pre-machined and cleaned joint faces together at temperatures of about 0.7 x melting temperature until bonding occurs. The door structure is ideally suited for fabrication by this technique. Since many of the joints are completed in one operation, distortion is reduced and heat-affected zone defects are avoided. Diffusion bonding is not yet available but is expected to be in commercial operation within the required timescales.

2.4.2 Fabrication

Discussions with manufacturers have indicated that there should be no significant problems in fabricating the door structure or in manufacturing the numbers required using the techniques described above. However, the following points should be noted:

- the door should be fabricated in three sections and finally welded together to complete the structure. Intermediate machining of components and sub-assemblies to be carried out where necessary to achieve the required accuracy;
- full scale, post weld, heat treatment is not recommended, though heating to a temperature in the range 300°C-600°C may help to stabilise the structure;
- the final assembly will require machining, along the interface, and a machining allowance of about 5 mm will be required;
- the manufacturing tolerances would be:

  on the width, better than ±2 mm

  on the length, better than ±6 mm

  on the overall radial dimensions, better than ±2 mm;
- at present non-destructive testing on this type of structure would be difficult due to the complexity of, and lack of access to, some welded joints. However, techniques are continually being improved and an acceptable ultrasonic technique may well be available when required;
- a lead time of one to two years will be required to: develop techniques, define schedules, obtain approvals, production engineer and procure plant. It is probable that one or two prototype doors would be manufactured during this period;
- it is possible that the welding process, excluding diffusion bonding, will generate small quantities of martensite in the region of each weld which may give rise to fatigue problems in a cyclical magnetic field.

2.5 Reliability

The shield door forms an integral part of the reactor structure and must therefore exhibit the necessary high degree of operational reliability in the environmental conditions. In addition the door systems must be reliable during the removal/replacement phases.

The design philosophy discussed in Section 2.2 has, as far as possible, been followed and the results of a provisional fault analysis are given in Table 3. This analysis suggests that, if duplication and comprehensive quality assurance are utilized none of the listed fault conditions will cause a serious interruption to reactor operation.

2.6 Door frame

The door frame will be fabricated from austenitic stainless steel and its geometry will follow the door profile as illustrated in Figs. 6, 7 and 8. The frame will be machined, attached to the reactor structure and if necessary re-machined. The seal contact surfaces are recessed, as a protection against accidental damage, and will require in-situ grinding to achieve the required surface finish. It is estimated that the frame can be manufactured and installed to tolerances better than:

±2 mm on width

±6 mm on height.

TABLE 3

SHIELD DOOR RELIABILITY ASSESSMENT

SIMPLIFIED FAULT TREE	PRECAUTION	FALL BACK/RECOVERY
Clamp System → Actuating mechanism fails → Deformation of connecting element	Overdesign, Mtls selection, Q.A.	Disconnection of fixed bracket using G.P.M. or use external actuator to operate clamps directly
Actuating mechanism fails → Drive shaft/bearing failure	Redundancy provided	
Actuating mechanism fails → Drive sprocket failure	Redundancy provided	
Actuating mechanism fails → Chain failure/breakage	Redundancy provided	
Clamp Fails → Driven sprocket failure	Redundancy provided	
Clamp Fails → Shaft/bearing failure	Overdesign, mtl. selection, Q.A.	
Clamp Fails → Failure of centering mechanism	Overdesign, mtl. selection, Q.A.	
Clamp Fails → Clamp mechanism failure	Overdesign, mtl. selection, Q.A.	
Clamp Fails → Structural failure	Overdesign, mtl. selection, Q.A.	
Coolant System → Break in pipe line causing large coolant loss	Overdesign, mtl. selection, Q.A.	Door replacement
Coolant System → Failure to make connections	Duplicate, by pass valves (?)	Use duplicate system or replace door
Coolant System → Failure to break connection	Overdesign, mtl selection & Q.A.	G.P.M. to break line elsewhere and cut pipe as necessary
Vacuum system → Failure to hold vacuum on test → Unsatisfactory seal	Q.A. procedure during installation	Door replacement
Failure to hold vacuum on test → Frame surface damaged	Q.A. during inspection	Re machine
Failure to hold vacuum on test → Door surface damaged	Q.A. during installation	Door replacement
Loss of pressure in seal → gas supply exhausted → Insufficient gas provided	Q.A. external source	Use external supply
Loss of pressure in seal → gas supply exhausted → Leakage	Q.A. external source	Use external supply or if severe replace door
Loss of pressure in seal → gas supply failure	Q.A. External source	Use external source or if severe replace door
Seal failure during operation	Duplication	Use back up seal/ replace door
Instrumentation → Any failure	Duplication	Use duplicate system
Position error dectectors → Detector failure	Duplication	Use duplicate system
Position error dectectors → Circuit failure	Duplication	
Structural failure → Loss of shielding integrity	Correct specification and design Material specification and Q.A.	Operational decision to ignore, patch or replace depending upon severity
Structural failure → Loss of vacuum		
Structural failure → Loss of water containment		
Structural failure → Distortion		
Structural failure → Faigue		

2.7 Estimated cost

The estimated cost of each door is including contingency £0.72M (1979 figures) broken down as follows:

- design/development cost written off over 25 doors £60,000
- manufacturing cost per door:

stainless steel structure fabricated and machined (50 tonnes @ £10,000/tonne)	£500,000
Mn-Fe spheres (90 tonnes @ £1,500/tonne)	£135,000
Lead (17 tonnes @ £1,000/tonne)	£17,000
Clamps, instrumentation etc.	£18,000

3. DOOR MANIPULATOR-TRANSPORTER (DMT)

3.1 Functional requirements

The functional requirements for the system are:

(a) to travel without a door from a previously defined parking area to a position adjacent to the relevant door while avoiding fixed obstacles and mobile plant along the access route;

(b) to engage the door lifting brackets, depressurise the seals, disconnect all services, unclamp and remove the door;

(c) to travel to a defined door servicing area where the door may be serviced on board the transporter or exchanged for a serviceable unit;

(d) to return to the doorway;

(e) to replace the door, re-clamp, re-seal and test, reconnect and test all services and disengage from the door lifting brackets;

(f) to withdraw, unladen, to a previously defined parking area.

Each of the above operations are to be carried out under fully automatic or remote control, or some combination of both. The reactor design life will be in the order of 30 years and the probable segment

service life will be two years so that, allowing a 100% contingency to cover unscheduled activities, 600 door removal/replacement operations will be required.

3.2 Design philosophy

The DMT design has been formulated to take account of the following general requirements:

(a) Area mobility

The DMT will be one of a number of mobile systems operating in the reactor servicing area. When these systems are defined some degree of integration may be possible but for the present a high degree of operational flexibility has been retained.

(b) Operational efficiency

The projected maintenance schedule requires that a single blanket segment exchange should be completed in less than 60 hours and it is therefore necessary to ensure the most efficient use of time while the DMT is operating within the reactor envelope.

(c) Reliability and availability

It is essential that the DMT should exhibit high operational reliability i.e. sub-system failure must not cause a major interruption to the maintenance schedule. It must be remembered that the mobile plant inventory includes general purpose remote manipulators (GPM) which will operate in support of the DMT and will be a significant factor in achieving high system reliability and that the manipulator overall duty factor is low. The necessary availability can be provided by duplicate, back-up DMTs and by utilising the time when the reactor is operating for regular maintenance.

(d) Protection

The consequences of a collision with fixed or mobile structures could be extremely serious and there should be a multi-level system of protective devices. Transfer speeds should be limited to levels which will not cause structural damage in the event of a collision.

3.3 Systems definition and evaluation

3.3.1 Area traverse

As stated in Section 3.1 the DMT is required to move from a parking location to a position in front of the selected door. Three types of system meet this requirement:

i A fully mobile DMT having three horizontal degrees of freedom and capable of following any selected route within the reactor servicing area.

ii A DMT which is fully integrated into the reactor structure, typically manipulative equipment mounted on an annular turntable.

iii A partially restrained DMT which moves freely between local fixed guidance systems situated in areas of restrained access.

These alternative systems are evaluated, using a 'figure of merit techniques', (Table 4) with the result that a free moving DMT with some fixed guidance is the most attractive.

The selected configuration is therefore:

- a DMT which has three horizontal degrees of freedom and permanently installed guidance systems within the reactor envelope and other areas of limited clearance.

TABLE 4

COMPARISON OF AREA TRAVERSING SYSTEMS

	Operational flexibility	Operational effeciency	Effect of services on other plant	Reliability	Availability	Maintainability	Control system complexity	Figure of merit
Fully mobile transporter	√√	X	√√[1]	√[3]	√√[5]	√√[5]	XX	6
Fully intergrated System	XX	√√	√[2]	√√[4]	√	X[6]	√	5
Partly restrained	√√	√	√√[1]	√[3]	√√[5]	√√[5]	X	9

1. Assumes fully self contained system
2. May place restriction on access of GPM etc
3. Providing on board back-up systems are included
4. Intrinsically robust system
5. Providing stand-by units are available
6. Maintenance to be carried out while the reactor is operating

3.3.2 Door manipulation

Two basic types of door manipulator have been identified (see Fig. 13) i.e. after initial alignment, using the Z- and β-axes, door removal/replacement is achieved by adjustment of:

(a) the three linear axes, Fig. 13a;

(b) preliminary siting of the three linear axes and final insertion using the γ-axis, Fig. 13b.

The type (b) system is selected because the maximum use can be made of pre-set datums e.g. the load carrying vee block (Section 3.6.2) and the simplest form of load carrying and balancing mechanisms axis.

3.3.3 Control

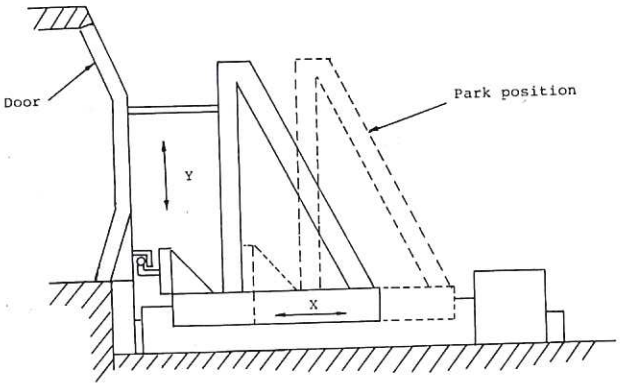
At the present time there is considerable incentive for the development of small, low cost, more powerful computers. The whole field is extremely volatile and it is difficult to predict developments over the next five years, let alone twenty years except to say that future systems will be extremely powerful by current standards. This trend will probably continue, for sufficent time to allow new generations of small computers to be incorporated into very sophisticated control systems.

A wide range of control systems can therefore be envisaged, the extremes being:

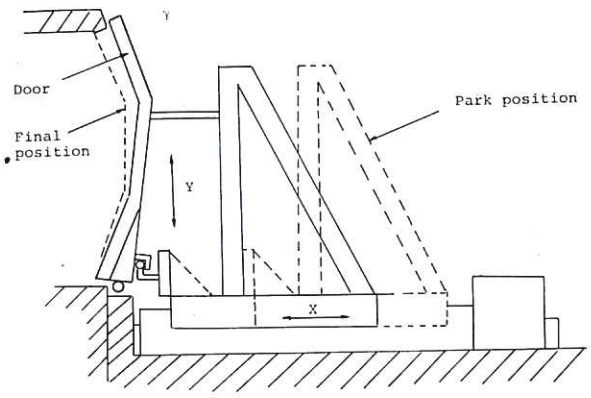
- manual remote control, of the DMT, from a central control point using a communications link to provide video and other information;
- automatic control by an 'on-board' computer which would be programmed to control the DMT in all normal and abnormal conditions.

Intermediate control systems would provide for manual and/or machine intervention as required.

Neither of these extreme cases appear to be technically or operationally attractive. Manual remote control would be inherently slow and would require numbers of highly trained (but under-utilised) operators. Full automatic control without data on the overall reactor and maintenance plant status would be inefficient and potentially hazardous. An intermediate type seems more appropriate and the system outlined below is suggested.



(a) Linear operation



(b) Rotational operation

Fig.13 Schematics of door manipulation systems.

The manipulator and DMT will each carry a computer which will be inter-connected via a hard wired link. These computers will be capable of controlling all normal operations and some fault rectification procedures (typically disengaging a faulty system and engaging a standby) but will be monitored by a supervisory computer. The relevant functions of the supervisory computer will be:

- to plan and integrate the routing of the DMT, within the maintenance area, with other mobile systems;
- to programme DMT operations relative to the overall maintenance programme;
- to respond to 'calls for help' from the on-board systems when they are faced with situations they cannot process;
- to supervise the DMT status as reported by the on-board systems;
- to display abnormalities to the human supervisor.

A manual override and remote control facility, with ample video coverage, will be provided to cover the eventuality of an unpredicted fault condition but it is envisaged that this facility will be seldom used.

3.3.4 Communications

The DMT will be capable of operating in two modes, automatic control and manual remote control, and the communications system must cater for both modes and provide the necessary video and other supervisory channels. The vehicle operating area will be enclosed by metal clad walls, contain a number of fixed and mobile metallic structures and (possibly) be electrically noisy.

Possible communications systems are:

- inductive loop: this system will have the bandwidth to cater for the probable level of data transmission but is unlikely to be able to carry a number of video channels even with relatively sophisticated signal processing;
- UHF/VHF radio: high frequency radio systems can provide the necessary bandwidth and it is probable that reflection from the walls will enable the signal to cover the whole operating area provided the signal strength is high enough;
- microwave radio: microwaves are extremely directional and are unlikely to be satisfactory in the maintenance area;
- optical link: optical systems having the necessary bandwidth, e.g. lasers, are extremely directional and may be obscured by smoke or airborne dust and are therefore unlikely to be suitable. However a recent report[8] discusses a system operating in the 'near infra red' using light emitting diodes and photo-diodes which may be suitable;
- acoustic link: acoustic systems are reported to be suitable for robot communications but do not have the bandwidth required for this application.

At the present time a UHF radio system would meet the requirements: however developments in this area are rapid and a better alternative may arise in the future.

3.4 Transporter parameters

3.4.1 General

The load carrying system for conventional vehicles consists of wheel or tracks connected to the chassis by solid or compliant linkages. In practice these systems produce high local floor loadings, require high torque for steering and may be difficult to manoeuvre - particularly in confined spaces.

Briaris and Stanbridge[4] investigated this problem with reference to blanket segment transport and concluded that a gas-film bearing system would generate lower floor loadings, require less steering torque and would, if allied to a suitable drive system, be highly manoeuvrable. The centre of gravity of the laden DMT will be fairly high but this is not likely to cause instability problems since the working criteria height of load C of G ≤ 4 x spacing between bearing pads, is achieved. A configuration in which the drive/suspension unit, i.e the transport is separable from the manipulator, is proposed because a failed transporter can be quickly replaced. An existing production transporter, Fig. 14, will handle 350 ton loads, has three degrees of freedom and is otherwise generally suitable.

The outline design of the transporter is illustrated in Fig. 15. It has an onboard compressor using the reactor hall gas. Its arrangement is such that it can be driven under the manipulator when operating with auxillary pads and when the main pads are pressurised will raise the manipulator clear of the floor. It is essential to achieve accurate location between the two elements of the system and two locating pins are provided as shown. In operation these pins will first be slightly raised, by individual pneumatic cylinders, so that they enter tapered holes on the under-side of the manipulator and then fully inserted as the transporter is pressurised. This final process will 'pull' the transporter into the desired position relative to the manipulator to within a tolerance estimated to be ±1 mm. In the event of a pneumatic system failure these pins should disengage from the transporter automatically but they are sited so that they can be disengaged by the GPM. The transporter load is carried on the four bearing plates as shown. A sub-assembly containing the rail clamping system and Z-axes mechanism, is fitted to each end of the transporter as shown.

The pneumatic and control cable connections between the transporter and the manipulator are located on the transverse bulkhead and are made automatically by the final vertical movement of the pallet (100 mm). The transporter shown in the figure contains its own power and gas supplies and is therefore virtually self-contained (see Section 3.8).

