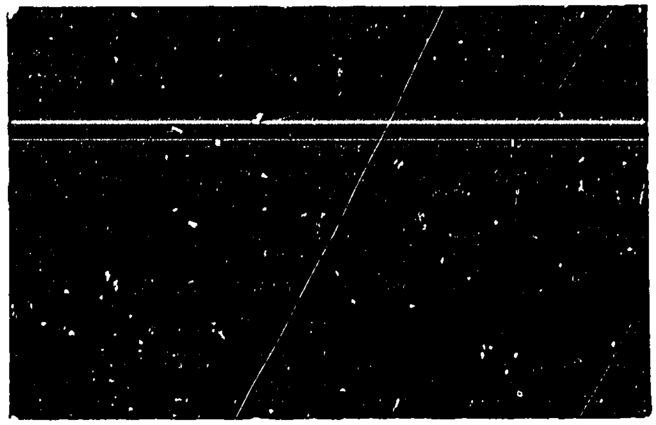
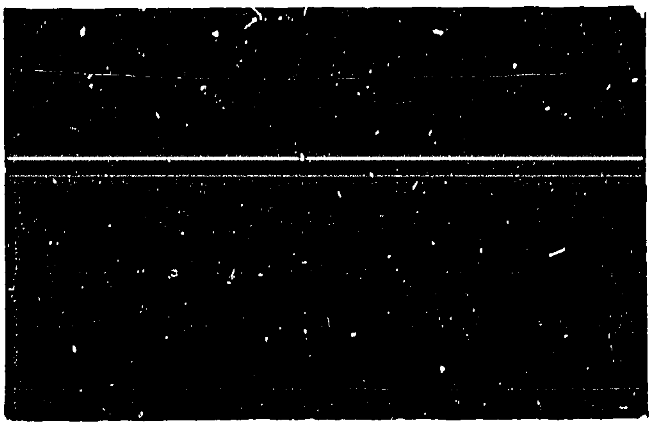
Canadian Fusion Fuel Technology Project





THE CANADIAN FUSION FUEL TECHNOLOGY PROJECT REPRESENTS PART OF CANADA'S OVERALL EFFORT IN FUSION DEVELOPMENT. THE FOCUS FOR CFFTP IS TRITIUM AND TRITIUM TECHNOLOGY. THE PROJECT IS FUNDED BY THE GOVERNMENTS OF CANADA AND ONTARIO, AND BY THE UTILITY ONTARIO HYDRO; AND IS MANAGED BY ONTARIO HYDRO.

CFFTP WILL SPONSOR RESEARCH, DEVELOPMENT, DESIGN AND ANALYSIS TO EXTEND EXISTING EXPERIENCE AND CAPABILITY GAINED IN HANDLING TRITIUM AS PART OF THE CANDU FISSION PROGRAM. IT IS PLANNED THAT THIS WORK WILL BE IN FULL COLLABORATION AND SERVE THE NEEDS OF INTERNATIONAL FUSION PROGRAMS.

Remote Handling Needs

Of The

Princeton Plasma Physics

Laboratory

Report # F82002

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Report of the Canadian Fusion Fuels Technology Project Remote Handling Task Force

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

1. EXECUTIVE SUMMARY

This report is the result of a Task Force study commissioned by the Canadian Fusion Fuels Technology Project to investigate the remote handling requirements at PPPL and identify specific areas where CFFTP could offer a contractual or collaborative participation, drawing on the Canadian industrial expertise in remote handling technology. The five man Task Force was drawn from Canadian industries which have high technology engineering resources and have made a commitment to support the Canadian fusion program.

The Task Force reviewed four areas related to remote handling requirements; the TFTR facility as a whole, the service equipment required for remote maintenance, the more complex in-vessel components, and the tritium systems.

The focus of attention has been given to the remote maintenance requirements both inside the vacuum vessel and around the periphery of the machine. These are identified as the principal areas where Canadian resources could effectively provide an input, initially in requirement definition, concept evaluation and feasibility design, and subsequently in detailed design and manufacture. The strategy for this involvement centers around the attachment of a core group of four specialists to the TFTR Remote Handling Group to investigate the remote handling requirements, evaluate concepts, define the chosen design, and provide the close liaison with PPPL subsequently required for the detailed design and manufacture of the equipment using Canadian industries with developed expertise in remote manipulator systems.

In the overall facility supportive requirements are identified in such areas as the mock-up facility, and a variety of planning studies relating to reliability, availability, and staff training. Specific tasks are described which provide an important data base to the facility's remote handling requirements. Canadian involvement in these areas is suggested where expertise exists and support for the remote handling work is warranted. Reliability, maintenance operations, inspection strategy and decommissioning are suggested for study.

Several specific components are singled out as needing development. The Toroidal Pumped Limiter for TFET is the most complex component. The design of this component to be serviceable from outside the vacuum chamber

would yield considerable benefits in machine availability. The feasibility study for this concept is proposed in parallel with the remote handling work, and would be within the capability of the same core group. Other items such as carbon tile fasteners, diagnostic drive mechanisms and antenna deployment devices are also possible work areas.

The tritium system components which are identified as requiring work are the puffer valve, the electrolysis cell for tritiated water processing, tritium area monitors, and the tritium purification system. Analysis of on-site inventories, releases and dispersion are also required. Most tritium work is beyond the mandate defining the Task Force, and some of the items are already under consideration through other CFFTP resources. The puffer valve is recommended for further development.

The Task Force found excellent opportunities to utilize the Canadian remote handling expertise and firmly recommends to CFFTP that the manipulator requirements at PPPL be pursued with Canadian participation.

2. INTRODUCTION

The Task Force has been constituted by the Canadian Fusion Fuel Technology Project (CFFTP) to report on the remote handling development and engineering needs at the Princeton Plasma Physics Laboratory (PPPL) on the Tokamak Fusion Test Reactor (TFTR) and the upgrade Tokamak Fusion Engineering Test (TFET) project. The basis of the appraisal was one three-day visit to PPPL during which discussions were held with a number of scientific and technical personnel. This resulted in interviews with specialists intimately involved in one or more of the major disciplines of management, science and technology. Each was a specialist in some aspect of the TFTR project and represented many man-years of experience specific to this machine. A list of the personnel and their areas of expertise is given in Section 7.1. The Remote Handling Workshop held at PPPL in July 1981, and a number of technical publications including the TFET proposal published in April 1982 provided background information.

The mandate of the Task Force was to:

(a) appraise the current and near-term engineering, technology and development needs of TFTR and TFET in the area of remote handling,

(b) identify specific areas where CFFTP could offer contractual or collaborative participation.

The Task Force looked at four areas in order to structure a comprehensive view of remote handling needs. These areas were; the overall facility including such topics as the mock-up facility, planning studies, machine availability and staffing; the service equipment including all manipulator requirements, inspection, leak detection, and repair devices; the machine components including fasteners, connectors, the vacuum vessel, the toroidal pumped limiter, diagnostics and RF heating; and tritium processes including valves, handling, purification and storage systems, and detectors.

As expected, the remote maintenance equipment itself provided the most direct opportunities for channelling the expertise represented by the Task Force. The other areas provided specific additions to the list of possible involvement areas, but more importantly, identified other work which has an important bearing on the development of remote handling. The intent to maintain a broad vision while focussing on the specific remote maintenance equipment thus resulted in a better understanding of interactive priorities and requirements.

The report briefly describes the TFTR and TFET projects in Chapter 3, in areas relevant to the Task Force mandate, without attempting to duplicate information available in technical publications and the TFET proposal. Chapter 4 outlines the concept, development, and design needs of TFTR and TFET centered around remote handling and including peripheral areas where the Task Force felt interaction might be beneficial or necessary. Chapter 5 summarizes the recommended action CFFTP could take to best meet the needs of those items where specific Canadian expertise exists.

The members of the Task Force were drawn from Canadian industries which have experience and expertise in the areas of remote handling and equipment design, and which have demonstrated an interest to support the development of fusion engineering in Canada. Section 7.2 provides a brief description of the companies represented.

3. BACKGROUND

3.1 Tokamak Fusion Test Reactor (TFTR)

The primary objectives of the TFTR are the generation and confinement of 5-10 keV reactor-grade plasmas in the tokamak magnetic-field configuration and the production of fusion energy on a pulsed basis from the reaction of deuterium and tritium. The TFTR will be used to study the physics of burning plasmas and the engineering aspects of a D-T burning tokamak operating with reactor-level plasma conditions. The overall TFTR program is intended to produce scientific and technical information, component hardware, and the design, construction and operating experience necessary for the future design, construction and operation of experimental fusion power reactors.

The design and construction of TFTR is a cooperative United States effort among scientists and engineers from government, national laboratories, industry and academia.

Ebasco, Inc., a nuclear engineering firm, has been awarded the prime industrial contract for engineering, design, procurement and installation activities, especially those related to the tokamak system, electrical power system and experimental area systems. Ebasco, and their major subcontractor, Grumman Aerospace Corporation, are working as a team to provide the project management, engineering, procurement, assembly and installation associated with these systems.

