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DESIGN AND OPERATION OF

REMOTE MAINTENANCE SYSTEMS IN JET.

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ABSTRACT

The JET tokamak is a joint European project aimed at proving the viability of nuclear fusion as a source of energy. A remote handling system is being developed for this large experimental facility. Force feedback servomanipulators and TV cameras are positioned at work locations by large transporters. Positioning and teleoperation are computer-assisted. Special tools are being devised to facilitate difficult tasks.

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 and density 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.

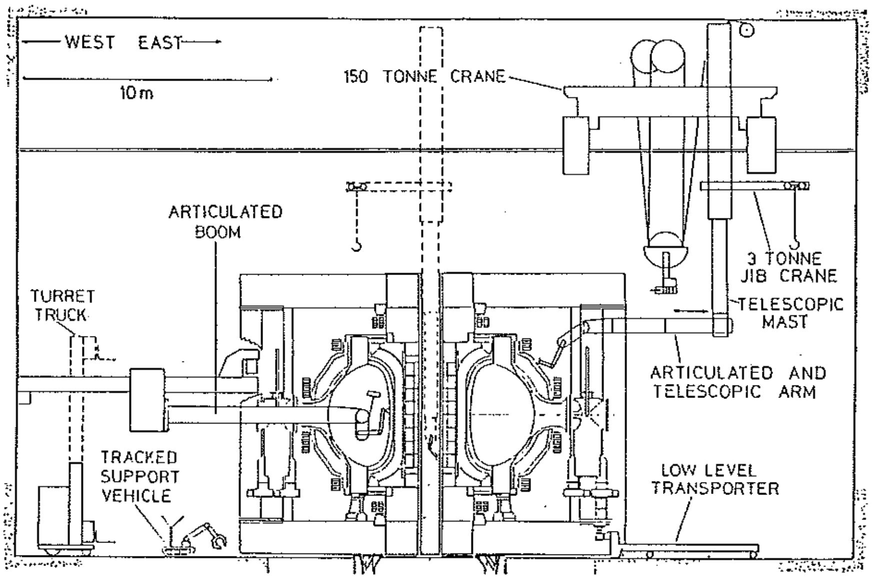

Fig. 1. Schematic layout of JET tokamak and remote handling equipment.

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 servo-manipulators for more complex operations such as connection of services, bolting, welding and cutting. A quick connector facilitates 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 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.[3]

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 two opposite horizontal ports. It can reach round half the circumference with a pay-load 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.

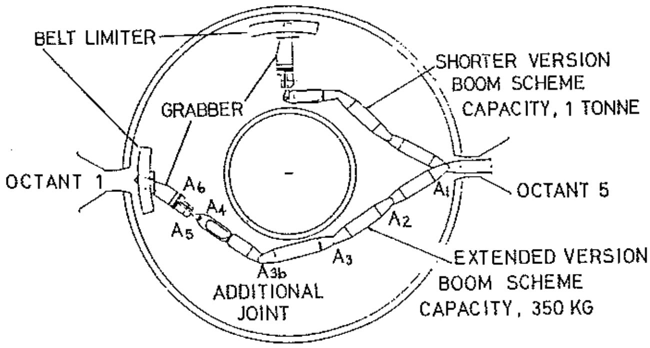

Fig. 2. Articulated boom in vessel. Plan view.

The boom consists of five segments canti-levered 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 servomanipulator 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).

Care was taken in the choice of materials to optimize strength vs weight. The first two segments are in stainless steel and the others in aluminium alloy. The boom extension is an aluminium/magnesium casting strengthened by hot isostatic pressing. As hydraulic fluids were excluded by the requirement not to risk con-tamination of the vacuum vessel, all the motors are electric. DC torque motors are directly coupled to the Harmonic Drive gearboxes. This gives us a good combination of high torque, small volume and weight and negligible back-lash, 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 power cut-off.

The boom carries three 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 two cameras are carried by orientable arms

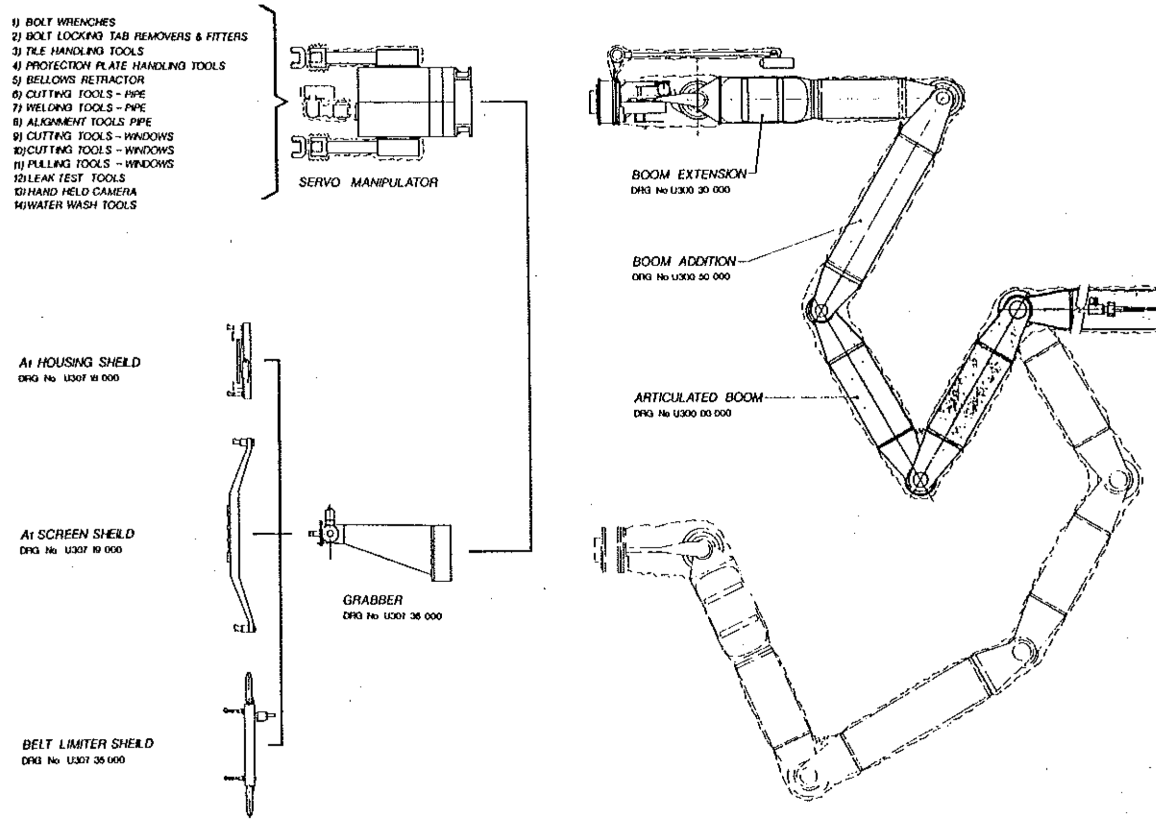

Fig.3. Articulated boom and end effectors.

branching from the boom extension. One of these is visible in figs.4,5. The arms have four 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 two 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 servo-amplifiers. 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 than 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

This transporter is being designed for access to areas on the outside of the vacuum vessel. It will be suspended from the crab of the main 150t crane, which was used for the installation of the machine. 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

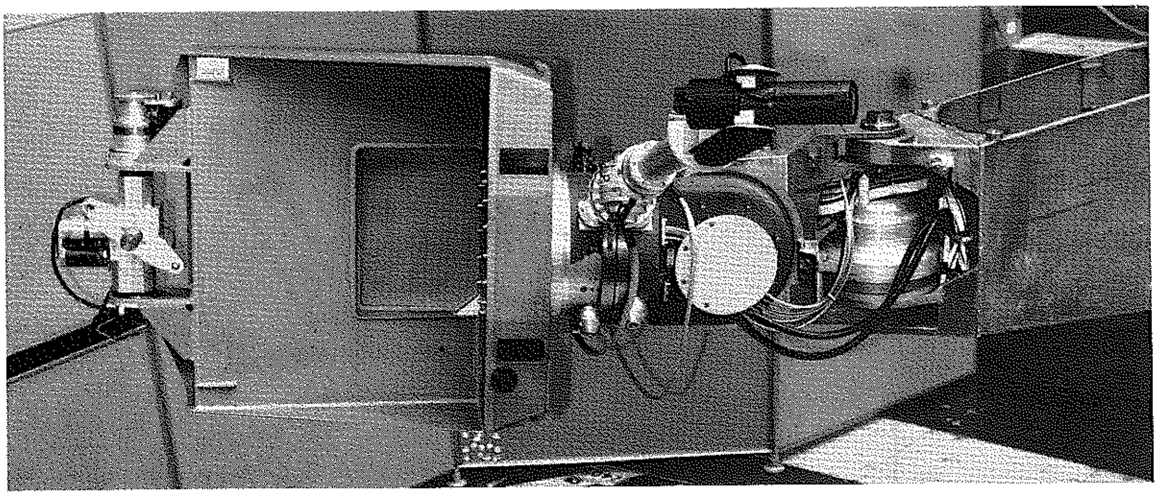

Fig. 4. Boom extension with TV arms and grabber.

150t ramshorn hook is motorized. This hook will be replaced by a shackle for remote engagement to lifting eyes. The mechanical repeatability of the position of the hook in any coordinate is 20 mm. To lift large, delicate structures such as the outer poloidal field coils a four-rope system with hydraulic laod equalizers is used. This system will also be used to raise to its location under the crab the structure which will support the telescopic arm (TARM).

The TARM consists of a vertical telescopic mast supporting a horizontal arm which terminates in two articulations and a pan/roll/tilt mechanism identical to that of the articulated boom. The control system will be similar to that of the boom, with single joint control, teach-and-repeat and resolved motion.

SERVOMANIPULATORS

The principal remote handling device for dexterous operations is the Mascot IV servomanipulator, two 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 a two-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 will have 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 counterweights, actuators and cooling system, weighs 110kg. 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 servosystems 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 20kg per arm in any direction and in any position of the working volume for a duration of ten minutes, and a continuous load of 12kg indefinitely, with an ambient temperature of 50°C. The grippers give a squeezing force of 24kg. 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 pressurised 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 150g with a force ratio 1:1.5. AC motors are used to ensure low friction.

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

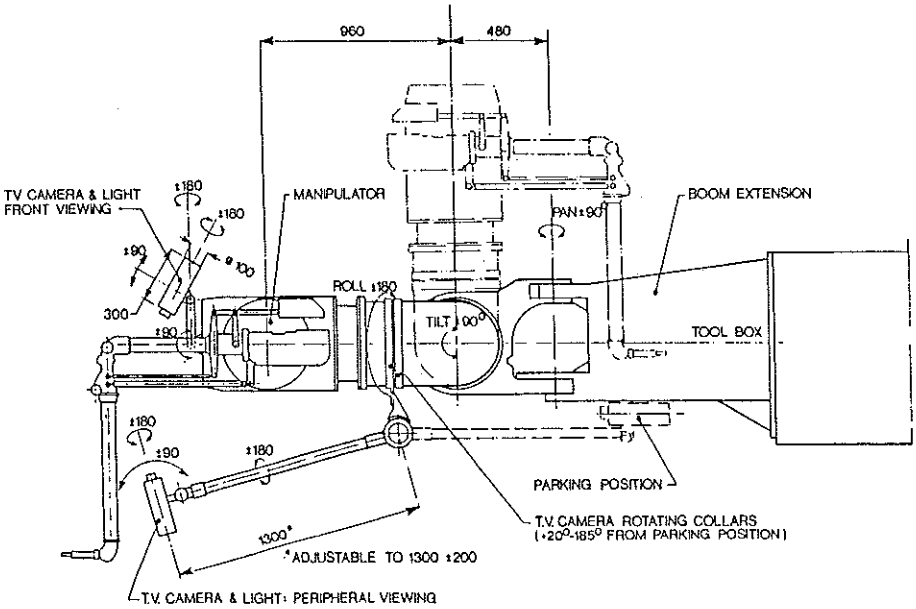

Fig.5. Servomanipulator and camera on boom extension.

