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LARGE TRANSPORTERS FOR TELEOPERATION ON JET

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ABSTRACT

After Tritium is introduced into the JET vessel, the activation levels will be such as to preculde man-entry into the Torus Hall. The remote maintenance equipment described herein has been devised over the last several years in order to be able to continue operation of the facility in the event of all but major machine failures. Computer assisted positioning of force-feedback servo-manipulators to all parts of the JET machine is effected by 2 transporters, one complete and the other in the design phase. Special cutting, positioning and welding tools have been procured to carry out specific tasks in areas of limited access.

INTRODUCTION

The JET tokamak (fig 1) consists basically of a toroidal vacuum vessel surrounded by coils that generate magnetic fields to confine and stabilize a hydrogen or deuterium plasma. At a later stage the plasma will be a deuterium/tritium mixture. This ionized gas will be heated by induced current and additional peripheral systems to bring it up to the temperature values needed to produce significant fusion reactions. The high energy neutrons emitted will activate the vacuum vessel and, to a lesser extent, the whole machine[1,2]. The layout and connections were designed with a view to remote operations.

However, because of the complexity of the machine and the unpredictability of remote operations on JET which, as an experimental device, is continually evolving and developing, a flexible Remote Handling system was required. Various transporters will be used to position where required on the machine either heavy-duty end effectors for handling particularly large components or dexterous force-reflecting servomanipulators for more complex operations such as connection of services, bolting, welding and cutting. Quick connectors facilitate the changeover.

To avoid contamination with beryllium or tritium, the joints and mechanisms of devices entering the vacuum vessel have to be protected with washable and disposable gaitering. All lubricated parts have to be sealed to avoid hydrocarbon contamination of the vessel.

TRANSPORTERS

For remote operations within the vacuum vessel the transporter is an articulated boom which enters through a port situated on the equatorial plane and can reach round to the opposite side of the Torus. A turret truck is provided to carry end effectors, manipulators and components and lift them up to be attached to the articulated boom. Outside the vessel a crane-mounted telescopic mast (TARM) will be able to position a manipulator all around the machine. It will work in combination with lifting facilities provided by the main hook of the crane or by an auxiliary jib crane mounted on the telescopic mast, and in areas not accessible from above, by a low-level transporter. A tracked roving vehicle provides backup services.

Articulated Boom for in-vessel operations

This transporter was built to JET design. In a Tokamak like JET the only convenient access to the Torus is through ports situated on the equatorial plane between the toroidal coils. The articulated boom enters the vessel through either of 2 opposite horizontal ports. It can reach round half the circumference with a payload of one tonne. We have now added another segment to extend the reach right round to the opposite port with a payload of 350 kg (fig 2). The alternative of a transporter running on tracks was discarded because of the difficulty of getting it through the port and because any fixtures inside the vessel would be susceptible to plasma damage. Umbilical cables would also pose an extremely difficult problem. The geometry is unsuitable for a telescopic boom.

The boom consists of 5 segments cantilevered off a trolley suspended from a beam which spans the gap between the wall of the Torus hall and the machine (fig 1). To compensate for misalignments and deflections due to the load (max 50 mm at full extension), the trolley allows for limited slew and tilt. The end segment, known as the boom extension, has pan/tilt/roll motions and terminates with a quick connector to which we can attach either the servo-manipulator or a grabber designed to lift the heavy limiters and antennas (fig 3). One section of the boom extension is an open structure providing a receptacle for tools to be used by the manipulator (figs 4,5).

The structure is gaitered to prevent contamination. Care was taken in the choice of materials to optimize strength vs weight. The first 2 segments are in stainless steel and the others in aluminium alloy fabrication. As hydraulic fluids were excluded by the requirement not to risk contamination of the vacuum vessel, all the motors are electric. DC torque motors are directly coupled to the Harmonic Drive gearboxes. This gives a good combination of high torque, small volume and weight and negligible backlash, which is essential to achieve the smooth control of velocity and position required to avoid damage to the vessel. The actuators are also backdriveable so that the joints can go loose for emergency retrieval in the event of the power cut-off.

The boom carries 3 CCTV B&W cameras with motorized zoom, focus and aperture control. One camera is mounted at the rear of the boom to monitor the entrance through the port. The other 2 cameras are carried by orientable arms branching from the boom extension. One of these is visible in figs 4,5. The arms have 4 degrees of freedom powered by D.C. rare earth motors coupled to Harmonic Drives.

The boom is controlled via microprocessors either from the control room or from a portable console. The operator has a joystick with which he can move one or 2 preselected joints at a time at variable speed. He can also finely adjust the position of the end effector with a resolved motion algorithm. There is a teach-and-repeat facility for repetitive motions such as insertion into the vessel and prepositioning in working areas. This applies to all the degrees of freedom (18 including the end effectors and camera arms). The main articulations are controlled in position with velocity feedback through pulse-width modulated servoamplifiers. To avoid overshoots due to the large dimensions of the boom and the elasticity of the joints, the acceleration is limited by software. Simulations were done to study the feasibility of the control system and optimize the feedback loop. With the boom fully extended, the tip can move at 0.5 m/s to a prescribed position with no overshoot and repeatibility better that 2 mm.

A powerful navigation aid is provided by a graphical model[4] of the boom in its environment which is connected in real time to the boom transducers. This can be used off line to teach preferred trajectories.

The Crane-mounted Telescopic Arm (TARM)

The crane was specified with the fine controls that would be required during remote operations. This turned out to be a bonus during the assembly phase. Positioning the 130 tonne octants within tolerances of about 1 mm was no problem. A trial of inserting one octant with TV viewing was successful. Minimum incremental displacements of the load were of the order of 0.2 mm in the vertical direction and 1 mm horizontally, with negligible swinging effects. All the crane motors are thyristor controlled. The load is continuously monitored by means of load cells. Given the elasticity of the ropes and the low controllable speeds, vertical contact loading can be kept below 300 kg. The rotation of the 150t ramshorn hook is motorized. This hook will be replacd by a shackle for remote engagement to lifting eyes. The mechanical repeatibility of the position of the hook in any coordinate is 20 mm.

