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Abstract

The Culham Conceptual Tokamak Reactor Mark II (CCTRII) has doors in the outer shield to facilitate servicing of the first wall, blanket and primary shield. Each shield door comprises a stainless steel structure, containing Mn-Fe spheres, weighing 170 tonnes which is cooled by borated water.

The transporter/manipulator is designed to operate within the reactor hall and to engage, manipulate and transport the shield door as required by the maintenance programme. The system is self contained and utilises pneumatic film support and electro-mechanical drive systems. Conceptually the system can be operated manually, by remote control, or under computer control.

1. INTRODUCTION

Studies of the technical feasibility and economics of magnetic confinement fusion reactors indicate that the integrated life of the blanket 'first wall' structure will be 5-20 MW yr/m^2, as determined by the combined effects of neutron irradiation and thermal stress fatigue in the structural material. At economic power ratings the first wall material will have to be replaced every few years and clearly the necessary reactor servicing downtime will have a considerable bearing on the cost of fusion energy.

The Mark II version of the Culham Conceptual Tokamak Reactor (CCTRII) was developed to incorporate adequate facilities for blanket servicing within the general Tokamak Reactor requirements (1) Fig. 1. Independent studies (2,3) have shown that this concept appears to have significant advantages in reducing reactor downtime for scheduled maintenance thus allowing more time for unscheduled repairs within economic total downtime allowances. The special features embodied in the design of CCTRII are to reduce the number of operations required to service the blanket first wall by incorporating large sub-assemblies and simplifying the sub-assembly exchange operations. In CCTRII the first wall blanket and inner shield is divided into 20 segments and access for replacing these segments is provided through large penetrations in the outer shield/ vacuum chamber (Fig. 2). These penetrations are closed by 'shield doors' with the twin functions of radiation shielding and vacuum containment. Removal and replacement of these 170 tonne doors including all surveillance, locking and testing operations will be accomplished by a transporter/manipulator which will operate in the reactor hall under automatic or remote control. Fig. 3 is a layout of the reactor hall showing access, air locks etc.

This paper describes the functional requirements and design solutions for the shield door and the remotely controlled transporter, and shows that the concept can be realised using present-day manufacturing technologies (4). With 100% allowance for fault rectification, the overall times estimated for door removal and replacement are ≅40 and 60 minutes respectively. Some development will be required e.g. to prove the pressurised vacuum seal, clamps and other details.

2. SHIELD DOOR

2.1 Functional requirements

(a) Magnetic - the materials used for the door should cause the minimum possible disturbance to the applied magnetic fields.

(b) Shielding - the radiation level at the outside of the door will be limited to about 4000 rad/h. This limit is set by the integrated dose in the magnet coils, assuming the use of organic insulation.

(c) Temperature - the neutron energy deposited in the whole outer fixed shield is approximately 34 MW. The coolant will be water at a temperature <100°C to eliminate pressurisation of the coolant system.

(d) Vacuum - the outer fixed shield, which contains the access doors, will form the primary vacuum enclosure and its base pressure will be $\leq 10^{-6}$ torr.

(e) Pressure - the normal pressure in the reactor hall will be <1.0 bar absolute. For design purposes the pressure differential across the door is assumed to be 1 bar.

(f) Emergency loadings - the reactor structure and access doors must be able to withstand:

- internal pressurisation, to 1 bar above the reactor hall pressure, caused by a coolant system failure;
- seismic loadings equivalent to a horizontal acceleration of 0.25 g.

(g) Reliability - the door and its systems should be such as to provide extremely high reliability and availability.

2.2 Design philosophy

The following design philosophy has been adopted:

(a) it is not useful to extrapolate long-term trends in manufacturing techniques so the design has been based upon currently available or foreseeable techniques;

(b) the doors must be interchangeable;

(c) to simplify maintenance procedures the more complex operating elements of any mechanism must be located on the transporter/manipulator;

(d) where possible, standby systems should be provided;

(e) all systems on the door must be tested prior to withdrawal of the transporter/manipulator.

2.3 Description

The shield door is an internally braced welded box structure of 45 mm 316 stainless steel plate (Fig. 4). The internal partitions are arranged to form a number of virtually closed compartments, the horizontal diaphragms being slotted to allow the free vertical passage of cooling water, (Fig. 5) 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 stiffeners 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 for e.g. special instrumentation etc. - providing they can be adapted to the horizontal withdrawal concept.

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. 7). 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.

The base of the door is fitted with a bracket with two rollers, which carry the weight of the door when it is installed in the reactor (Fig. 4). An extension of the door bracket is engaged by the transporter to lift the door. Thus the door weight is always carried on the bracket eliminating differential deflection of the door. The weight of the door and its contents will be ≅170,000 kg and the overall dimensions are given in Fig. 5.

Normal and abnormal horizontal loads acting on the door are transmitted to the structure by means of remotely-operated clamps, (Fig. 6) whose actuating points are located above and below the injector port (Figs. 4 and 5).

2.4 Shielding

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 thermalise the 1 MeV neutrons) and finally absorption of these thermalised neutrons. A good arrangement of materials is a homogeneous mixture of iron, water and boron which, in the shield door, is approximated by manganese steel spheres and borated water. Manganese steel is a cheap, non-magnetic, medium Z material whilst the borated water is the coolant.