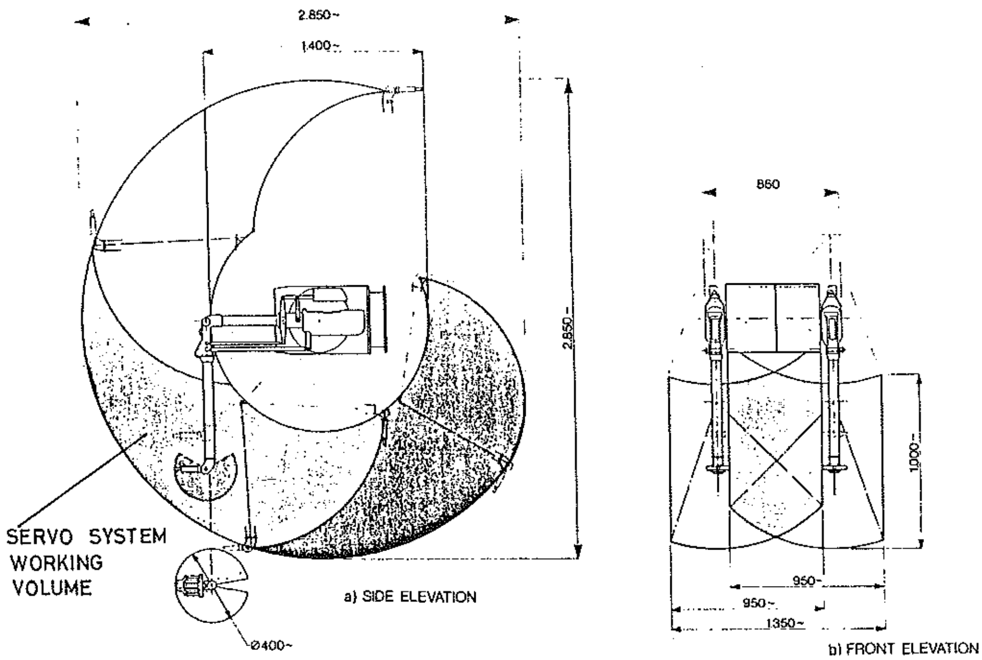

Fig.6. Mascot slave working volume.

Inertia reflected to the operator, which has to be small so that it does not mask external dynamic loads. This is 9kg 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, e.g. 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 max. speed of the wrist at no load is 0.83 m per sec.

The control system of Mascot IV, is microprocessor-based and algorithms will be provided for computer-aided manipulation, such as tool weight compensation, teach-and-repeat and constraint of the trajectory on given planes or lines. It includes a serial data link with 16 bit words and a sampling rate of 250Hz, 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). The design of these end effectors has been kept as simple as possible. Their function is simply to pick up the components off the turret truck, carry them into the vessel and hang them in position on the vessel wall, or vice versa. The components rest on two simple 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 motorised 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 has been inserted in the articulated boom control system. The two CCTV cameras branching from the boom allow simultaneous viewing of two hooks.

Four end effectors have been made so far, one for the equatorial limiters, now obsolete, one for the "belt" limiters, and two for the radio frequency antennae. To keep down the weight the end effectors were designed as box structures and built in titanium alloy. 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 two motorised pan and roll pivots so that it can orient the end effectors both horizontally and vertically. This is to allow the end effector and 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

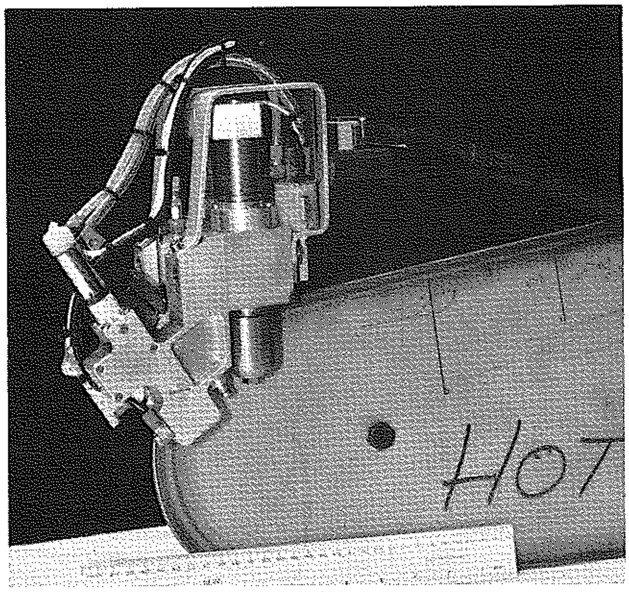

Fig.7. Compact welding trolley.

A significant example is the cutting and welding trolley (fig.7) designed to cut and re-weld, if necessary, any of the large vacuum joints. The geometry of these joints was standardised 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 two driving rollers at a "toe-in" angle, the trolley can negotiate sharp turns, down to 60 mm radius.

Other special tools being developed at present are very compact devices for cutting and welding the standard pipe joints.

IN-VESSEL INSPECTION[5]

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 four TV probes through small apertures in the top of the vessel without 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. With the boom these operations were quicker and easier than they would have been otherwise. A trial was done of inserting a manipulator 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 100m 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 insertion of direct lighting which we expect to greatly improve matters.

CONCLUSION

The task before us now is to get all the Remote Handling equipment together into a working system. Extensive trials will be done on partial mockups simulating components expected to require remote maintenance to establish handling procedures. During the next shutdown it is intended to insert all the new belt limiters and antennae using the articulated boom and end effectors. The cooling water pipes will be installed using the special cutting and welding tools. Every effort will be made to take advantage of the 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 required for the various operations and whether any other components have to be modified before the D-T phase.

ACKNOWLEDGMENTS

The author thanks all his colleagues of the JET Remote Handling Groups, whose work forms the basis of this paper.

REFERENCES

1. M HUGUET and E BERTOLINI "Main features implemented in the JET facility for Deuterium-Tritium Operation" 7th Topical Meeting on Technology of Fusion Energy - ANS Reno USA June 86.

2. J DEAN et al., "Preparation for D-T Phase Operation in JET", Proc. SOFT Conf., Avignon (1986).

3. P D F JONES, D MAISONNIER, T RAIMONDI, "Design and Operation of the JET Articulated Boom". Proc. 11th Symposium on Fusion Engineering, Austin (1985).

4. U KUHNAPFEL, K LEINEMANN, "Graphic Support for JET Boom Control". Proc. International Topical Meeting on Remote Systems and Robotics in Hostile Environments, Pascoe (1987).

5. T RAIMONDI, R CUSACK, L GALBIATI, "The JET In-Vessel Inspection System". Proc. SOFT Conf., Avignon (1986).

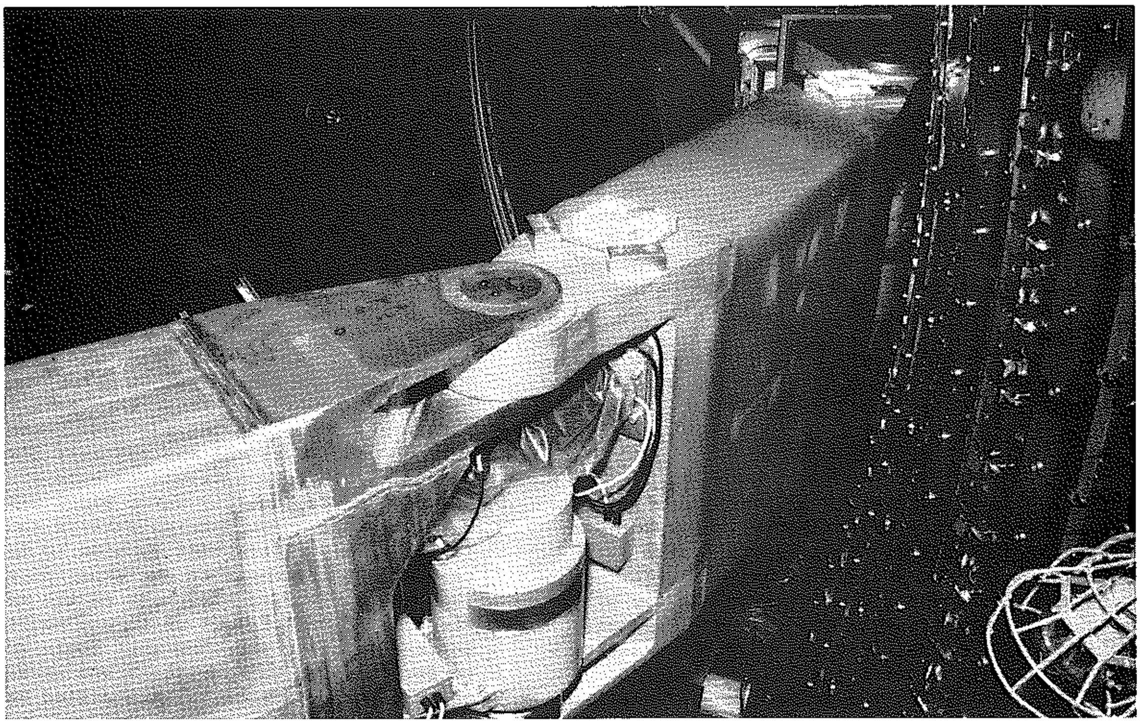

Fig. 8. Removal of nickel limiters with a gripper mounted at the end of the boom.

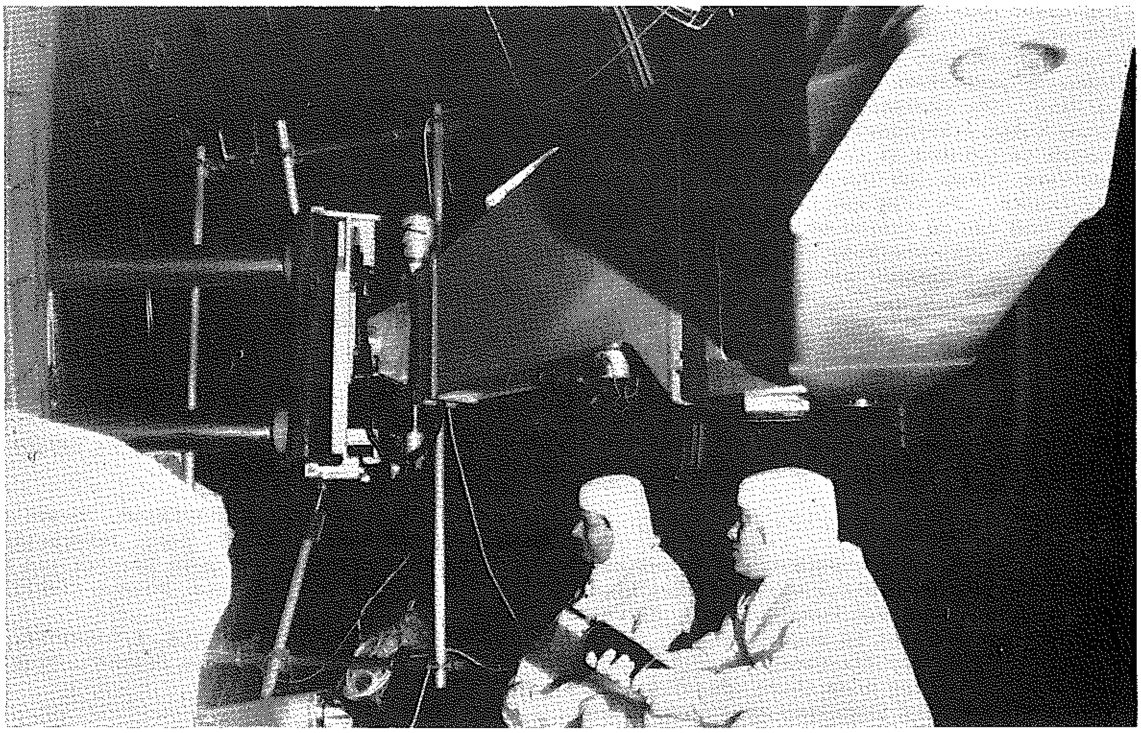

Fig. 9. Manipulator mounted on boom for trials in the vessel.