The TARM, at present in the detail design stage and due for delivery at JET in early 1989, will be readily attached to the main JET 150 tonne crane via the 4-wire rope system originally specified for lifting the large JET poloidal coils while not curtailing its operating modes. Fig 10 shows a schematic of the TARM motions (all major axes are designed with zero backlash drive units) and Fig 11 shows the operating configurations required to enable the Mascot to access positions not only above, below and down the central core of the Torus, but also halfway across inside the vessel in order to work in conjunction with the articulated boom during installation of heavy components. Fig 12 shows a CAD-generated view of the support structure required to achieve the 270 degree rotation of the main mast to the 4 operating positions North, South, East and West of the main crane crab while not interfering with it.

These different operating positions (B1 axis, fig 10) are required in order to be able to cover the full Torus Hall area with the main hook. A special 250 kg jib crane (crane K, fig 10) is positioned on the moving vertical telescope so as to be able to lift very long diagnostic equipment out of the top of the machine. A 6 tonne jib crane with motorized hook will carry out most lifting operations in conjunction with the MASCOT. Under the vessel where overhead access is impossible, the low-level transporter can lift heavy components.

The vertical mast can be coupled directly to a MASCOT for access down the middle of the machine, (or the neutral injector SF6 Tower) or the horizontal telescope may be attached with a purpose designed remote attachment system. A limited (+10°, -15°) tilt action (A1) allows for deflection compensation and also allows the MASCOT to reach 0.9 m below the floor level for basement maintenance.

A gaiter on the horizontal part protects against contamination during in-vessel operations. Three additional TV cameras provide operational viewing.

In order to minimize cable requirements and for ease of commissioning, the service modules are all attached to the upper 'fixed' part of the TARM. These include power supplies and local controllers for the drive units, signal conditioning for sensors and TV cameras, MASCOT slave power supplies, MASCOT cooling, welding power supply, welding gas supply, high pressure water supplies for tools, air supply for tools and air make-up for gaiters.

The microprocessor based control system will be similar to that of the boom with single joint closed loop servocontrol, teach and repeat and resolved motion. Control is possible from either a portable operator station ('handbox') with display and joystick functions, a Remote Handling workstation (RHWS), a part of JET's RH equipment suite, or the Remote Handling graphics station (GWS) a standalone component.

During operations, a high level of monitoring is carried out to assure the integrity of the control system and operations being executed. When error conditions are detected, the operator is supplied with diagnostics indicating the fault. If system faults occur, operability is maintained with some degradation in function or performance.

SERVOMANIPULATORS

The principal Remote Handling device for dexterous operations is the MASCOT IV Servomanipulator, 2 of which have been constructed on the basis of the MASCOT III model previously developed by ENEA, Rome. A third, earlier model which has been used for testing has been overhauled and brought up to date.

The servomanipulator consists of 2-armed master unit and a slave unit, kinematically similar. Their movements are linked together by force-reflecting position servomechanisms, giving the operator controlling the master unit the tactile sensation of doing the work. The slave has a camera mounted on it to give front views, side views being provided by the cameras on the boom extension. A complete slave arm and shoulder assembly including counter-weights, actuators and cooling system, weighs 110 kg. The transversal dimensions of the body are 405 mm x 860 mm.

Fig 5 shows the geometry of the slave arm. The working volume covered by the servosystems is shown by the etched areas of fig 6. An indexing motion is provided on each of the slave arms so that the working volume of the servo-systems can be displaced over a range of 180°. In this way the overall angular range of the shoulder motion is 270° in side elevation.

The manipulator can exert a force of 20 kg per arm in any direction and in any position of the working volume for a duration of 10 minutes, and a continuous load of 12 kg indefinitely, with an ambient temperature of 50°C. The grippers give a squeezing force of 24 kg. Each servoactuator of the slave incorporates a brake coupled to an overload slipping clutch, which intervenes in case of any malfunction or overload of the servosystem.

The ratio of the forces exerted by slave and master is selectable via function keys set to the following values:

Arms	1:1.5,	1:3	and 1:6
Gripper	1:1.5,	1:3	and 1:9

Other ratios can be chosen using a keyboard.

The slave unit is washable. For this purpose its arms are protected by polyurethane gaiters which are slightly pressurized to prevent the ingress of contaminated air.

The dexterity of the servomanipulator depends to a great extent on the following characteristics:

Sensitivity, defined for a given force ratio by the maximum starting load which must be applied to the slave tongs when the arm is perfectly balanced to make the servosystems just move. This is better than 150 g with a force ration 1:1.5. AC motors are used to ensure low friction.

Stiffness, defined as the ratio between the load applied and consequent displacement between master and slave. For 1 kg applied by the slave the displacement is less than 1 mm.

Inertia reflected to the operator, which has to be small so that it does not mask external dynamic loads. This is 9 kg with force ratio 1:3 on the worst movement. It could be reduced by electronic compensation methods, such as acceleration feed-forward.

Damping, which has to be high enough to limit the overshoot of the position response to a step variation of load within acceptable values. Overshoot is less than 50% at the wrist at full load.

Maximum operating speed: it must be possible to use all the movements freely up to a reasonably high speed without feeling, on the master side, forces which depend on the speed, eg viscous damping or the opposite tendency to accelerate, in both no load and full load conditions. This is achieved in practice by adjusting velocity feed-forward signals. The maximum speed of the wrist at no load is 0.83 m/sec.

The control system of MASCOT IV, is microprocessor-based and algorithms are provided for computer-aided manipulation, such as tool weight compensation, teach-and-repeat and constraint of the trajectory on given planes or lines. It included a serial data link with 16 bit words and a sampling rate of 250 Hz, which has been shown to give unimpaired time response and granularity compared to the earlier analogue system.

END EFFECTORS

To handle heavy components, the servomanipulator is replaced at the tip of the articulated boom by special-purpose handling fixtures (fig 3) whose function is to pick the components off the turret truck, carry them into the vessel and hang them in position on the vessel wall and vice versa. The components rest on hooks either on the turret truck, on the end effector or on the vessel wall. They are transferred from one to the other by engaging the eyes on the component onto the receiving hooks and disengaging the other hooks by slipping them out from underneath. A motorized safety latch is provided to make sure the component is not jerked off the hooks. For the transfer operation finely controlled movements are required in all directions with TV viewing. For this reason a resolved motion algorithm was inserted in the articulated boom control system. The 2 CCTV cameras branching from the boom allow simultaneous viewing of 2 hooks.