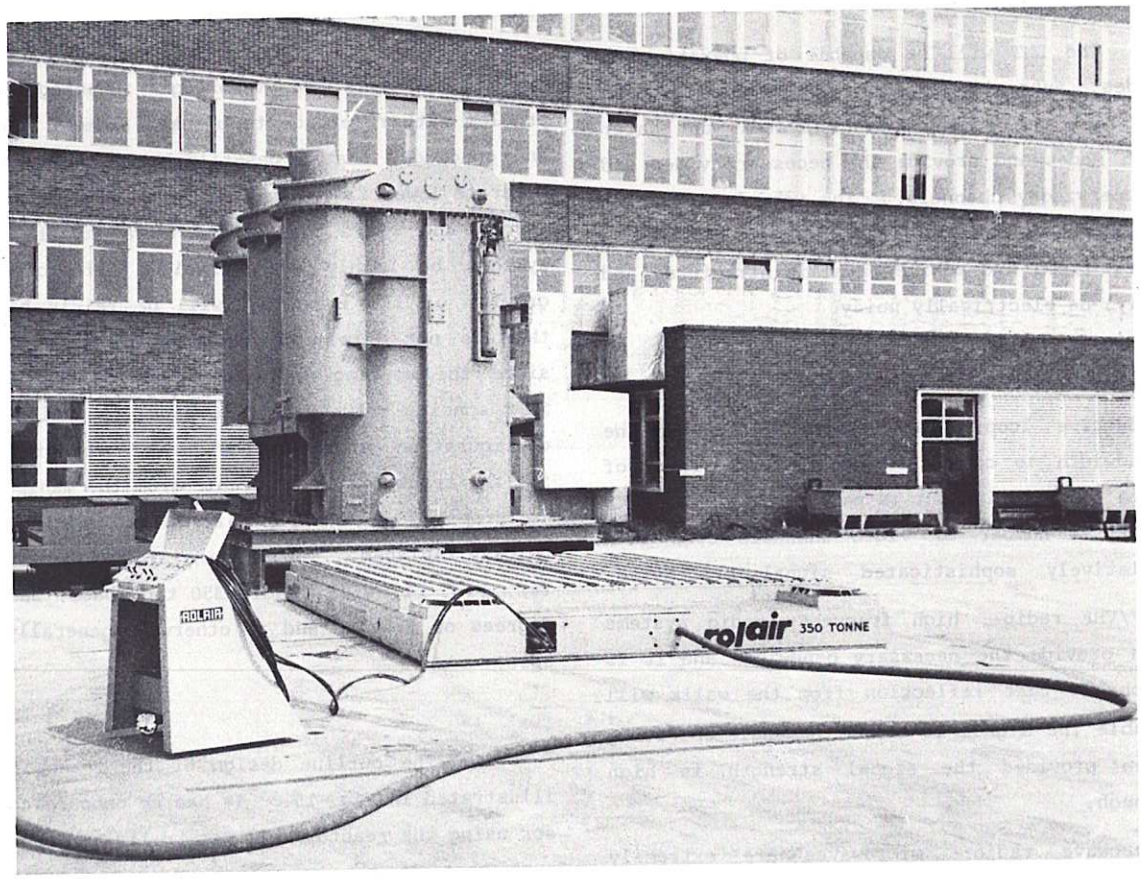


Fig.14 Commercially available 350 tonne transporter (by courtesy of Rol Air, Newbury).

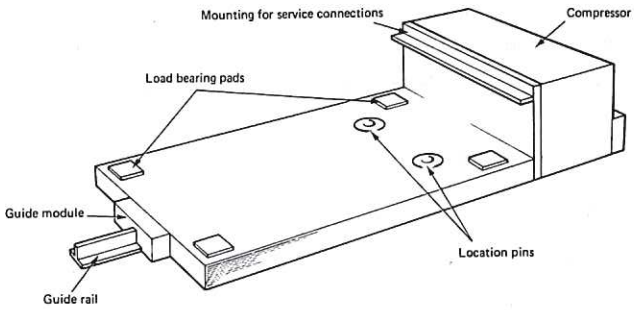


Fig.15 Transporter Unit.

The transporter would be fitted with numerous eye bolts for emergency retrieval (using winches) and connections for emergency control power and gas supplies.

3.4.2 Stability

Appendix D10 contains an assessment of the stability in normal operation and for various fault conditions and shows that the DMT is stable under all conditions for the maximum defined speed of 0.5 m/s.

3.4.3 Final approach guidance

The final approach guidance system is used to ensure rapid entry into the reactor envelope and for datum fixing.

Radial guide rails are fitted to the floor of the servicing area, between each pair of toroidal field coils running from the fixed shield structure to just outside the reactor envelope. Conceptually the guide rails take the form of inverted tee sections bolted to the floor. Post installation adjustment being carried out by the GP robot.

At both front and rear of the transporter there are guidance modules incoporating: rail clamps, and Z and β-axis adjustment mechanisms. One form of clamp, illustrated in Fig. 16, is held open by a pneumatic cylinder during rail engagement and held shut by springs. Traverse along the guide rail will be achieved by using the driving wheels and the final position will be set by a tapered bolt. Drive shut-off and bolt operation will be initiated by a detector sensing a discontinuity in the rail.

3.4.4 Area guidance

It will not be necessary for the control system to know the transporter's position and attitude to a high degree of accuracy during most of its

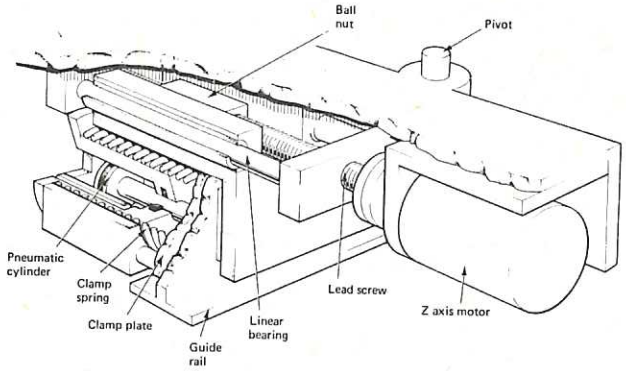


Fig.16 Transporter guidance module.

operating cycle; accurate data will only be required when the transporter is lining up to engage one of the fixed guidance rails.

There is a range of techniques suitable, for position and attitude fixing, for industrial vehicles e.g. inertial, beacons, markers, odometry, map correlation etc., some of which are commercially available at the present time. As with computers, in view of the extensive development to be anticipated during the next twenty years no firm selection is given. However the following should be remembered when specifying the system:

- the operating environment is likely to be electrically noisy;
- the area which will contain a significant number of metallic structures will be complex in shape and some of its boundaries will be liable to change.

3.4.5 Vehicle/environment protection

The loaded transporter/manipulator weighs about 250 tonnes and has a maximum speed of 0.5 m/s. According to the outline control scheme (Section 3.3.3), the supervisory computer will be responsible for environmental protection by virtue of its traffic control function but additional protection will be required to cover control system failure. Such failures, leading to accidental impact, may occur in the supervisory computer, the communications link or the on-board system. Two levels of protection should therefore be provided, one operating via the on-board computer system and one operating directly on the vehicle drives. The operating principles of the two protective systems should be different to avoid common mode failures. The protective systems should have a range of ≧1 metre, to cater for possibility of a two vehicle collision. Appropriate sensor systems would include: ultrasonic and acoustic ranging, optical triangulation and parallax processing. Two or more of these systems can be operated together again to avoid common mode failures. Protective systems will be required on both transporter and manipulator with an override to be used during link up. An override will also be required for use when the system is required to operate in confined areas.

3.5 Manipulator structure

3.5.1 Chassis

The manipulator chassis (Fig. 17, 18 and Appendix D4) consists of a flat base plate with downward projecting plates, which have compliant faces, attached to each long side and two transverse box section beams welded at either end. The transporter fits into the recess which is formed and is located using holes at the rear of the base plate. The base plate carries four, externally actuated jacks (mounted in the box section beams) which support a table made up of two longitudinal rectangular beams connected by stiffners. The top surfaces of the longitudinal beams are extended to provide the X-axis bearing surfaces. The floating table carries a 40,000 kg counter weight to balance the weight of the door during weight transfer.

The overall dimensions are: 5500 mm long x 3000 mm wide. Dimensional tolerances will not be critical except those relating the bearing surfaces to the floor, to each other, and to the transporter location points.

3.5.2 X-axis table

The construction of the slide table is similar to the chassis in that longitudinal stiffness is provided by two box section beams and lateral stiffness by welded transverse plates (Fig. 17 and Appendix D3).

The thickened bottom faces of the beams are extended and formed to provide the structural support for the X-axis recirculating roller bearing units which allow the table to traverse in the X direction but restrain it laterally and vertically.

The leading edge of the table is fitted with a full width bracket which carried the stationary elements of the Y-axis system.

3.5.3 Frame structure

The frame structure is required to carry

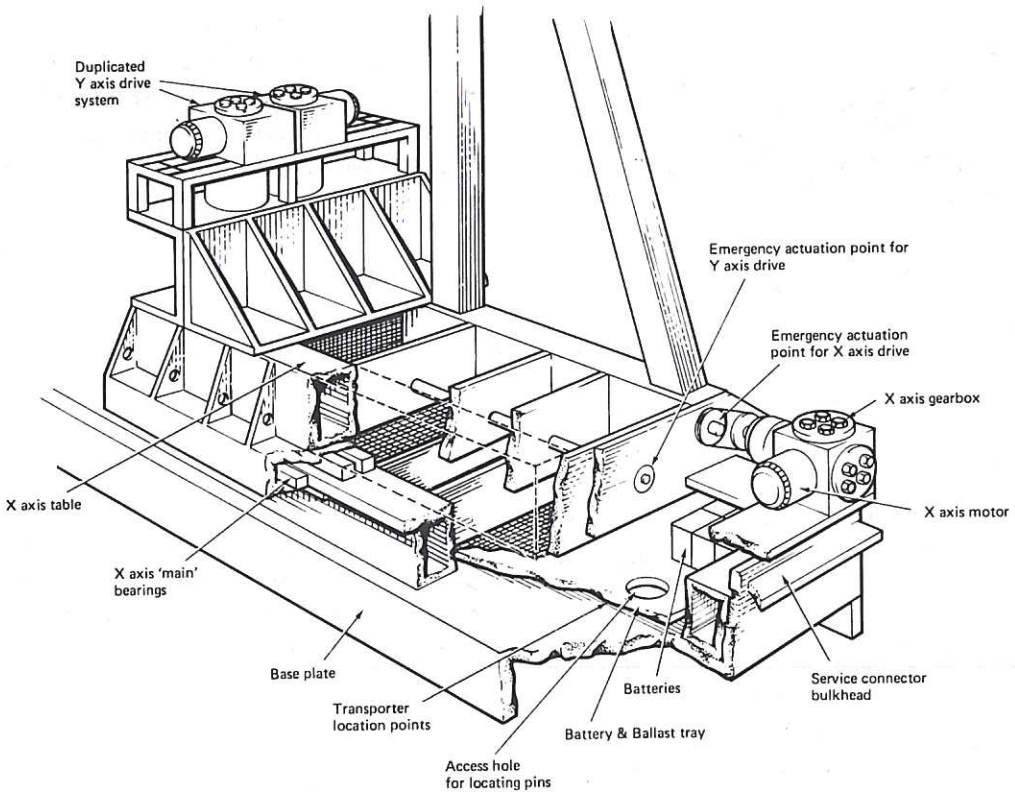


Fig.17 Manipulator chassis and X asis system.

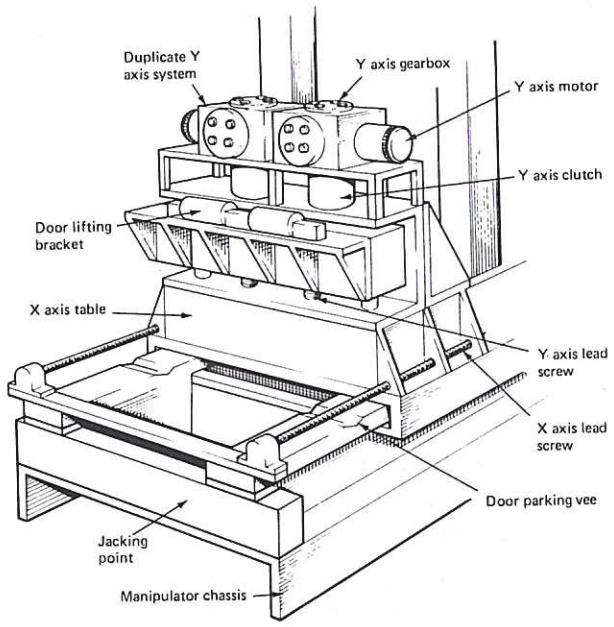


Fig.18 Front view of manipulator showing Y axis configuration.

the y-axis system and the door clamping mechanisms. This structure comprises two vertical, cross linked, box section columns supported at the rear by two beams angled at 15° to the vertical - all columns being mounted on the X-axis table (see Fig. 3). The frame structure has been designed for collision impact loadings because the principal operating loads are only the balancing forces on the door (see Appendix D2).

3.6 Design of door manipulative system

3.6.1 General

The philosophy which has evolved with respect to axes drive reliability is:

i sub-system failure should not cause a significant interruption to the planned programme;

ii to cater for the the possibility of a major system failure means must be provided to allow the remote manipulator to convert the system into the transport configuration, i.e. the door in the park position and all axes locks engaged.

This philosophy has been incorporated in the design as follows:

- duplicate drives are provided which are reversible or contain demountable ball nuts;
- each drive will be provided with a fitting to accept a rotary input from an actuator positioned by a GPM.

3.6.2 Type of axis control

Full positional control of any axis would require a minimum of two position error detectors per axis to be fitted to the door. Each detector

would engage a datum surface on the frame and therefore provide a position error signal for the control system. Allowing for duplication (for improved reliability) and the possibility of a sensor supplying signals to more than one axis, some 8-10 sensors will be required. However on the grounds of reliability and maintainability the number of fully servo controlled axes should be limited.

In the selected system the door bracket is fitted with offset rollers which seat on vee blocks on the reactor structure (Fig. 6) so that the roller is located in X and Y. Once the roller has been correctly seated the door is rotated, using the roller as a pivot, until it is completely entered into the frame. Thus, for final approach if the X-, Y- and γ-axis motors can be operated at slow speed in a torque controlled mode, sequence control can be used without the need for position feedback.

Initially the reactor hall floor will be level with respect to the reactor structure, subsequent movements being small and occurring slowly so automatic adjustment of the α-axis is not included. Regular inspection of the reactor hall will be required and the levels of the X-axes table slides will be pre-set, as required, using the jacking points (Fig. 18).

Final approach to the reactor is controlled by a radial guide rail. This guide rail will be subjected to intermittent loadings and, while provision can be made for its adjustment, it is doubtful if its positional accuracy (in the Z direction) can be held to better than ±2 mm. An analysis of the transporter, door and frame tolerance is given in Appendix D9, which shows that if fairly tight manufacturing tolerances can be maintained the total maximum frame/door gap will be 36 mm. However it is essential to minimise and equalise the door/frame clearances - from overall dimensional considerations and to achieve the highest vacuum sealing and shielding performances - so servo controlled adjustment for the Z-axis is included which should reduce the maximum total gap to ≤18 mm.

Servo adjustment of the Z- and β-axes is also desirable because guide rail adjustment may be difficult to perform when the reactor is operating, due to the presence of other plant, and, when the reactor is shut down, may occupy an unacceptable proportion of the time available for servicing.

The principal reason for avoiding full feedback control for all the machine axes is the need to minimise the number of position error detectors to be mounted on the door. However, rotary or linear position encoders fitted to each relevant axis element will provide an intermediate information level, improving performance and fault rectification.

3.6.3 Component selection

(a) Actuators

Hydraulic systems can be designed to provide high power to weight ratios, are readily controllable but are prone to leakage. Small leaks could be difficult to clean up with remote machines and large leaks, caused by burst pipes, could be catastrophic bearing in mind the cleanliness requirements for the vacuum system(s). Leakage protection systems are never entirely satisfactory and therefore hydraulic systems should only be incorporated if they utilise a fluid such as demineralised water. Such systems are not currently available.