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PRIMARY VACUUM PUMPS FOR THE FUSION REACTOR FUEL CYCLE

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PRIMARY VACUUM PUMPS FOR THE FUSION REACTOR FUEL CYCLE

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Abstract

The primary vacuum system for a Tokamak type controlled thermonuclear reactor with one Gigawatt thermal output is analysed. The need for recovery, purification and recycling of Deuterium-Tritium fuel to the reactor leads to the following basic requirements for vacuum pumps at the reactor exhaust:

- effective pumping speed ~ 250 m^3s^{-1}
- inlet pressure ~ 0.1 Pa
- outlet pressure ≧ 10 Pa (at full flow rate of ~ 25 Pa m^3s^{-1})
- compatibility with Tritium, nuclear radiation, static and dynamic magnetic fields, mechanical shock and up-to-air accidents.
- no contamination of pumped gases (primarily D-T and ^{4}He) by vacuum pump media such as lubricants, operating fluids (vapours) or gases other than D-T and ^{4}He.

Based on present experience, the turbomolecular pump appears suitable. It would, however, require a substantial development effort both in technology and unit size to meet the requirements. There remains some doubt about its compatibility with mechanical shock, radiation, magnetic fields and sudden up-to-air accidents etc.

Therefore, alternative pumping principles are proposed, all shown to work at least in laboratory size models:

- Thermodynamic pumps for transport pumping to replace turbomolecular pumps.
- Selective storage pumps for effluent processing in situ.

The proposed systems require development efforts similar to the turbomolecular pump, but are shown to meet all requirements without the need for large protective valves.

Selective pumps, pumping none of the Hydrogen isotopes (but Helium and impurities such as DTO, CO_2, Methane) or combinations of thermodynamic transport pumps and regenerable volume getter pumps are shown to perform the major processing task, i.e. purification and recycling of DT, directly at the reactor exhaust.

Introduction

A worldwide research effort is devoted to develop controlled thermonuclear fusion to a practically inexhaustible energy source.

A fusion reactor [1] will burn Deuterium and Tritium nuclei - both isotopes of Hydrogen - by fusing them to α-particles (^{4}Helium nuclei) with a very high energy yield. Neutrons are set free in this process, carrying an energy of 14 MeV, and α-particles with an energy of 3.5 MeV. The fusion reaction takes place at temperatures exceeding 100 million degrees, way beyond the melting point of any known substance. A possible solution for controlling this reaction is confinement in a magnetic field; at this temperature, the Deuterium and Tritium gas mixture is fully ionised. Charged particles in a magnetic field are confined to corkscrew trajectories along magnetic field lines and can only slowly diffuse perpendicularly to the field mainly due to collisions with other particles. If the magnetic field configuration is chosen such, that the field lines follow the contours of the reactor vessel wall, this slow diffusion leads to a temperature gradient in the boundary layer of the plasma (i.e. the hot ionised gas). Thus, the magnetic field serves as a thermal insulator between the hot plasma core and the vessel walls. The vessel walls can then be built from available materials, kept well below their melting point with suitable cooling techniques.

The energy lost by the plasma due to this thermal conduction and by radiation, is supplied by the 3.5 MeV α-particles. The α-particles, also confined in the magnetic field, transmit their energy to the plasma via collisions with fuel particles [2].

The 14 MeV neutrons, the second reaction product, are without electrical charge and hence not confined in the magnetic field. They deposit their energy mainly in a shield (blanket) surrounding the vessel walls in form of thermal energy, which can be converted to electrical power by standard technologies, ie steam turbines and generators [3].

The best confinement [4] for hot plasmas has so far been achieved in toroidal geometries (Tokamak [5]) and therefore the inside of a fusion reactor may look rather like the vacuum vessel of JET (the Joint European Torus), Fig.1.

In the following, we will analyse the vacuum pumping requirement for a fusion reactor and try to propose feasible solutions.

1. Primary Vacuum Systems requirements for a Fusion Reactor

The fusion reaction as described above depends to a very high degree on the purity of the Deuterium-Tritium plasma. Any admixture leads to a dilution of the reacting plasma and to additional radiation losses via Bremsstrahlung. Both effects become increasingly severe with increasing atomic number Z of added impurities [6]. Hence, the reactor vessel has first to be evacuated, the vessel walls must be conditioned and leaktight to ultra high vacuum standards [7]. Once we have established a burning plasma, we will have to remove the ^4He reaction product, keeping the α-particle concentration in the plasma at a maximum of 5%. Further undesirable admixtures (impurities) will also have to be removed. They result from interaction of energetic plasma particles with the reactor first wall and consist primarily of Hydrocarbons, as the use of graphite protection tiles in areas of high power loading appears at present unavoidable. We also expect Oxides such as DTO, CO, CO_2, resulting from chemisorbed oxygen not fully removed by wall conditioning. Assuming that the concentration of these impurities can be kept reasonably low

(~ 1%) by appropriate choice of first wall materials and suitable plasma parameters (e.g. low boundary layer temperature), the vacuum pumping requirements are dominated by the removal of ^4He "ash".[1)]

Before any vacuum pumps can be used, the ions must be "scraped" off the plasma boundary, neutralised and recombined to gases which can leave the magnetic confinement. The study of such removal devices (divertors or pump limiters) is part of the worldwide fusion research effort. Based on results of this research, we can expect to pump the gas mixture at the reactor exhaust at a total pressure of ~ 0.1 Pa [8,9].

With an energy yield of 17.5 MeV (= 2.8×10^{-12} Joule) per fusion event (see introduction), we require 3.57×10^{20} events per second to generate one gigawatt (thermal) fusion power. Hence we have to feed 3.57×10^{20} D-T molecules per second and to remove the same amount of ^4He atoms. This amount corresponds to a mass flow rate of 5.93×10^{-4} mol s^{-1} or 1.33 Pa $m^3 s^{-1}$ under normal conditions. With the previously discussed condition that the ^4He concentration in the exhaust gas should not exceed 5% (for reasons of plasma dilution), its partial pressure in the exhaust gas mixture (at 0.1 Pa, see above), has to be kept at a maximum of 5×10^{-3} Pa. Hence, we require an effective pumping speed of ~ 250 $m^3 s^{-1}$ for ^4He at the reactor exhaust.

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1) Note: all examples given in this paper (e.g. for effective pumping speeds) are based on this assumption and hence represent the minimum requirements for a fusion reactor vacuum system. The actual design of a real system will depend on input data from advanced experiments such as JET, based on the study of Deuterium-Tritium plasmas. Lacking such data, we restrict the vacuum pumping requirements to the basic task of ^4He removal. Further studies on impurity removal and waste processing (tritiated Hydrocarbons, DTO) will have to be done at a later stage.

The conventional approach to pumping would be the use of transport pumps (e.g. turbo-molecular pumps with an effective pumping speed of 250 m^3s^{-1}). With transport pumps, we pump indiscriminately the whole available gas mixture, hence we would exhaust ~ 25 Pa m^3s^{-1} of DT gas along with the ^4He. This ^4He-DT mixture would then have to be processed (i.e. ^4He separated from DT) and the DT fuel recycled to the reactor.

Alternatively, we may find a solution to process the mixture directly at the reactor exhaust with selective pumps removing ^4He and other impurities, thus making an external DT processing loop unnecessary.

Before proceeding further, we will summarise all requirements imposed on primary vacuum pumps either by the process itself or by the vicinity of the reactor:

- effective pumping speed ~ 250 m^3s^{-1}
- total pressure at pump inlet ~ 0.1 Pa, partial pressure of ^4He ~ 5×10^{-3} Pa, partial pressure of impurities (DTO, CO, CO_2, Hydrocarbons) ~ 1×10^{-3} Pa
- Outlet pressure (in case of transport pumps) ≧ 10 Pa at full throughput of ~ 25 Pa m^3s^{-1}.
- compatibility with Tritium, i.e. use of organic lubricants and organic electrical insulators inside the system is prohibited.
- compatibility with nuclear radiation; dose rates in the order of 10^8 Gray per annum near the reactor exhaust demand exclusive use of inorganic materials such as metals and ceramics.
- compatibility with static and dynamic fields: in the order of 0.1 Tesla or higher, such fields prohibit use of fast moving conductors (e.g. metal turbopump rotors, electrical drive motors), active magnetic bearings (turbopumps) and large cryopanels at 4 K due to eddy current heating.
- compatibility with mechanical shock; at the present state of reactor development occasional malfunctions cannot be completely ruled out:

plasma disruptions will impart accelerations in the order of ~ 100 m s^{-2} on the reactor vessel and closely coupled vacuum equipment.

- compatibility with up to air accidents: sudden venting of vacuum systems may happen (e.g. due to coolant pipe or vacuum line rupture). Vacuum pumps should be robust enough to withstand such accidents.
- the gases pumped by the vacuum system (primarily D-T and ^4He) should not be contaminated by vacuum pump media such as lubricants, operating fluids (vapours) or gases other than D-T and ^4He. Otherwise, the task of purifying and recycling of D-T to the reactor would become more complex.

2. Transport pumping to a remote processing plant

Under the term "transport pump" we understand a device, which compresses a gas mixture, ideally without affecting its composition, thus permitting its transport via lines of relatively small diameter over some distance to a suitable processing plant. This method is the most familiar and in present fusion experiments applied exclusively, using turbomolecular pumps [7]. Other well known transport pumps, mercury and oil diffusion pumps, can be fully ruled out because they contaminate the process both upstream and downstream with their operating medium to an extent which makes them unsuitable for fusion reactor applications.

2.1 Turbomolecular pumps in present fusion experiments.

Commercially available turbomolecular pumps are the primary high vacuum pumps in all present large fusion installations - JET in Europe, TFTR in the USA, JT60 in Japan. They have proven to work reliably and, with some minor modifications for Tritium containment and remote maintenance handling [10], [11], have been shown to meet fully the Tritium compatibility requirements during the final operating stage of JET [12].

All these present experiments, however, operate on a low duty cycle with maximum pulse times of 30 seconds (JET) and long intervals between pulses of typically 600 to 1800 seconds. Pumping speed requirements during pulses are nil (no closed fuel processing cycle required) and modest effective pumping speeds in the order of 10 $m^3 s^{-1}$ cover all the needs of wall conditioning and pumpdown to a low enough base pressure between pulses.

The situation in a fusion reactor system will be quite different: pulse times will be thousands of seconds, only interrupted by short dwell times of ~20 seconds. Consequently, the vacuum system at the front end of the fuel cycle will run at full throughput continuously.