Four end effectors have been made and used successfully so far, one for the equatorial limiters, now obsolete, one for "belt" limiters, and 2 for the radio frequency antennae. To keep down the weight the end effectors were designed as box structures and built in welded titanium alloy or alluminium alloy using a salt-brazed bath technique. They are attached to a grabber which in turn is mounted on the boom via a quick connector which facilitates the change-over of end effectors and servomanipulators. The C-shaped grabber (fig 4) has 2 motorized pan and roll pivots so that it can orient the end effectors both horizontally and vertically. This is to allow the end effector component to be folded back into the grabber for entry through the vacuum vessel port and then swivelled to the required position for attachment to the vessel wall.

SPECIAL TOOLS

For operations in areas where access is difficult, or which require high precision or large forces, special tools are being developed. These will be positioned by the manipulator. Efforts were made during the design phase of the machine to standardize and simplify components so that the number and complexity of such special tools could be kept to a minimum.

A significant example is the cutting and welding trolley (fig 7) designed to cut and reweld, if necessary, any of the large vacuum joints. The geometry of these joints was standardized in the form of edge-welded lips. The automatic trolley runs along the lip joint with no need for additional guides. Its rollers bring the lips together, reducing initial gaps, and reliable TIG autogenous welds are achieved. Arc voltage control is used to follow irregularities. Pulse welding makes it possible to work in any attitude.

The TIG torch can be replaced by a nibbler which cuts the joints ready for rewelding without leaving debris. It can also trim one lip flush with the other, so that edge welding becomes possible even if the initial positioning of the lips to be joined is not precise. By mounting the 2 driving rollers at a "toe-in" angle, the trolley can negotiate sharp turns, down to 60 mm radius.

Other special tools which have been made and used are very compact devices for cutting and welding the standard pipe joints in confined spaces.

IN-VESSEL INSPECTION

Periodic inspections of the interior of the vacuum vessel have to be done to check for damage due to plasma disruptions. A system was developed to scan the vessel using 4 TV probes through small apertures in the tip of the vessel withoug breaking the vacuum. The main difficulties in this project were compressing the optics and electronics into the small diameter available, and providing sufficient illumination since the vessel has been carbonized. This was overcome by using high-energy flashlight and digital frame-grabbers. The system is completely automatic, with microprocessor control. The vessel surface was divided into viewing areas and for each of these "named positions" the orientation, viewing and lighting parameters were optimized and stored on disc. The operator calls up the named positions using a keyboard or mimic diagram and the camera is pointed at the desired location with aperture, focus and flash intensity as previously chosen. In this way a series of photos are taken and can be stored on disc or tape for comparison with previous shots. Digital filters are used to enhance contrast and reduce flickering.

As there was a drawback in that the vessel had to be cooled down to below 50°C to do an inspection we are now working on modifications to make the system usable at 300°C. Tests done on a prototype confirm that we can insert a cooling jacket without danger to the glass probe.

OPERATION

At this stage a considerable amount of the principal Remote Handling equipment has been designed, procured and commissioned. The articulated boom was used in summer 1985 to remove nickel limiters and fit Radio Frequency antennae, hands on and in early 1987 to fit 32 belt limiters and 8 new Radio Frequency anntenae, weighing up to 350 kg, from one entry port (see figs 8,9). With the boom these operations were quicker and easier than they would have been otherwise. The special pipe cutting positioning and welding tools were also used with considerable success. A trial was done of inserting a MASCOT mounted on the boom into the vacuum vessel. The cutting and welding trolley was used in the assembly of the machine to trim and weld all the octant joints (about 100 m in all). Good quality welds were obtained and no leaks have occurred. Several inspections have been carried out with the In Vessel Inspection System. In some areas it was difficult to get a clear picture. Some more apertures have now been made available for direct lighting and the picture is greatly improved.

CONCLUSION

The task now is to get all the Remote Handling equipment together into a working system. Extensive trials will be done on partial mockups from 1988 simulating components expected to require remote maintenance to establish handling procedures. Every effort will be made to take advantage of future shutdowns to get experience using the Remote Handling equipment on the machine. These trials will alert us to any shortcomings in the equipment and show what tools are requird for the various operations and whether any other components have to be modified before the D-T phase.

ACKNOWLEDGEMENTS

The authors thank all their colleagues of the JET Remote Handling Groups, whose work forms the basis of this paper.

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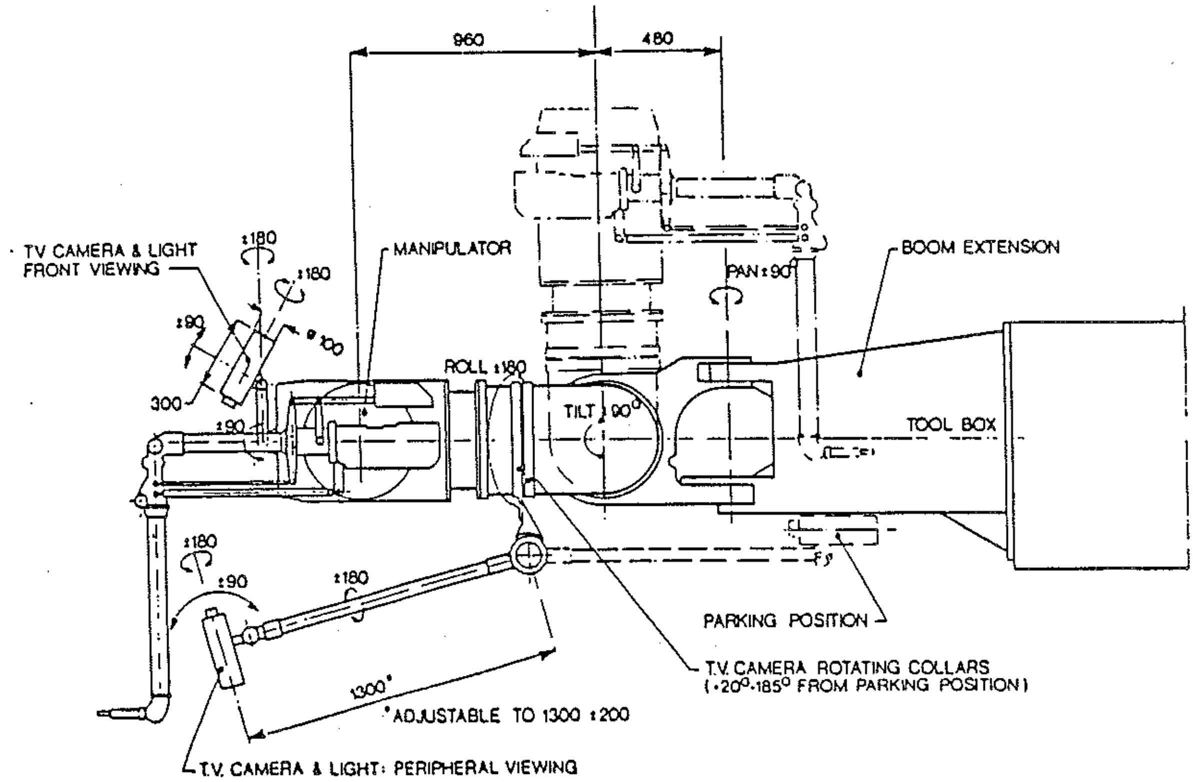