There is, at the present time considerable activity in the development of small electric motors principally in extending the range of available types e.g. brushless d.c. systems. These developments cover the power range required for the transporter say 0.5-25 kW. However modern permanent magnet or stepping motors have the required performance and reliability for all the manipulator drives and electro-mechanical actuation is therefore selected.

(b) Bearings

Graphite impregnated bearing materials have been extensively and successfully used for slow speed applications in nuclear radiation environments and reliability criteria[9] suggests that the sleeve type of bearing has the lowest failure rate compared to alternatives. This type of bearing is therefore proposed for the manipulator main axis bearings except the X-axis where the local design favours a 'flat bed' configuration incorporating re-circulating roller bearing units. Ball or roller bearings are proposed for the higher speed rotary and thrust bearings.

(c) Transmission system

Each axis power train will comprise: two ballnuts mounted back to back to minimise backlash, a lead screw, a clutch and the necessary shaft and

thrust bearings. Where necessary a gearbox is included to match motor torque/load characteristics.

The characteristics of each axis transmission system are discussed in Appendix D6.

(d) Position error detectors

Position error detectors are required to:

i control the position of the DMT in the Z direction during door pickup. The active elements of the sensor and the connecting cable will be permanently installed on the manipulator;

ii control the position of the door in the Z direction during replacement. The active sensor elements will be fitted to the door and temporary connections made to the manipulator. If these sensors are required for door removal as well they must withstand the local radiation environment for a minimum of two years.

(e) Sensors

Sensors will be required for each machine function to provide interrupts to the control system and to protect against component malfunction. Sensors and interlocks should be selected from the wide range of available types to avoid common mode failure.

3.6.4 Linear axes configurations

The X- and Y-axes take the form described in Section 3.6.3(c) and illustrated in Fig. 17 and 18. In each case the ball nuts are attached to the movable elements and provision is included for emergency, external, actuation i.e.:

- for the X-axis - an idler shaft, terminating in a coned nut, which is parallel to, and drives, the lead screw via a chain transmission;
- for the Y-axis - the lead screw is extended (downwards) to terminate in a 90°, 1:1, reversible gear box whose own drive shaft terminates in a coned nut adjacent to that for the X-axis.

In each case two parallel drive systems are provided, one in use the other being clutched out until required. The movable elements of each axes are fitted with fail-safe pneumatically operated pins to lock the axis during manipulation of other axes and area traverse.

Z-axis adjustment is achieved by moving the DMT sideways using the guidance modules described in Section 3.4.3. Redundancy is not provided since transporters are readily interchangeable. Axis locks are not required.

Position feedback for the three linear axes will be provided by shaft encoders fitted to the lead screws. In addition the Z-axis will be provided with position servo control using signals from the position error detectors (see Section 3.6.3(d)).

3.6.5 Rotary axes configuration

The γ-axis mechanism is fitted near the top of the frame structure (see Figs. 3 and 19) and rotates the door using the foot roller as a pivot. The door engagement system is discussed separately in Section 3.7.2.

Door rotation is achieved by increasing or decreasing the separation between the latch mechanism and the drive module using one of the duplicate drive systems. The drive mechanisms are contained in the module structure and in this case the lead screw is attached to the movable element (the engagement module), the ball nuts being driven by geared motors. During manipulation of other axes and area traverse, the door is angled back and locked in the cradle welded to the upper part of the frame structure.

Locking pins, sensors and interlocks are provided in a similar manner to those for the linear axes.

β-axes adjustment is obtained by manipulation of the two Z-axis actuators.

3.7 Interfacing systems

3.7.1 Clamping (Fig. 20)

Section 2.3.4 describes the door mounted elements of the clamping system and specifies the locations of the actuating points, viz a row of six above the injector port and a similar row below. Two actuating systems are provided on the transporter (see Fig. 3) which differ only in the method of mounting; therefore only the upper system is discussed below.

An operating unit and a standby unit are provided each containing:

- a driving mechanism, to rotate the clamp actuators, consisting of a torque limited pneumatic motor and socket wrench. The unit has a

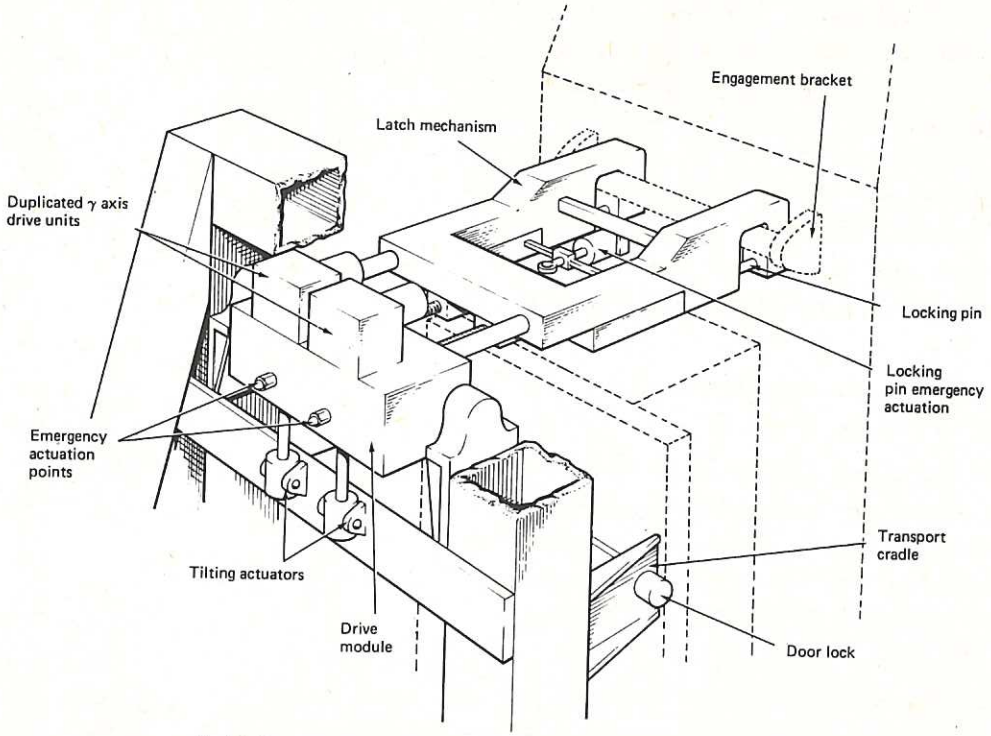


Fig.19 Upper attachment mechanism and γ axis drive and tilt actuators.

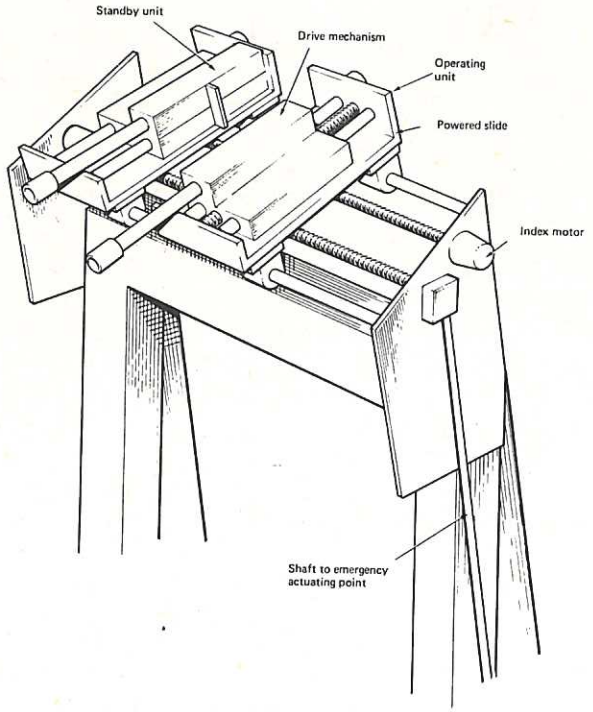


Fig.20 Upper clamp actuators.

compliant mounting or linkages to cater for system misalignments;

- a powered slide comprising a motor, lead screw and ballnut arranged to feed the driving mechanism along the axes of the door mounted actuators;
- an indexing assembly comprising motor, lead screw, ballnut enabling the driving mechanism to be aligned with specified actuating points.

The two actuating mechanisms are independent except for the common, index motion, bearing shafts. The system is arranged so that all drives are reversible and/or accessible to external actuators. There are two options provided to recover from failure conditions either to use the standby system to disengage and push the failed unit to its parking area or to use the emergency actuation points.

3.7.2 Upper attachment mechanism (Fig. 19)

The engagement bracket i.e. the static element, is mounted on the door, and the active elements on the transporter are: a latch mechanism, the γ-axis system, and the tilting actuators.

The latch mechanism consists of two fixed aperture jaws which engage the door element when the assembly is rotated by the tilting actuators. Each latch is secured by a pneumatically operated spring loaded locking pin housed in the lower half of the rear jaw and engaging an opening in the forward jaw. Engagement and locking are confirmed by (pneumatic) sensors. In fault conditions, these pins can be withdrawn using the centrally mounted common pneumatic cylinder.

The complete γ-axis and latch mechanism assembly is gimbal mounted and its angle of tilt is set by the duplicated pneumatic cylinders attached to the transporter frame.

Assuming the initial equipment status: γ-axis at furthest extension, mechanism tilted upwards to clear the door element and engagement lock in 'out' position, the system operation will be:

- the assembly is tilted until the underside of the jaws rest on the bracket;
- the jaws are pressed down onto the engagement bracket by the index mechanism pneumatic cylinders while the γ-axis motor is operated to retract them. When sufficient retraction has been achieved the whole assembly will rotate to engage the door;
- the door lock operates.

The system must be provided with sufficient compliance to cater for misalignment of the transporter.

3.7.3 Load carrying element (Figs. 18 and 21)

The lifting element is attached to the Y-axis carriage and comprises a stiffened right-angled bracket fitted with a roller. The roller is required because the bracket is used to control the door movement in X and Y and carries horizontal forces while traversing vertically and vice versa. The door removal and replacement operations are illustrated schematically in Fig. 21.

3.7.4 Services

As defined in Section 2.3.9 two types of service are required by the door, i.e. 'installation' services and 'operational' services.

The proposed system for installation services is illustrated in Fig. 22 and comprises:

- a service module carrying instrumentation connections and mechanical actuators which mates with a panel on the door by means of four attachment screws located at the corners;
- a clamping plate, which can pick up and release the service module, and which is fitted with powered wrenches to engage and operate the module attachment screws;
- a retractable boom to advance and withdraw the clamping plate.

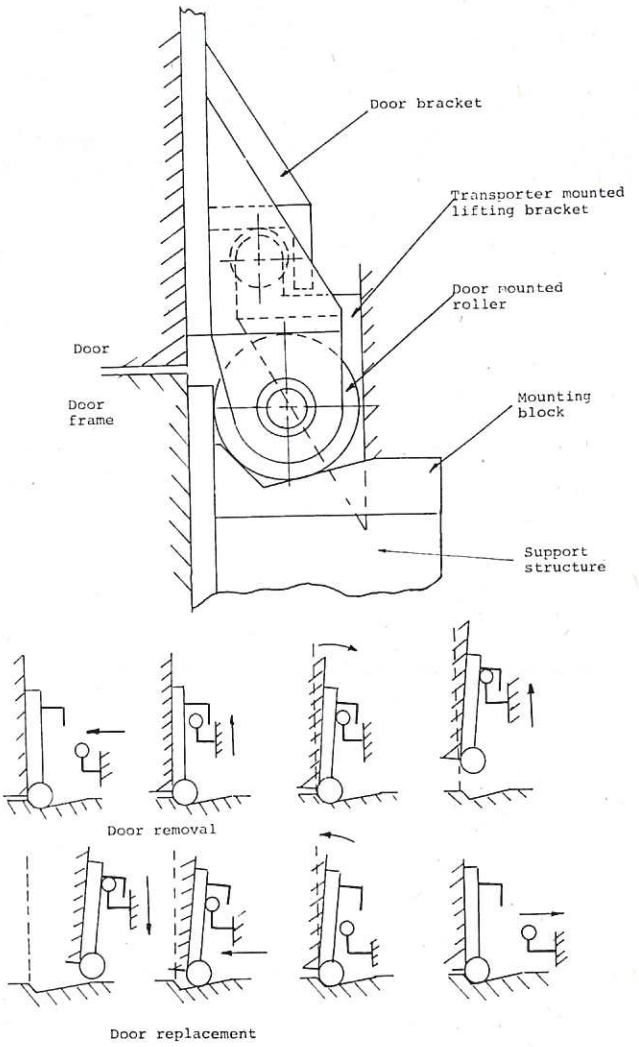


Fig.21 Load carrying elements and operating sequence.

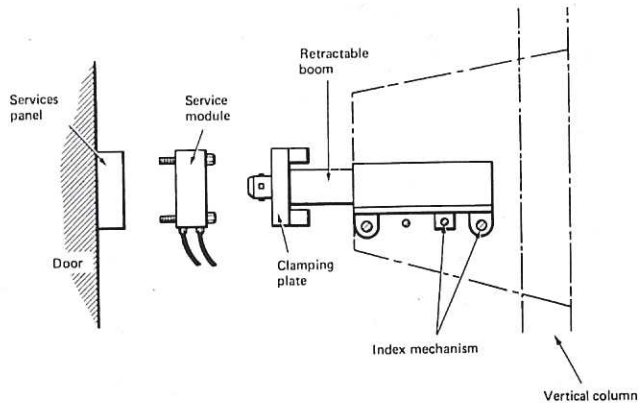


Fig.22 Installation service module and mechanisms.

Two systems are provided, one operational and one standby, their operation being similar to that of the clamping system described in Section 3.7.1.

The operational services are located as shown in Fig. 6 with their axes parallel to the Z-axis. The largest items will be the inlet and outlet cooling water connections, fixed with Grayloc

clamps. Systems to operate the clamps and move the fixed elements clear of the access path will be required at the locations shown in Fig. 3.

3.8 DMT services

3.8.1 Gas supply

The reactor hall atmosphere e.g. helium will be used as the lifting gas and will be supplied at a pressure of 6 bar. The various options for providing this gas are evaluated in Table 5 and Appendix D7 which indicate that on-board compression will be the most suitable, provided that the reactor hall pressure ≧0.9 bar.

Provision for the connection of external supplies of high pressure gas will of course be provided on the transporter for use in case of an on-board system failure.

3.8.2 Electrical supply

Electrical power will be required for traction, gas compression, door manipulator drives, lighting, cameras and control. As with gas supply there are a number of options which are evaluated in Table 6. This shows that both on-board storage and external supply are attractive options. Appendix D8 discusses the numerical aspects of both these systems and concludes that both will be technically

TABLE 5

GAS SUPPLY OPTIONS - TRANSPORTER UNIT LIFTING PADS

TYPE OF SYSTEM	State of the art	Safety	Reliability	Interference with other systems	Flexibility	Figure of merit
Self contained system — Gas storage — Under pressure	✓✓	✓	✓✓	✓✓	✓✓	9
Self contained system — Gas storage — As liquid	✓	✓✓	✓	✓✓	✓✓	8
Self contained system — Gas storage — In adsorbing medium	x	✓✓	✓	✓✓	✓	4
Self contained system — Compressor — Self contained prime mover — Oxygen-hydrogen system open cycle	xx	xx	xx	✓✓	✓✓	-2
Self contained system — Compressor — Self contained prime mover — Heat source + closed cycle engine	xx	x	xx	✓✓	✓✓	-1
Self contained system — Compressor — Self contained prime mover — Battery-electric motor	✓✓	✓✓	✓✓	✓✓	✓✓	10
Self contained system — Compressor — Self contained prime mover — Fuel cell-motor	xx	xx	xx	✓✓	✓✓	-2
Self contained system — Compressor — Self contained prime mover — Flywheel	xx	xx	xx	✓✓	✓✓	-2
Self contained system — Compressor — Externally fed prime mover — Electric motor	✓	✓✓	✓✓	x	✓	5
External supply — Umbilical — Ceiling — Movable boom	✓✓	✓✓	✓	✓	✓	7
External supply — Umbilical — Ceiling — Fixed supply point quick release connector	✓✓	✓	✓✓	x	✓	
External supply — Umbilical — Wall — Fixed supply point quick release connector	✓✓	✓	✓✓	x	✓	5
External supply — Umbilical — Floor — Fixed supply point quick release connector	✓✓	✓	✓✓	x	✓	5

TABLE 6

POWER SUPPLY OPTIONS DMT

TYPE OF SYSTEM	State of the are	Safety	Reliability	Interference with other systems	Flexibility	Figure of merit
Self contained systems — Electrical storage — Battery	✓✓	✓✓	✓✓	✓✓	✓✓	10
Self contained systems — Electrical generation — Oxygen/hydrogen system	xx	xx	xx	✓✓	✓✓	-2
Self contained systems — Electrical generation — Heat source + closed cycle engine	xx	x	xx	✓✓	✓✓	-1
Self contained systems — Electrical generation — Fuel cell	xx	xx	xx	✓✓	✓✓	-2
Self contained systems — Electrical generation — Flywheel	xx	xx	xx	✓✓	✓✓	-2
External Supply — Umbilical — Ceiling — Movable boom	✓✓	✓✓	✓	x	✓	5
External Supply — Umbilical — Ceiling — Fixed supply point - quick release connector	✓✓	✓	✓✓	x	✓	5
External Supply — Umbilical — Wall — Fixed supply point - quick release connector	✓✓	✓	✓✓	x	✓	5
External Supply — Umbilical — Floor — Fixed supply point - quick release connector	✓✓	✓	✓✓	x	✓	5
External Supply — Pickup — "Live" rail	✓✓	✓✓	✓✓	xx	xx	2
External Supply — Pickup — "Live" grid	x	x	xx	✓	✓	-2

acceptable. However, the battery system is selected on the grounds of greater flexibility. The manipulator batteries (15 tonne) will form a part of the required 40 tonne counterweight located at the rear of the system. Each transporter unit will require 16 tonnes of batteries and these are located under the compressor - possibly in a removable pack.