The neutron flux attenuation in the manganese iron produces a significant gamma flux, which is attenuated by a layer of lead on the outer surface of the door, (Fig. 5). The attenuation factor of the shield door is $\cong 10^{-3}$ requiring a minimum shield thickness of $\cong$0.5 m. To obtain the same attenuation in the clearance gap between the door and the fixed shield, the door is locally thickened to 750 mm with two 20 mm steps, (Fig. 7).

2.5 Vacuum sealing

The proposed seal is a helium pressurised seal made from radiation resistant elastomer and located in the outer step. The advantages of the pressurised seal are the short 'closure time' and the ability to absorb the door-frame gap manufacturing tolerances - estimated at between 4-12 mm. Two seals are provided (Fig. 7) with an evacuated interspace to control tritium loss, pressure gas permeation and for seal monitoring. Since the seals would be replaced at every door removal, the required service life is $\cong$3 years and seal performance should not be degraded at the estimated dose $\cong$4000 rad/hr i.e. 10^8 rad total. Such seals are in general use in many fields but further development will be required for this application. In the event that a satisfactory material configuration cannot be developed, a 'weld-sealed' joint can be used.

2.6 Cooling

For cooling purposes, the door box structure is subdivided forming three parallel cooling circuits. The shield configuration - packed spheres in flowing coolant results in effective heat exchange. The calculated maximum temperature of the door structure is 50°C with a coolant flow of 90 kg/s, assuming insulation is fitted on the inner surface of the door to limit radiation from the blanket segment at ≅350°C.

2.7 Services

The door is provided with two types of services i.e.

(a) Operational services (coolant, instrumentation) which are arranged so that connections are made parallel to the Z-axis to avoid placing constraints upon access inside the reactor envelope.

(b) Installation services (vacuum, instrumentation etc.) which are supplied by the transporter - connections being made along the X-axis.

2.8 Manufacture

Arc and electron beam welding, and thermal diffusion bonding are all possible and suitable techniques for fabrication of the door structure. Dimensional tolerances of both the door and door frame will be: overall thickness and width ±2 mm and overall length ±6 mm. If presently available NDT techniques are not suitable for inspecting weld quality etc., developments in ultrasonic systems are anticipated which should meet requirements.

3. TRANSPORTER

3.1 Functional requirements

The functional requirements which have been defined for the transporter are:

(a) To travel 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 the transporter or exchanged for a serviceable unit.

(d) To travel back to the doorway when reactor servicing is complete.

(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 to a previously defined parking area.

Each of the above operations are to be carried out under automatic or remote control, or some combination and will take place in the areas illustrated in Fig. 3.

3.2 Design philosophy

The transporter has been designed to incorporate the following general requirements:

(a) a high degree of reliability and availability;

(b) rapid operation within the reactor envelope;

(c) free and safe mobility within the work environment.

3.3 System configuration

The transporter system comprises a door manipulator, a transport module, a surveillance system and a control/communications system.

(a) Transport module

The transport module utilizes pneumatic lift for load carrying and four steerable driving wheels to control direction of motion, attitude and velocity (i.e. the system can provide three horizontal degrees of freedom). The module (Fig. 8), carries batteries and a compressor and is therefore completely self-contained apart from the necessary external control signals. The compressor is used to compress 'lift gas' from the reactor hall atmosphere to 6 bar for use in all pneumatic systems on the transporter/manipulator.

Permanent guide rails are installed, within the reactor envelope and other areas of limited access, which are engaged by guide modules fitted at the front and rear of the transport module.

(b) Manipulator

The door manipulation system (Fig. 9) is designed to provide five axes of motion (see Fig. 4 for definition of the axes) i.e.:

- X,Y and γ-axis — operating against pre-set limit switches, torque limits or time outs;
- Z and β-axis — position servo-controlled;
- α-axis — not provided - mid-life adjustments can be made to the system as required.

All axes are provided with on-board position error detectors and feedback for self-checking and as an aid to fault diagnosis. The Z- and β-axes operate using door-mounted position error detectors.

The manipulator also carries the following ancillary systems:

(a) clamp actuators;

(b) operational services 'make and break' systems;

(c) installation service connections and the associated actuators and test equipment.

Hydraulic drives for the manipulator axis control were rejected because of the consequences of leakage in a remotely serviced area. The manipulator drives therefore comprise: an electric motor, a clutch, a lead screw and a ball nut together with the associated bearings. A gearbox is introduced where it is necessary to match motor torque/speed characteristics to load demand. All active elements are provided with duplicate drive systems (units being clutched in and out as required) and with emergency actuation points accessible to actuators, typically to be carried by the back-up general purpose robot. The manipulator carries batteries and is self contained apart from possible requirements for external control signals and gas supplies.

(c) <u>Control, surveillance and communication</u>

Computer systems development is extremely rapid and there is little to be gained by attempting to predict the configuration of a suitable control system for this application. The transport module and the manipulator will each carry a computer, inter-connected by a hard wired link. These computers will be capable of sequentially controlling all normal operations and some fault rectification procedures (typically disengaging a faulty system and engaging a standby) under the supervision of a 'main frame'. Typically the relevant functions of the main frame will be:

(1) to supervise the transporter safety and status as reported by the on-board systems and to display abnormalities to the human supervisor;

(2) to plan and integrate the routing of the transporter and other mobile systems, within the maintenance areas;

(3) to programme system operations relative to the overall maintenance programme;

(4) to respond to 'calls for help' from the on-board systems when they are faced with situations they cannot process.

A manual override and remote control facility will be provided for use in an unpredicted fault condition but it is envisaged that this facility will be seldom used. In addition to the system mentioned in (1) above, direct surveillance will comprise steerable TV cameras fitted so as to cover all system functions and work areas.