Fig 1 Servomanipulator and camera on boom extension

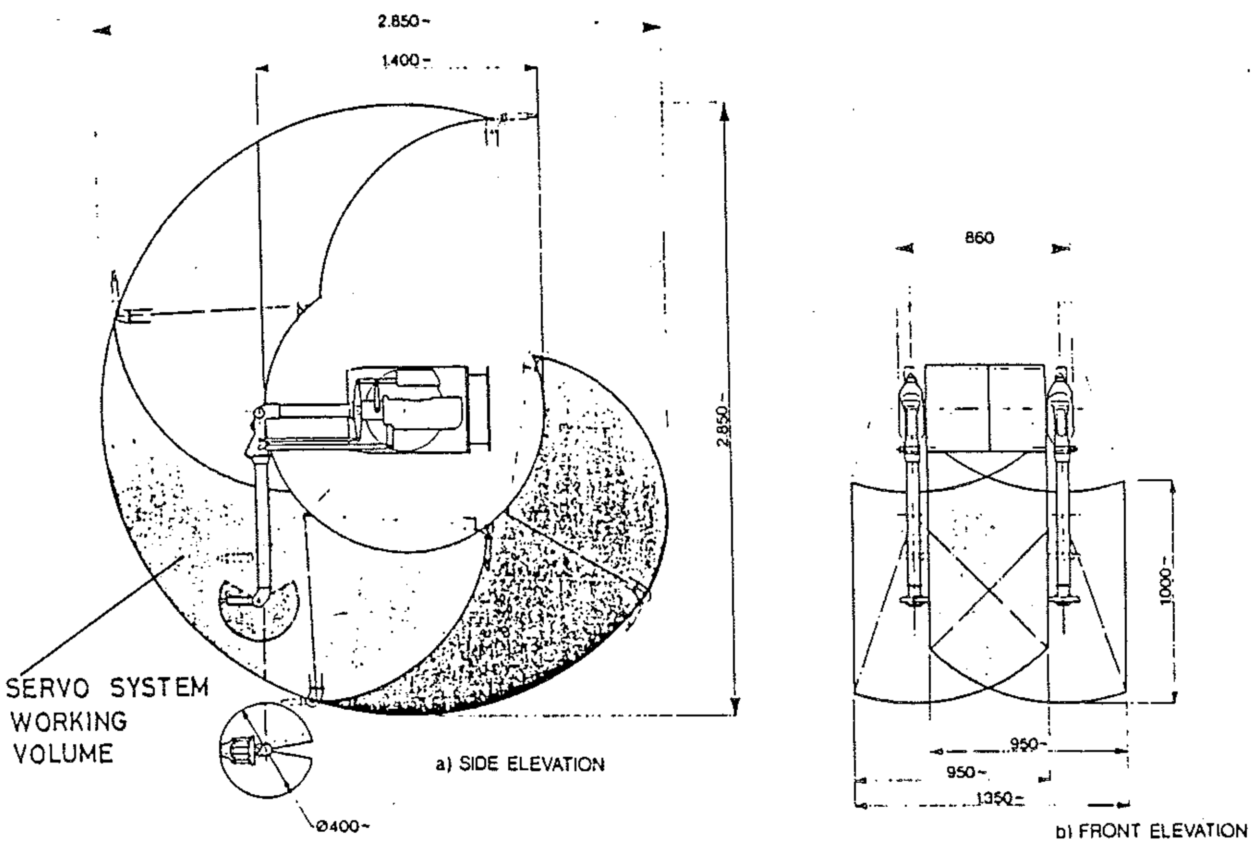

Fig 2 Mascot slave working volume

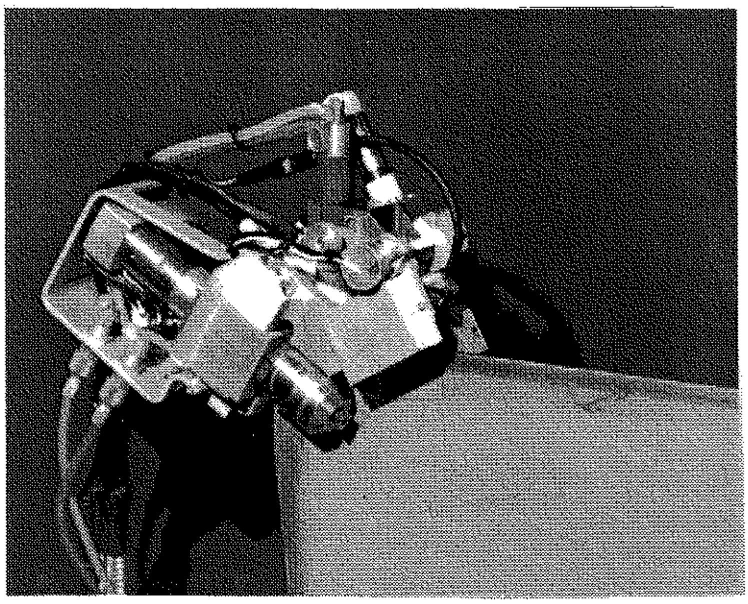

Fig 3 Compact welding trolley