3.9 Reliability assessment

The transporter/manipulator system will be required to perform about 600 door replacement operations during the reactor lifetime and it is therefore possible that the design principles given in Section 3.6.1 are over elaborate in that duplicated and emergency systems are both provided. However it has been shown that both can be provided if operational analysis shows they are necessary. A high level of transporter reliability is not necessary as this unit can be easily changed.

A preliminary fault analysis for the manipulator is given in Table 7 and it is concluded that none of the listed faults will cause a serious holdup provided that the specified on-board systems are installed and that crane and floor mounted

TABLE 7

D.M.T. RELIABILITY ASSESSMENT

SIMPLIFIED FAULT TREE	PRECAUTION	FALL BACK/RECOVERY
Main axis failure: Motor failure; Gear box failure; Clutch failure (open)	Duplicate system and emergency actuation	Operate duplication or emergency systems as required
Main axis failure: Clutch failure (closed); Lead screw jams; Ball nut jams	Accessible ball nut and duplicate system	Disconnect ball nut using using GP robot and use duplicate system
Main axis failure: Main bearing failure; Structural deformation	Over design, mtl. selection and Q.A.	Use external jacks to make safe and withdraw* transporter
Main axis failure: Sensor failure; Axis lock failure (disengaged)	Duplicate system	Use duplicate
Main axis failure: Axis lock fails (engaged)	Attachment for external actuator	Use ext. actuator
Clamp system failure: Index fail: Motor	Duplicate system & emergency actuator	Use duplicate to clear failed unit
Clamp system failure: Index fail: Bearings	Overdesign, mtl. selection & Q.A.	Use external jacks to clear*
Clamp system failure: Index fail: Lead screw/ball unit	Accessible ball nut	Disconnect & use duplicate system
Clamp system failure: Index fail: Sensors	Duplication	Use duplicate
Clamp system failure: Feed failure: Disengaged	Duplication	Use duplicate
Clamp system failure: Feed failure: Engaged: Motor failure	Duplicate system & emergency actuator	Use duplicate to clear failed system
Clamp system failure: Feed failure: Engaged: Transmission failure	Accessible ball nut	Disconnect ball nut and use duplicate to clear jammed system
Clamp system failure: Feed failure: Sensors	Duplication	Use duplicate system
Clamp system failure: Rotary drive failure	Duplication	
Clamp system failure: Structural failure including index mechanism shafts	Over design, mtl. selection & Q.A.	Use external jacks to clear (if necessary) and replace transporter *
Failure to engage door: Failure of upper attachment mechanism: Tilt mechanism: Bearings	Over design, material selection, Q.A.	Use External jacking point*
Failure to engage door: Failure of upper attachment mechanism: Tilt mechanism: Actuators	Duplicate + access for ext. actuator	
Failure to engage door: Failure of upper attachment mechanism: Lock mechanism failure: To engage	Duplicate + access for ext. actuator	Use duplicate or external actuator as required
Failure to engage door: Failure of upper attachment mechanism: Lock mechanism failure: To disengage	Duplicate + access for ext. actuator	
Failure to engage door: Failure of upper attachment mechanism: Structural failure	Over design, material selection, Q.A.	Use external jacking points*
Failure to engage door: Failure of upper attachment mechanism: Sensor failure	Duplication	Use duplicate
Failure to engage door: Structural failure of load carrying system: To engage	Overdesign, material section, Q.A.	With draw & use spare D.M.T.
Failure to engage door: Structural failure of load carrying system: To disengage	Overdesign, material selection, Q.A.	With draw & fit spare door using spare D.M.T.
Failure to engage door: Failure to "make" connections to operational services: Water	Duplication	Use duplicate system or withdraw
Failure to engage door: Failure to "make" connections to operational services: Instrument		
Failure to engage door: Failure to break connections to operational services: Water		
Failure to engage door: Failure to break connections to operational services: Instrumentation		
Failure to engage door: Failure to "make" connections to installation services: Gas	Duplication	Use duplicate system or withdraw
Failure to engage door: Failure to "make" connections to installation services: Vacuum		
Failure to engage door: Failure to "make" connections to installation services: Instrumentation		
Failure to engage door: Failure to break connections to installation services: Gas		
Failure to engage door: Failure to break connections to installation services: Vacuum		
Failure to engage door: Failure to break connections to installation services: Instrumentation		

* The jacking points are not shown on the illustrations but it is probable that the necessary brackets and supporting structure can be provided for either tension or compression jacks

remote manipulators can access the transporter.

3.10 DMT operating sequences and timings

The operating sequences and estimated timings are given in Fig. 23 and Appendix E. The total time, from guide rail acquisition to departure, for the DMT to collect the door is estimated to be 25 minutes and the equivalent replacement operation is estimated to take 45 minutes.

3.11 Estimated costs (1979 figures)

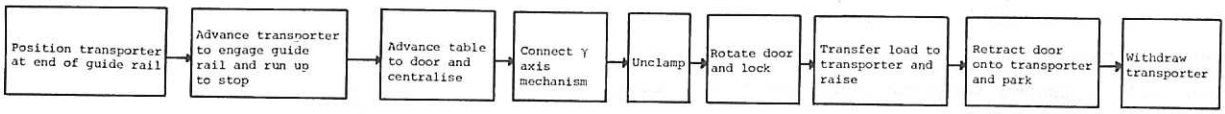
The estimated cost for one DMT is ≅£0.6M made up as follows:

	Per unit
Manipulator	
Total design and development cost written off over 2 units	300,000
Main axis drives	60,000
Clamp actuators	20,000
Services interfaces	15,000
Structure (structural steel @ £3500/tonne)	70,000
Computer and control system	75,000
Batteries	12,000
total	£552,000
Transporter	
Design development costs written off over 5 units	3,000
Manufacture including compressor	15,000
Batteries	3,000
total	£21,000

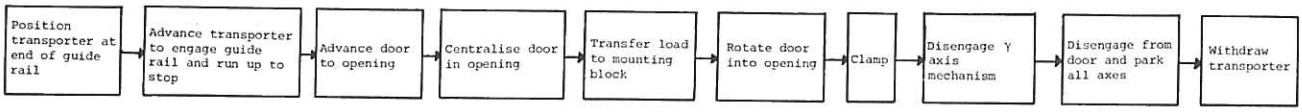
4. INTEGRATION WITH THE CCTRIIB CONCEPT

4.1 Door support

In order to avoid the problems associated with differential settlement/deflections the reactor foundations must support the doors (each weighing ≅200,000 kgf) directly or via the fixed shield structure, see Fig. 24. A preliminary analysis (Appendix F1) suggests that the door weight plus the structure selfweight plus emergency over-pressurisation will cause the bottom disc to deflect by about 3 mm if the structure is steel - which would probably be acceptable. However, the case of a concrete structure has also been considered[10] and it concluded that the bottom disc will require additional support even without the additional weight of the doors. To provide future design flexibility it



DOOR REMOVAL OPERATIONS



DOOR REPLACEMENT OPERATIONS

Fig.23 Operating sequence for door removal and replacement.

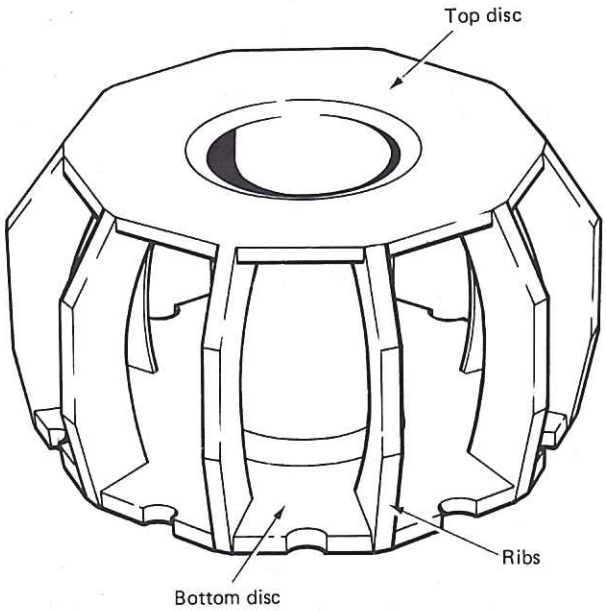


Fig.24 Reactor fixed shield. For clarity this sketch only shows 10 doorways.

is proposed to extend and reinforce the coolant duct shield to give additional support to the bottom disc and to carry the doors (Fig. 25). Preliminary analysis (Appendix F2) shows that there is sufficient room between the D coils to provide an adequate structure.

The proposed system for connecting the concentric coolant duct to the segment utilises mechanically actuated Graylock couplings[11] Fig. 25 shows the duct in the position it will be in just prior to clamping (or just after unclamping) and it can be seen that it is necessary to displace the duct vertically downward to provide uninterrupted access for the segment servicing machines. The bellows is included to allow displacement without the necessity of breaking the seal between the coolant duct and the fixed shield. The means for achieving the necessary displacement has not been considered but it might be provided by allowing the duct to deflect, within the material elastic limit, at some downstream location. The proposed scheme is therefore compatible with the concept for segment replacement providing the segment transporter and other servicing machines can span the increased length introduced by the door support brackets (see Fig. 26).

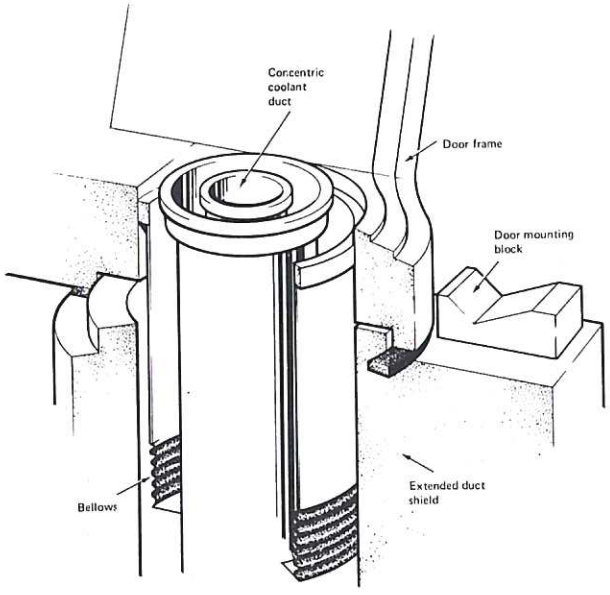


Fig.25 Door structural support and coolant duct.

4.2 Height of reactor hall floor

The DMT design requires that the reactor hall floor should be 1 m below the door sill. There are no apparent technical objections to this requirement and inspection suggests that servicing machines can be designed to make the transition (see Fig. 26).

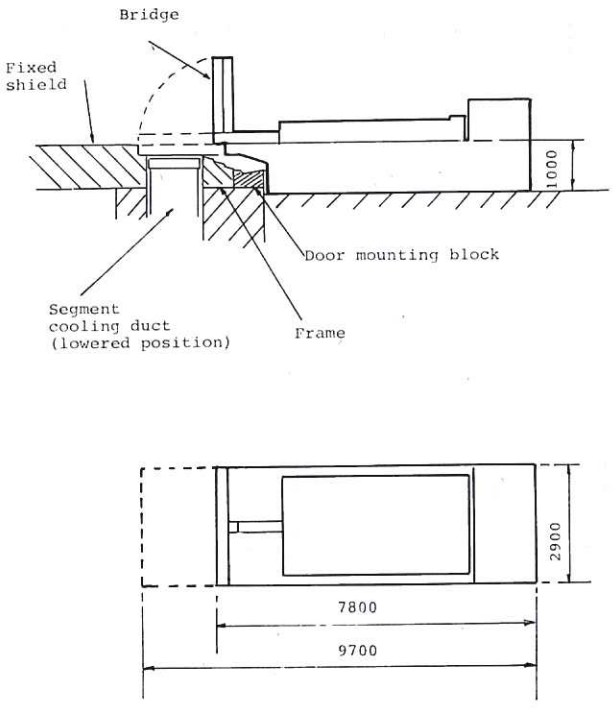


Fig.26 Schematic of segment transporter.

5. CONCLUSIONS

5.1 Shield door and frame

(a) General

The door is a welded and machined, stainless steel tank structure. It is filled with manganese steel balls which will be cooled by a flow of treated borated water. The edges of the door structure are shaped to form a radiation lock and to contain the vacuum seals. Clamps are provided to carry the operational and emergency loadings.

(b) Manufacture

The door design is such that it can be manufactured at the present time, although a lead time of one to two years will be required for pre-production activities. Manufacturing tolerances are expected to be ±2 mm on width and ±6 mm on height or better. A potential problem area will be the provision of adequate non-destructive testing.

The frame can be manufactured and installed to tolerances similar to the door though in-situ machining may be required.

Development over the next twenty years will introduce improved manufacturing techniques and thus modifications to the proposed designs. The designs have not been optimised - more refined design techniques will almost certainly provide a more economically viable structure.

(c) Cooling

The total energy input to the door will be ≅860 kW. A coolant flow of 90 kg/s of water will limit the door maximum temperature to less than 50°C. Coolant failure will not become critical until a time >12 minutes has elapsed. Decay heat removal will not be required.

(d) Radiation shielding

The radiation dose from the 750 mm long interface gap will be of the same order as the dosage through the bulk shield.

(e) Cost

The estimated cost of each door is £0.72M.

(f) Further evaluation requirements

It is suggested that the following work should be carried out to confirm the shield door concept:

- design and development of vacuum seals;
- evaluation of alternative clamping systems and a more detailed study of the effects of clamping forces on the door;
- evaluation of potential fatigue problems associated with ferro-magnetic materials generated near weld runs;
- evaluation of the consequences of segment and door coolant failures.

5.2 Door manipulator-transporter

(a) General

A DMT design is proposed which comprises:

- a self-contained transporter, utilising pneumatic lifting pads and having three horizontal degrees of freedom;
- a door manipulator which carries its own power supply and can provide five axes of motion. Two axes are fitted with positional servo-mechanisms, the remainder being designed to operate against preset hardware and software limits.

(b) Manufacture

The proposed design uses currently available components and is well within the present state-of-the-art for equipment of this type.

(c) Control and communication

Considerable use will be made of computers to plan and control the operations of the DMT, a typical system including onboard processors and a stationary supervisory computer. However it is unlikely that an automatic control system will be sufficiently flexible and reliable to allow the exclusion of manual override and remote control facilities and a communications link which includes a number of video channels e.g. UHF, is therefore required. Local guidance systems will be provided to facilitate rapid manoeuvring and datum setting, particularly within the reactor envelope.