TFTR is the largest fusion facility currently under construction in the U.S. First plasma is scheduled at the end of 1982, and assuming that the upgrade Tokamak Fusion Engineering Test (TFET) is approved, will be operated in a series of increasingly complex modes until about 1986. Between 1987 and 1988 the machine will be operated without tritium to allow tritium activity and neutron activation to reduce to a level where the TFET modifications can be made to the machine without general need for remote handling.

Ohmic heating and diagnostics will be implemented during 1983. Neutral beam injection will begin in 1984, and full power capability will be reached in 1985. The tritium systems will be operational in 1985 and first tritium on site is planned for mid 1985. Tritium will be first used in the machine in 1986, with the remainder of that year devoted to increasing levels of D-T operation. Remote handling of in-vessel components will be required by the end of 1986. Prototype ICRF heating will be demonstrated in 1986 and 1987 in preparation for use in TFET. The machine cooldown period of 1987 to 1988 will be used to develop the physics and engineering parameters needed for TFET operation. Dismantling of the TFTR machine will commence in 1988. First plasma for TFET is planned for 1989.

The TFTR machine is currently being assembled in the Test Cell. All major machine components have been manufactured and operational tests are proceeding in parallel with the assembly. Auxiliary systems such as control, vacuum, cooling and power are being commissioned. All systems necessary for first plasma will be interactive before the end of 1982.

The vacuum vessel is 304LN stainless steel, approximately 7.5 meters across and 2.2 meters high, assembled in 10 segments containing a total of 14 inconel bellows and approximately 250 ports with bolted and gasketted flanges. The vacuum vessel is assembled by bolting and seal-welding one segment at a time, each segment installed with two toroidal field coils fitted precisely against the central support column. The vacuum vessel is designed to operate in the range of 10^{-9} Torr.

In-vessel components consist of protective plates, bellows cover plates, bumper limiters, neutral beam armour, inspection devices and diagnostics. A total of several hundred devices will be installed inside the vacuum chamber. Designs for all of these devices exist and will be manufactured as their need in the experimental program warrants. Diagnostic devices enter the vacuum vessel through the smaller ports, usually bellows coupled to permit insertion and extraction without compromising the vacuum.

Remote handling of in-vessel components is required for the following reasons:

(a) neutron activation,
(b) tritium contamination,
(c) weight of components,
(d) difficulty of access,
(e) demonstration of remote handling capability.

For TFTR, some of these reasons will not become critical until a number of years into the experimental program. Some can be satisfied by other procedures such as plastics for tritium contamination, lifting fixtures for heavy components and clean room procedures for contamination reduction.

TFTR will not be activated until about 1986, and then only to modest levels. However, the demonstration of remote handling capability is essential in order to confidently design equipment for upgraded facilities, where engineering and machine performance are gaining increasing prominence.

The tritium system for TFTR must be capable of handling and storing approximately 5 grams of tritium. The tritium will be used once only, then collected, measured and analyzed and returned to the supplier for purification. Currently licensed depleted uranium containers will be used to transport the tritium and similar vessels will be used for on-site storage.

The tritium system includes facilities for extracting the tritium from the shipping containers, analyzing the tritium for purity, contaminants and other characteristics, injecting precise quantities into the vacuum vessel and removing and processing the residue.

The tritium handling system has been manufactured and tested with hydrogen and deuterium. Tritium tests will not be performed until tritium is accepted on site in 1985.

3.2 Tokamak Fusion Engineering Test (TFET)

TFET is an upgrade of TFTR proposed to extend the capability of TFTR and provide a more complete and extensive development of both the physics and the engineering needed for the next generation Fusion Engineering Device (FED). The objectives of TFET are to:

(a) Demonstrate reliable high-level deuterium-tritium operation and perform experiments utilizing the fusion products.
(b) Demonstrate remote handling of tokamak components.
(c) Demonstrate long-pulse energy and particle control and plasma handling in a highly-conductive vacuum vessel.
(d) Demonstrate ICRF heating in a large D-T tokamak.
(e) Provide a facility to demonstrate current drive as an approach to steady-state tokamak operation.

The upgrade facility will require a new vacuum chamber, with different port arrangements and assembly technique. Bellows will be eliminated and bolted sections with seal welding will be designed. Other major equipment that will be required include the ICRF antennae and power system, a toroidal pumped limiter, reliable and capable remote handling equipment, additional shielding around the machine and the test cell, an on-site tritium purification system, and a site capability for tritium inventory increased from about 5 grams to about 50 grams.

All major TFTR coil systems, structures and auxiliary systems will be reused, with appropriate changes, where necessary, to achieve the goal of 20 to 30 second pulses.

The cost of the TFET upgrade is estimated at U.S. $300 million. Design and fabrication of various systems will commence in 1983. Assembly of the upgrade machine will be done in 1988 and 1989 with first plasma planned for the end of 1989. The scientific and engineering developments will be undertaken over the span of about 5 years after which the facility would be decommissioned, or a further program proposed.

The TFET has been planned to fulfill an important role in the development of fusion in the scientific and technical area between the capabilities of TFTR and FED. The TFET proposal has been submitted to DOE, and funding of the project is expected to commence in 1983 for concept work and 1984 for commitment of capital expenditures. TFET will represent a significant upgrade of TFTR capability, while efficiently utilizing much of the existing equipment and services. Concept designs exist for all major new equipment and systems. Concept analysis, preliminary and detailed design and manufacture is required in most cases.

The major design parameter in the TFET vacuum vessel is the elimination of bellows. A segmented vacuum vessel with bolted and seal-welded joints is proposed, with some analysis required to consider an all-welded construction. Cutting and rewelding an all-welded vessel might prove prohibitively difficult, especially since the operation would have to be performed remotely. The flange arrangement will be different from TFTR, and will require generally more large ports, particularly for the toroidal pumped limiter and the ICRF antennae. The possibility of using a tracked in-vessel manipulator will require the feasibility analysis of a suitable track and its effect on the port geometry.

In-vessel components consist of basically the same equipment as TFTR with some very significant additions in the form of ICRF antennae, toroidal pumped limiters and protective tiles without backing plates in the area of the neutronics experiments. All of these devices require some preliminary design appraisal, firming of specifications and detailed design. Some specific items like the carbon tiles without backing plates will need development of fastening methods.

The high power operation of TFET will make remote handling devices essential for more of the machine components and surrounding equipment than previously conceived for TFTR. Also, the TFET upgrade will have as one of its goals, the development and demonstration of remote handling technology for use in the fusion engineering demonstration machine to follow.

There are a number of reasons for remote handling of in-vessel components. These are:

1. Avoiding the high man-rem penalty due to activation products in the machine components.
2. Avoiding the potential hazard and operating difficulty of hands-on maintenance of tritiated components.
3. Reducing in-vessel contamination by excluding personnel.
4. Retaining the options of cover gas use or isolation of the in-vessel atmosphere during maintenance or repair operations.
5. The weight and complexity of some components would require mechanical aids even with hands-on maintenance.

Unlike TFTR, when TFET begins operation, the activation product induced radiation levels will quickly reach levels which will make hands-on maintenance difficult and expensive. A reliable, proven remote handling system will therefore be required from the start of TFET construction so that maintenance operations can be commissioned before the machine is activated.

Two remote handling systems are required, one that can enter the vacuum vessel to service the in-vessel components, and one that can reach specific equipment surrounding the machine.

A number of concepts exist for each system. Basically, the in-vessel manipulator can follow one of two philosophies. The first is a boom attached to a suitable carriage that approaches the vessel at one of the large ports. The boom enters the vessel through the port opening, extends unsupported along the vessel centreline to the work area, then performs the required function either totally unsupported, or aided by one or more extendable supports.

The boom of the remote handling system must be capable of entry into the vacuum vessel from two ports approximately, but not necessarily exactly, 180^{0} apart on the torus. That means that the reach of the manipulator will have to be somewhat greater than 90^{0}, say 120^{0}, which is equivalent to about 6 meters along the axis of the vessel. In addition to that, about 3 meters minimum is required to pass between two toroidal coils and through the entry flange. Thus a nominal 10 meter reach is required for this device.

The second concept is a device which is deposited into the vessel through the same port and proceeds to the work area by continuous support from the vacuum vessel, either from permanent tracks, temporary support pads or wheeled guidance mechanisms.

The maximum weight of the heaviest component will be about 800 pounds. Since interfacing fixtures will probably be required during replacement operations, the arm capacity must be greater. 1200 pounds has been chosen as the design capacity.

The remote handling of the out-of-vessel components will take advantage of an existing bridge crane which can position a remote handling system above most work sites. The manipulator will be suspended from the bridge, with a number of degrees of freedom, and will have generally high lifting capacity as well as dexterity to be able to service both heavy and complex components. Possibly additional facilities will be required to reach the equipment beneath the machine.