2.2 Turbomolecular pumps in the fusion reactor scenario.

Whilst trying to achieve the high effective pumping speeds (at least 250 $m^3 s^{-1}$) as derived in chapter 1, we are faced with some rather unfavourable boundary conditions imposed by the close vicinity of the reactor: high nuclear radiation and high magnetic fields. The radiation severely limits the choice of electrical components (insulators), magnetic fields impede fast rotation. Both together hamper the implementation of advanced design concepts required for full Tritium compatibility: in order to avoid the use of organic lubricants one could develop turbopumps with magnetic bearings. The feedback control of active magnetic bearings required for accurate rotor positioning would be severely upset by external variable fields. Passive magnetic bearings required to bear the weight of the rotor could be built by using strong permanent magnets. However, suitable magnets for this application (e.g. Samarium-Cobalt) deteriorate rapidly in neutron radiation fields.

One can find a compromise by moving away some distance and by installing radiation and magnetic shielding between reactor and pumps, but only by paying tribute to the most basic law of vacuum technology:

$$\frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S} , \quad (1)$$

where S_{eff} is the effective pumping speed at the entrance of duct of conductance C with a pump of speed S installed on its exit.

To give an example (see ref [13]: under molecular flow conditions, a tube of uniform circular cross-section (diameter D[m], length L[m] has a conductance C $[m^3s^{-1}]$ for gas molecules with a mass M[amu] and a temperature T[K] of:

$$C = 38.1(TM^{-1})^{1/2}D^3L^{-1} \quad (2)$$

With M = 5 amu for DT, T = 300K, a tube of 1.36 m diameter and 10 m length has a conductance of 75 m^3s^{-1}. With a turbomolecular pump of 50 m^3s^{-1} at its end, we obtain an effective pumping speed of 30 m^3s^{-1}. We would need 8 such ducts to obtain the required pumping speed of 250 m^3s^{-1}. The actually installed pumping speed would be 400 m^3s^{-1}.

If we were to increase the duct length by 5 m in order to insert some radiation and magnetic shielding, the conductance of each duct would drop to 50 m^3s^{-1}. Hence, on the end of each of the 8 ducts we would have to install two turbopumps of 42 m^3s^{-1} pumping speed each instead of one with 50 m^3s^{-1} in the previous case. The pumping speed has nearly doubled by increasing the duct length by 50%.

This example clearly shows, that a future use of turbomolecular pumps will require substantial development of unit sizes over the present state of art (eg. from 3.5 m^3s^{-1} up to 50 m^3s^{-1}). In addition, since long ducts prohibit achievement of the required pumping speeds, such pumps would have to be compatible with nuclear radiation and magnetic fields. Hence, advanced technologies such as ceramic rotors and gas bearings and gas turbine drives have to be considered [14].

Such a development would have to be matched by a parallel and not less difficult task, the development of large all-metal valves. They are needed for isolation during maintenance and have to incorporate all the well known features of mechanical precision and sealing surface finish. And yet, such vacuum systems consisting, as described above, of multi-ton bakeable precision equipment will be expected to survive accidents like sudden venting or coolant pipe rupture in the reactor. It appears unlikely that large all-metal valves could close fast enough for pump protection without causing a destructive mechanical shock. Furthermore, these systems would still be so close to the reactor that full remote maintenance is required.

This situation certainly deserves some thinking about alternatives which are better compatible with the reactor environment and contain no or only slowly moving parts. They should not require large isolation valves, either by virtue of their inherent robustness or by use of new concepts employing small active pump modules in process loops.

2.3 Thermodynamic transport pumps

Pure thermodynamic effects, ie. interaction of molecules with suitably arranged inert hot and cold surfaces, or diffusion driven by a temperature gradient across a porous wall, are known to produce pressure differences in vacuum systems. Put to proper use, these effects may well be used to build actual vacuum pumps, both in the high and medium vacuum pressure range.

2.3.1 Thermodynamic pumping in the high vacuum range.

In 1970, Hobson described a Thermal Accommodation Pump [15] based on the effect that molecules thermally accommodate to surfaces and that their behaviour on impact depends on their velocity and on the surface quality:

- fast (hot) molecules hitting a smooth, cold surface are - particularly under small angles of incidence - reflected specularly.
- slow (cold) molecules hitting a smooth, hot surface are independent of the angle of incidence reemitted following the familiar cosine law.
- both fast (hot) and slow (cold) molecules are reemitted by surfaces rough on a molecular scale following the cosine law, independent of the angle of incidence.

These statements, an oversimplified summary of Hobsons careful and much more detailed study, explain pumping effects in systems containing dissimilar surfaces at different temperatures.

Hobson demonstrated the viability of this concept by building a 28 stage accommodation pump. The 28 active stages consisted of smooth Pyrex glass tubes being connected in series by 28 "decoupling" stages consisting of roughened (leached) Pyrex glass. This pump, half immersed in LN_2 (ie. operating in a temperature gradient between 77 K and 300 K) yielded a compression ratio of 23.3, ie. about 1.1 per stage.

Following his basic observations, we conceived arrays suitable for large pumping speeds. In the process, we got rid of the main encumbrance of his device. By using individual heat sources and heat sinks for each stage, we avoid the decoupling stages (required in a design using one common heat source and heat sink), which lead to unnecessary conduction (pumping speed) losses.

As a consequence, our devices require only hot-rough and cold-smooth surfaces. "Hot" molecules, thermally accommodated to hot surfaces and emitted following the cosine law, re-accommodate to cold surfaces, but with a certain degree of specular reflection, giving rise to transport phenomena in suitable geometries.

Two possible configurations are shown in Fig 2:
Smooth-cold and rough-hot surfaces are arranged such that molecules are preferably transported in the indicated flow direction, following the reflection laws outlined above.

A single-stage model featuring the basic geometry, has been shown to work in a proof of principle experiment, (ref. Fig.3): A diaphragm with a slit (10 mm wide, 200 mm long) separates two volumes V_1 and V_2 of a vacuum chamber. A tape heater (19 mm high, 200 mm long) is arranged perpendicular to the diaphragm underneath the slit. A plate 20 mm below the diaphragm completes two rectangular ducts on either side of the heater tape. Diaphragm and lower duct plate are kept at room temperature by water cooling, the heater tape can be heated up to 900 K. These ducts and the heater surfaces are the areas of importance for the pumping effect: the heater "accelerates" particles by thermal accommodation, the cool duct walls permit some degree of specular reflection of "hot" particles, thus molecules are preferentially pushed into the lower chamber.
An adjustable gas flow Q can be directed either into the upper volume V_1 or the lower volume V_2, which is pumped with a turbomolecular pump of 110 ℓs^{-1} pumping speed. The pressures P_{11} (pressure in V_1, flow into V_1), P_{12} (pressure in V_1, flow into V_2) and P_2 (pressure in V_2) are measured with capacitance manometers (gas independent)

Note: in equilibrium for a given flow Q the pressure P_2 in V_2 is the same for either gas inlet location, only given by

$$P_2 = \frac{Q}{S_{eff}} \qquad (3)$$

This setup permits measurement of the two parameters, by which any transport pump can be fully characterised, ie. its forward conductance c_f and its reverse conductance c_r. As a consequence of the second law of Thermodynamics, c_f and c_r can only be different from each other when we feed energy into a system from outside, ie. rotate a turbo pump, form a steam jet in a diffusion pump or, in our case, heat the tape heater. In equilibrium, ie. once the gas flow Q and the pressures are constant, we obtain:

Gas into V_2 : $P_{12} c_f - P_2 c_r = 0$ (4)

Gas into V_1 : $P_{11} c_f - P_2 c_r = Q$ (5)

Equation (4) gives directly the ultimate compression ratio γ (no net flow across the device):

$$\gamma = \frac{c_f}{c_r} = \frac{P_2}{P_{12}} \tag{6}$$

Equations (4) and (5) together yield:

$$c_f = \frac{Q}{P_{11}-P_{12}} \tag{7}$$

$$c_r = \frac{Q}{P_{11}-P_{12}} \frac{P_{12}}{P_2} \tag{8}$$

Results for the compression ratio achieved for various gases with the heater temperature held constant at about 800 K are shown in Fig 4.

The results show, that this device - just like the turbomolecular pump - works in the molecular flow regime up to a pressure limit where the mean free path becomes smaller than the heater/duct dimensions or, in case of the turbopump, the rotor/stator blade size. Due to its "striking" similarity with the turbo-molecular pump - molecules are struck and accelerated by moving rotor blades respectively hot surfaces and their kinetic energy thus gained is eventually converted to potential energy (pressure) by reaccomomodation to the stator blades, respectively cold surfaces - we prefer to call this device Thermomolecular Pump (with due apology to J P Hobson, who called his demonstration device Thermal Accommodation Pump).

A further similarity between thermo- and turbomolecular pumps is a substantially higher compression ratio for the heavier gases (see Fig. 4).

With the knowledge of c_f and c_r from our single stage experiment, we can derive the corresponding $C_{F,n}$ and $C_{R,n}$ for a pump with n stages. This can be derived by mathematical induction from a case where we know the result: if we connect a number N of turbomolecular pumps in series, each one containing a number n of identical stages, we know that the pumping speed of this series is independent on N, i.e.

$$C_{F,N-1} - C_{R,N-1} = C_{F,N} - C_{R,N} = C_{F,N+1} - C_{R,N+1} \tag{9}$$

This being valid for any number N, it is also valid for the number n of stages in each element of the series, i.e.

$$C_{F,n-1} - C_{R,n-1} = C_{F,n} - C_{R,n} = C_{F,n+1} - C_{R,n+1} \tag{10}$$

This being valid for any number n, we can reduce n to 1 and obtain

$$C_{F,n} - C_{R,n} = c_f - c_r = c_f(1-\gamma^{-1}) \tag{11}$$

where γ is the single-stage compression ratio of equation (16).

We further know, that the compression ratio $C_{F,N} : C_{R,N}$ of a series of N pumps is equal to the N-th power of the compression ratio of individual pumps. This applies also to the number n of stages within each individual pump, i.e.

$$\frac{C_{F,n}}{C_{R,n}} = \gamma^n \tag{12}$$

Equations (11) and (12) together yield

$$C_{F,n} = c_f \left(\frac{1-\gamma^{-1}}{1-\gamma^{-n}}\right) \tag{13}$$

$$C_{R,n} = c_f\, \gamma^{-n} \left(\frac{1-\gamma^{-1}}{1-\gamma^{-n}}\right) \tag{14}$$

In vacuum technology, one usually defines a "pumping speed at zero pressure", which is the volume displacement per unit time without compression, in our case:

$$S_{o,n} = C_{F,n} - C_{R,n} = c_f(1-\gamma^{-1}) \tag{15}$$

Equations (15) and (12) show, that the main development aim should be directed towards improving the single-stage compression ratio, e.g. an improvement of γ from 1.1 to 1.2 increases the pumping speed for the same inlet area by a factor of ~ 2 and simultaneously reduces the number of stages for the same compression ratio also by a factor of ~ 2.