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

Typical potential communications systems include: inductive loop, microwave radio, UHF/VHF radio, optical link and acoustic link. We propose a multiplexed UHF/VHF system since bandwidth requirements are adequate, whilst attenuation and absorption characteristics exclude the alternatives, though two decades of development may well modify this conclusion.

3.4 System operation

The transporter/manipulator will leave a designated parking area and pass along a route defined by some central authority (typically a main frame computer) to a point adjacent to the end of the relevant guide rail. The transporter position and attitude will be adjusted so that both guide modules engage the guide rail and will then advance until the position indicator is sensed. A tapered bolt will then 'pull' it into the radial datum position and it will be lowered by depressurising the gas film bearings.

The X-axis table will then advance until the lifting brackets overlap and the γ-axis mechanism will engage the door. Operational services will be disconnected and the door unclamped. The γ-axis motion will rotate the top of the door clear of the frame and the Y-axis motion operate to achieve weight transfer. All systems will then operate sequentially to set the door in the 'park' position on the transporter.

The transporter/manipulator will then withdraw and proceed to the door servicing area.

From guide rail acquisition to departure the above cycle of operations is expected to take about 25 minutes. Door replacement follows essentially the same procedure, in reverse, but takes about 45 minutes, the time difference being taken up by longer Z-axis adjustment and testing procedures.

Times for area traverse will vary, depending upon the site of operations, but will be in the order of 15 minutes.

4. CONCLUSIONS

The shield door/transporter required for the CCTRII concept is within the current state-of-the-art for such structures. With such large elements to be transported and manipulated it is difficult to visualise radical changes to the system design so that the future will only bring minor changes, e.g. improved component design.

The operating times for the relevant servicing operations are compatible with the timescales allowed for routine servicing. The transporter/manipulator system operations are specified to take place sequentially but it is probable that improved control systems will allow times to be reduced e.g. by enabling tasks to be carried out in parallel. Transporter/manipulator sub-system failures should not affect cycle times significantly because the back-up facilities will cover possible failures.

The transporter/manipulator concept will not require umbilical cables or hoses because the system carries its own energy supply. Consequently other mobile plant will have freedom of manoeuvre within the servicing area.

The study of the blanket segment (5) and this work together provide 'in principle' design solutions for the blanket and door structures and the transporter/manipulators for the CCTRII blanket and shield. Also the MANTIS machine (6) being used and developed at CERN, Geneva, fulfils the other major requirement for a back-up manipulator and a general purpose, routine, servicing machine. Together these studies indicate outline solutions for the servicing of a Tokamak fusion reactor blanket and shield. It now remains to develop the whole nuclear island design consistent in every detail with the basic principles illustrated in the Culham Conceptual Tokamak Reactor Mark II (1).

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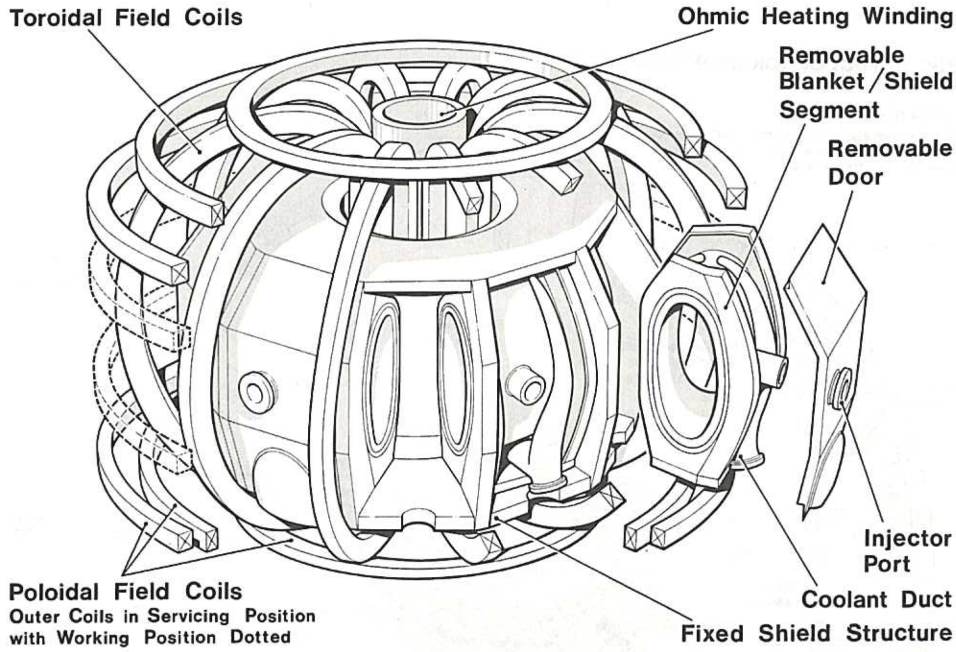

Fig.1 Tokamak fusion reactor, showing removal of blanket segment. For clarity this sketch shows only 10 segments and toroidal field coils. Moving the outer poloidal coils and the shield door(s) gives access for disconnecting the duct joints and instrumentation and replacing the segments.