A final design must be adopted in order to incorporate the remote handling requirements into the machine components. A dexterous manipulator, which could function as the end effector for both the in-vessel and bridge mounted manipulators, has been purchased and will undergo evaluation.

A remote handling group has been defined in the TFET proposal which will start to work on concepts of the remote manipulator system, the control and visual systems needed to operate the equipment, possible mock-up areas where maintenance tasks can be programmed and rehearsed and a variety of planning, operations and availability studies.

Considerable concept work has already been completed on a number of options, and the dexterous manipulators on site will be considered for integration into the remote handling system. The work remaining is to coordinate all the in-vessel component requirements and reduce the maintenance equipment options to one set of design specifications, then proceed with detailed design and development of the maintenance system.

Most of the work should be completed in the next three years so that a prototype machine can be made available around 1986.

TFET will require about an order of magnitude greater tritium inventory than TFTR, with commensurate increases in handling capacity. This will necessitate increases in on-site storage, a larger and perhaps more precise injection system, and on-site purification. The on-site purification of the used tritium will be preferred to reduce the otherwise frequent shipments of tritium between PPPL and the supply source. Other system components, such as secondary containment, may need upgrading. With the larger on-site quantities, the reduction of in-process inventory may be important. Considerations of release, safety, dispersion, and accounting may also require more study.

An on-site tritium extraction system for the tritiated water of the clean-up system is being studied. This would reduce significantly the volume of low activity waste and specifically liquid waste which requires expensive disposal.

An important parameter of any tritium system is the amount of tritium in the process at any one time outside of the storage containers. Since the integrity of any process system cannot be absolute, the less tritium is available for dispersion the easier it will be to stay within the site operating limits, or regulatory guidelines. This aspect of the TFET tritium system may benefit from further design. Similar priorities apply to individual system components, particularly valves.

When the vacuum vessel is accessed for maintenance or repair, a procedure of regulated air flow will be utilized to reduce tritium escape to the test cell. Nevertheless for major opening of the vacuum vessel such as would be needed during the in-vessel manipulator use, a localized portable containment system might be required.

Tritium contributes to the inaccessibility of the machine and as such, affects the remote handling requirements. Other than that, the storage, processing and use of tritium will not require remote maintenance above that already contained in system components like glove boxes.

4. TFTR/TFET REQUIREMENTS

The primary goal of the Task Force was to determine the remote handling needs at PPPL. In order to place the requirements in the proper context with other scientific and technical undertakings, the Task Force investigated four major work areas. These were:

(a) The Facility as a whole which included such items as planning, machine availability, staffing and decommissioning.

(b) The Service Equipment, defining all remote maintenance and inspection devices.

(c) The Machine Components, concentrating mainly on in-vessel equipment, and

(d) The Tritium Process including transport, storage, injection, containment and decontamination.

Programs for both TFTR and TFET were considered, with emphasis placed on those tasks where Canadian expertise and industrial resource already exists. Therefore, this outline of requirement is not all-encompassing. Rather, some prejudgement was exercised by the Task Force in dealing with only those tasks within the remote handling and equipment design resource capabilities of CFFTP participating companies.

A further selection from this list is made in the following chapter to take into account a rational involvement strategy within the guidelines suggested by international collaboration agreements, resource limitations and contractual expectations.

4.1 Facility

The overview of the facility requirements in remote handling resulted in the identification of the mockup facility as being a central element in the maintenance system, useful for development of the handling equipment, the machine components and the procedures, ranging from feasibility analysis to operations planning. The other topics in this section pertain to studies, analyses and personnel training, all in support of remote handling, either as a lead-in to determine design parameters, or as a follow-on to set operating guidelines.

4.1.1 Mockup System

A full scale mockup exists of approximately 90° of the TFTR. Only the vacuum vessel is functional, the remainder of the major components are modelled in general shape only. This mockup has been used to develop some access specifications, port geometry and in-vessel components. With the addition of more of the minor components, this facility could be used to develop the remote handling system concept. Because the vacuum vessel is a functional model and dimensionally accurate, the mockup facility would allow remote handling technique development and testing.

A mockup area exists beside the test cell with crane rails similar to the test cell, although continuity with one crane is not feasible. Ample space is available for the mockup arrangement, plus a second mockup of the TFET vacuum vessel.

The mockup system for TFET could be expanded to allow computer programming of maintenance sequences. The use of a mockup system would add reliability to any maintenance operation on the machine, as well as reduce access time with the associated savings in downtime, contamination and tritium release.

Since one of the important missions for TFET is to develop remote handling techniques and systems, a fully instrumented mockup system would be useful in remote handling development in its own right.

A mockup system capable of being used to develop component access and location has been identified as required. The same facility will be used to develop and rehearse remote handling procedures. A definition study is required to evaluate the various uses of the mockup system, and to determine what degree of similarity and complexity is required. A cost-benefit analysis to aid in defining the mockup limits is needed to firm up the design specifications.

4.1.2 Machine Availability

Since neither TFTR nor TFET will be operated as a power-producing device, machine downtime does not have the same financial and service penalties that apply to power reactors. However, the capital cost of the equipment, the large scientific and technical staff and the need to fulfill an ambitious program of experiments and development still demand considerable attention be given to the maximizing of machine availability.

The parameters that will affect availability are:

(a) Component and System design,
(b) Component and System reliability,
(c) Routine maintenance planning,
(d) Repair and modification planning,
(e) Training, simulation and mockup facilities,
(f) Availability of expertise,
(g) Availability of spare components,
(h) Remote handling system.

The machine components for TFTR have been designed primarily to meet technical and scientific requirements, with a reasonable amount of attention paid to accessibility, reliability and remote handling. The TFET system will require more attention to the remote handling aspects with need to develop fasteners, modular system and other aids to increasing availability. A comprehensive analysis of all the parameters making up machine availability would be a significant aid in planning operation, maintenance and repair strategy, as well as defining manpower, equipment and facility requirements.

4.1.3 Planning Studies

A project of the scale of TFTR requires coordinated planning at project, system and sub-system levels. The organization structure at PPPL is working well and achieving the necessary management, scientific and technical goals, with good interaction between these disciplines. A shortage of specific engineering skills, and the priorities placed on scientific goals has left some technical sub-systems in need of attention in order to provide the necessary inputs to the remote handling systems planning. Some of these specific topics are:

(a) Reliability analysis of machine components,
(b) Remote handling requirements,
(c) Tritium release and dispersion estimates,
(d) Machine availability and utilization,
(e) Operating and maintenance strategies,
(f) Decommissioning procedures,
(g) Resource allocation.

It is appropriate that some of these topics await the funding decision for TFET, as the upgrade planning would require considerably different approaches to such topics as remote handling, tritium and resource allocation. As soon as the overall project plan is approved, some of these sub-systems will receive attention during the initial years of TFTR operation and TFET design.

4.1.4 Staffing and Training

The staff complement at PPPL has had the benefit of several machines developed, designed, built and operated over a number of years. This has evolved personnel skills in most of the areas necessary to undertake the TFTR program. In addition, both specialists and skilled manpower have been drawn from a variety of industries for tasks ranging from planning through development to system commissioning. The substantial size of the PPPL total undertaking has afforded good continuity of skills and provided the technical and scientific challenges to attract good people.

A number of areas have remained sparsely attended due to various combinations of priorities, budgets and available expertise. Some of these areas are:

(a) Remote handling systems technology,

(b) Tritium release and atmospheric dispersion,

(c) Innovative mechanical equipment design.

PPPL has set up a management system which can provide both administrative guidance and technical direction in the selection of priorities. When the machine becomes operational, this requirement will be even more important and will require careful priority identification of scientific achievement, technical requirements and operations constraints. The management system will need access to skilled staff, hence will need to undertake training programs to augment the availability of personnel by contracting or staff attachments. Advance planning of these requirements will greatly facilitate achieving the operating goals set for the facility.

The benefits of staff attachments to PPPL are fully recognized. This process is used frequently in all three areas of management, science and technology. Ample sources of attached staff exist both from industry and other fusion facilities permitting PPPL to be selective and demand high levels of expertise and experience. Any attachments, therefore, will have to be of a high caliber, as well as addressing a specific and important need at PPPL.

TFTR/TFET ranks among the prominent fusion facilities in the world and its operating plan will undoubtedly maintain it in that role. Currently, the selection criteria for staff attachment is such that the qualifications and scope of work must be equivalent to those that would be required if the candidate were being hired permanently for the same purpose.

4.2 Service Equipment

During the first four years of operation of TFTR, hands-on maintenance will be possible, although not always desirable. When tritium is introduced, and the neutron activation of the machine components begins to build up, increasing reliance will be necessary on remotely servicing in-vessel components, and to a lesser degree, the multitude of devices surrounding the machine proper.

In more advanced machines such as TFET, all of the in-vessel routine maintenance and repair will have to be done remotely, and many of the diagnostic devices, the neutral beam systems, tritium systems and other components on the near periphery of the machine will also require remote handling.