When we actually use the pump in a system with inlet pressure P_{in} and foreline pressure P_{out}, we obtain the mass flow Q through the pump:

$$Q = C_{F,n} P_{in} - C_{R,n} P_{out} \qquad (16)$$

This is valid throughout the molecular flow regime, i.e. as long as c_f and γ are independent on pressure. If we were to use a multi-stage pump near its limit in the transition flow regime, we would have to resort to a stage by stage analysis based on a complete set of data for c_f and c_r as a function of pressure in order to obtain a self consistent set of values for Q, P_{in} and P_{out}. Based on results from our single-stage experiment (we have e.g., measured for Deuterium at 4×10^{-1} Pa values of c_f=19,2 ℓ $cm^{-2}s^{-1}$ and c_r = 16,7 ℓ $cm^{-2}s^{-1}$) we can expect a pumping speed of 2.5 ℓ cm^{-2} s^{-1} for geometries shown in Fig 2. This means that 5 pumps with ~2m^2 inlet area each and 50 stages (which gives a pump height of ~1m if we would build it with a single stage height of 2cm) would be sufficient as primary pumps for our process, yielding a compression ratio of ~100.

Power consumption of such a pump can be roughly estimated:
If we assume a thermal emmissivity of ε=1 for the hot surfaces at 800K and of ε = 0.1 for cooled surfaces at 300 K we obtain a radiative heat transfer of ~ 250 kW (total hot surface area ~ 100 m^2). Operated with Deuterium at an average pressure of 1 Pa, we obtain an additional conductive loss of ~ 250 kW. The total power input of ~ 500 kW requires a cooling water flow of ~ 5 ℓs^{-1} (ΔT ~ 20K) to hold the cooled surfaces at 300 K. In comparison, present state-of-art turbomolecular pumps would require roughly 10 kW electrical power

for an equivalent pumping speed, but their inherent fragility (a single defective rotor blade destroys the complete pump) makes reliable operation near the reactor doubtful.

In contrast, a thermomolecular pump is very robust (failure of a single heater affects pump performance only marginally) and hence can be placed directy at the reactor exhaust. With its compression ratio of ~ 100, we can achieve substantial improvements in duct dimensions, e.g. a diameter reduction by a factor of two and a simultaneous increase in length by a factor of ten (eq (2), chapter 1). Downstream of this duct we can then use processing equipment not subjected to nuclear radiation and magnetic fields with drastically reduced remote handling requirements.

2.3.2 Thermodynamic pumping in the forevacuum range

If one has to operate above the foreline pressure limit of the thermomolecular pump, which, for reasons of feasible mechanical structure sizes (again not unlike turbopumps) will be near 10 Pa, there is another thermodynamic principle at hand to cover the pressure range of 10 to 1000 Pa.In this pressure range, conventional vacuum systems usually employ roots blowers (see e.g. ref [13], p215) to bridge the performance gap between high vacuum (turbomolecular) pumps and rotary vane pumps.

The application of pure thermodynamic pumping principles (inert materials, no moving parts) can be extended to higher pressures by using the Knudsen effect [16]. Its principle is shown in Fig 5:

Two volumes V_1 (at temperature T_1, gas density n_1, pressure P_1) and V_2 (with T_2, n_2, P_2), are separated by a porous wall subjected to the temperature gradient $T_1 \rightarrow T_2$. The size of the pores is such that, for the gas densities regarded, molecular flow conditions obtain throughout the wall. In equilibrium (ie. all quantities constant), an identical flow of molecules passes the wall in opposite directions, ie. $Q_1 = Q_2$. Under these conditions, we know from dynamic gas theory [16]:

$$Q_1 = Q_2 \rightarrow \quad n_1 \cdot \sqrt{T_1} = n_2 \cdot \sqrt{T_2} \tag{17}$$

$$P_1 \propto n_1 \cdot T_1 \tag{18}$$

$$P_2 \propto n_2 \cdot T_2 \tag{19}$$

Hence:
$$\frac{P_2}{P_1} = \frac{\sqrt{T_2}}{\sqrt{T_1}} \tag{20}$$

This has again been tested in a proof of principle experiment in the apparatus of Fig 3, using a layer of alumina granulate (grain size 0.35 mm) as porous wall, with room temperature on one side and ~800 K on the other side. Compression ratios of ~1.4 for H_2, D_2 and He and of ~1.15 for Ar and N_2 at an operating pressure of 10 Pa (mean free path ~1 mm) were achieved.
The effect is not far from the one predicted by dynamic gas theory (1.63 from equation (20)for $T_1 = 300$ K, $T_2 = 800$ K) for the gases we have to pump, such as Hydrogen, Deuterium, Helium. The good agreement is possibly due to their high thermal conductivity, which permits build-up of the temperature gradient across the porous wall. Without any further improvements, this scheme would already permit a compression ratio near 10 for only six cells in series. The upper pressure limit is inversely proportional to pore size. In an optimised device we would have to reduce the pore size by one order of magnitude for each decade in pressure. The technically achievable pressure limit may be somewhere near 1 kPa corresponding to a pore size of 10 µm. At this pressure range, dry mechanical pumps can take over if required by the process.
It should be further noted that such "Knudsen Effect Pumps" with their high compression ratio for the light gases ideally complement the Thermomolecular

pumps discussed in chapter 2.3.1, which exhibit a preference for the heavier gases.

The power consumption of a 12-stage Knudsen effect pump with 2.5 m^3s^{-1} pumping speed at 10 Pa would be about 500 kW (rough estimate from the proof of principle experiment). If connected close to the thermomolecular pump, such a Kundsen effect pump would permit removal of subsequent process equipment (purification, waste treatment) as far as ~ 100 m away from the rector with a duct diameter of less than 0.5 m.

The above examples show the potential of thermodynamic pumping principles for fusion applications, where their rather low efficiency from a viewpoint of pumping capacity versus power consumption is more than compensated by their inherent robustness and compatibility with the unfriendly reactor environment. They would, however, like turbopumps, still leave the effluent processing task to a remote plant.

3. Selective storage pumps - processing in situ.

Selective pumps may be used to perform the effluent processing near the reactor. In contrast to the transport pumps discussed in chapter 2, selective pumping effects are based on physical and/or chemical properties of the gases pumped. Hence they exhibit a preference for certain gases and pump others to a negligible extent. The gases pumped are stored in this type of pumps and, depending on the pumping mechanisms, can be either recycled or stay permanently pumped. Examples for such storage pumps are:

- Cryocondensation pumps use the physical properties of the gases pumped. A cold surface inside a vacuum system reduces the partial pressure of gases to their vapour pressure at the temperature of the cold surface. For example H_2O can be pumped by surfaces cooled with LN_2 (77K), all gases except ^3He

and ^{4}He are pumped by surfaces cooled with LHe (4.2K). All pumped gases are released when the cryosurface is warmed up. Since these pumps do not pump ^{4}He, they are unsuitable as actual primary pumps on the reactor. They would also pose a substantial Tritium release hazard: during one hour of operation of our model reactor they would store 40 moles of DT containing 120 g or 1.2 x 10^6 Cie of Tritium.

- Ion getter pumps can be modified such, that they do not pump Hydrogen isotopes, but impurities including Helium, which meets exactly our requirement.
- Chemical (volume or Titanium sublimation) getter pumps remove all chemically active gases including hydrogen, but they do not pump noble gases, and chemically rather inert gases like Methane only with low efficiency. Some of these pumps are still quite attractive due to the fact, that they pump hydrogen at reasonable temperatures (300 to 600K) and permit its recovery at higher temperatures, but retain pumped impurities like H_2O, CO, CO_2.

The two latter types of pumps will be discussed in more detail.

3.1 Modified ion sputter pumps for Helium and impurity removal.

Some 10 years ago [17] the author was faced with the following problem:
A sealed 14 MeV neutron generator tube was designed, containing 2000 Cie (0.75 Std ℓ) of Tritium and the same amount of Deuterium (0.75 Std ℓ). This generator used the mixed beam technique: 200 keV D^+ and T^+ ions bombarded a target and produced 14 MeV neutrons via the fusion reaction with the D/T implanted in the target by the ion beam. The ion source was supplied by DT from a Uranium bed, the DT recycled from the target was pumped by a regenerable Zr-Aℓ getter cartridge (discussed in chapter 3.2).
The ion beam had to be kept free from impurities to minimise target ablation by sputtering.

An analysis showed, that the Zr-Aℓ getter was capable of pumping all impurities normally encountered in a well conditioned UHV system. In this particular case, however, comparatively large quantities of Helium were released: a continuous influx of ^{3}He from the Tritium decay (2.76×10^{-7} Pa m^{3}s^{-1}) and ^{4}He during generator operation (3.7×10^{-8} Pa m^{3}s^{-1}). This He gas load, neither pumped nor retained by either Zr-Aℓ getter or Uranium bed, would have led to a large pressure rise (~ 10^{-5} Pa s^{-1}) in the sealed system. Hence, a pump was required compatible with the sealed vacuum system (UHV, no moving parts) to remove Helium from a DT gas mixture. The solution was found in modifying an ion getter pump. These pumps usually employ Titanium alloy cathodes and pump chemically active gases including Hydrogen on a continuously produced (by sputtering) fresh getter film. They also pump noble gases by burial underneath sputtered cathode material.

In order to avoid pumping of Hydrogen isotopes, we replaced the Titanium cathodes in a standard triode ion getter pump (Varian [18]) by Iron. This material has no chemical affinity to Hydrogen, low solubility and a high diffusion coefficient for Hydrogen [19]. Hence, DT pumped by burial immediately diffuses back to the vacuum system whereas Helium stays buried. Furthermore, this pump was found to pump impurities like CO, CO_2 and Methane, as Carbon and Oxygen are chemically retained in the sputtered Iron film. With the addition of this pump, we had a vacuum system for the DT neutron generator (ref. Fig 6) featuring all the basic requirements of a fusion vacuum system:

- pumping and purification of DT with a regenerable volume getter;
- compression of DT (for ion source feed) by recycling the volume getter to a Uranium bed;
- Helium removal by an Iron sputter pump. This device also supported the volume getter in pumping other impurities as well.

Quantitative measurements of the pumping speed of Iron sputter pumps for Helium and typical impurities (CO_2, air, H_2O, CH_4) in the presence of a 0.1 Pa Hydrogen partial pressure are presently being prepared at JET.

Lacking these quantitative data, we estimate that for direct Helium and impurity removal at the reactor exhaust we may require between 25 m^2 and 250 m^2 of active module area for the required pumping speed of 250 m^3s^{-1}. The upper limit of 250 m ould result in a system too large to consider, but even with 25 m^2 as the design goal, the range of pumping speed required would still be so large (250 m^3s^{-1}) in comparison with present state-of-art pump unit sizes (up to 1 m^3s^{-1}), that the standard technical approach will be no longer viable: it makes no sense, neither technically nor economically, to envisage individual conventional pump units (comprising the usual inlet flange, housing, feedthrough and magnet). This appears even more prohibitive by the need for remote refurbishment of spent units, with a life expectancy of 1000 to 2000 hours.

As a consequence, we have to design the active component - the array of sputter cathode and inner/outer anode - as a relatively cheap and discardable unit, remotely inserted into a reusable pump housing, comprising all permanent features. Please note a further deviation from the design of standard ion getter pumps: in conventional triode pumps, the pump housing itself serves as outer anode. In our particular application it appears preferable to make the outer anode, containing the bulk of collected impurities, as part of the discardable submodule. In doing so, we also reduce Tritium permeation drastically, as the outer anode is subjected to a substantial flux of energetic neutrals produced by charge exchange on the sputter cathodes. A non negligible fraction of Tritium, if implanted in a single-walled pump housing would permeate to the ambient atmosphere.

The basic design of such a system is shown in Fig 7: A pump unit containing up to 15 submodules of 0.1 m^2 effective area each, is equipped with vacuum lock facilities to replace individual submodules on-line. The submodules consist only of cathode/anode arrays (with the necessary stand-off insulators); they are, once in the actual pump module, provided with electrical energy via suitable feedthroughs and contact rails. Reciprocating push-rods move the submodules in turn from the feed station to the dump station. This system is based on state of the art mechanical components for in-vacuo manipulation (standard linear motion feedthroughs). Also electrical feedthroughs and reliable all-metal gate valves of the sizes required are readily available.