(d) Operation

It is essential that the design of the transporter should be integrated with that of other mobile plant operating in the service area to ensure compatability of control systems, local guidance systems etc. It is also desirable to ensure the highest possible degree of module interchangeability.

(e) Cycle time

Door removal, from guide rail acquisition to departure will occupy 25 minutes. Door replacement will occupy 45 minutes.

(f) Cost

The DMT cost is estimated to be £0.6M.

(g) Further evaluation requirements

It is suggested that the following items should be investigated:

- design of axis drive systems to ensure that reversibility and/or remote servicing is practical;
- modification to the DMT design to limit the pick-up of contamination and to facilitate remote decontamination.

5.3 CCTRII servicing

(a) The study suggests that the utilisation of special purpose machines to service the reactor provides considerable cost benefits in terms of minimising reactor down times.

(b) Inspection suggests that the same, or very similar, transporter units can be utilised by all the mobile equipment operating in the reactor hall.

6. ACKNOWLEDGEMENTS

The author would like to thank a number of people for their assistance with the work described in this report including: Messrs. D.L.D. Marsh and A.A Gibbs of the Structural Division of W.S. Atkins & Partners for the structural design of the door and for their comments in other areas; Mr. A. Palit for his calculation of neutron streaming in the interface gap; and Mr. J.T.D. Mitchell of Culham Laboratory for his helpful advice and comments.

I am also indebted to a number of individuals and organisations for finding time to advise on specific areas including AEA Winfrith, Jack Dean Eng. Ltd., Fairey Engineering, Firth Brown, Dr. Hughes of Leeds University, O.H. Steel Founders & Engineers, Vickers Nuclear Engineering Division and the Welding Institute.

7. REFERENCES

1. Carruthers, R. et al. Culham study group report of fusion reactors and the environment, CLM-R-148, 1975.

2. Mitchell, J.T.D. Blanket replacement in toroidal fusion reactors. Invited paper at ANS 3rd Topical Meeting on Technology of Controlled Nuclear Fusion, Santa Fe, p.954, 1978.

3. Fuller, G.M. and Zahn, H.S. The impact of the fusion reactor design approach on the maintenance of first wall/blanket modules. Proceedings of 26th Conference on Remote Systems Technology, ANS Washington, p.325, 1978.

4. Briaris, D.A. and Stanbridge, J.R. Design of the segment structure and coolant ducts for a fusion reactor blanket and shield. Culham report CLM-R-184.

5. Mitchell, J.T.D. Private communication.

6. Horne, R.A. MANTIS - A compact mobile remote handling system for accelerator halls and tunnels. Proceedings of 26th Conference on Remote Systems Technology, ANS Washington, p.325, 1978.

7. Bartle, P.M. Diffusion bonding - a look at the future. Welding Journal, pp.799-804, November 1975.

8. Gfeller, F.R. and Bapst, U. Wireless in house data, communication via diffuse infra red radiation. Proc. IEEE, Vol.67, No.11, pp.1474-1486, November 1979.

9. Greene, A.E. and Bourne, A.J. Reliability technology. Wiley Interscience, NY, 1977.

10. W.S. Atkins & Partners. Preliminary study of the feasibility of using concrete for the fixed shield of the Culham conceptual Tokamak Reactor Mk.IIB. Report 5069401/ST/AAG, 7 September 1979.

11. Briaris, D.A. and Stanbridge, J.R. The feasibility of remotely separating and rejoining the main coolant pipe of a fusion reactor. Culham report CLM-R-174.

12. Yoshikawa, H. et al. Outgassing rates before, during and after bake-out for various vacuum and first wall candidate mayerials of a large tokamak device. Proceedings of 7th Int. Vac. Congr. and 3rd Int. Conf. Solid Surfaces, p.367, Vienna, 1977.

13. Brown, J.H. Private communication.

14. Hitchon, J. Private communication.

SHIELD DOOR DESIGN

A1. PRESSURE RISE IN REACTOR DUE TO COOLANT SYSTEM FAILURE

In the assumed system configuration the blanket segment contains 150 breeding cells. Each cell is connected to inlet and outlet helium coolant manifolds by a system of coaxial pipes. Motorised stop valves are fitted up-stream and down-stream from the segment and the contained volume is assumed to be 40 m^3, based upon 20% segment volume plus 10 m concentric duct length. The valves will operate, i.e. go from fully open to fully closed, in 30 seconds. The reactor hall atmosphere is at 0.9 bar pressure.

The coolant parameters are:

Inlet pressure	=	60 bar
Inlet temperature	=	350°C
Exit temperature	=	750°C
Flow rate	=	60 m/s
Flow area	=	0.98 m^2

It is assumed that failure will occur at the most highly stressed point of the coolant system i.e. at or near the breeder cell. Gas leakage into the reactor will therefore be made up of:

(a) Leakage, which is compensated by fluid entering the system, for 30 seconds.

(b) Leakage into the vacuum space after the valves are closed due to the fluid pressures balancing.

Using the following assumptions:

(a) the inlet and outlet pipes are broken so that the break is modelled by flow from opened ends at inlet and outlet, each assumed to have an area = 0.005 m^2;

(b) the free volume inside the reactor is 2000 m^3;

(c) the expansion will be adiabatic.

First order analysis indicates that the pressure inside the fixed shield will rise to about 2 bar (absolute) during the 30 seconds it takes the segment cooling circuit shut off valves to operate and subsequently rise to over 6 bar (absolute) as the leakage gas is heated by the hot internal structures which are themselves subjected to afterheating. Since protective devices (relief valves, bursting discs) can be installed and the pressure rise time is fairly long it is unnecessary to design the fixed shield/door system to cater for the high internal pressure.

Since the door is required to withstand 0.9 bar differential, acting inwards, it seems logical to apply the same figure to the outwardly acting fault case i.e. for design purposes the maximum pressure differential acting across the door is taken to be 0.9 bar.

A2. DESIGN LOADINGS

(a) Design loadings

Pressure loading - a reversible pressure difference of 90 kN/m^2 (0.9 atm) across the full thickness of the door has been used to represent:

- the operating condition of high vacuum inside the reactor vessel together with near atmospheric pressure in the containment building;
- the fault condition of internal overpressurisation due to a coolant system failure which is limited by protective devices (Section A1).

(b) Pressure inside the door compartment due to the shielding materials

In addition to the above pressure loadings arising from the door's rôle as a vacuum seal, there is an internal pressure exerted by the metal spheres and borated water in the door compartment. This was calculated as follows, assuming a 10 m high, unpartitioned door (assumed worst case).

It can be shown that the pressure variation with depth in a wide container filled with pebbles and water is given by:

$$p_h = \rho_w h + K_1(1-v)(\rho_B-\rho_w)h$$

where

p_h	=	active pressure at depth h
ρ_w	=	(weight) density of water
ρ_B	=	(weight) density of spheres
K_1	=	0.751 and is calculated from geometrical parameters
v	=	void ratio

This equation is similar to the standard form (Ref. A1) which contains the Rankine factor K_2 in

place of K_1 so that $K_1=K_2=0.751$. The Rankine factor is used in the modified version of Jansens equation (Ref. A1) for narrow, deep containers which considers 'arching' of the pebbles, i.e.:

$$p = (\frac{h}{h_2})qm \quad 0<h<h_2$$

$$p = qm \quad h \geq h_2$$

where

$h_2 = \frac{K_2 r}{\tan\mu}$ (= 1.454 m)

r = hydraulic radius of container = 0.273 m

μ = angle of friction between spheres and wall and $\tan\mu$ = coefficient of friction taken as 0.25

qm = $Dr/\tan\mu \cong 40$ kN/m²

D = bulk density of submerged spheres.

The internal pressure distribution is shown in Fig. A1, and it can be seen that a design pressure of 140 kN/m² is suitable which when taken with atmospheric pressure gives a maximum differential across a door 'skin' of 250 kN/m².

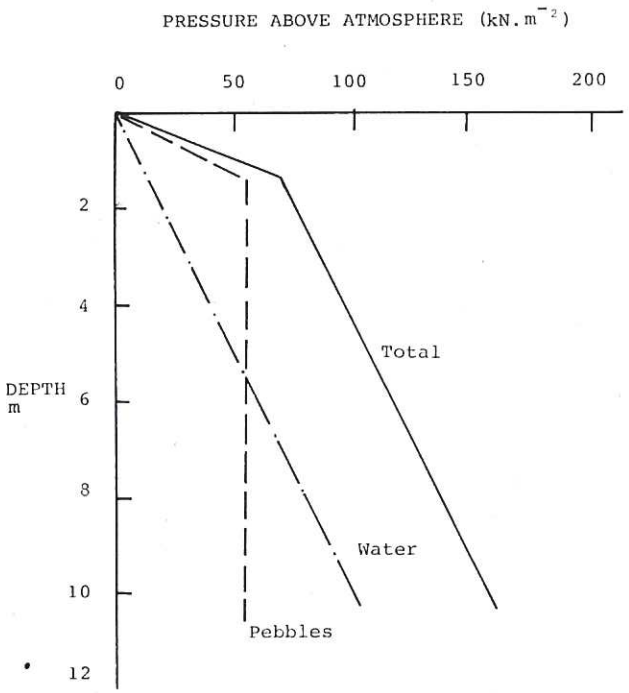


Fig.A1 Door internal pressure distribution.

A3. MATERIAL PROPERTIES

Type 316 stainless steel has been selected, having assumed properties as follows (Ref. A2):

Young's modulus of elasticity = 183 kN/mm²

Working stress = 135 N/mm².

A4. STRUCTURAL DESIGN

Taking as an example external pressure case A2(a) the loading on the door is shown (in plan) in Fig. A2.

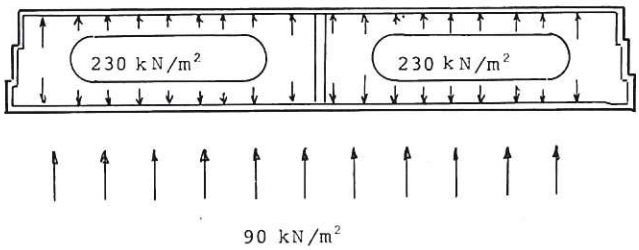


Fig.A2 Loadings on door.

The responses to this loading comprise:

- a 'bulging' of the door halves either side of the central vertical plate. This latter acts in tension to hold the door together in the centre, see Fig. A3(a);
- deflection of the entire door inwards under atmospheric pressure. This mode is not centrally restrained, see Fig. A3(b).

The door analysis was performed using simple elastic bending theory. In the cases described in Fig. A3(a) and (b) the section in flexure comprised

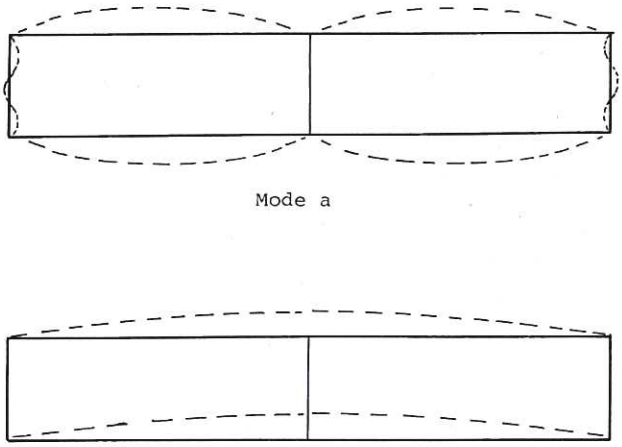


Fig.A3 Loading responses.

a horizontal stiffner with a 750 mm wide 'flange' of door outer skin (750 mm being the distance between stiffners). The beam end reactions from this

analysis were applied to the vertical side plate in order to evaluate its bending stresses.

Approximate bending stress in horizontal element:

Door front or rear face diaphragms ≅ 70 N/mm²
Door side face ≅ 15 N/mm²

In addition the bending stresses in the side plate as a vertical element were calculated to be 40 N/mm² assuming clamps at every third diaphragm level i.e. at 2250 mm centres.

Force/clamp = 300 kN

A5. LOAD CARRYING BRACKET

The local geometry does not place any significant dimensional restraint on the load carrying bracket and its design has not been undertaken at this stage. The design of the bracket should be such that the kinetic energy contained by the door, when the Y-axis is moving at its maximum speed, is translated to strain energy (during weight transfer) without exceeding 0.1% proof stress.

The door weight is carried by the reactor structure via two 300 mm diameter rollers specified according to the empirical formula for bridge rollers (Ref. A3).

The load carrying bracket is illustrated in Fig. 16 and its position on the door is shown in Fig. 5.

A6. CLAMPS

(a) Design loadings

The principal function of the clamps is to transfer all normal and abnormal forces, which act on the door, to the fixed shield structure.

The normally applied load is produced by the operational, 0.9 bar, pressure differential which acts inwards, i.e. F_N=3.6x10⁶ N total.

Abnormal loads are:

- a seismic force F_s due to an 0.25 g horizontal acceleration acting inwards or outwards, F_s= 50,000 N total;
- a force due to internal pressurisation of 1.8 bar (a differential of 0.9 bar) acting outwards.

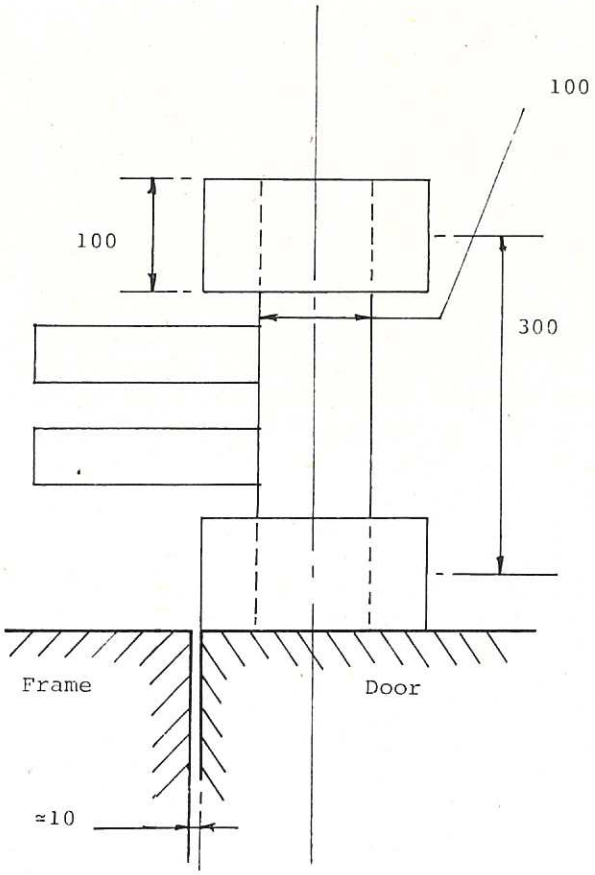
The design case total is therefore 4.1x10⁶ N acting in either direction.

There are twelve clamps fitted to the door - six on the upper module and six on the lower module. However, since the door will tend to rotate about its foot roller under the action of all radial loads, the upper set of clamps will carry the largest loads.

Assuming that the line of action of the applied load is through the door centre of gravity and the upper set of clamps act at the centre of gravity of the upper module the total load to be transferred by the (six) clamps, is by moments, 3.08x10⁶ N and the load per clamp is 500 kN.

(b) Design

The principal dimensions of the clamp are given in Fig. A4.



(All dimensions in mm)

Fig.A4 Principal clamp dimension.

Analysis of the shaft by simple bending theory gives a maximum bending stress of 90x10⁶ N/m² and a maximum shear stress of 76.2 N/m² when the shaft is 100 mm diameter.

The bearing sizes shown are conservatively designed and have a factor of safety of greater than 2.

The clamp plates are sized so that bending and shear stresses $\leq 200 \times 10^6$ N/m^2.

The helical springs are provided to centre the clamp and return the jaws to the open position and it should be noted that there is ample space available to incorporate any changes required by detail design. This design of clamp should be able to cater for mis-alignment of 2 cm or more.

The ring springs are provided as energy absorbers to cater for radial door movements introduced by the applied loads. As above there is no significant geometrical constraint to the size of the energy absorbers.