The motivation to develop remote handling systems at this point are:

(a) Develop equipment and procedures for remote handling for the point in time when remote operations will be necessary on TFTR and TFET.

(b) Develop and demonstrate remote handling systems and remotely serviceable components for the ultimate application in fusion power reactors.

(c) Facilitate the safe and clean handling of in-vessel components especially those that are heavy or bulky.

The development of service equipment requires, at least to some extent, that the machine parameters are firmed, including such items as access, components to be serviced, fastening systems, and connections. In a highly physics-oriented facility, the freezing of machine design parameters is a difficult task, since the state-of-the-art is continually advancing, and the machine must be at the forefront of existing concepts and thinking. Nevertheless, such commitments are essential if the machine is to be built at all, let alone on schedule and within budget.

Princeton's remote handling conceptual design work was reviewed in 1981 at a remote handling workshop, where a number or recommendations and observations were made, some conflicting, indicating further concept review is required. Due to changes in TFTR priorities, much of this evaluation work remains outstanding and will now be undertaken under TFET funding, taking into account the added needs of the upgraded facility.

The program for remote handling on TFET will be developed in parallel with the concept and detailed design of the vacuum vessel and the in-vessel components. This will allow the necessary interaction between the machine design and the remote handling system design to optimize both the equipment and its means of servicing and repair.

Extensive use of a mockup will be incorporated into the design phase to allow development and optimization of concepts. It is very necessary to check out each remote operation using mockup hardware to build up confidence in the component design, the handling equipment and the operator skills. This mockup system will be most useful throughout the design phase of the equipment and it will continue to be a valuable facility for remote handling development in its own right, as well as the developing and proving of unscheduled repair techniques.

The TFET remote handling plan identifies the need for three types of remote handling -

(a) scheduled maintenance,
(b) unscheduled maintenance and repair,
(c) contingency operations.

The first two tasks will be thoroughly developed and the handling capabilities will be integrated with machine design. There are a few major contingency operations, such as a sector replacement, which will be given conceptual feasibility analysis, but may require further development of equipment or procedures at the time of need.

The general strategy of maintenance needs definition and a firming of requirements. This work should be closely allied with machine availability studies and equipment reliability analysis.

The overall concept of remote handling includes two basic units - an In-Vessel Manipulator (IVM) for working inside the vacuum vessel and a Bridge-Mounted Manipulator (BMM) working outside the vacuum vessel. These two units, aided by handling fixtures, television systems and computer controls will cope with all remote handling tasks.

The current concepts for both the IVM and BMM tend to a philosophy of directly replacing human capabilities with robot devices. A commercial dual-arm manipulator module has been acquired for evaluation consisting of two dexterous arms. Its application is planned for both the IVM and BMM in a way which would minimize the need for special fastener devices on the machine components and its use would emulate the capabilities of humans with hand tools. As remote handling techniques develop, the design could be optimized to take advantage of the non-human capabilities of remote handling systems such as simultaneous insertion of sets of fasteners, continuous rotation of wrist members, and greater force, weight and accuracy ranges. Early concept trade-off studies should be used to investigate which philosophy will yield the greatest return on the investment for remote handling development.

4.2.1 In-Vessel Manipulator

Two concepts have been considered for the In-Vessel Manipulator:-

(a) A cantilevered arm which reaches in through a port with a 3 manipulator module at the end containing two dexterous arms and one power arm (studied by Grumman Aerospace).

(b) A self-propelled 3 manipulator pack which is placed on tracks within the vacuum vessel (studied by Westingnouse Hanford).

The Grumman concept was favoured for TFTR. However, with the changes for TFET which simplify the vacuum vessel design, the track concept will be reconsidered. Both concepts have one short power arm for manoeuvring the in-vessel components into position and two identical "dexterous" manipulators for inserting fasteners and operating service tasks.

Neither the cantilever or track concept has been taken beyond the feasibility study phase, but more work has been carried out on the cantilever than the track design concept in establishing overall system configuration, working envelopes and dynamic analyses.

The concept work was supported by detailed analyses for each maintenance task. The Grumman study clearly established a working concept, but it was not apparent that the concept had been further evaluated to optimize manipulator configurations or to determine fully operational scenarios for lighting, viewing, access, etc.

The TFTR machine design has been completed with remote handling feasibility taken into account. The TFET machine design will be completed with more thorough interaction with handling system capabilities, since the remote maintenance requirements will be much more demanding. Therefore, the concept evaluation of the remote handling system will be undertaken as soon as the TFET project funding is assured.

Dexterous master/slave manipulators are commercially available devices with relatively low development requirements for specific applications PPPL has purchased a TOS manipulator for evaluation. The current philosophy behind operation of the dexterous arms is direct replacement of man, which leads to the arm gripping a hand tool to manipulate nuts and bolts.

It is unlikely that commercial hardware exists in a suitable configuration for the power arm requirements. Joint design may require development in order to produce a sufficiently high torque and compact configuration for the IVM application. The ability to feel force and maintain compliance is state-of-the-art. For the dexterous manipulator, there is a choice between replica control and joystick control. An evaluation study is required to assess the best mode for this application.

The design of the transport boom needed to deliver the manipulator with tools and components into the vacuum vessel will depend on the choice of IVM concepts, either cantilevered or tracked. If the cantilevered system is adopted, the transport boom will have a horizontal plane joint configuration. The joints must be capable of holding the combined weight of manipulators, components, handling devices, tools, etc., and would approach 2000 lbs. The compliance of the arm would be a very important design parameter. Torsional loads will also be applied, their extent depending upon applied manipulator torque and whether stabilization braces are used. Such a design is undoubtedly within the state-of-the-art but will not be an off-shelf item. The torsional loads in particular will require careful design of the transport boom joint and computer programmed compensation at the working end to prevent contact with the vacuum vessel.

With the TFET changes in vacuum vessel design, and significant concept options for major in-vessel components, a concept trade-off study is required to identify the design parameters for the IVM study.

For handling large components, the favoured concept is to use strongback devices. The components would have guide pins which render the item self-supporting once placed in position, the strongback being relatively simple and used for purely handling purposes. Fasteners would be inserted and tightened with one of the small dexterous manipulators mounted on the IVM. These concepts have not been developed beyond the sketch stage.

For TFET, there is an alternative strongback approach which should be evaluated early in the concept design stage. This alternative approach is to provide more special mechanism design in the strongback or special end-of-arm tooling which could simplify manipulator performance requirements, manipulator vision and lighting requirements and reduce the residence time inside the vacuum vessel.

4.2.2 Bridge-Mounted Manipulator

The bridge-mounted manipulator (BMM) depends on a test cell bridge crane to provide it mobility around the periphery of the tokamak. The equipment to be serviced by the BMM is not only widely distributed around the machine, but also spans a range of weights from large shielded components to complex diagnostic devices. The BMM therefore must be equally as dexterous as the in-vessel manipulator, but capable of handling greater loads. Interfacing with a third remote manipulator may be required, located on the floor below the test cell and servicing the diagnostic equipment beneath the machine.

Some bridge-mounted manipulator systems are commercially available, and it may be possible to use off-the-shelf equipment in part such as PAR manipulators. However extensive modifications may be required to interface with a commercial dexterous module such as the TOS purchased for evaluation.

Technically the BMM itself may have lower requirements than the IVM due to less stringent failsafe specifications, as access to the work area in case of manipulator failure is not as limited as for the IVM.

The BMM design will be developed in parallel with the IVM, since both devices must sometimes cooperate on common tasks where operations from both sides of the vacuum vessel are required, or where the BMM must aid the

IVM in transferring components either out of the vacuum vessel or into the mockup area or hot cell.

An evaluation was performed some time ago on the tasks required to be performed by the BMM. A failure analysis of the components and systems which must be serviced by the BMM is required, followed by a specification of BMM task requirements.

If the tracked IVM concept is re-evaluated, increased complexity of the BMM may be required to manoeuvre the IVM into and out of the vessel. The method of servicing the diagnostic equipment underneath the tokamak will need evaluation. Most likely a dexterous module dedicated to this area will be required, with the BMM used for interfacing between the diagnostics area and the test cell.

The studies on which the BMM performance requirements will be based should be done together with the same work for the IVM, so that uniform operating specifications result, and the various interface areas are properly attended.

4.2.3 In-Vessel Inspection

Commercially available devices exist such as periscopes and boroscopes which can be used to perform in-vessel inspection. However, whether or not these devices can fulfill the needs of tokamak vessel inspection must still be determined. The purpose of in-vessel inspection is to ascertain component and structural integrity either between shots or, more thoroughly, at regular intervals of say one week. The inspection devices must be able to view all areas of the inside of the vacuum vessel in sufficient detail to find cracks in protective carbon tiles, fractures in welds, plasma damage to components, and loose or missing equipment or pieces.