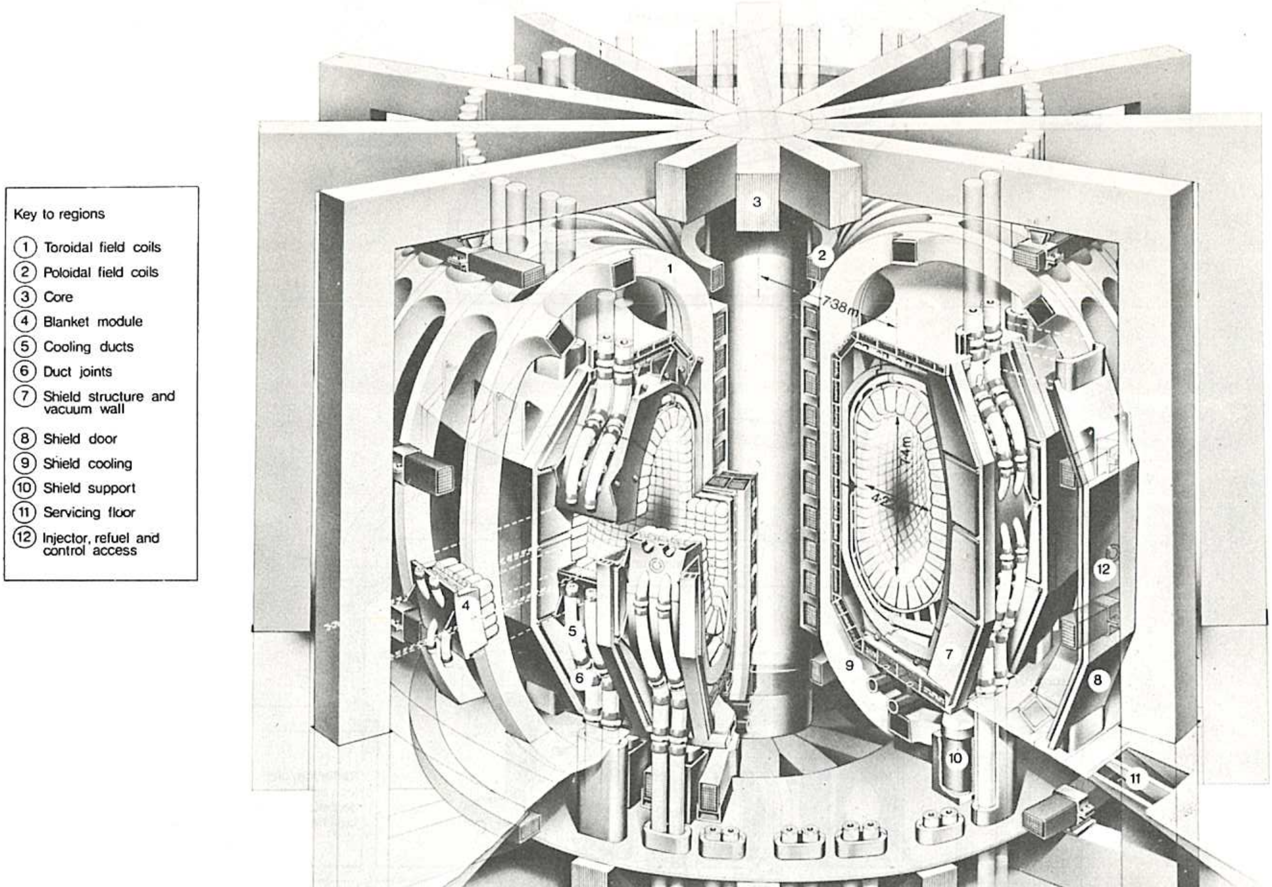

Fig.2 Culham Conceptual Tokamak Reactor Mk II.