The problem of residual Tritium in discarded units can easily be solved by subsequent heat treatment at very high temperatures in a vacuum furnace. If necessary, they could even be melted down, thus permitting 100% Tritium recovery and compact disposal of activated materials. Such auxiliary recovery systems can be permanently installed as part of the process line.

3.2 Volume Getters - reversible pumping for D/T, irreversible pumping for DTO/CO/CO_2.

Even in case of direct Helium and impurity removal at the reactor exhaust, we may still require large pumping speeds for D/T:

- to help flushing out the ^{4}He ash, in particular since the gases in the reactor exhaust are in the viscous flow regime (duct diameter 150 cm, mean free path at 0.1 Pa is ~ 10 cm)
- to achieve plasma density control, ie. to pump away D/T or to resupply it (properly purified) as required for reactor operation,
- to achieve fast pumpdown between reactor pulses - a short dwell time being essential to minimise thermal cycling fatigue for all core components

(first wall armour, blanket, vacuum vessel). This could well lead to higher than presently anticipated pumping speed requirements, in particular if D/T is only slowly desorbed from internal walls.

As in the D/T neutron generator, the ideal pumping method for this purpose appear to be the volume getter systems.

Such pumps, presently used inside the TFTR vacuum vessel [20] for plasma density control, are particularly suited for regenerable Hydrogen (D/T) pumping. They are, however, vulnerable to excessive (irreversibly pumped) impurity loads, which eventually lead to saturation (further reactivation no longer possible), and to excessive Hydrogen inventories, making the getter alloy flaking off its substrate (formation of metal hydrides causes volume expansion of the getter material). Getters well suited for Hydrogen pumping and purification are the binary alloy Zr-Al and the ternary alloy Zr-Va-Fe, known under the manufacturers brand names ST 101 and ST 707 [21].
For reasons of their vulnerability mentioned above, volume getter pumps should be isolated from the reactor, whenever large and "dirty" gas loads have to be handled, ie. during venting, first pumpdown, bakeout, and wall conditioning by Glow Discharge Cleaning. We should therefore use the elegant design features offered by this pumping method: volume getters only need the appropriate temperature environment for their different operation modes:

- pumping : ST 707 300-500 K; ST 101 500-700 K
- D/T recycling : ST 707 ~ 700 K; ST 101 ~ 800 K
- activation : ST 707 ~ 800 K; ST 101 ~ 1000 K

This means (assuming the use of ST 707), we should keep the reactor pumping chamber at 500 K and transport modules as required to recyling or reactivation chambers at 700 K, respectively 800 K, ie. using a process loop rather than individual pumps. Such a system is shown in Fig 8, its main element, the passive (discardable) pump module in Fig 9.

It is clearly evident, that this approach would offer the following advantages:

- flexible pumping speeds, proportional to the number of modules in the pumping chamber.
- economy, since the (consumable) modules contain no temperature control devices, and consist basically of shaped sheet metal.
- full compatibility with the reactor environment with all-metal, only slowly moving modules in critical areas; the more complex reprocessing stations and transport mechanisms can be located at any suitable distance.
- the getter modules can be completely removed and isolated from the reactor during venting, first bakeout and wall conditioning.
- only few and small valves would be required.

As in the case of the modular Iron sputter pump, there appear no major mechanical design problems for relatively slow motions in vacuo - the individual modules pass through the pumping chamber within ~ ½ h. Residual Tritium can be recovered by high temperature treatment (including meltdown if required) in a vacuum furnace downstream of the disposal valve.

4. Combinations of Transport - and Selective Pumping Principles

By a suitable combination of transport and selective pumps we can achieve high pumpings speeds for both ^4He and DT and simultaneously separate ^4He from DT. We have applied this method recently in a leak detection system [22]: We connected a turbomolecular pump with a pumping speed of 0.1 m^3s^{-1} and a compression ratio of 1000 to the JET torus. On its foreline, we connected a mass spectrometer and an ST707 volume getter pump with 1 m^3s^{-1} pumping speed for Deuterium. Thus, we obtained in the mass spectrometer a ^4He partial pressure of ~ 1×10^{-4} Pa (~ 1×10^{-7} in the torus) and a D_2 partial pressure of ~ 2×10^{-6} Pa (~ 2×10^{-5} Pa in the torus).

We can apply the same method in large fusion vacuum systems (ref. Fig 10):

- we connect a thermomolecular pump with 250 m^3s^{-1} pumping speed and a compression ratio of 100 directly to the reactor exhaust.
- this transport pump is followed by a volume getter system with 250 m^3s^{-1} pumping speed. In this first pumping chamber, we now have a ^4He partial pressure of 0.5 Pa in a background of 0.1 Pa DT.
- we repeat this process once more with a transport pump of 2.5 m^3s^{-1} and a volume getter system of 25 m^3s^{-1} pumping speed, and obtain ^4He at 50 Pa in a DT background of 1×10^{-2} Pa.
- we finally can remove ^4He together with 200 ppm DT via a mechanical pump and remove the DT in a subsequent getter bed.

This example shows how combinations of transport and selective pumps can be used to design vacuum systems which perform a major part of the reprocessing task.

5. Appendage pumping for diagnostic instrumentation

So far, we have discussed solutions for the main reactor vacuum system. However, there will be unavoidably a certain number of small auxiliary vacuum systems connected to the reactor vessel. These auxiliary systems are usually isolated from the reactor during certain operation modes such as maintenance, bake-out and wall conditioning. They are necessary to maintain vacuum in instrumentation for measurement and control of plasma parameters, or to maintain a guard vacuum, typically in secondary containments of power (RF,DC) or mechanical feedthroughs.

To reduce the complexity of such auxiliary vacuum systems, we propose the following approach:

- all auxiliary systems should use individual volume getter pumps (see chapter 3.2)
- if necessary, such pumps can be supplemented by Iron sputter pumps as described in chapter 3.1., to pump noble gases and other inert impurities such as methane.
- roughing resp. recycling of D/T (by heating the volume getter) is to be done through the main vacuum system at suitable occasions, eg. during reactor roughing resp. bakeout or standby periods.
- in order to minimise proliferation of control systems, the Iron Sputter pump should be used for pressure monitoring.

Following this proposal, we will be able to install compact and reliable auxiliary vacuum systems with a minimum hazard of Tritium release.

Summary

We have tried to demonstrate, that faced with a new challenge on a scale as grand as controlled thermonuclear fusion, we should not react by merely scaling up available vacuum technology, nor should we try to find one unique solution for all aspects of the problem. Much critical thought is essential - and it is the main purpose of such exotic proposals as thermodynamic pumping and selective "ash" removal to provoke further thought - to meet the complex requirements of this new challenge in a flexible, efficient and economical way by combinations of suitable modular approaches and implementation of modern production line techniques.

However, no matter how impressive such new technology may appear, we should not overlook the turbomolecular pump. It is the best UHV pump presently available and will retain its niche in fusion technology, if not in the frontline, ie. directly at the reactor exhaust, then still in very important functions, like pumpdown, bakeout, wall conditioning and standby. The turbopump is ideally suited for these operation modes since they require pumping speeds of only 50 m^3s^{-1} total. This pumping speed can be achieved by present technology with a modest development effort towards full Tritium compatibility and reasonable unit sizes in the order of 5 to 10 m^3s^{-1}.

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References

[1] P H REBUT et al., The JET Project, EUR 5516e, Commission of the European Communities, Luxembourg 1976, p.2.

[2] Ref [1], p.28.

[3] R. BUENDE, Evaluation of the Energy Required for Constructing and Operating a Fusion Power Plant, Proc. 12th SOFT, Juelich, Germany, Vol.2, p.837, 1982, Pergamon Press, Oxford.

[4] D V BARTLETT et al., Energy Confinement with Ohmic and Strong Auxiliary Heating in JET. Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, Japan, Nov. 1986, paper A-II-3, IAEA-CN-47.

[5] Ref [1], p.4.

[6] K J DIETZ, K SONNENBERG, Impurity Control in JET, Bulletin APS, Vol. 30, No.9, 1985.

[7] E USSELMANN et al., Vacuum System and Wall Conditioning in JET. Proc. 13th SOFT, Varese, Italy, Vol 1, p.150, 1984, Pergamon Press, Oxford.

[8] O GRUBER et al., ASDEX Upgrade - Startup and Operation, in "Tokamak Start-up", ed. H Knoepfel, 1985, Plenum Press, New York.

[9] R W CONN, Tokamak Pump Limiters, J. Nucl. Mat 128 and 129 (1984), p.407.

[10] D G GOETZ, Turbomolecular Pump for Use on Plasma Fusion Experiments. Proc, 12th SOFT, Juelich 1982, Vol 1, P 285, Pergamon Press.

[11] K ABBEL, J HENNING, H LOTZ, New Turbomolecular Pumps for Application with Radioactive Gases, eg. Tritium.
Vacuum, Vol 32, Nr 10/11, P 623, 1982.

[12] R LAESSER, K -H KLATT, D TRIEFENBACH, J L HEMMERICH.
Tritium Compatibility Measurements of Turbomolecular Pump Oil in a Miniaturised Viscosimeter. J Nucl Materials, to be published.

[13] A ROTH, Vacuum Technology, 2nd ed., 1982, North-Holland, p.84.

[14] Y. MURAKAMI et al., Performance Test of a Ceramic Rotor Developed for Turbomolecular Pumps for Fusion Use. J. Vac. Sci. Technol. A, to be published.

[15] J P HOBSON, Accommodation Pumping - A new Principle for Low Pressures
J Vac Sci and Technol, Vol 7, p 351, 1970.

[16] M KNUDSEN in: R W POHL, Einfuehrung in die Physik, Der Knudsen Effekt, Vol 1, p 301, § 177, 13th ed. 1955, Springer.

[17] J L HEMMERICH, work on 14 MeV Neutron Generator Vacuum Systems at The Cyclotron Corp., Berkeley, California, 1976/77, unpublished.

[18] VARIAN ASSOCIATES, Catalogue 1975, section on "Ion Getter Pumps", Palo Alto, California, USA.

[19] H WENZEL, KFA Juelich, private communication, 1976.

[20] B FERRARIO, M BORGHI, J CECCHI, J SREDNIAWSKI, Response of Zr-Al Getter Material to the Anticipated TFTR In-Torus Environment, Proc 11th SOFT, Culham 1980, Vol 1, p 375, Pergamon Press. and:
J L CECCHI et. al., Initial Limiter and Getter Operation in TFTR, J. Nucl. Materials 128 & 129, p1, (1984).

[21] Up-to-date information on the getter systems ST 101 and ST 707:
SAES GETTERS S.p.A., Via Gallarate 215, 20151 Milan, Italy.

[22] T WINKEL, J L HEMMERICH, Helium Leak Detection in JET in the Presence of High Deuterium Partial Pressure.
J. Vac. Sci. and Technol. (A), to be published.