REFERENCES

A1. Reynolds, C.E and Steedman, J.C. Reinforced Concrete Designers Handbook. 8th Edition, Cement and Concrete Association, 1974.

A2. ASME Boiler and Pressure Vessel Code. Section 3, App.1, ANSI/ASME BPV III-I-A, 1977.

A3. Kempes Engineers Year Book, 1973.

NEUTRON STREAMING

It is necessary to provide a clearance gap between the door and the frame, and bearing in mind that the transmission through a rectangular duct is approximately given by

$$T_s = \frac{t}{2L}$$

(t = thickness and L = length), it will be necessary to provide one or more steps. If the number of steps = n, i.e. there are (n+1) straight sections (legs), the transmission T_s is:

$$T_s = \left(\frac{t(n+1)}{2L}\right)^{(n+1)}$$

provided that a direct line of sight path is not possible. This simple expression is not valid in practice if n>3 and requires that the thickness (t) << length (L) << width (w). Typical duct dimensions will be t=0.02 m, L=0.5 m and W=10 m or 3 m, thus the above requirements are met.

The total transmission through a duct approximates to the transmission through the bulk shield (T_b) plus the transmission through the duct (T_s) and the transmission ratio, (T_r) where

$$T_r = \frac{T_s + T_b}{T_b}$$

indicates the effectiveness of the duct design.

The above equations were solved for two and three leg systems and three values of T_b (in the range 10^{-3}-10^{-4}) for a range of duct thicknesses. The results (T_r plotted against t) are shown in Fig. B1 and B2 for 0.5 m and 0.75 m duct lengths respectively. Interpreting the specification (2.1.2) to mean $T_r \leq 1.5$ and using a value of t≅1.0 cm (Appendix D9.2) it can be seen that a 0.5 m long duct will not cover the $T_b=10^{-4}$ case which may be specified during detail design. This case will be adequately covered by a 0.75 m long duct with three equal legs (two steps) each step to be approximately 2 cm to provide adequate overlap.

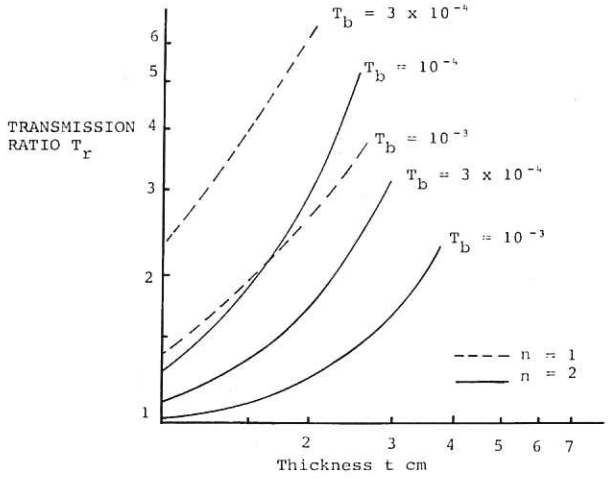


Fig.B1 Transmission ratio of 0·5 m long interface gap.

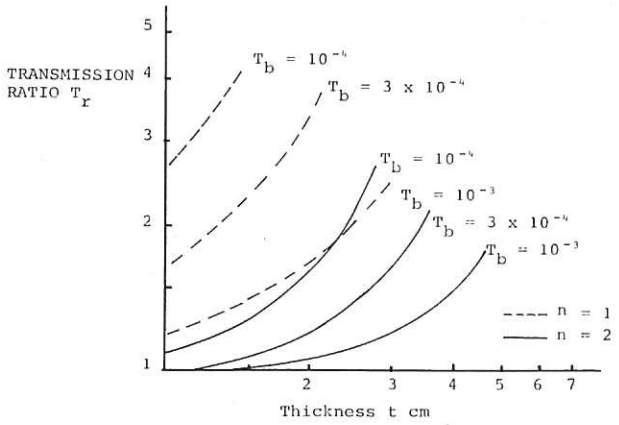


Fig.B2 Transmission ratio of 0·75 m long interface gap.

To avoid the significant cost of making the whole door 0.75 m thick, 0.25 m x 0.25 m corner fillets have been added around the door edge (Fig. 7 and 8). This is compatible with the segment and fixed shield design (Ref. 4).

SHIELD DOOR COOLING

C1. HEAT TRANSFER COEFFICIENTS

The specified arrangement for the shield door, i.e. a tank containing Mn-Fe spheres is analogous to a packed bed. Previous work (Ref. C1) has suggested that a flow velocity of 0.25 m/s will be satisfactory.

Reynolds number for flow in a packed bed is defined by:

$$Rn = \frac{D_p G_o}{\mu} \qquad (1)$$

where

D_p = particle diameter, m
G_o = superficial mass velocity, kg/m²s (based on total cross section without spheres)
μ = kinematic viscosity, kg/ms.

The following correlations for packed beds are given by McAdams (Ref. C2):

$$0.687 \left\{\frac{D_p G_o}{\mu}\right\}^{-0.327} = \left\{\frac{h}{C_p G_o}\right\} \left\{\frac{C_p \mu}{K}\right\}^{2/3} \qquad (2)$$

and Denton (Ref. C3)

$$\frac{h}{C_p G_o} = 0.58 \left\{\frac{D_p G_o}{\mu}\right\}^{-0.3} \left\{\frac{C_p \mu}{K}\right\}^{-0.7} \qquad (3)$$

where

h = heat transfer coefficient, W/m²°C
C_p = fluid specific heat, J/kg°C
K = thermal conductivity, W/m°C

Equation 2 is stated to be relevant to liquid flow for Reynolds numbers in the range 120-2000 and equation 3 is valid for liquid turbulent flow.

Fixing the particle size is an optimisation of the following:

- ease of manufacture - large sizes (say >50 mm) will be costly to manufacture;
- system pressure - pressure drops through the bed should be as low as possible and since $\Delta P \propto 1/D_p$ the particle diameter should be as large as possible;
- need to minimise edge effects from heat transfer and shielding equipment - particles should be as small as practical.

It is not possible to carry out this optimisation at the present time so an arbitrary selection of sphere diameter is made i.e. 50 mm. Subsequent calculations will show that this size is generally satisfactory.

Using this particle size and the properties of water, measured at 50°C, it can be shown that Reynolds number will be ≅1800. Equations 2 and 3 will both apply (approximately) and calculated values of 'h' are 2117 and 2091 W/m²°C respectively. A value of h=1500 W/m²°C has been used for subsequent calculations.

C2. BED APPARENT THERMAL CONDUCTIVITY

(a) Stagnant conductivity of bed filled with helium

McAdams (Ref. C2) reproduces a set of curves relating the system component conductivities for packed beds with stagnant interstitial fluid for various void fractions in the form:

$$\frac{K_B}{K_g} = f\,\frac{K_s}{K_g}$$

where

K_B = bed conductivity, W/m²°C
K_g = fluid conductivity, W/m²°C
K_s = particle conductivity, W/m²°C.

Using parameters for Mn-Fe spheres and helium and taking a representative value of 0.35 for voidage gives:

$$K_B = 1.2 \text{ W/m°C.}$$

(b) Stagnant conductivity in water filled packed bed

Yagi et al (Ref. C4) quote a semi-experimental correlation of the type:

$$K_e^\circ/K_g \text{ versus } K_s/K_g$$

where

K_e° = radially effective thermal conductivity in stagnant packed bed, W/m²°C
K_g = fluid thermal conductivity, W/m²°C
K_s = thermal conductivity of solid, W/m²°C

from which $K_e^\circ = 3.86$ W/m²°C.

(c) Apparent conductivity of active bed

Yagi et al (Ref. C4) quote the relationship:

$$\frac{K_e}{K_g} = \frac{K_e^\circ}{K_g} + (\alpha\beta)\,(N_{pr})\,(N_{RN})$$

where

K_e = radially effective thermal conductivity, W/m²°C
K_e° = effective thermal conductivity in packed bed with motionless fluid, W/m²°C
K_g = fluid thermal conductivity, W/m²°C
$\alpha\beta$ = factor depending upon particle and tank dimensions = 0.07 from published curves
N_{pr} = Prandtl number
N_{RN} = Reynolds number

from which K_e = 292 W/m²°C.

C3. PRESSURE DROPS THROUGH BED

An approximate value of the pressure drops through a packed bed is given by (Ref. C5):

$$\Delta P = \rho \left\{ \frac{4 f_m (1-\varepsilon)^{3-n}}{\phi_s^{3-n} \varepsilon^3} \right\} \left(\frac{L}{D_p}\right) \left(\frac{V^2}{2g}\right)$$

where

ΔP = pressure drop, lb/ft²
P = fluid density, lb/ft³
f_m = friction factor = 1
ϕ_s = shape factor = $\frac{\text{Area of sphere equivalent to volume}}{\text{Actual area of pebble}}$ = 1
ε = void factor = 0.35
L = length of bed, ft
D_p = particle diameter, ft
V = $\frac{G}{\rho} = \frac{\text{fluid mass velocity}}{\text{fluid density}}$, ft/sec
n = exponent (from curve = 1.95)

Using properties for water, assuming a bed length of 12 ft (3.6 m) and converting the result:

ΔP = 11,000 N/m² ≡ 0.11 bar

Note: The door should be divided into three sections (top, middle and bottom), each having inlet and outlet manifolds, so as to ensure good flow distribution, particularly in the centre section which contains the main penetrations.

C4. ENERGY INPUTS TO DOOR

(a) Thermal radiation

The geometrical relationship between the inner surface of the door and fixed shield is fairly complex. For this design study the following simplifying assumptions are made.

The external surface of the segment and door are rectangular and parallel and separated by an 0.5 m gap. The segment surface is 350°C and the door internal surface 70°C. The emissivity is assumed to be 0.4.

The radiation heat exchange is:

$$Q = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}\ \sigma A (T_1^4 - T_2^4)$$

where

ε_1 = emissivity of shield, 0.4
ε_2 = emissivity of door, 0.4
σ = Stephan Boltzman constant, 5.669×10^{-8}
A = surface area 10 m x 3 m
T_1 = 350°C
T_2 = 70°C

Substitution of these values in the above equation gives a heat input to the door of about 58 kW.

(b) Neutron absorption

The reactor thermal output will be 3400 MW and it is estimated that 1% will be dissipated in the outer, fixed, shield (Ref. C6).

By proportion the heat input to a door from neutron absorption will be approximately 800 kW.

Assuming that the door is divided into five 100 mm slices, the overall attenuation is to be 10^{-4} and that the energy distribution is exponential, the rate of energy deposition due to neutron absorption will be:

Section	Neutron heating kW
0.0-0.1	673
0.1-0.2	106
0.2-0.3	17
0.3-0.4	2.5
0.4-0.5	0.5

C5. TEMPERATURE DISTRIBUTIONS

A rigorous analysis of temperature distributions in the door is outside the scope of this project and the subsequent analysis is designed to provide upper and lower limits.

The door is divided into three separate zones each having its own independent cooling system and it is assumed that one-third of the total energy input to the door occurs in each zone.

(a) Lower limits

Basic assumption - infinite radial thermal

conductivity, i.e. a flat temperature distribution through the door.

Heat input to section of door Q = 285 kW

Assumed mass flow of coolant $\dot{m}$ = 30 kg/s

Heat transfer coefficient, h = 1500 W/m²°C

Total heat transfer area of 50 mm dia. spheres = 390 m²

Temperature rise of water = $\Delta T = \frac{Q}{\dot{m} C_p}$

where

C_p = specific heat of water

from which

ΔT = 2.27°C.

Logarithmic mean temperature difference = ΔT_m:

$$\Delta T_m = \frac{Q}{hA} = 0.49°C.$$

From which the following temperatures can be deduced, assuming a water inlet temperature T_c = 35°C:

Water outlet temperature, T_H ≅ 37°C

Temperature at bottom of door, T_1 ≅ 36°C

Temperature at top of door, T_2 ≅ 38°C

(b) Upper limits

Basic assumption - radial heat transfer is ignored and the system is analysed assuming five independent, 100 mm wide, vertical slices.

The energy distribution in the door is assumed to be as defined in the previous section. The calculated parameters are given in the following table:

Section	0.0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5
Heat input, kW	243	35.3	5.7	0.83	0.17
Heat trans. area, m²	78	78	78	78	78
h	1500	1500	1500	1500	1500
$\Delta T_m = Q/ha$	2.0	0.3	0.05	0.01	0.001
Fluid mass flow, kg/s	6	6	6	6	6
$\Delta T = Q/\dot{m} C_p$	9.7	1.4	0.23	0.03	0.01
T_c °C	35	35	35	35	35
T_H °C	44.3	36.4	35.23	35	35
T_1 °C	37.5	36	35.5	35.5	35.5
T_2 °C	47	37	36	36	36

This temperature distribution is illustrated in Fig. C1.

(c) Conclusion

The actual temperature distribution will be between the upper and lower cases discussed in the previous paragraphs, i.e. the maximum temperature of the door will be less than 47°C and the maximum short range temperature difference 10°C, though slightly higher temperatures may occur in regions not adjacent to the coolant flow e.g. adjacent to the vacuum seals.

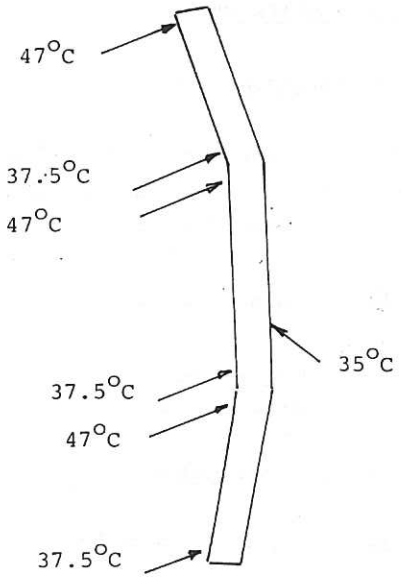


Fig.C1 Vertical temperature distribution on shield door.

C6. SENSITIVITY OF SYSTEM TO COOLANT FAILURE

In the event of a coolant failure, which does not involve loss of water, it is desirable to limit the maximum cooling water temperature to 90°C to avoid pressurisation.

The rates of temperature rise will be 0.014°C/s for the case of infinite transverse conductivity and 0.06°C/s if there is no transverse mixing. The time to reach 90°C will therefore be ≧12 min.

In the unlikely event of a coolant failure which involves loss of water from one of the door sections the system temperature will rise and cause the door to expand until it jams in the frame. Assuming that the minimum total transverse clearance at operating temperature is 10 mm (see Appendix D9.2) the temperature rise to cause jamming will be about 290°C and will take about 45 minutes.

Note: None of the above cases include heat losses from the door surfaces.

C7. POST SHUTDOWN HEATING

C7.1 Initial assumptions

(a) The door has been normally cooled, drained and removed from the reactor so the ambient condition is: helium gas at 0.9 bar and 20°C.

(b) Heat loss is by natural convection.

(c) Heat transfer is through two vertical, parallel, plates of dimensions 3 m wide x 12 m high.

C7.2 Heat transfer coefficients

From Ref. C7 $Nu = C\,[Gr.Pr]^{n}K'$, i.e.:

$$\frac{hx}{K} = C \left\{\left(\frac{g\beta\rho^2\Delta T x^3}{\mu^2}\right)\left(\frac{C_p\mu}{K}\right)\right\}^{n} K'$$

where

h	=	overall heat transfer coefficient, $W/m^2°C$
x	=	characteristic length of system, m
K	=	thermal conductivity, W/m°C
C	=	constant
g	=	acceleration due to gravity, m/s^2
ΔT	=	temperature difference $(T_{wall} - T_{fluid})$
C_p	=	specific heat, J/kg°C
n	=	an index
K'	=	a dimensionless correction factor
ρ	=	density, kg/m^3
μ	=	fluid viscosity, kg/m s
β	=	coefficient of volumetric thermal expansion $\cong \frac{1}{Tf} K^{-1}$
Tf	=	absolute bulk fluid temperature, °K.