Schematic Layout of Tokamak Reactor Hall

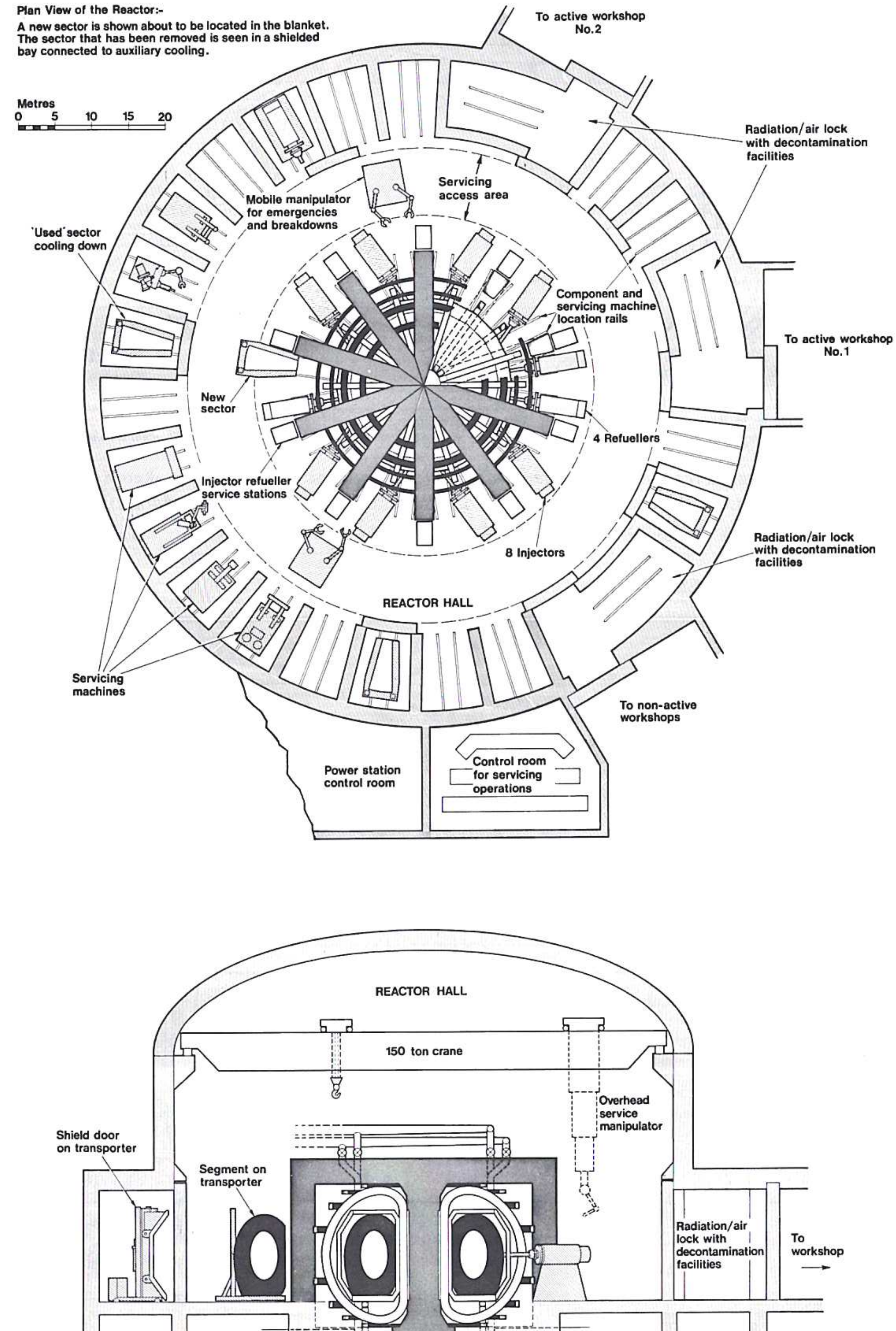

Fig.3 Toroidal fusion reactor hall showing servicing access, segment and machine cells and air locks to maintenance workshops.

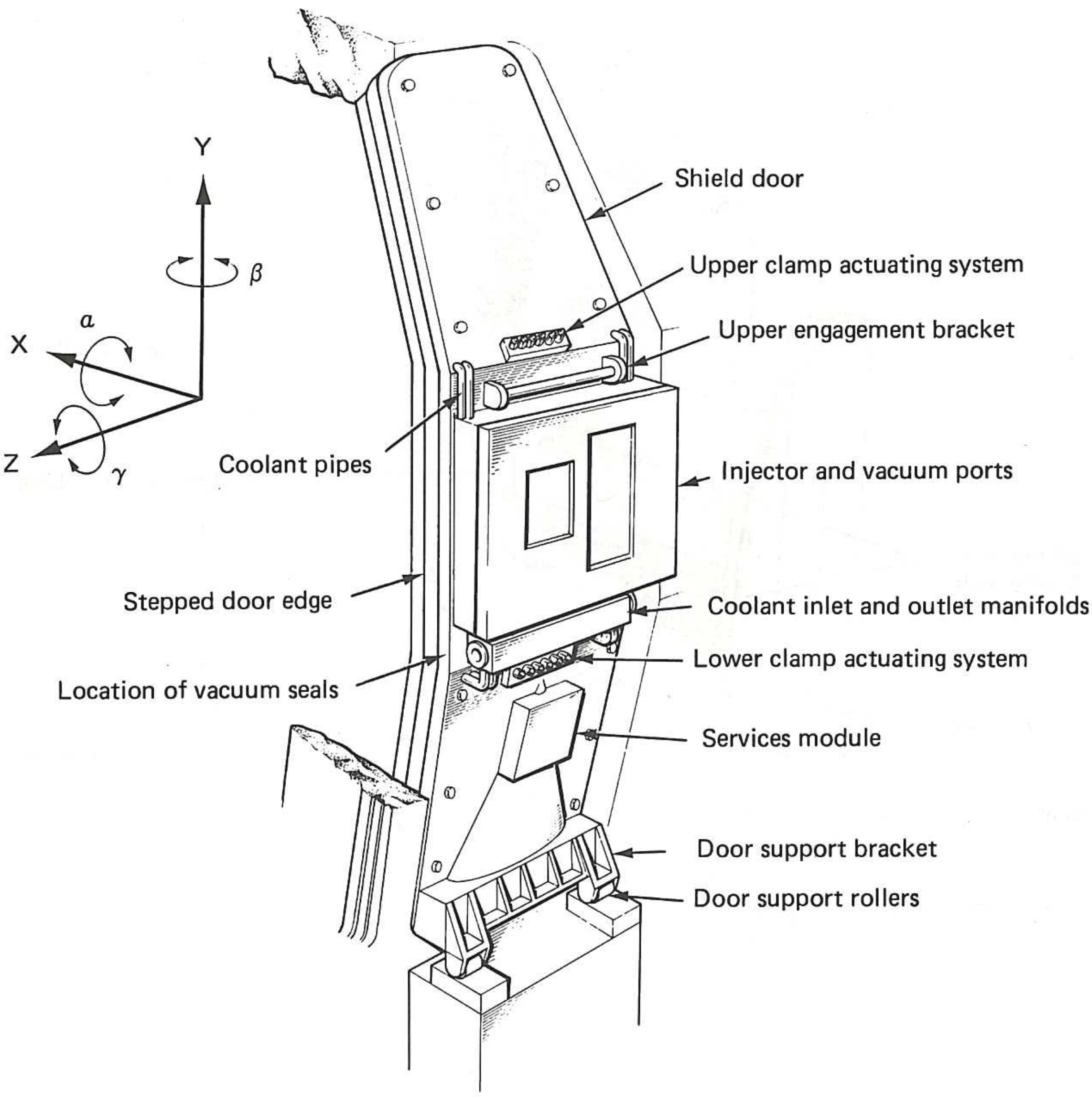

Fig.4 Shield door showing method of mounting and principal systems together with definition of axes of motion.