The question of how small a fault in a weld is significant, or how small a crack in a tile will cause problems, has not yet been determined. But the probability exists that these features must be recognizable in sufficient detail and with sufficient assurance that a high degree of resolution will be required. This means either many inspection devices, or very capable ones, or ones that can move close to the surface to be inspected.

Work in this area has been of concept nature only, and considerable reliance is presently put on the availability of suitable commercial devices. The fact that these devices cannot remain inside the vacuum vessel during plasma operation, and still must be capable of operation without breaking vacuum, makes the availability of suitable devices less assured.

Since frequent and detailed inspections of the same surfaces must be made, some form of computer aided image comparison is indicated so that changes can be found without time consuming and potentially unreliable visual inspection.

Just how critical the need for detailed fault determination is, is difficult to assess, and an analytical approach to answer this question is appropriate. The input parameter to the analysis would be materials strength and failure mode technology, the effects of possible disruptions in the plasma, and electrical, magnetic and thermal cycles.

To some extent, a practical approach to this determination can also be made since the machine can be operated in increasing levels of stress, and inspections carried out during the period when the vessel will be open for a variety of scientific and technical reasons. However, every access to the vessel is costly in downtime and manpower and the largely experimental nature of large scale plasma control will require frequent checks of the devices exposed to plasma disruptions. Therefore, this analysis will be given high priority.

Following the definition of what is to be seen, the next step will be to investigate the equipment commercially available to meet the requirements, and conceptualize their method of insertion and use. It is expected that development of mechanical deployment devices which can function in a vacuum will be required.

4.2.4 Vacuum Vessel Leak Detection

The vacuum vessel has approximately 250 penetrations of various sizes. The port flanges are bolted, with double metallic seals, and the space between the seals is accessible for pumping, or leak detection. Tubing has been installed for these connections but a scanning system to monitor leaks in the interseal space will not be procured. The leakage through the ports is not expected to be a problem, therefore the decision was made not to design a system to monitor and isolate leaking flanges.

When the operation of the machine progresses to the point where remote operation of the flange covers is required, the leak checking would become more important, as remote installation of the flange seals would preclude the hand-fitting that is required to obtain low leakage rates.

The leak detection system would include completion of the tubing connection, installation of a scanning device, detector instrumentation, and a means to inject tracer gas.

A more difficult problem but one of perhaps lower probability of occurring is leak detection of the vacuum vessel itself, primarily the bellows. This requires a detector device that can move around the vacuum chamber to sniff for leaks at relatively close proximity to the vessel structure. Although the detection technology is quite routine, the access and mobility of the device, and the isolation of a small leak area are problems that need concept design.

4.2.5 Cutting and Welding Machines

The TFTR vacuum vessel has bellows sections between solid vessel sectors which are welded construction. Most of the components in the vessel are bolted, as are all flanges, but in some cases, seal welding may be desirable. The TFET vessel will be constructed from bolted and seal-welded solid sectors. In the event of a major machine repair which would require moving a vessel sector, remote cutting and welding machines would be required.

Considerable development, both at PPPL and other facilities, has resulted in welding machines adequate to perform the tasks of sector seal welding. The outstanding technical problem remaining is one of accurate component alignment rather than the welding process itself. An exception to this would be if the need arose to perform structural welding remotely, as the development has been quite specific in the narrow application of track-guided welding of thin sections.

Other applications of cutters and welders will be generally small items such as pipes and small flange seals. Devices to perform these tasks have been developed extensively for use in the fission nuclear industry, hence the technology exists. What is required are procedures and fixtures for specific applications.

The work required in this area includes:

(a) assessment of cutting and welding requirements,

(b) assessment of the state-of-the-art existing in equipment and procedures,

(c) assessment of the development and equipment requirements to meet specific TFTR and TFET needs.

4.3 Machine Components

4.3.1 In-Vessel Component Fasteners

Approximately 200 components will be installed inside the vacuum vessel. Many of these will perform a variety of difficult functions and, for TFET, still require development and design. Most of the components must be capable of replacement, possibly by remote means. The transient magnetic forces exerted by the field coils and thermal stresses during a plasma pulse require that all in-vessel components are held with locked fasteners. In addition, any surface which may be subjected to plasma disruption must be protected by armour to prevent ablation or melting.

The general concept chosen for TFTR is to use a deformed thread helicoil insert with captive bolts. However, this system is not optimum for repetitive insertion and extraction of bolts since the helicoils themselves may need replacement after a relatively few operations, generally in the 20 to 40 range.

The larger components requiring "contingency only" remote handling use a standard type bolt with pre-loading on the shaft to ensure adequate locking, etc. On TFET, these would also need remote handling.

A comprehensive evaluation of more suitable fasteners is justified. Further work is needed to determine manipulator torquing requirements and techniques for handling fasteners. The philosophy adopted at PPPL is that threaded fasteners are proven devices that work and that a manipulator would be able to operate them. However, if someone came up with a better system that could be proven reliable and cost-effective, it would be considered.

A special development requirement exists in the area of carbon tile fastening. Where backing plates can be used, the tiles can be fastened from behind, and the entire assembly mounted inside the vacuum vessel in such a configuration that the mounting bolts are not exposed to the plasma. However, in TFET, the tiles covering the area of the neutronics bays have a need to be as thin as possible in order to provide the best experimental conditions. Therefore, backing plates are not desirable and some form of direct fastening to the vacuum vessel wall is preferred.

A present concept being evaluated is a carbon bolt threaded in flush with the tile surface by a special tool. Concept analysis, development and testing of this device, or another idea, is required.

4.3.2 Toroidal Pumped Limiter Mounting

The toroidal pumped limiter is one of the largest components inside the TFET vacuum vessel. It currently is the item which requires the IVM to be capable of handling 800 pound loads. If this device could be designed to be replaced without the use of the IVM, then the design specification for the load carrying capacity of the IVM could be significantly reduced. An additional benefit would be realized in significantly lower down time for a change operation that does not involve opening the vacuum vessel to permit IVM use.

The limiter is a complex device that must perform a precise technical function while dissipating substantial amounts of energy and withstanding large electromagnetic forces. Its surface is protected by carbon tile, it must be precisely positioned in relation to the vacuum vessel wall, it must make good electrical contact from one blade section to the next, and it must be connected to cooling lines and provide optimum geometry for particle neutralizing and pumping.

The pumping duct through which the limiter mounting structure must pass is restricted in size by the space between the toroidal coils, PF coils and other components. In order to change the limiter without the IVM, the device must be withdrawn through the pumping duct. In order to accomplish this the blade must be folded, or turned in a way to allow it to fit inside the duct. Several concepts of this procedure have been investigated but so far, the IVM has been needed, if only to support the blade as it is turned sideways.

Innovative mechanical design is required that can solve the space and orientation problems without compromising the technical design, and without needing support from the IVM.

4.3.3 Vacuum Vessel Segmentation and Removal

A concept exists for the replacement of a TFTR segment in the unlikely event of structural damage from a plasma disruption. The segment weld joints are designed to permit remote cutting and rewelding and all major components such as TF coils can be removed, or moved out of the way.

If this actually has to be done, a new segment would have to be manufactured, as no spares exist, unless the defective segment can be repaired. Also, the remote devices required to cut, remove and reweld the segment would have to be manufactured and tested. The machine downtime could be a year or more in order to perform such a sector replacement.

Operations planning and a cost-benefit analyses of the level of preparedness required could significantly reduce the impact on the scientific and engineering programs.

The TFET upgrade proposes installation of a new vacuum chamber, diagnostics, ICRF drivers and other devices. The TFTR vacuum chamber would therefore have to be dismantled and removed. The upgrade changeover is planned over a time-span of 1½ years, starting in 1988.

Since the TFTR vacuum chamber will be activated, detailed procedures will be required to optimize operations and minimize man-rem exposure and contamination of other equipment. A plan already exists for low power operation in the last year of TFTR use to permit the machine to cool down. Further operations planning, development of equipment for vacuum vessel removal, decontamination procedures and schedule optimization are tasks that will require attention within the next four years.

The TFET vacuum vessel will be assembled without bellows. Currently, two concepts exist for assembling the segments. The bolted and seal-welded arrangement is favoured. However, because the gaps between the TF coils are needed for large ports, the bolted joints will lie under the TF coils, hence will be inaccessible.

The second concept of structurally welding the segments has the advantage of a simpler geometry and better access. But, the problem of coping with the distortion and misalignment during assembly and segment replacement seems too difficult to warrant this approach. A technical analyses of these procedures from the point of view of remote handling, together with a cost-benefit analyses and down-time evaluation is required to allow a clearer choice between these alternatives.

4.3.4 Connectors

Wherever possible, interconnections for all machine components are made from outside the vacuum vessel in order to simplify in-vessel interfaces. This philosophy has been adopted with the mechanical design largely dependent on access for manned operations.

It may be advantageous for TFET to consider methods more dedicated to remote operations such as remotely controlled mechanisms. Concept studies and economic trade-offs are required early during TFET concept design so that connector design specification can be firmed with a uniform approach for all equipment.