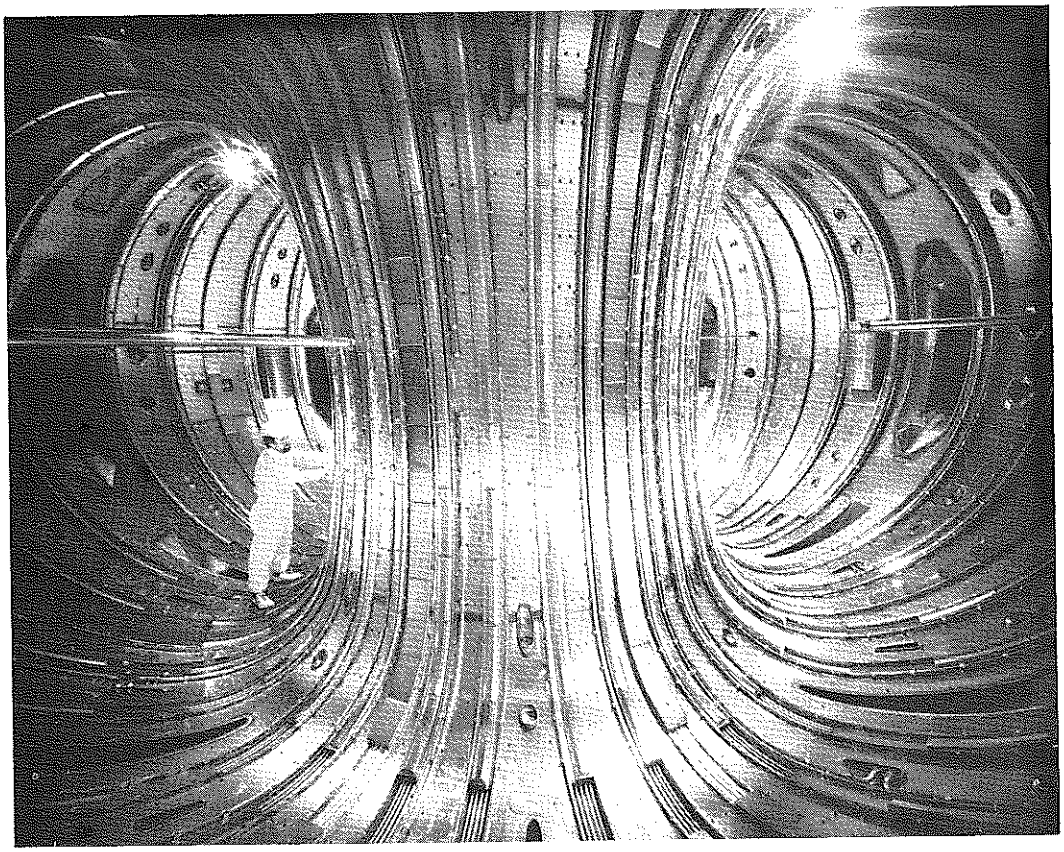

Fig.1 The JET vacuum vessel; apart from a somewhat larger size, a fusion reactor vessel may look quite similar.

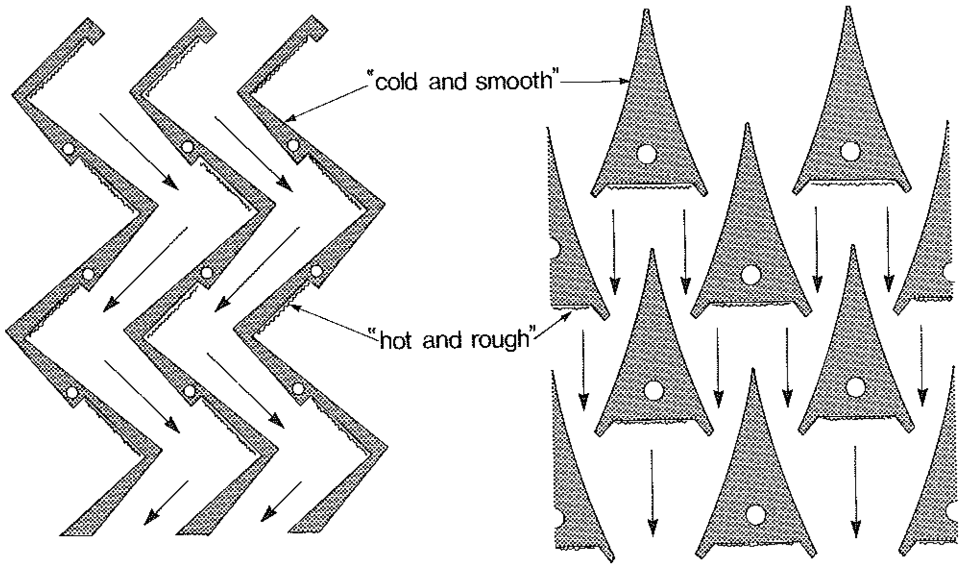

Fig.2 Thermomolecular pumping arrays, offering ease of scaling to large pumping speeds and adequate compression ratios. They can be built from simple extrusions. A wide variety of shapes is possible, optimisation will have to be based on an interactive development by experiment and Monte-Carlo methods.

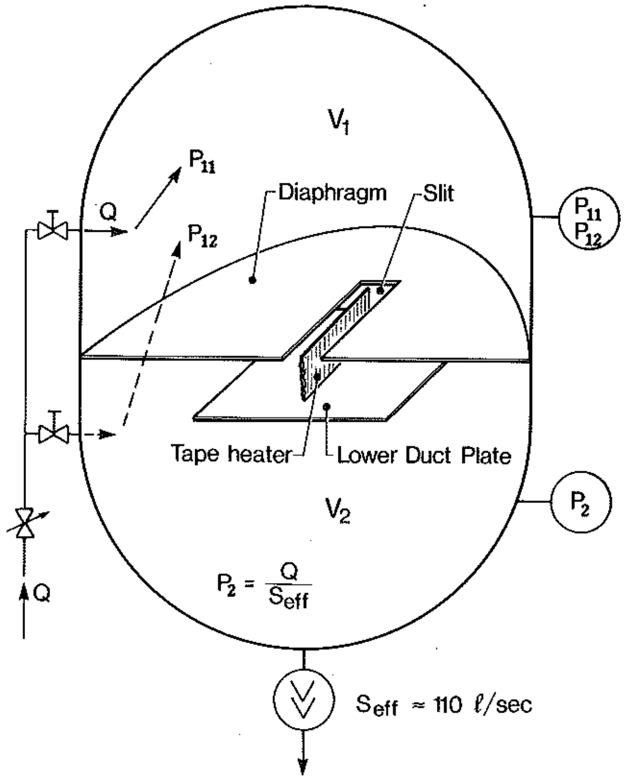

Fig.3 Thermomolecular pump, proof of principle experiment for a single stage.

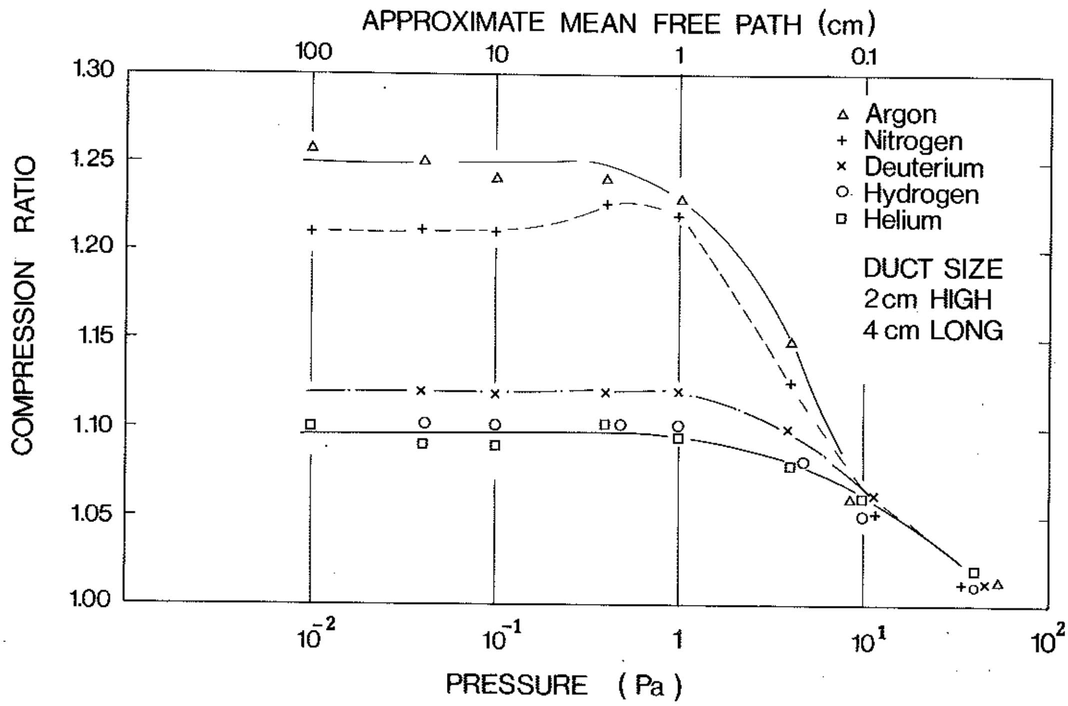

Fig.4 Compression ratio for single stage thermomolecular pump as function of pressure for various gases. The heater tape used was graphite at ~900K, the cold surfaces at ~300K were copper with no special surface treatment.

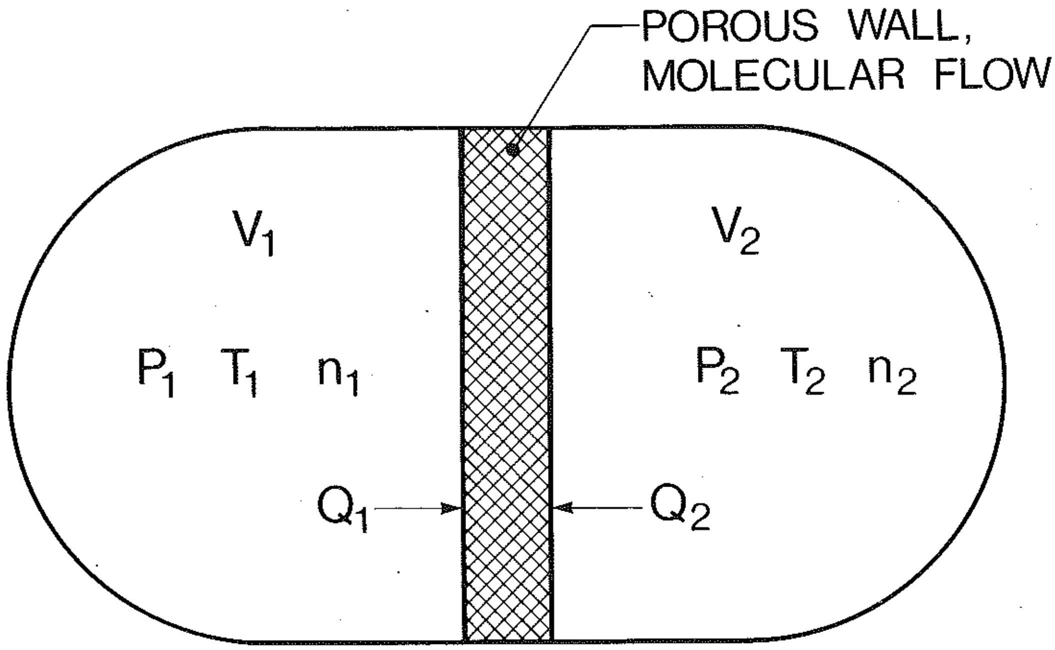

Fig.5 Knudsen effect, principle; the equilibrium condition $Q_1 = Q_2$ yields $P_1 : P_2 = \sqrt{T_1} : \sqrt{T_2}$ (see text)