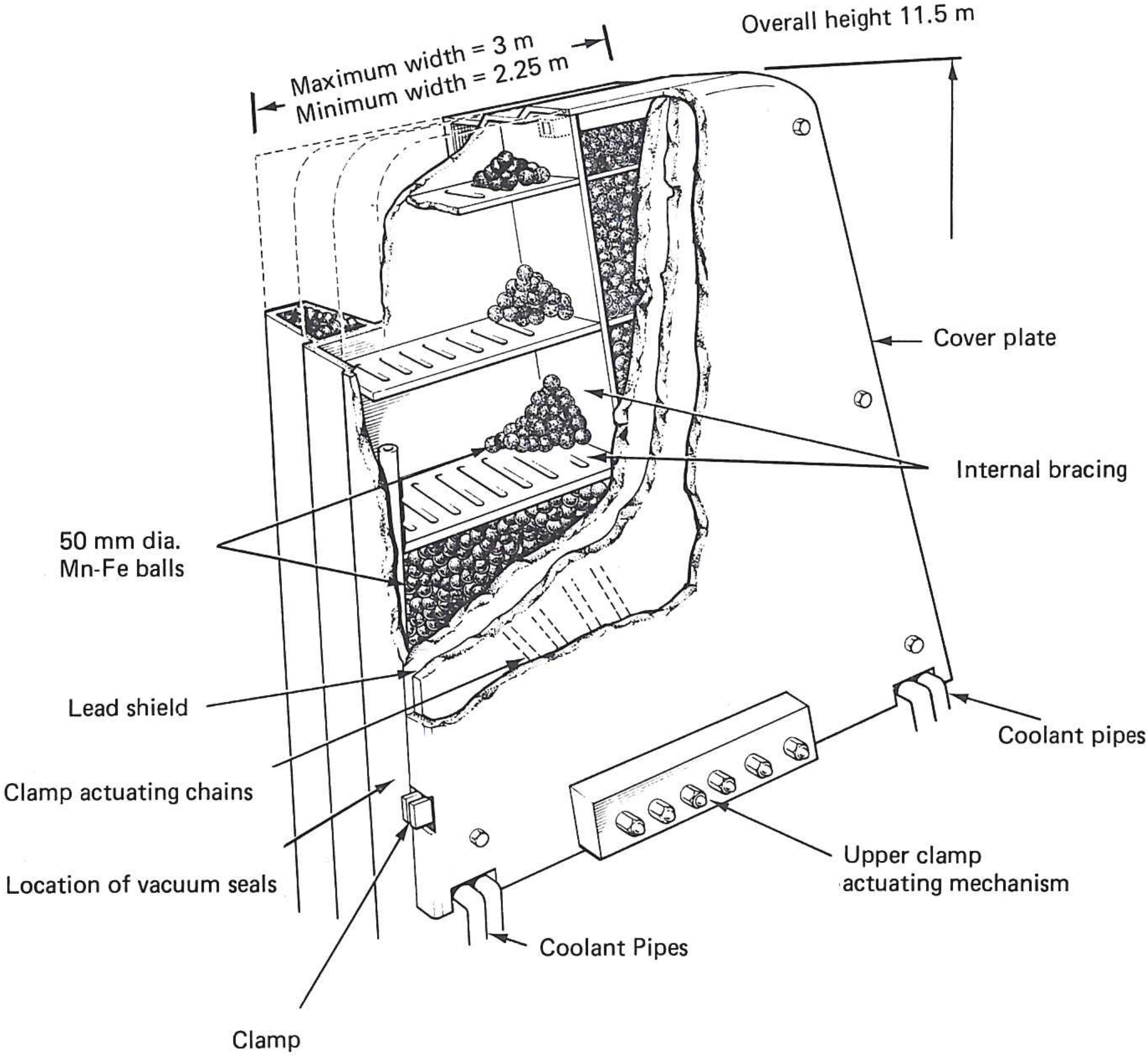

Fig.5 Construction of shield door showing internal structure and filling and overall dimensions.