4.3.5 Diagnostic Equipment

Diagnostic equipment is used primarily to monitor the plasma to determine the tokamak operating parameters and provide research and control information. Diagnostics can be as simple as a thermocouple or as complex as a laser scanning system. In all cases the diagnostic devices make use of one of the many ports, which is dedicated for that device. Occasionally the diagnostic device must move before, during or after a shot, in which case it is usually bellows-coupled to the vacuum chamber. With a maximum of two degrees of freedom these mechanisms are fairly straightforward.

Considerable changes to diagnostic equipment will be required for TFET due to different measurements and parameter changes and the significant increase in the duration of a pulse. For TFET, this means use of more radiation hardened materials instead of shielded commercial equipment and more remote handling for adjustment, replacement and repair.

A significant amount of the diagnostic equipment is located in the space underneath the machine and penetrates the vacuum vessel by means of the vertical ports in the bottom of the vessel. This will involve a manipulator mounted on the floor below the tokamak in addition to the bridge-mounted manipulator servicing the Test Cell. This manipulator will be required to reach up approximately 20 ft. to the machine base where the diagnostic equipment is located. Operation of this device would probably be manually aided from behind shielding. The close proximity of the operators and more relaxed access requirements may permit the purchase and adaptation of commercial manipulator equipment.

This area of remote handling needs to be considered in the overall concept of the remote handling evaluation and in creating standards and guidelines for remote handling in diagnostic equipment design.

For the diagnostic equipment, there are two areas of application of engineering expertise. One is in the diagnostic equipment itself and the other is in the location and support services. Diagnostic equipment may be available to perform the desired function but must usually be adapted to the available space and orientation. Also, because of remote maintenance constraints, some redesign of control devices and support services will be required.

Diagnostics are essential for both the operation of the machine and research data gathering, therefore these devices will receive prime consideration. At PPPL, diagnostics development has proceeded in parallel with the design, construction and operation of all of the fusion devices, so the diagnostics for TFTR are well in hand. For TFET, however, additional development is required particularly in making these devices remotely operable and maintainable.

4.3.6 RF Heating

RF injection is much more suitable for continuous heating of long pulse plasmas than neutral beams are. With the development of efficient high power injectors, this method of plasma heating will replace neutral beams. Power transfer to the plasma is more efficient, and there is less need for protective coverings on in-vessel components. In addition, less complex equipment is required, and perhaps of greatest importance, the complexity can be removed from the near vicinity of the tokamak. This will greatly ease the space limitations around the periphery of the machine.

Two of the neutral beam injectors will be retained for the TFET configuration. In addition to the power transfer physics, which must yet be developed, the high power RF wave launchers will need development, especially in the areas of radiation resistant materials and remote maintenance capability.

A maximum of 20 MW of RF heating will be introduced into the vessel through four ports and will use either a resonant chamber or deployable antenna to transfer the power to the plasma.

If the resonant chamber approach is used then most of the design requirements will center around an analytical approach to the cavity configuration for optimizing power transfer to the plasma. If the deployable antenna concept is used, then in addition to the port and cavity design, the mechanical drives and deploying mechanisms for the antenna would need development.

The decision as to what mechanism of RF injection to use will be made in the year following TFET funding approval to permit ample time to develop the physics and hardware, and test a prototype on TFTR before the TFET design is frozen.

4.4 Tritium Processes

The design of the tritium system for TFTR is frozen and it is presently under construction with most major components already on site. It will be a once through system. Pure tritium will be obtained from Savannah River in currently approved LP12 (12 litres, 33,000 Curie tritium load) shipping containers. The tritium is transferred to, and stored in, a uranium cell as uranium tritide and can be regenerated as required in a glove box unit. The glove box unit has the capability of accepting a larger existing shipping container, the LP50 (50 litres, 190,000 Curies tritium load).

Transfer of the tritium from the sealed off tritium handling area to the machine is through a double-walled piping system. Metering of the tritium into the machine is accomplished by a puffer valve. The excess gas and reaction products are removed from the machine by the vacuum system. Gaseous tritium waste is collected and shipped back to Savannah River. Tritiated water will be collected by a separate system and will be shipped to Los Alamos Laboratories for disposal.

During D-T reactions in the machine, some tritium will be forced back into the Neutral Beam (N.B.) boxes leading to tritium buildup after a period of use. Fast shutoff valves were developed to isolate the N.B. units from the vacuum vessel but they are not being installed, primarily for economic reasons and space limitations.

Total allowable site tritium inventory is currently 5 grams (50,000 Curies). Analyses have been done to determine the probable tritium dispersion and hold-up during normal operation and various accident scenarios. These analyses indicate that PPPL's own on-site and release activity levels, which are considerably more stringent than regulatory limits, can be met.

The proposed upgrade of TFTR to TFET would lead to many more experiments being performed with tritium and to longer duration of individual shots. Consequently, a much greater amount of tritium will be required to service TFET than TFTR. Because of this, consideration is being given to a closed loop tritium system containing a purification subsystem. Preliminary evaluation of purification methods indicates that gas chromatography is advantageous on the basis of space requirements, throughput rate and the small tritium inventory required. However, most gas chromatography purification technology is military classified information, thus not readily available at present. Therefore, this system will require further development.

On site breakdown of collected tritiated water by electrolysis is also being considered. Electrolytic cells capable of reliably handling water with activity greater than 50 Curies/litre will be required.

With the closed loop system, the existing LP50 shipping containers, receiving and transfer glove box facilities, etc., are considered to be adequate to service TFET.

Because of the greater throughput of tritium and higher site inventory, more detailed release calculations and inventory estimations will be required. Also, improved capability for real time monitoring of tritium in very low concentrations is required for area monitoring and personnel protection.

4.4.1 Tritium Valves

A very specialized valve is required between the tritium system and the vacuum vessel to inject a precisely metered slug of tritium gas during D-T operation.

A metering valve has been developed and tested on site. It is considered adequate for TFTR operation, although improved performance would be desirable. For TFET, a higher capacity valve is required.

Another valve requirement exists for a very large, fast-acting shutoff valve in the neutral beam injection line to prevent backstreaming of tritium into the neutral beam box. The valve must be open during the short period of neutral beam injection and then close quickly. This valve must fit approximately a one meter duct and operate in the range of a hundred milliseconds.

A prototype valve was developed and tested and performed satisfactorily except for less than desirable sealing when closed. Because of high cost and extreme inaccessibility, these valves will not be used for the four N.B. systems of TFTR and the present plan is undecided for the two N.B. injectors which will remain for TFET. If either analysis or use shows that an unacceptable amount of tritium backstreams into the N.B. boxes, then the further development or manufacture of these valves will be made necessary.

4.4.2 Electrolytic Cell Development

The dissociation of high activity tritiated water on site is preferred once D-T operation is commenced, since the amounts involved make disposal by shipment to Los Alamos difficult. Because of space constraints, electrolysis is the preferred method. However, commercially available cells are damaged if water with an activity greater than 50 Curies/litre is processed. Hence the development of radiation resistent cells is required. To be used by TFET, this technology will have to be demonstrated by mid-1985.

4.4.3 Tritium Detectors

Better tritium detectors are required which will measure low concentrations in real time and distinguish between tritium gas and tritiated water (T_2O, TDO). Such devices are required for safety monitoring at low concentrations and fast response times, as well as for integration for long term release monitoring. Some commercial equipment is presently available, but improved performance is required in order to meet safety and regulatory guidelines. Although TFTR will have only 5 grams of tritium on site at any one time, this system should be in place and operating in 1985 to demonstrate safety procedures, tritium accounting and release control.

4.4.4 Surface Coatings

The retention of tritium on surfaces is a most important contributor to a high tritium level in a facility. Studies of surface treatments and coatings have been made to minimize the amount of tritium contained within process system materials. However, little development or analyses of tritium adsorption has been done on surfaces outside the process system such as paints, floors and concrete. Epoxy paint is currently used extensively in the tritium containment areas, primarily based on common practice, and in the absence of data on adsorption and retention. Because of the relatively small amount of tritium licensed for on-site residence, minimizing in-process retention as well as in-facility adsorption are important considerations.

Studies are required to more accurately determine adsorption phenomena on coating materials, the effect of surface finish, temperature and humidity, and the presence of hydrogen. Decontamination procedures for various materials and surface finishes will also be required in the event of non-routine releases of tritium into the containment structure.

4.4.5 Tritium Purification

During D-T operation of TFTR the used tritium will be returned to the supplier for purification. Because of the larger quantities involved, TFET operation will necessitate on-site purification. The gas chromatography method has been identified as a potential candidate by a preliminary evaluation of purification concepts. A more thorough evaluation is required with cost-benefit analyses, availability of technology, risk assessment and development requirements taken into account.

This system is required for operation in 1989 but earlier commissioning, perhaps in time for use on TFTR in 1986 would be advantageous.