Applying the parameters for helium gas gives:

$$Pr.Gr = 2.5 \times 10^9\ \Delta T.$$

Turbulent convection occurs when $Pr.Gr > 10^9$ and from Wong (Ref. C7):

$C = 0.0246$

$n = 0.4$

and

$$K' = \left\{\frac{Pr^{1/6}}{1+0.494Pr^{2/3}}\right\}^{2/5} = 0.83$$

from which

$$h = 1.47\ \Delta T^{0.4}\ W/m^2°C.$$

C7.3 Energy inputs

The relevant dimensions and shield materials are given in Fig. 4 and 7. Only those elements which are likely to make significant contributions to decay heating are included. The activating neutron fluxes were obtained by scaling from the data in Ref. C8, and assuming the overall attenuation to be $3x10^3$. The neutron spectra in comparable regions were also assumed to be the same as those given in the reference.

The activation reactions considered were as follows:

Mn-55 (nγ) Mn-56)	
Fe-58 (nγ) Fe-59)	Thermal neutron
Cr-50 (nγ) Cr-51)	activation
Ni-64 (nγ) Ni-64)	
Fe-54 (np) Mn-54)	
Fe-56 (np) Mn-56)	Fast neutron
Ni-58 (np) Co-58)	activation
Ni-60 (np) Co-60)	

The internal heat generation rates were calculated to be 1 kW/m^3 at the inside face and 1 W/m^3 at the outside face assuming infinite irradiation and zero decay. The spatial variation of the heat release rate was obtained by ignoring the migration of the electrons and taking the photon source distribution to be exponential. The heat generation rates are upper limits.

C7.4 Energy balance

Energy deposition in the door is described by the equation:

$$Q = Q_o e^{-\lambda x}$$

and the temperature distribution by

$$\frac{d^2T}{dx^2} + \frac{Q}{K} = 0$$

where

Q	=	Heat generation rate at distance x from the inboard face of the door W/m^3
Q_o	=	heat generation rate at x = 0 W/m^3
T^o	=	temperature °C
K	=	stagnant conductivity of helium filled bed W/m°C
λ	=	attenuation constant = 13.8

Solution of these equations using the appropriate boundary conditions gives the quantities of heat which must be convected through the inboard and outboard door faces (62 and 10 W/m^2 respectively) for the door to remain at constant temperature.

From Section C7.2

$$h = 1.47\ \Delta T^{0.4}\ W/m^2°C$$

so that the temperature difference required to dissipate 62 W/m^2 will be 14.5°C.

However from Section C5 the minimum, calculated, surface temperature on the inboard surface of the door is 35.5°C so that the minimum ΔT is 35.5°-20°= 15.5°C, i.e. the door temperature will fall and cooling is not required.

REFERENCES

C1. Hobbs, W., AERE, Harwell. Private communication.

C2. McAdams, W.H. Heat transmission. (Third Edition) McGraw-Hill Kogakusha Ltd., 1954.

C3. Denton, W.H. The heat transfer and flow resistance for fluid flow through randomly parked spheres. Proceedings of the General Discussion on Heat Transfer, I.Mech.E., 11-13 September 1951.

C4. Yagi, S., Kunii, D. and Wakao, N. Radially effective thermal conductivities in parked beds. Proceedings of the 1961-62 Conference in International Developments in Heat Transfer, ASME.

C5. Perry, R.H. and Chilton, C.H. Chemical Engineers Handbook. (5th Edition), McGraw-Hill, 1973.

C6. Mitchell, J.T.D. Private communication.

C7. Wong, H.Y. Heat transfer for engineers. Longman Group Ltd., 1977.

C8. Iida, H. et al. Induced activity and dose rates in the JAGRI Experimental Fusion Reactor (JXFR), JAERI M6639, 1976.

TRANSPORTER DESIGN

D1. DESIGN LOADINGS

The principal dimensions and lines of actions of the principal loads are shown in Fig. D1.

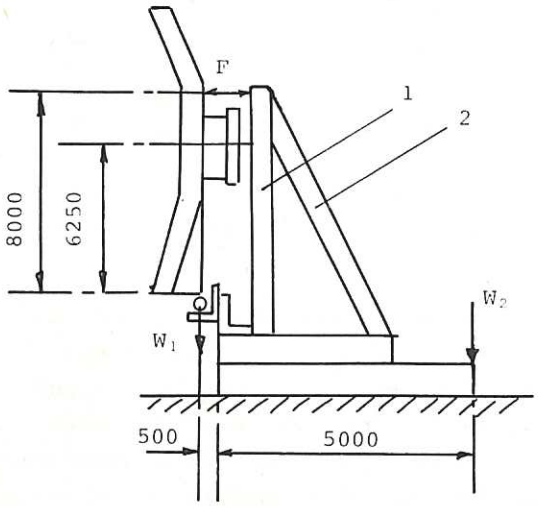


Fig.D1 Transporter – principal dimensions plus loadings. (All dimensions in mm)

W_1 = weight of door (200,000 kgf)
W_2 = weight of counterweight (40,000 kgf)
F = balancing force.

During normal operation the maximum value of F will occur when the door is in the transport position leaning towards the frame structure.

Four accident conditions are possible:

(a) door impacting on fixed structure during γ-axis operation - the maximum speed being 0.0125 m/s;

(b) door impacting on fixed structure during X-axis traverse - the maximum speed being 0.0167 m/s;

(c) the transporter colliding with a fixed stop during area traverse - the maximum speed being 0.5 m/s;

(d) the door colliding with a fixed stop during area traverse - the maximum speed being 0.5 m/s.

The accident conditions are likely to induce greater stresses in the frame than those caused by normal operation and since the maximum amount of energy is transferred to the frame in case (c) this case is selected as the design case.

D2. FRAME DESIGN

The material used for the frame is a structural steel having a Youngs modulus = 200×10^9 N/m^2 and an allowable stress of 200×10^6 N/m^2.

Impact during sideways traverse will not stress the frame very highly since much of the available energy will be absorbed in rotating the door about a bottom corner.

The principal failure mode, during impact while travelling in a forward or reverse direction, will be buckling of one of the columns. The forces involved will be much the same and since column 2 is longer than column 1 impact during forward traverse will produce the greater effect and is therefore chosen as the design case.

Kinetic energy of door relative to frame $\frac{Mv^2}{2}$ = 25,000 N-m

Energy to be absorbed by one column pair = 12,500 N-m

By Castigliano:

$$U = \sum_{i=1}^{i=m} \frac{F_i^2 L_i}{2A_i E}$$

where

U = strain energy
F_i = load in member i of a frame
L_i = length of member i
A_i = area of member i
E^i = Youngs modulus

which reduces to:

$$\delta_n = \frac{\partial U}{\partial P} = \sum_{i=1}^{i=m} \frac{F_i L_i}{A_i E} \frac{\partial F_i}{\partial P_n}$$

where

P_n = the external loads.

Applying this equation to the frame structure gives:

$$\delta = \frac{234F}{AE} \qquad (1)$$

where

F = applied load
A = A_i

but

$$\frac{F\delta}{2} = 12{,}500 \text{ N-m} \qquad (2)$$

Combining equations (1) and (2) gives:

$$F = 6.34 \times 10^6 \sqrt{A} \ N \qquad (3)$$

The critical buckling load on a column is given by:

$$P_{CR} = \frac{\pi^2 EI}{4L^2} = \frac{F}{\sin 15}$$

and

$$F = \frac{\pi^2 EI \sin 15}{4L^2} \qquad (4)$$

Fig. D2 graphs a range of solutions to equations (3) and (4) for various box section beams. From the graph it can be seen that a 0.4 m x 0.4 m x 0.02 m thick beam will be satisfactory from both buckling and energy absorption criteria.

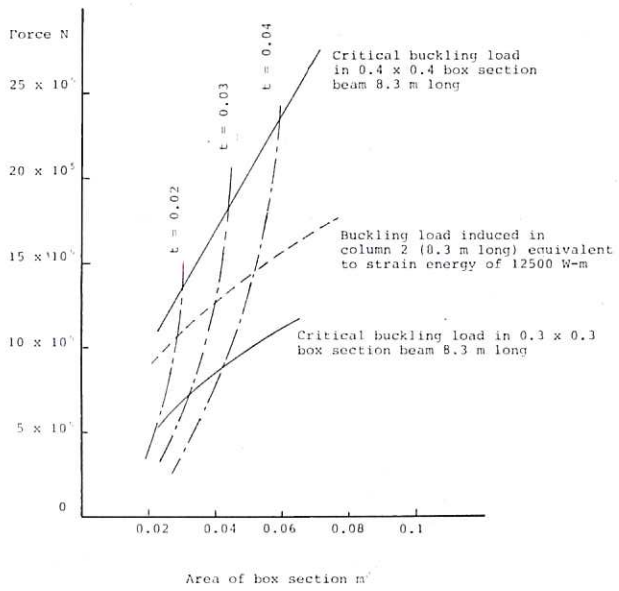


Fig.D2 Buckling loads in column 2 of frame structure.

Using the value of applied force obtained from the graph (approx. 1.1×10^6) the values of bending and compressive stresses induced in the beam are:

$$\sigma_B = 19.16 \times 10^6 \ N/m^2$$
$$\sigma_c = 36 \times 10^6 \ N/m^2$$

i.e. well within the allowable limits.

D3. DESIGN OF X-AXIS TABLE

Each frame column pair is supported on a longitudinal box section beam which is itself supported on recirculating roller bearings.

The arrangement of forces which occur during impact are illustrated in Fig. D3. Analysis of these cases using simple bending theory indicate that a beam having a section modulus of 12×10^{-3} m³ is required - typically a beam of dimensions 0.55 m wide x 0.825 m high x 0.04 m thick.

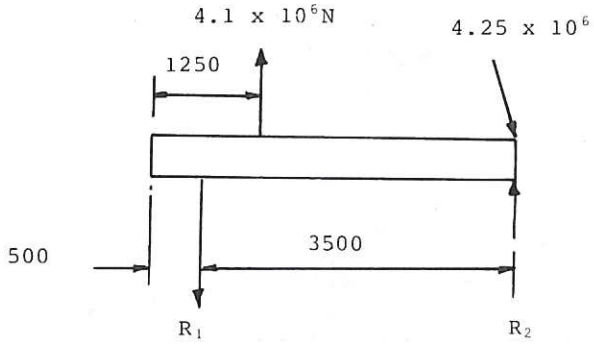


Fig.D3 Inpact forces acting on the X axis table. All dimensions in mm.

The forces acting on each longitudinal beam are equal and their plane of action passes through the bearings. Therefore there will be no significant bending in the transverse direction except that which is caused by the door load on front bracket and the design can be arranged to give the required degree of transverse stiffness.

In general there are no geometrical or weight constraints to the design of the X-axis table so that there is freedom to increase or decrease both the longitudinal and transverse stiffness as required.

D4. CHASSIS DESIGN

The chassis is made up of two fabrications i.e. a transversely stiffened base plate and a floating table which is supported by a jack located at each corner of the base, Fig. D4(a), ball and socket load bearing elements being used to provide location in X and Y.

The construction of the 'floating' table is similar to that of the X-axis table, i.e. two, cross-connected rectangular beams. Each beam carries half the applied loads and each can be treated separately in the longitudinal bending cases.

Four cases have to be considered i.e.:

- longitudinal and transverse stiffness when the transporter is stationary;

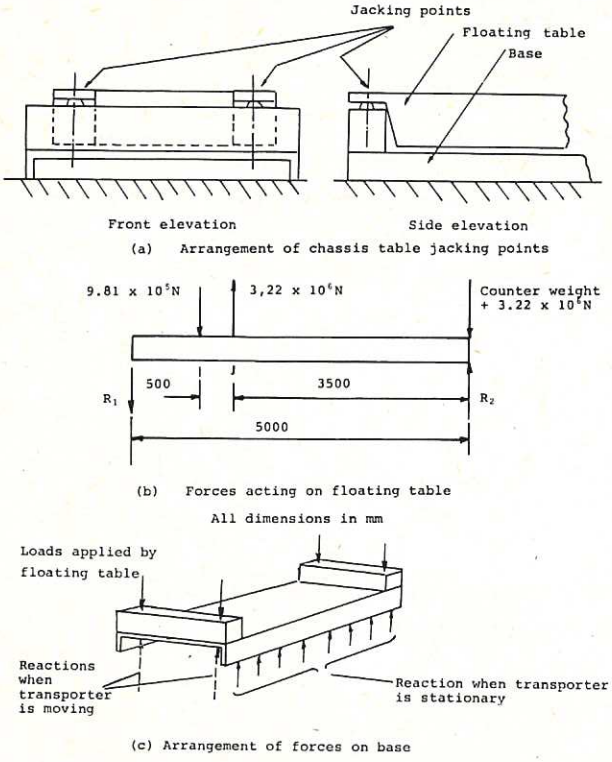


Fig.D4 Chassis and applied forces.

- longitudinal and transverse stiffness when transporter suffers impact while travelling at 0.5 m/s.

In general transverse bending is not significant and there is ample room to provide as many transverse stiffners as required. The system of forces acting on the 'floating' element is illustrated in Fig. D4(b) and analysis by simple bending theory, assuming a design stress of 200×10^6 N/m^2 gives a beam having a section modulus of 0.021 m^3 i.e. 0.6 m wide x 0.9 m high x 0.05 m thick.

The base comprises a flat plate with bearing elements faced with compliant material down each side and two transverse box section stiffners at either end. The system of applied loads is shown in Fig. D4(c) and it can be seen that the only significant bending occurs in the transverse direction when the system is parked. There is no significant dimensional constraint applied to these beams and their design has not therefore been covered.

D5. BEARINGS

Bearing sizes are selected using manufacturers design guides. The characteristics of the main axes bearings are given in Table D1.

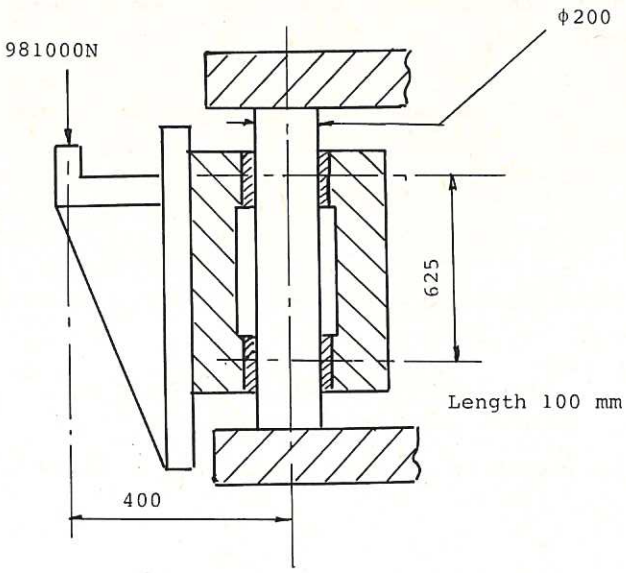
TABLE D1

BEARING CHARACTERISTICS

Axis	Total transmitted load kgf	Type	Co-efficient of friction
X	200,000	Recirculating roller	0.01
Y	159,000	Graphite impregnated sleeve	0.1
Z	250,000	Pneumatic film	0.001
γ-linear	negligible	Graphite impregnated sleeve	0.1
γ-rotary	4,600	Graphite impregnated journal	0.1

In general bearing sizes are not analysed since there is adequate room to cater for the likely size range. However it is necessary to consider the Y-axis bearings since they are highly loaded and in an inaccessible location.

The loading system is as shown in Fig. D5. Analysis by simple bending theory requires that the shaft diameter is 200 mm and the bearing length is estimated to be 100 mm using the manufacturers design guide.



(All dimensions in mm)

Fig.D5 Schematic of Y axis bearing assembly.

D6. AXES POWER AND TRANSMISSION SYSTEMS

Table D2 gives details for the power and torque requirements for the driven elements of each axis. Motor and gearbox elements have not been specified

TABLE D2

AXES POWER SYSTEM REQUIREMENTS

Axis	Maximum static load N	Maximum dynamic load N	Maximum speed	Maximum accel-eration	Maximum rotational speed of lead screw rpm	Maximum lead screw torque N-m	Power require-ment kW
X	1.96×10^4	3.34×10^3	0.0167 m/s	0.0167 m/s^2	100	33	0.5
Y	2.13×10^6	1.67×10^3	0.0083 m/s	0.0083 m/s^2	12.5	13,000	17.5
Z	1.26×10^3	2.1×10^3	0.0167 m/s	0.0167 m/s^2	200	4	0.3
γ	8.6×10^4	1.27×10^3	0.0011 rad/s	0.001 rad/s^2	21	639	1.5

since there will be a wide range of units for selection based upon performance, reliability and cost criteria. Each axis has been checked and motor/gearbox combinations having the required combinations of characteristics are currently available.