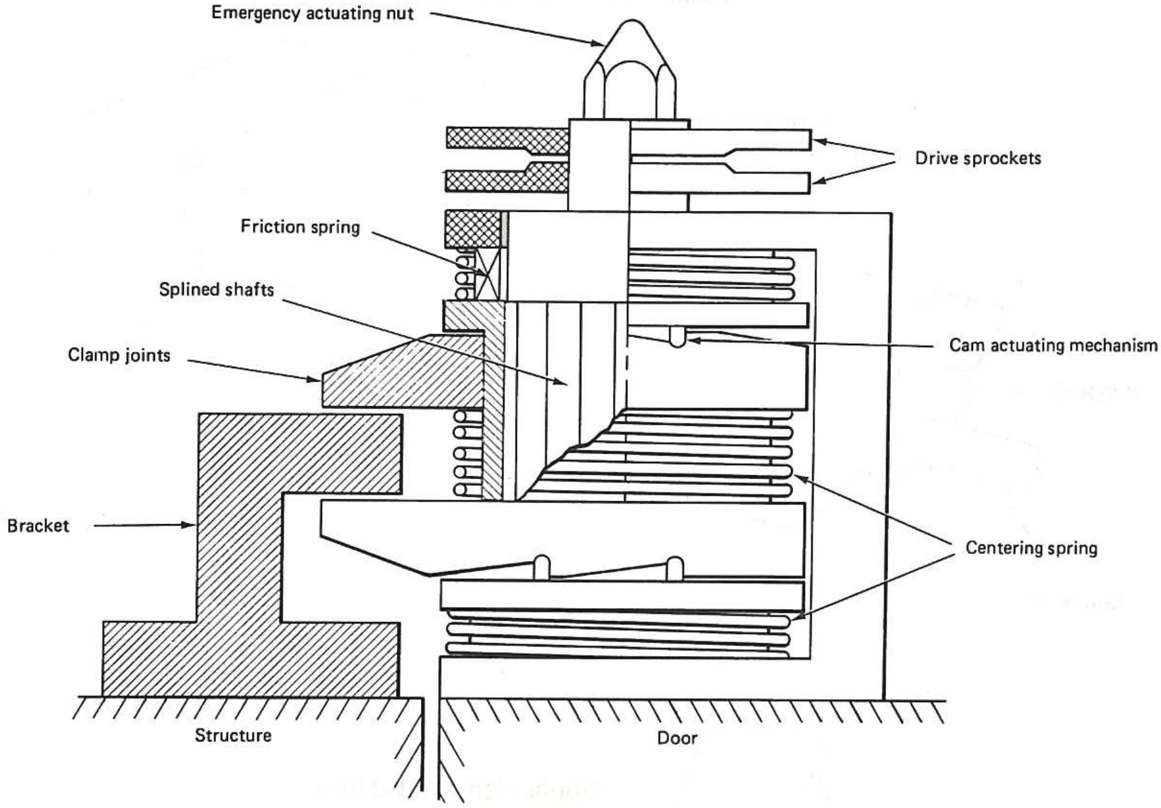

Fig.6 Door clamp.

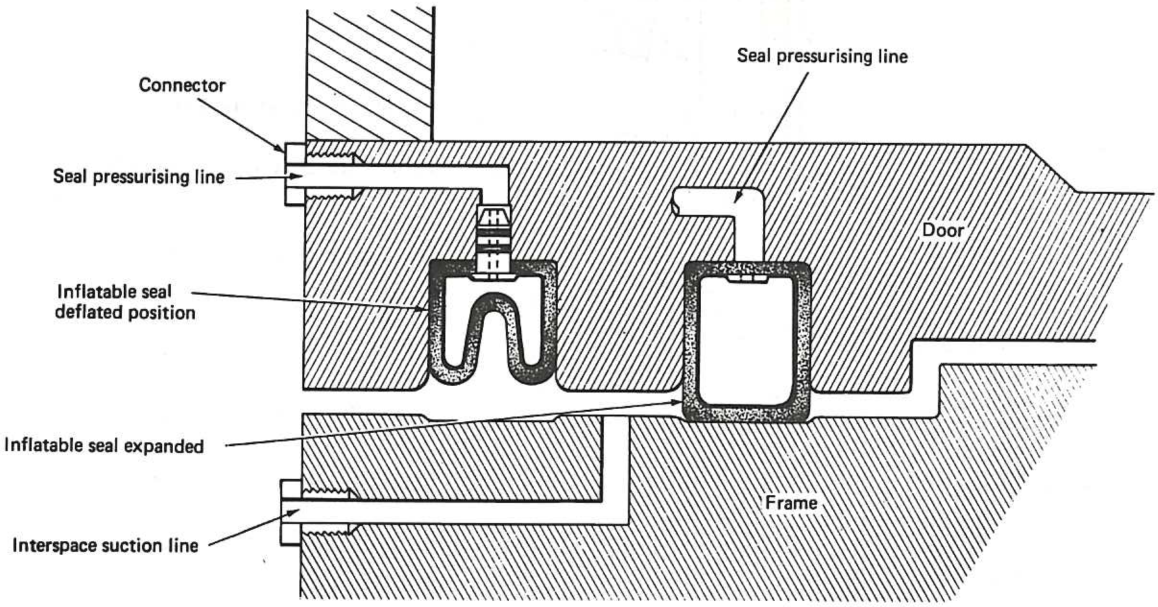

Fig.7 Layout of vacuum seals, and pressurising and test ports.