4.4.6 Tritium Storage Mechanisms

Depleted uranium has been chosen as the storage medium for TFTR use, and mechanisms similar to the LP series of shipping containers will be used for storage. Further evaluation of the system to examine the concepts for filling and emptying the containers is required, with specific attention to safety, quantitative and qualitative analysis, and the effect of helium and other contaminants.

4.4.7 Tritium Release Calculations

For TFET operation, licencing to permit the larger tritium inventory will require safety studies involving pathway analyses and release calculations. Since there are few civilian establishments which deal with large quantities of tritium, and because of the significant chemical and physical differences between tritium and gases that might be released from nuclear fission plants, these techniques are not well established. Development of the analytical methods with testing, where appropriate, is required.

There will be three contributions to the tritium release from the site:

(a) routine operation,
(b) maintenance operations,
(c) accidents.

All three of these sources must be analyzed separately, and then release reduction concepts evaluated to come up with the most cost - and safety - effective approach to each factor.

4.4.8 Tritium Inventory

The tritium systems will be designed specifically to reduce the in-process inventory. Because of its tenacious affinity to most materials, the in-process inventory could be significant. Work is required to better understand retention mechanisms, adsorption, absorption and chemical behaviour.

The work in this area falls into two categories. Theoretical studies of tritium behaviour and specific accounting of inventory in the TFTR/TFET tritium systems. Both tasks are required, the latter being of more practical and immediate need, particularly when the high throughput of TFET commences.

5. CFFTP POSSIBLE COLLABORATION

There are a number of specific areas centered around remote handling where the resource base available to CFFTP could provide state-of-the-art as well as cost-effective service. The organizations from which CFFTP can draw expertise have developed their capabilities in a broad range of high technology projects including the development, construction and operation of CANDU nuclear power reactors, design of the space shuttle remote manipulator system, research and development in fusion physics, particle physics and other scientific undertakings, high technology engineering of a variety of specialized electromechanical systems for reactors, accelerators, process industries and experimental facilities, development of tritium process systems, containment, monitoring and concept studies in a broad range of subjects from management through technical evaluation to operations planning.

The projects identified in this section represent areas where CFFTP can propose collaboration with PPPL. The key to successful participation in PPPL projects is a clear and detailed understanding of what is required from both a physics and a technical point of view. Most of the projects would benefit from, if not depend on, close liaison with PPPL in the form of staff attachments to the TFTR project. For this reason the primary recommendations to CFFTP is to propose an attachment of a core team of specialists to the Remote Handling Group at PPPL to undertake the front end studies and evaluations of remote maintenance requirements.

Although direct involvement of CFFTP member companies in fusion projects has been infrequent, the overriding requirement of all the listed work is state-of-the-art technical expertise and experience in remote handling mechanisms and complex mechanical systems, and in their application to unusual and unprecedented projects. Successful precedents exist where the Canadian firms with remote handling expertise have collaborated with U.S. organizations on complex projects.

Canadian research undertakings span nearly as broad a range as most industrialized nations, but the funding is inadequate to maintain specialized industries to service each branch of science. Therefore, Canadian industries have evolved with a unique capacity for innovative application of their skills to many differing sciences and technologies. It is this innovative expertise which can be combined with scientific and engineering resources to undertake the projects described in this section.

5.1 Remote Handling Equipment

The work associated with the design and supply of the remote handling equipment is by far the best opportunity for the application of Canadian technology. Considerable feasibility and concept work has already been completed, but a strong need exists for an expert team to undertake the systematic analysis of technical and scientific requirements for both the in-vessel manipulator and the bridge-mounted manipulator leading to an engineering specification of the systems. The subsequent design and supply will be the high cost and high profile portion of the work but it will be the tasks leading up to the design and supply contract which will determine the ultimate compatibility of the remote handling hardware with the goals of the PPPL project.

5.1.1 In-Vessel Manipulator

The scope of work for the in-vessel manipulator would be:

(a) identify the remote handling requirements and priorities,
(b) evaluate possible concepts,
(c) develop the existing concepts until a decision can be made on one in-vessel manipulator concept,
(d) develop the concept through a preliminary design,
(e) design, manufacture and evaluate a prototype system in the PPPL mockup facility and identify development requirements,
(f) undertake a detailed design, specification and cost estimate,
(g) manufacture, test and deliver to site,
(h) install, test and commission.

This project requires expertise in:

(a) interpretation of performance requirements of in-vessel components,
(b) operations analysis of the remote handling system,
(c) application of remote handling technology and philosophy,
(d) human factors engineering,
(e) servo mechanisms,
(f) dynamic modelling and analysis,
(g) software development and design,
(h) joint, servo and gear box design,
(i) end effector and mechanical interface design.

The first step to undertake for this project would be to propose the attachment of a team of specialists to the Remote Handling Group at PPPL. This team would undertake the first four tasks in the scope of work over a time span of approximately one year. It should be emphasized that this team should be experts in the field of remote manipulators and complex electromechanical equipment.

The makeup of this team would be:

(a) a physicist experienced in mechanical equipment design who could provide liaison between the PPPL scientists and the engineering team,

(b) a remote handling systems engineer experienced in remote manipulator design, with a broad background of mechanical systems to permit evaluation of a variety of remote handling concepts,

(c) a controls system engineer familiar with servo systems, and experienced in translating mechanical performance specifications to hardware.

(d) a senior designer-draftsman capable of translating the engineering ideas to design concepts, also experienced in remote manipulator technology.

The concept evaluation would be done on site where the very necessary interaction between machine component requirements and remote handling design can take place. The detailed design and manufacture could best be done where the combined resources of the engineering companies can be brought to bear, and where optimum manufacturing facilities can be utilized.

To make best use of the mockup equipment available at PPPL, the prototype development and testing could be done on site. This would also permit the participation and training of the operators and technical staff.

The benefits of participation in the project would be the opportunity to supply the remote handling system hardware for PPPL. There are a number of other facilities where such equipment could be needed, each application being of the low production quantity and high technology type. The existing Canadian resource developed from CANDU reactor refuelling machines, the space shuttle arm and other remote handling applications will provide an excellent technology and manufacturing base for this project.

5.1.2 Bridge-Mounted Manipulator

The bridge-mounted manipulator requires very similar scope of work and expertise as the in-vessel manipulator. In identifying the remote handling requirements, particular attention will be required in such areas as the diagnostics space underneath the machine and within the igloo area. This implies some special access capabilities as well as heavy lift ability to remove shielding.

Since the use of the bridge crane as a base for the manipulator mounting has obvious advantages over other support methods, the only concept variables to evaluate will be the form and complexity of the manipulator itself and the philosophy of end-effector use.

The most cost-effective approach to this project would be to use the same specialist team working on the in-vessel manipulator, and do both projects in parallel. The additional benefit of this approach would be optimized co-ordination between the two systems and a possible sharing of common maintenance tasks. The bridge-mounted manipulator will have access from the Test Cell to the entrance of the Mockup Area, and as such, will provide the common link for activities in the two areas.

The hardware supply for this system has ample potential for specialized equipment development since the operating requirements will range from moving heavy shielding blocks to performing dexterous activities on complex diagnostic equipment. Again, the remote handling technology developed in the nuclear and aerospace industries can be directly applied to this project.

5.2 In-Vessel Components

The Toroidal Pumped Limiter for the TFET configuration offers a unique opportunity to apply innovative mechanical systems design to the mounting of this device. The object of the design would be to develop a limiter system which could be serviced through the pumping duct without use of an in-vessel manipulator. The benefits to the facility operators would be substantial, reducing considerably the length of time the machine would be down during limiter maintenance while at the same time reducing the performance specifications for the in-vessel manipulator.

The limiter blade operating specifications, hence design, is presently still evolving as the plasma characteristics and limiter functions are developed. Since the limiter blade size and its contact characteristics with adjacent blades are the prime source of complexity for a system capable of being removed through a limited size duct from outside the vacuum vessel, the concept design of the mounting arrangement can proceed while the performance specifications are developed. Such design parameters as blade shape, distance from the vacuum chamber wall and cooling requirements can be added after the basic feasibility design is completed.

This project must commence with a thorough understanding of the space limitations outside the vacuum vessel, the structural and cost trade-offs of port geometry and size, and the scientific and technical requirements of the limiter system. This portion of the work would require the designers to spend some time on site working with a number of different groups and individuals responsible for various aspects of the space constraints, vessel design and physics. Three months would be adequate for this task.

Once the design constraints are well understood, the feasibility design and concept design can proceed utilizing an optimum resource team in Canada. This could require a further 9 months.

Detailed design and manufacture of a prototype could take 18 months, or more if special material supply constraints are encountered. Testing of the prototype might be done on the mockup system at PPPL which could exist by that time. Production manufacture of the full complement of 20 limiters for TFET would be required by 1988.