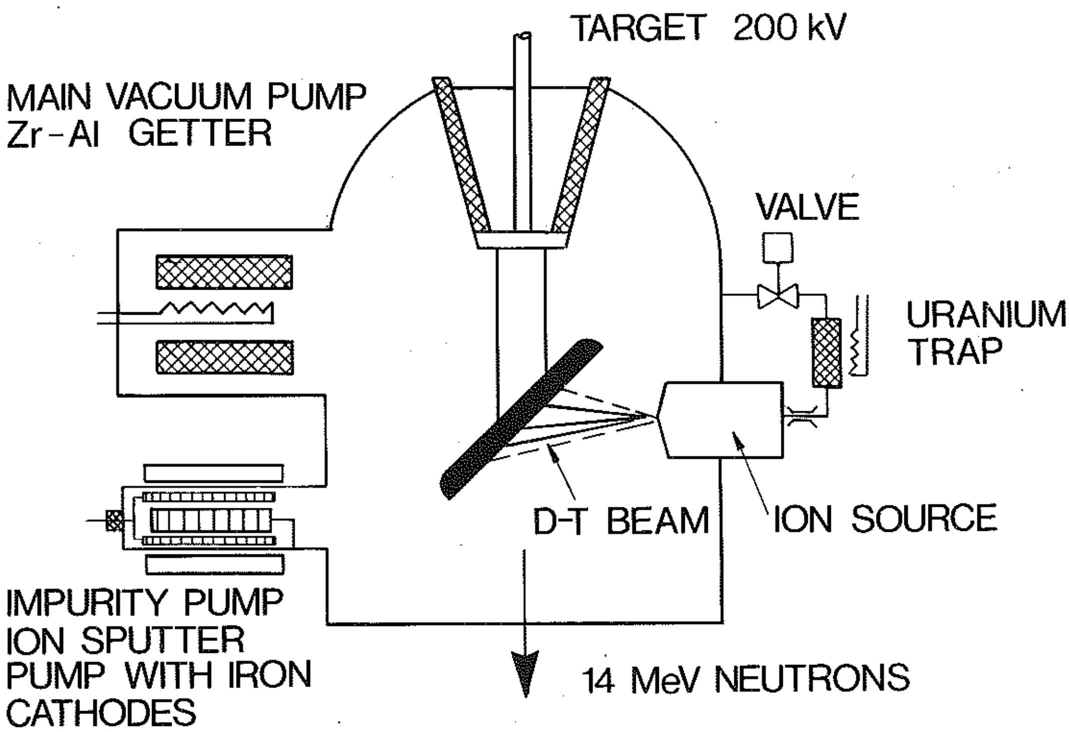

Fig.6 Vacuum system for D/T neutron generator with D/T vacuum pump (ST 101 getter) recycled to a compression stage (Uranium trap). Impurity removal, mainly ^3He and ^4He, via Iron Sputter pump. Pressures resp. flow rates are controlled via getter temperatures, using the sputter pump as the only instrumentation on the system.

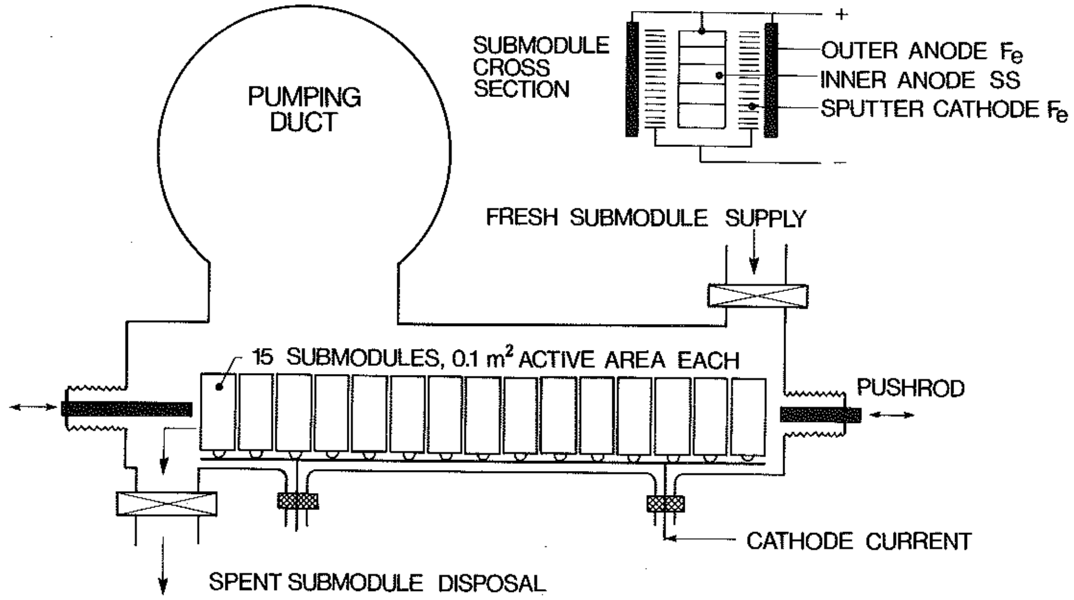

Fig.7 Iron sputter pump for selective removal of ^{4}He and other impurities, featuring remote unit replacement by use of production line techniques. A common external permanent magnet (not shown) provides the magnetic field.

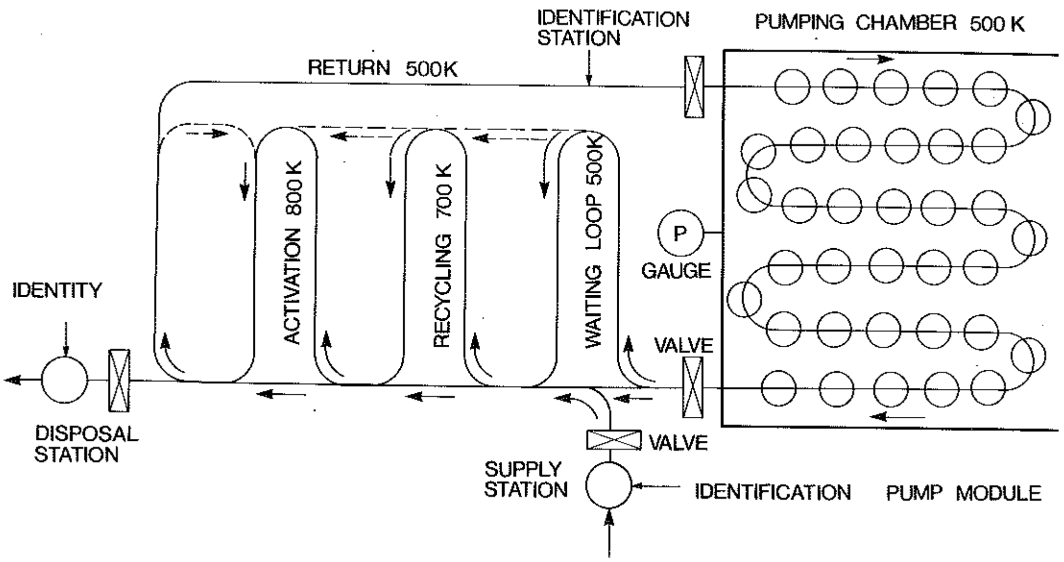

Fig.8 Modular volume getter system with external reprocessing facility; after passing the Pumping chamber, the modules are guided through processing loops according to their time/pressure/temperature record.

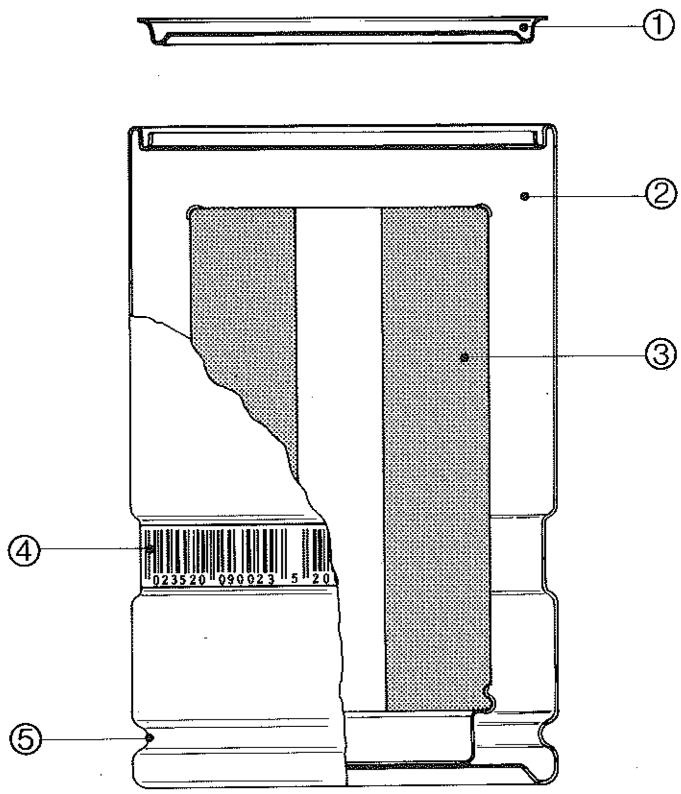

Fig.9 Volume getter module, shown in a design for direct process application inside its shipping container (2), which protects the getter cartridge (3), confines debris in case of getter flaking and carries a 'Supermarket' style identity label (4). A groove (5) near the bottom assists handling, e.g. during removal of lid (1).

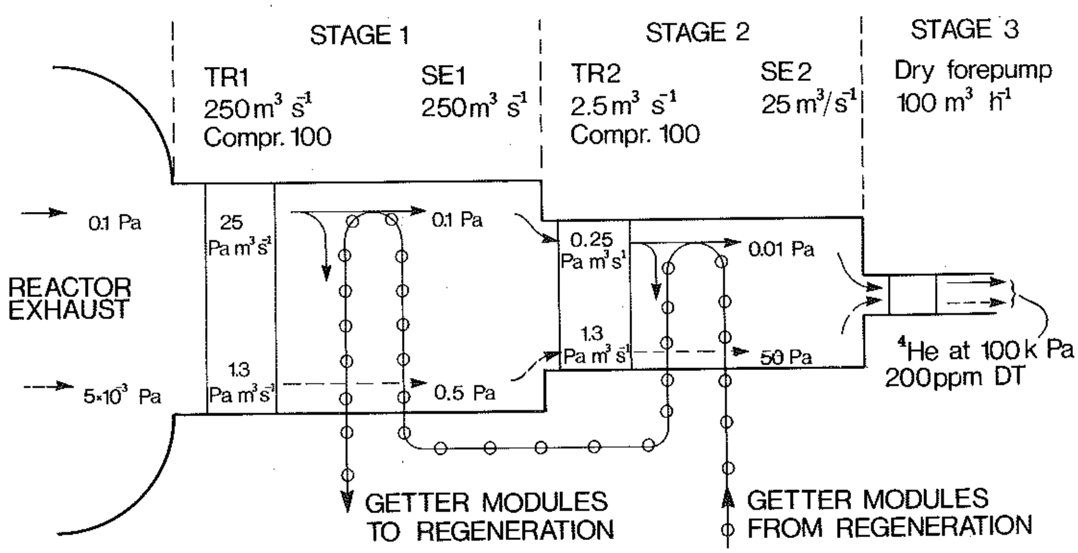

Fig.10 Example for a cascade of transport pumps (TR1, TR2) alternating with selective pumps (SE1, SE2), separating DT and ^4He. This particular configuration would deliver ^4He at 1 bar with 200 ppm DT. Due to only 1% DT capacity loading in SE2, the modules would first pass through SE2, then through SE1. External process loop as shown in Fig.8.