D7. GAS SUPPLY

D7.1 Estimated demand

The loaded and unloaded masses of the transporter are estimated to be 250,000 and 50,000 kg respectively.

It is estimated that the demand for gas will be:

loaded - 0.1 m^3/s (at STP)
unloaded - 0.02 m^3/s (at STP).

The assumed operating cycle allowing a generous factor of safety (≅6) is:

2 hours operation in the loaded condition
2 hours operation in the unloaded condition

per mission, giving a total requirement of 860 m^3 of gas at STP.

D7.2 Lifting gas

The atmosphere in the reactor hall will probably be helium and this gas is used by the transporter.

D7.3 Source (Figure of merit ≧5, Table 5)

(a) Pressurised storage

Assuming storage at 200 bar, the storage volume required will be about 4.5 m^3. The total volume of the storage system will therefore be in the order of 12 m^3 assuming standard cylinders.

(b) Cryogenic storage

The specific gravity of liquid helium is 0.14 so the volume required for the specified operating cycle will be about 1 m^3. The storage container will therefore occupy a volume of about 2 m^3 when the necessary insulation is added.

The energy requirement to evaporate and pressurise the necessary quantity of helium will be in the order of 100 kWh.

(c) Compression

Discussion with compressor manufacturers indicate that a 50 kW (approximately) compressor will be capable of delivering the required quantity of gas at 6 bar from an ambient pressure of 0.9 bar. The energy requirement will therefore be in the order of 120 kWh. This compressor will incorporate cooling (water circulation through a radiator) and will fit within an envelope having the dimensions:

3 m long x 2 m wide x 2.5 m high.

(d) From a central storage facility via a supply hose

An economic hose diameter for the maximum required quantitiy of gas will be in the order of 70 mm, say 100 mm outside diameter. There is sufficient space on the transporter to install two powered storage reels each containing 45 m of hose.

D7.4 Assessment

The compressor based system is selected because it is the most flexible and reliable and occupies a

reasonably small volume.

D8. ELECTRICAL SUPPLY

D8.1 Estimate of required capacity

It is assumed that the operating cycle for the transporter system will be made up as follows:

- leave park;
- travel to door site;
- pick up or replace door;
- return to parking location;
- re-park;

and that the maximum cycle duration allowing for detours to change doors etc., will be 10 hours.

The energy requirements are assumed to be made up as follows:

- For the door manipulator:

Location of demand	Demand kW *	Duration of demand h **	Energy storage requirement kWh
γ-axis	1.5	2	3
X-axis	0.5	2	1
Y-axis	17.5	2	35
Z-axis	0.3	2	0.6
Lighting etc.	5	10	50
Control & sensors	1	10	10
			99.6
Contingency approx. 50%			50
			≅ 150 kWh

* see Table D2
** the longest mission is predicted to take <1 hour (see Section 3.10 and Appendix E) so an ample factor of safety is provided

- For the lifting pallet:

Estimated driving torque 700 N-m

Estimated driving wheel speed ≅0.5 rev/s

Estimated power requirement 2.5 kW

∴ Power demand from transporter is estimated as follows:

Location of demand	Demand kW	Duration of demand h *	Energy kWh
Traction	2.5	4	10
Steering (est.)	1	1	1
Lighting etc.	2.5	4	10
Control & inst.	1	10	10
			31
Contingency approx 30%			9
			≅ 40 kWh

* see note on previous table

Should on-board (cryogenic) storage or on-board compression of gas be used an additional 100 kWh or 120 kWh will be needed, i.e. total storage capacities of 140 kWh and 160 kWh respectively.

D8.2 Battery system (Figure of merit ≧5, Table 6)

The characteristics of various types of storage batteries are provided below.

Type	Energy density kWh/m³	Power/ weight ratio kWh/kg
Lead acid	100	0.05
Nickel cadmium	80	0.06
Silver zinc	180	0.01
Prospective (type unspecified)	170	0.1
Prospective - solid state	330	0.2

For this requirement energy density is of greater significance than power to weight ratio.

It is assumed that low cost (£50/kWh) batteries having the same characteristics as silver-zinc will be available within the required timescale and these characteristics are therefore used.

Battery requirements for the transporter and door manipulator are given in the table for various types of gas supply system i.e.:

Transporter

Type of system	Battery volume m³	Battery weight kg
External gas supply or pressurised storage	0.22	4000
Croyogenic storage	0.78	14000
On-board compression	0.89	16000

Door Manipulator

Battery volume	0.83 m³
Battery weight	15,000 kg

D8.3 Cable supply (figure of merit ≧5, Table 6)

The maximum demand for electrical power will be:

- for the lifting pallet - 8.5-60 kW depending whether or not on-board gas storage is required;
- for the manipulator 30 kW.

It is assumed that power will be transferred as three-phase a.c. and conditioned on-board. It is also assumed that all the power will be transmitted via a single cable to the pallet and distributed to the manipulator as required. A cable in the order

of 30 mm diameter will be satisfactory to meet this requirement.

D8.4 Assessment

Both types of system appear feasible, however, on-board storage is selected on the grounds of greatest flexibility.

D9. ASSESSMENT OF TRANSVERSE CLEARANCES

D9.1 Clearance required when no Z-axis adjustment provided on transporter

(a) Position of guide rail relative to datum centre line, ±2 mm tolerance.

(b) Transporter manufacturing tolerances and compliance:

- transporter unit (TU) centre line (CL) to rail CL, ±1 mm;
- location bolt relative to TU CL, ±0.5 mm;
- compliance in location system, ±1 mm;
- location point relative to chassis CL, ±0.5 mm;
- X-axis table CL relative to chassis CL, ±0.5 mm;
- Y-axis CL relative to X-axis table CL, ±0.5 mm.

Total cumulative tolerance on transporter, ±4 mm.

(c) Door manufacturing tolerance edge to CL, ±1 mm.

(d) Manipulative clearance per side (including allowance for rail angular misalignment) 8 mm.

(e) Frame manufacturing tolerance edge to CL, ±1 mm.

The maximum total gap will be 36 mm.

D9.2 Clearance required when Z-axis adjustment provided

(a) Door manufacturing tolerance edge to CL, ±1 mm.

(b) Positional accuracy of servo, ±1 mm.

(c) Manipulative clearance, 4 mm per side.

(d) Frame manufacturing tolerance, ±1 mm.

The maximum total gap will be 18 mm and the minimum total gap 10 mm. The maximum and minimum gaps on one side of the door will be 10 mm and 4 mm respectively.

D10. TRANSPORTER STABILITY

The DMT will be least stable when:

- the pneumatic lifting system fails, down one side, while it is travelling sideways at full speed;
- the DMT is hit at the top following a similar pneumatic system failure.

Case 1

Geometric analysis shows that, after a pneumatic system failure, the DMT will be tilted at an angle of about 2.5° and it would have to be tilted to an angle of 13° for it to turn over.

The kinetic energy contained by the loaded DMT moving at 0.5 m/s will be approximately 31,000 N-m. In order to turn over the DMT will have to be tilted an extra 10.5° (i.e. the system centre of gravity will have to be raised by 120 mm) which requires an energy input of about 176,000 N-m.

Therefore the DMT is stable.

Case 2

An energy input of 176,000 N-m is required to overturn the DMT and the top of the DMT will travel through 1.6 m before overturning.

This scenario is not possible within the conceptual reactor hall.

SCHEDULES OF DMT OPERATIONS AND TIMINGS

TABLE E1

DOOR REMOVAL

OPERATION NUMBER	AXIS	DESCRIPTION OF OPERATION	ESTIMATED TIME - SECS
M1	Y	Axis raised from parking position to travel height	15
M2	Y	Y axis lock engaged	5
M3	X	X axis lock disengaged	5
M4	X	Table accelerated under program control to constant speed and then decelerated to zero in pre set time.	20
M5	Z	Servo centralises line of X axis by adjusting Z axis.	25
M6	X	Pick up mechanism runs upto door and stalls Control system senses stall condition	25
M7	Y	Timed movement of axes, sufficient to cause overlap of fixed and moving brackets	25
M8	γ	Lower lead screw and maintain pressure on cylinder	5
M9	γ	Retract lead screw until axis engages	10
M10	γ	Engage γ axis 'engagement' lock	5
M11		Engage and disconnect all services	180
M12	γ	Sequentially unclamp door	180
M13	γ	Programmed acceleration, constant speed and deceleration for pre set time	40
M14	γ	Switch to torque controlled mode, run upto stop and stall Stall condition read by control system	10
M15	γ	γ axis lock engaged	5
M16	Y	Slow traverse in torque controlled mode to make contract with bracket and stall Condition read by control system	5
M17	Y	Programmed acceleration, constant speed traverse and deceleration. Weight transfer occurs - set to travel height	25
M18	Y	Y axis lock engaged	5
M19	X	Programmed acceleration, constant speed and deceleration to low speed for pre set time	40
M20	X	Conversion to torque controlled mode-run upto stop and stall Stall condition read by control system	15
M21	X	X axis lock engaged	5
M22	Y	Disengage Y exis lock	5

M23	Y	Slow speed traverse until door is parked	25
		Total	680
		Contingency 100%	680
		Estimated time for pick up	1360

TABLE E2

DOOR REPLACEMENT

OPERATION	AXIS	DESCRIPTION OF OPERATION	ESTIMATED TIME - SECS
M30	Y	Axis raised, lifting door from parking position, to travel height	15
M31	Y	Y axis lock engaged	5
M32	X	Axis lock engaged	5
M33	X	In preset time - table accelerated under program control to constant speed and then decelerated to slow speed and switch to torque control mode	30
M34	X	Table advances at slow speed in torque controlled mode until reading obtained on both X axis sensors	10
M35	Z	Z axis is adjusted to centralise door leading edge in widest gap	25
M36	X	Table advances at slow speed, in torque controlled mode until both sensors indicate large step input	10
M37	Z	Z axis is adjusted to centralise door leading edge in "middle" step	25
M38	X	Table advances at slow speed in torque controlled mode, until both sensors indicate large step input	10
M39	Z	Z axis is adjusted to centralise door leading edge in narrowest gap	25
M40	Y	Y axis lock disengaged	5
M41	Y	Y axis lowered at low speed until door foot bearing contacts door and continues while weight is transferred	25
M42	Y	Y axis continues lowering at low speed for present time	10
M43	X	X axis advanced in torque controlled mode slowly, allowing door wheel bearing roller to move down inclined plane to stop	25
M44	Y	Y axis lowered at low speed in torque controlled mode for preset time to clear door bracket	10
M45	γ	γ axis lock disengaged	5
M46	γ	Programmed acceleration, constant speed and deceleration for preset time	50
M47	γ	Switch to torque controlled door stop and stall Stall condition read by computer	20
M48		Sequentially engage and operate door clamps	180

M49		Inflate and test seal	300
M50		Connect and test services	400
M51	γ	Disengage γ axis engagement lock	5
M52	γ	Rotate engagement mechanism clear of bracket	10
M53	γ	Retract lead screw - operate for present time	20
M54	Y	Raise Y axis to transfer height	15
M55	Y	Y axis lock engage	5
M56	X	Retract table to park position	30
M57	X	Engage X axis lock	5
M58	γ	Rotate γ axis to parking position	10
M59	Y	Disengage Y axis lock	5
M60	Y	Lower Y axis to parking position	15
		Total	1310
		Contingency 100%	1310
		Estimated time to replace door	2630

TABLE E3

FINAL APPROACH

OPERATION NUMBER	ACTUATOR	DESCRIPTION OF OPERATION	ESTIMATED TIME - SECS
		Transporter assumed to be positioned and oriented correctly at end of the radial guide rail + floating on gas film pads	
T1	Transporter drive wheels	Advance transporter so that leading edge guide module engages radial guide rail i.e. by predetermined amount	10
T2	Leading edge rail clamp	Clamp guide rail with leading edge guide module	5
T3	Transporter drive wheels	Advance transporter to engage following edge guide module	10
T4	Follower clamp	Clamp guide rail with tracking edge guide module	5
T5	Tapered bolt	Engage tapered bolt to "pull" transporter into correct radial location	5
T6	Gas film pads	de pressurise film pads	5
T7	Tapered bolt	Retract tapered bolt	5
		Total	45
		Contingency 50%	23
		Total time to enter/leave reactor envelope	68

FIXED SHIELD SUPPORT

F.1 DEFLECTION OF BOTTOM DISC UNDER APPLIED LOADS

The assumed system configuration is shown in Fig. F1.

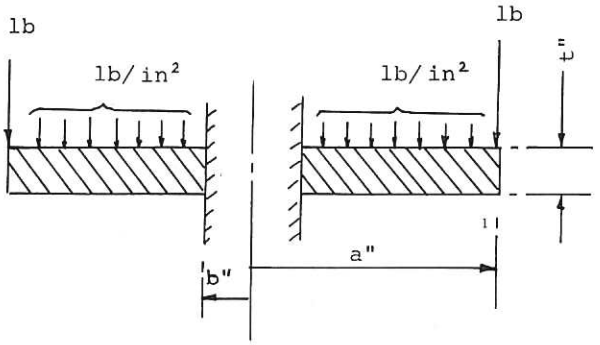


Fig.F1 Assumed loading on bottom disc.

From Roark (Ref. F1) for loads applied by the doors:

$$y_1 = -\frac{3W(m^2-1)}{4m^2\pi Et^3}\,[a^4(3m+1)-b^4(m-1)-2a^2b^2(m+1) - 8m\,a^2b^2\log\tfrac{a}{b} - 4a^2b^2(m+1)(\log\tfrac{a}{b})^2] \div [a^2(m+1) + b^2(m-1)]$$

and for the segment loads plus emergency overpressure

$$y_2 = -\frac{3w(m^2-1)}{16m^2Et^3}\,[a^6(7m+3)+b^6(m-1)-a^4b^2(m+7) - a^2b^4(7m-5)-4a^2b^2[a^2(5m-1) + b^2(m+1)]\log\tfrac{a}{b}-16a^4b^2(m+1)(\log\tfrac{a}{b})^2] \div [a^2(m+1)+b^2(m-1)]$$

where

W	=	circumferential load (doors) $\cong 9\times10^6$lb
w	=	distributed load (segment plus over-pressure) $\cong$ 50 lb/in^2
E	=	Youngs modulus 28×10^6 lb/in^2
m	=	$\frac{1}{V}$
V	=	Poissons ratio = 3.3
a	=	outer radius = 406 inches
b	=	inner radius = 262 inches
t	=	thickness = 28 inches
y	=	deflection inches

from which y_1 = 0.072 inches (1.83 mm) and y_2 = 0.05 inches (1.27 mm).

F.2 FEASIBILITY OF USING THE COOLANT DUCT CASING AS ADDITIONAL STRUCTURAL SUPPORT (Fig. 24)

W.S. Atkins & Partners (Ref. 10) have evaluated the structural feasibility of using concrete as the fixed shield material during the course of which they conservatively define the axial loading on the overhung section of the door as 4000 kN per segment.

Using the method given in Ref. F2 for axially loaded short columns, taking the cube strength for concrete as 50 N/mm^2 and 410 N/mm^2 for steel and assuming 1% reinforcement gives a required bearing area of 0.5 m^2. Since the duct outside diameter is 1200 mm the required diameter for the modified shield will be 1500 mm. This can be accommodated between the 'D' coils.

REFERENCES

F1. Roark, R.J. Formulas for stress and strain. 4th Edition, McGraw Hill Book Co.

F2. British Standards Institute. Code of Practice - Structural use of concrete, 1972.

HER MAJESTY'S STATIONERY OFFICE

Government Bookshops

49 High Holborn, London WC1V 6HB
13a Castle Street, Edinburgh EH2 3AR
41 The Hayes, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
Wine Street, Bristol BS1 2BQ
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY

Government publications are also available through booksellers