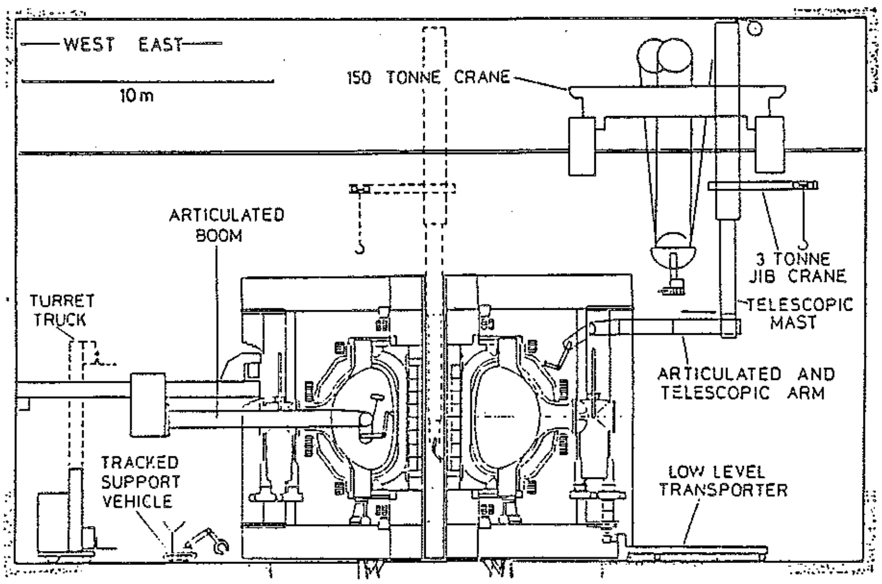

Fig 4 Schematic layout of JET tokamak and remote handling equipment

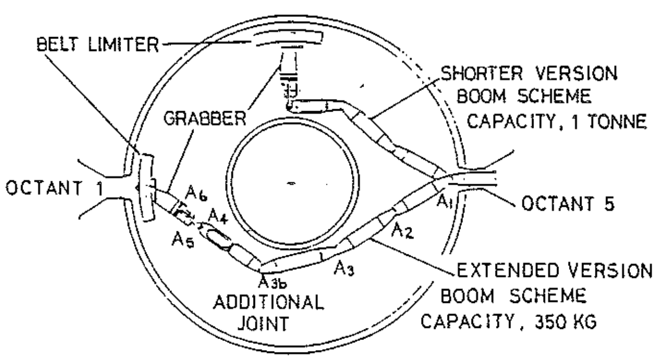

Fig 5 Articulated boom in vessel. Plan view