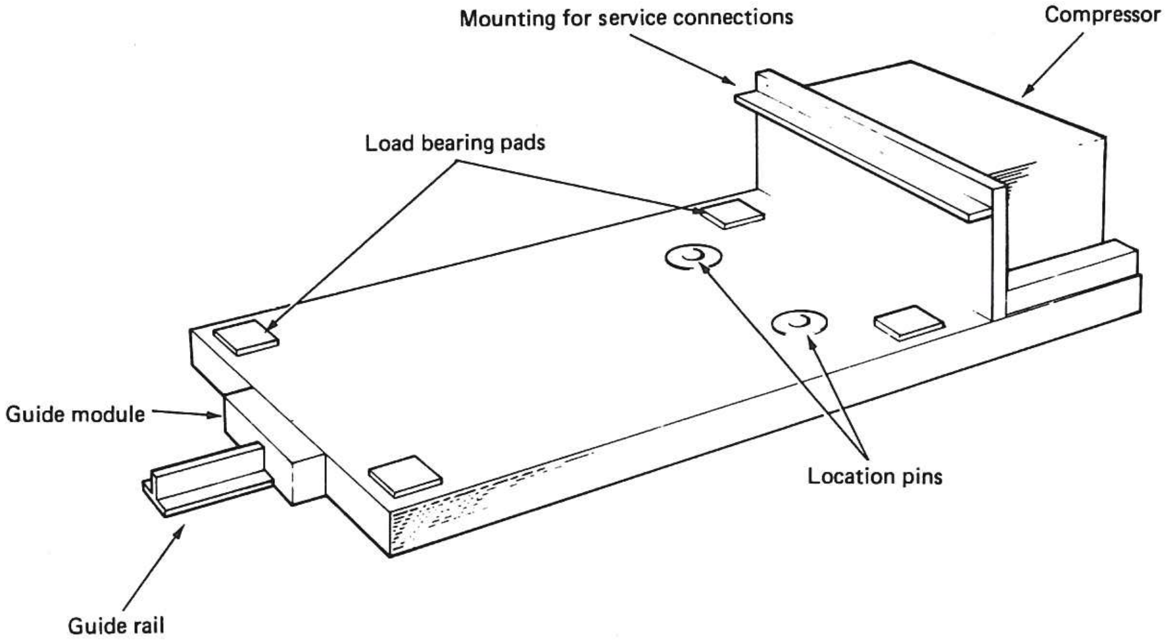

Fig.8 Transport module.

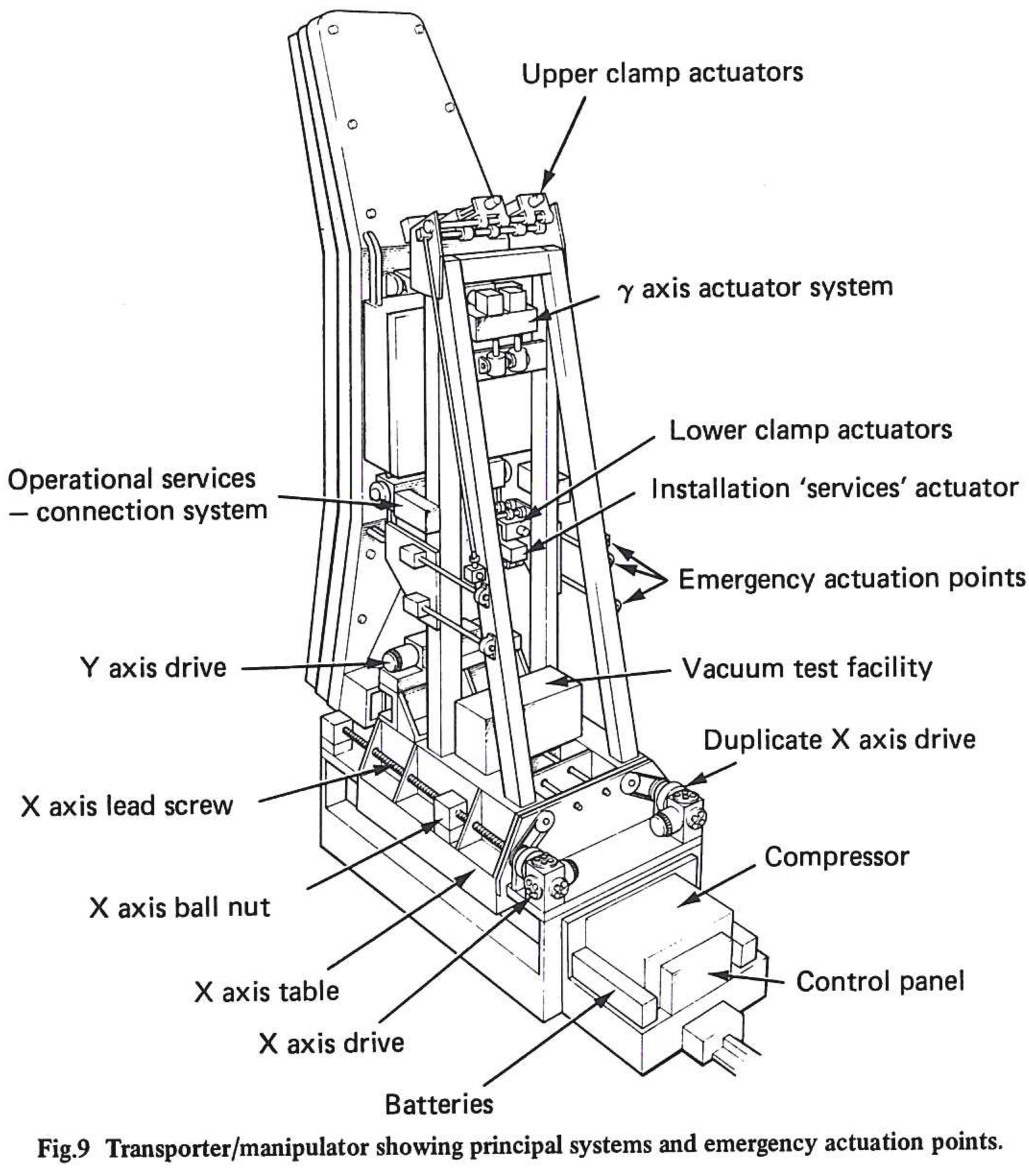

Fig.9 Transporter/manipulator showing principal systems and emergency actuation points.