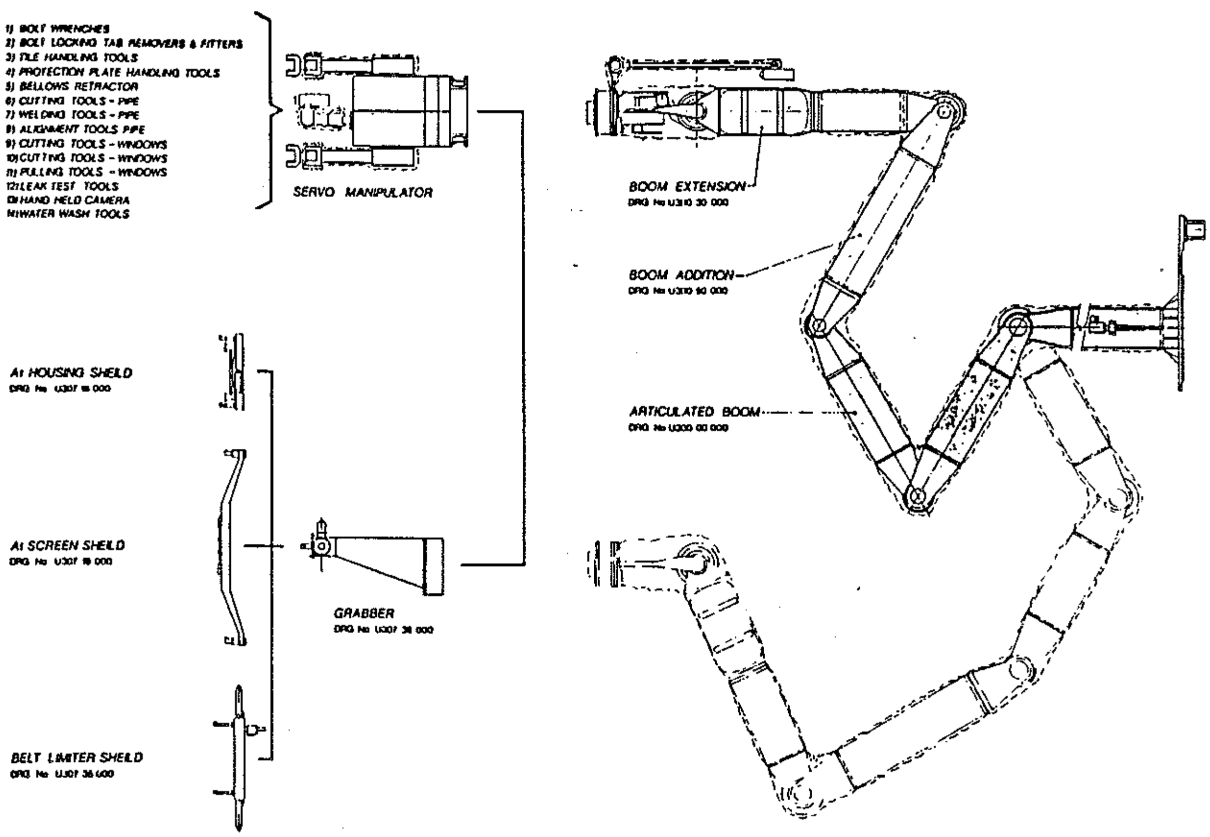

Fig 6   Articulated boom and end effectors

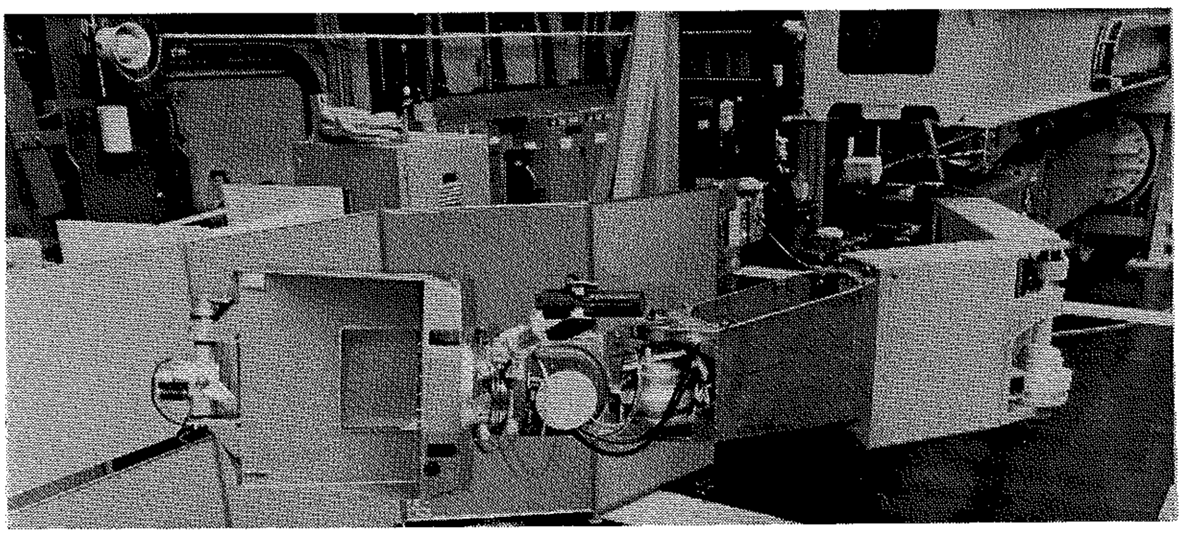

Fig 7   Boom extension with TV arms and grabber

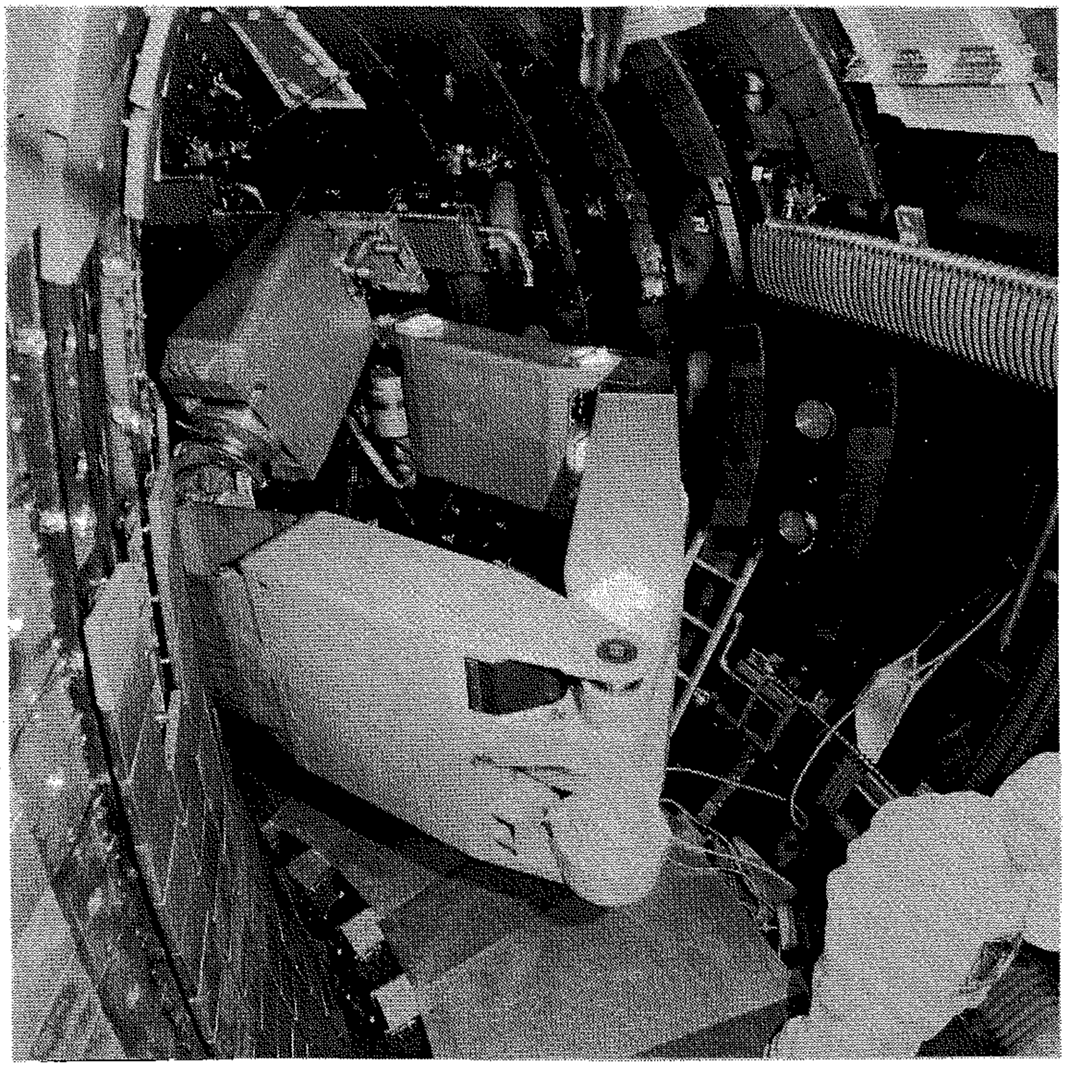

Fig 8 Belt limiter installation at boom entry port

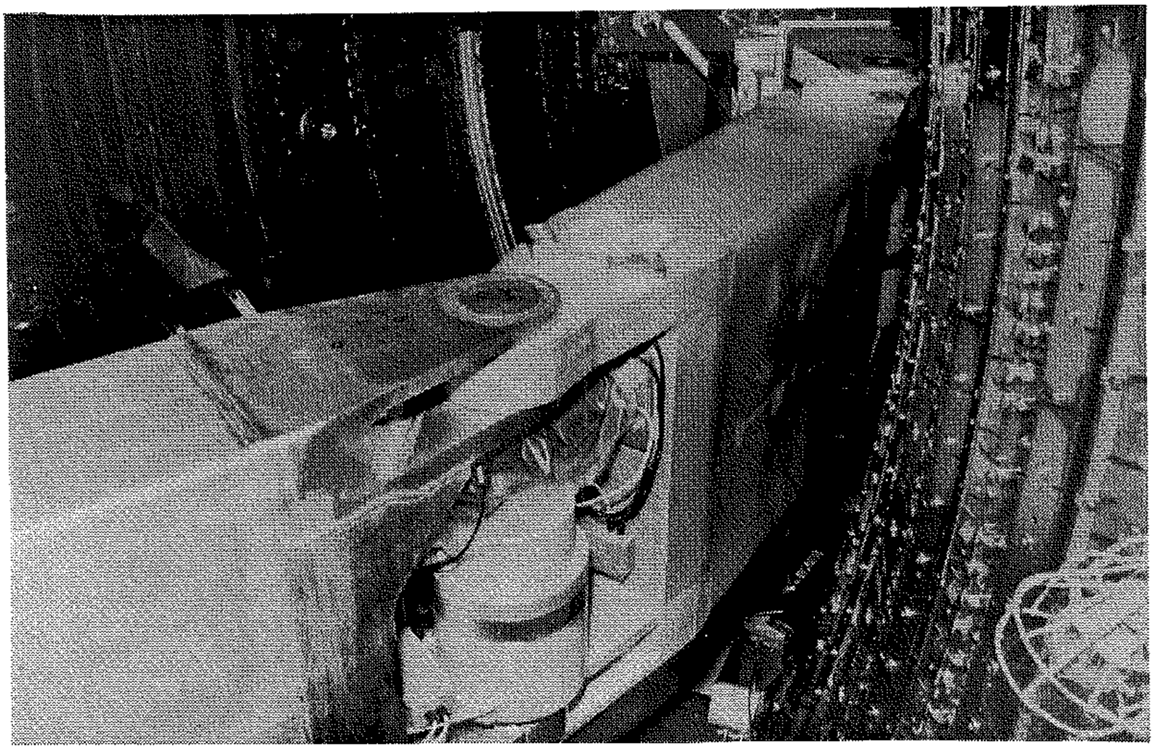

Fig 9 Manipulator mounted on boom for trials in the vessel

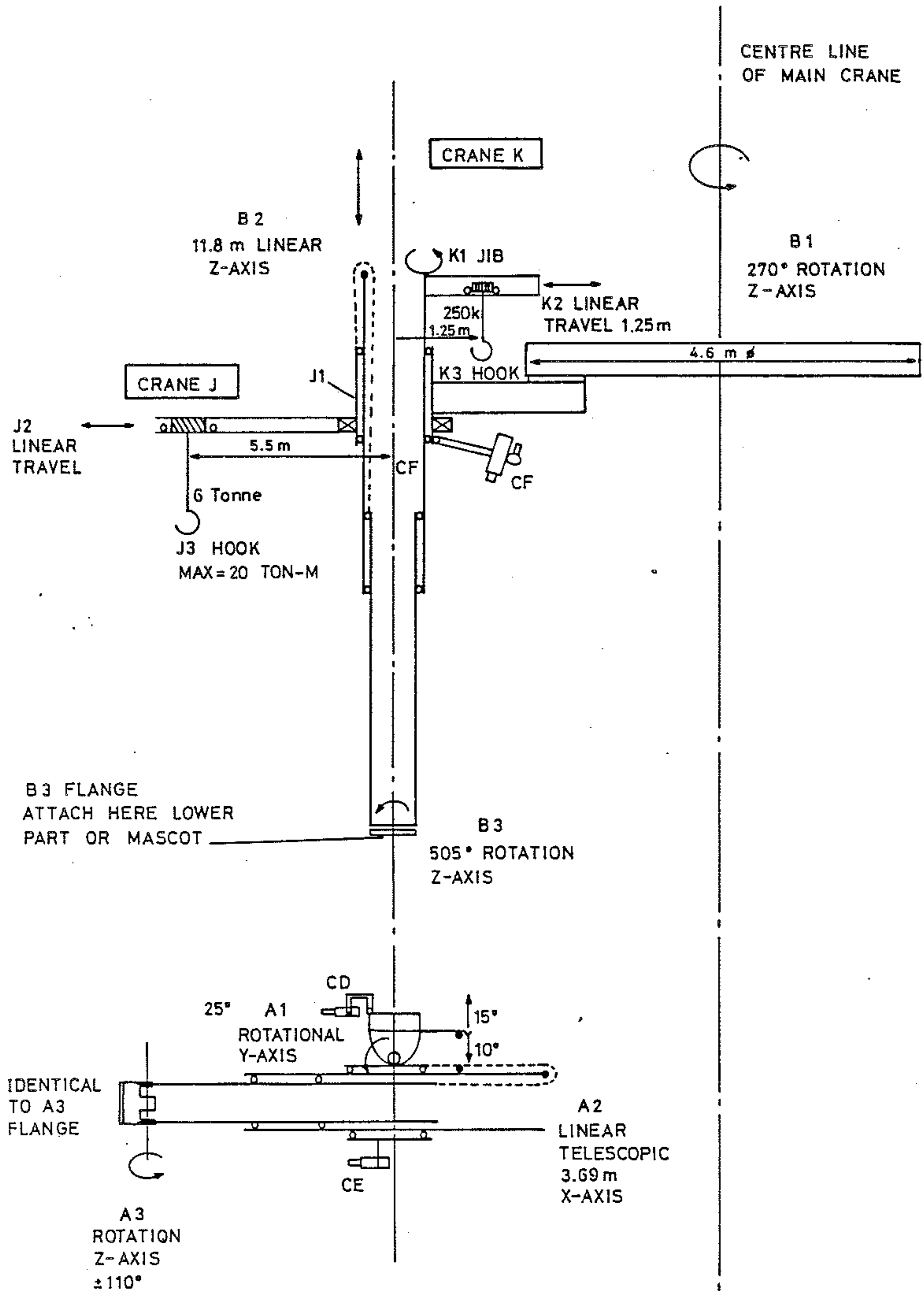

Fig 10 TARM movements - schematic

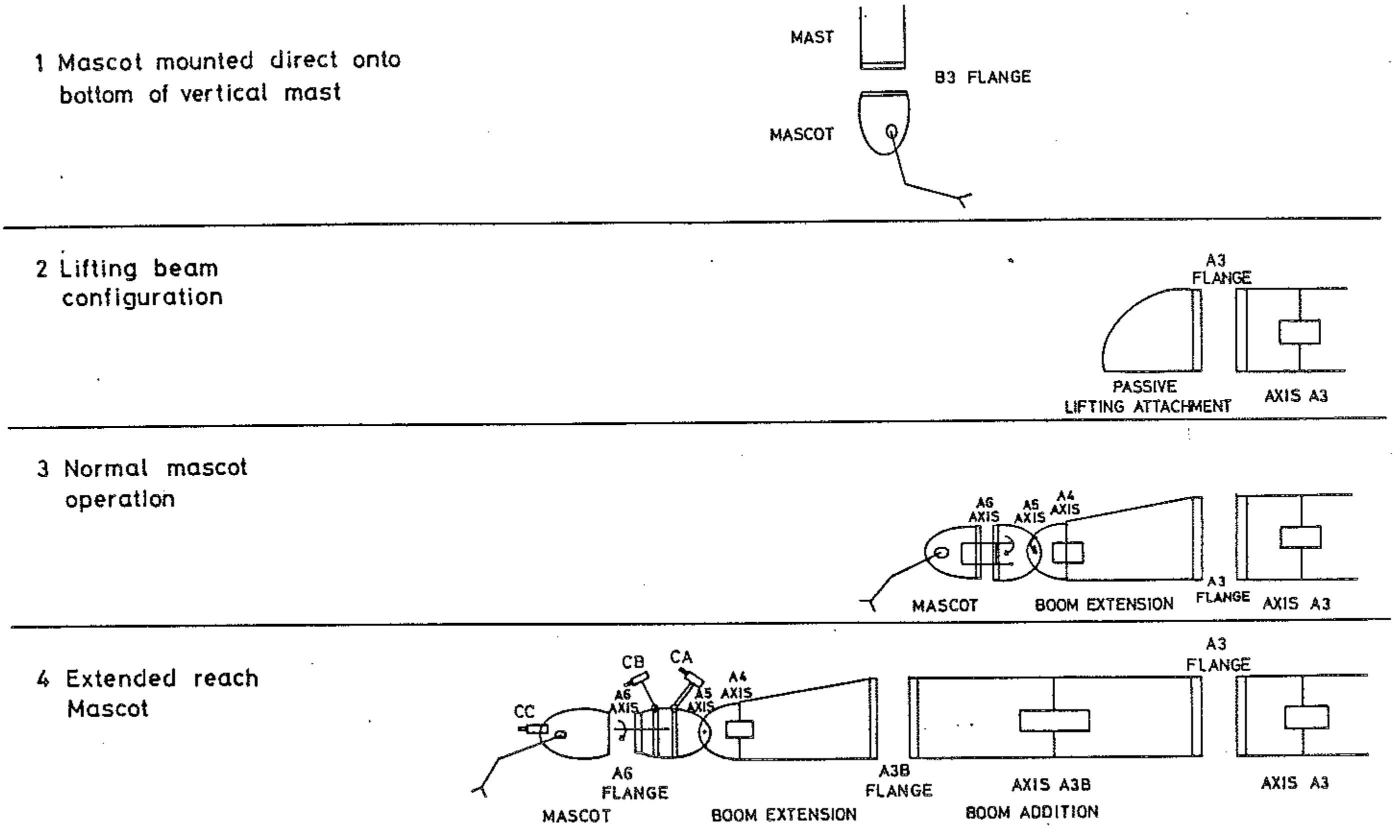

Fig 11 TARM operating cofigurations

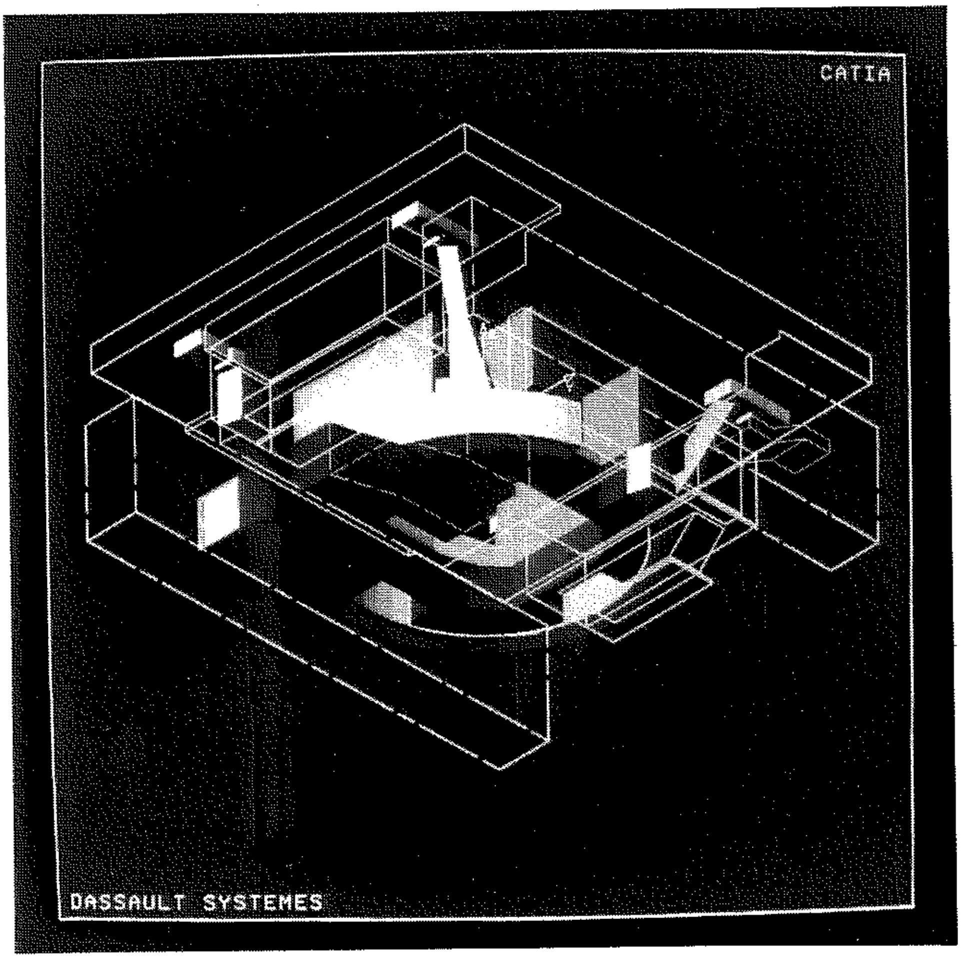

Fig 12 CAD generated view of TARM upper part