This project would provide CFFTP with involvement in a high profile tokamak component with the possibility of limited production manufacture. Other fusion machines may not require such a device, but will inevitably require complex equipment for which design of unique mounting arrangements would be of great benefit. Once the capability to successfully apply the CFFTP resources to fusion devices is demonstrated, this involvement could be extended to many other fusion requirements.

5.3 In-Vessel Inspection

This project is primarily a study, combining an appraisal of inspection requirements, state-of-the-art commercial equipment availability, and concept design of possible hardware installation. An integral part of the work could involve computer aided image comparison techniques.

The mockup of TFTR should be used to develop the study findings and evolve a system which could be designed and built to service TFTR early in its operating life.

The scope of work would be:

(a) determine inspection requirements for welds, armour, and other surfaces,
(b) survey available devices and computer imaging systems,
(c) conceptualize an inspection system to meet overall machine requirements,
(d) identify development requirements and economic trade-offs,
(e) undertake specific development on the TFTR mockup.

In determining the inspection requirements the skills used would parallel the work done in CANDU reactors for the development and monitoring of pressure tubes, calandria tubes, bellows joints and restraints. The computer image comparison systems, fiber optics devices and TV systems would have to be researched on a world-wide basis to determine the state-of-the-art. The study portion of the work could take one year. The amount of development and demonstration required would depend on the findings of the study, and would conceivably run in parallel with the second half of the study work.

5.4 Operations Analysis

In order to design a remote handling system, a number of areas must be studied peripheral to the maintenance equipment itself. Determinations must be made of the tasks the system will have to perform, how frequently, under what conditions and in what time frame.

There are four topics that could be dealt with under this title:

(a) reliability and machine availability,
(b) scheduling of machine operation,
(c) scheduling of repair and maintenance,
(d) decommissioning.

All these are interactive and require co-ordinated analysis. Because of the need to evaluate equipment, procedures and priorities for each major system, this work would best be done at PPPL. As in most of the other projects, emphasis should be placed on the specific skills necessary to perform the work, backed up by a capability to bridge the gap between the project and the input sources, be they technical equipment or physics programs. Usually, this expertise does not reside in one man, so a team approach will yield better results. The resource of the remote handling team could be used to fill this requirement, with one additional analytical expert on site to take the lead role in the study planning and co-ordination.

This work should proceed in a systematic manner probably through the entire duration of the TFTR program, first dealing with TFTR, then addressing TFET in parallel with the design effort so that when TFET is commissioning, there will exist manuals for the reliability, operation and maintenance of all major systems.

Decommissioning is important to PPPL for two reasons. First, the TFTR machine will have a limited life after which it will be in effect decommissioned and replaced by TFET. Second, the TFTR decommissioning provides a good base for analyses of facility decommissioning which could be provided by PPPL as an input to the national fusion program.

5.5 Tritium Processes

The investigation of the tritium-related requirements did not turn up near-term needs involving remote handling. Most of the studies, development and design identified for tritium systems in the previous chapter are beyond the mandate of this Task Force. Some of these items are already being addressed by other collaborative undertakings where CFFTP is focussing Canadian tritium expertise on specific projects.

One development requirement in the tritium systems involving mechanical equipment should be mentioned here for possible follow-up; the puffing valve which meters tritium into the plasma.

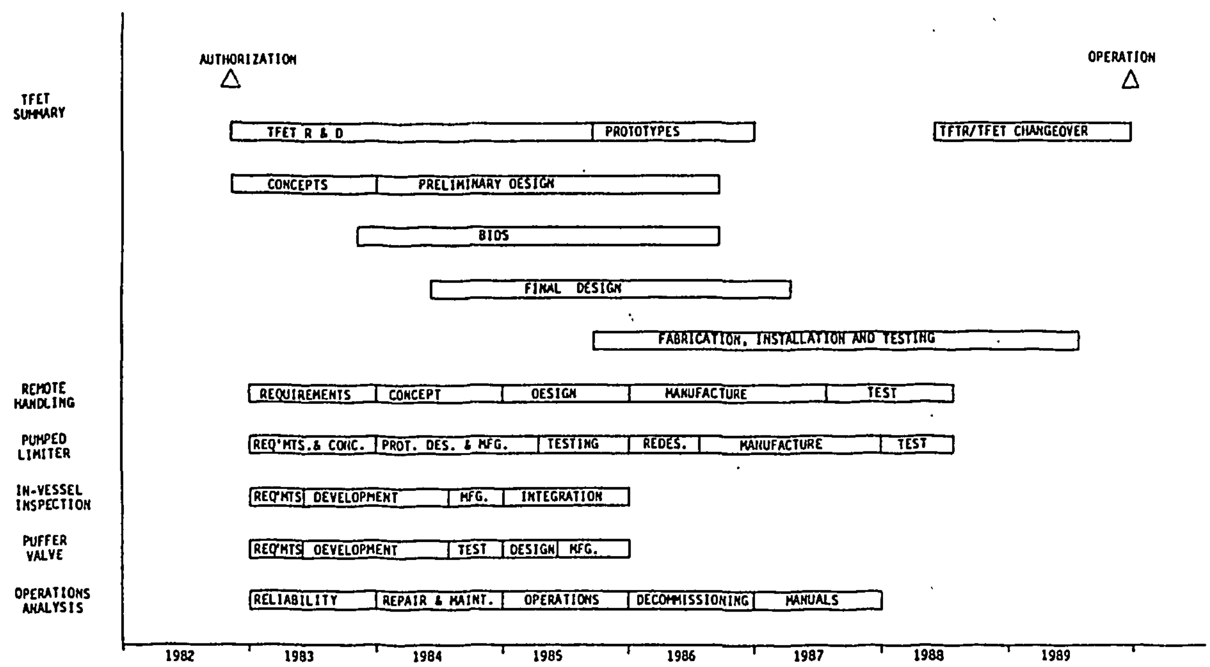
The present valve design will satisfy the requirements of TFTR, but TFET will require considerably higher flow rates. Because of proximity to the vacuum vessel, this valve will require remote handling for maintenance and repair, therefore low maintenance and good reliability are important design considerations. Some of the other requirements for such a valve are:

(a) high flow rate at low pressure drops,
(b) fast opening time (1 msec or less),
(c) fast response flow control immediately after opening,
(d) good valve sealing,
(e) leak tight construction,
(f) small trapped volume,
(g) vacuum compatible,
(h) operation unaffected by high magnetic fields.

The existing valve uses a piezoelectric actuated ball on a butyl rubber seat. Elimination of elastomer materials would be desirable, as well as improvements in performance, specifically leak tightness and flow regulation capability. A new valve is required in time to test it on TFTR prior to the upgrade. Therefore, it must be available by about 1985 or 1986.

The design requirements of the puffing valve are easily identified and can be isolated from the facility. Development and testing of the prototype would be important functions that could be undertaken with hydrogen, so a tritium facility is not essential.

5.6 Schedule of Activities



6. CONCLUSION

The field of remote handling has been identified as one of the prime areas through which the Canadian Fusion Fuels Technology Project can become involved in the mainstream of world fusion development. By marshalling existing resources in Canadian industry, utilities and universities, and focussing then on appropriate projects where a real need exists and where Canadian expertise is already well developed, CFFTP can establish a reputation and visibility as a capable supporter of fusion power development.

The prime objective of this Task Force was to investigate the work at PPPL on TFTR and TFET in order to determine if such an opportunity existed, and to research the requirements and strategy of an appropriate proposal.

The proposed scope of work for TFET includes the development, application and demonstration of remote handling technology on a level and within a time frame ideally suited for the resource base available in Canada. Both the in-vessel manipulator and the bridge-mounted manipulator concepts contain many elements of technology and hardware developed and applied by Canadian industry teams in both the CANDU nuclear reactor program and the space shuttle remote manipulator system. Innovative design of complex mechanical systems to meet demanding scientific requirements has been applied in a variety of reactor, cyclotron and space applications. The supportive studies of reliability and operating and maintenance scheduling have been amply demonstrated by exemplary operation of Canada's nuclear power reactors.

It should be pointed out that the definitions of the principal tasks in the report center around the TFET program proposal. For the original TFTR operations plan remote handling did not have as important a place, and many of the components identified as requiring development did not exist.

There are two reasons for proceeding with the work defined in this report regardless of the program course. One is that without TFET, the operations plan of TFTR would have to be upgraded anyway in order to bridge the gap left by a stretched engineering demonstration schedule, resulting in renewed importance of remote handling at least, if not the need to demonstrate RF heating and active limiters. The second reason is that the TFET proposal has matched a gap in the fusion engineering demonstration program with the availability of the only major machine currently in a position to fill that gap. The fit is too good to pass up.

This Task Force can therefore confidently urge that CFFTP develop the opportunities identified in this report without delay.

7. APPENDIX

7.1 Contacts at PPPL

Don Grove	TFTR Program Head
Roy Little	TFTR Technical Systems Division Head
John Citrolo	Engineering Manager
Erik Perry	Remote Handling System Head
Peter Titus	Remote Handling
Carl Pierce	Tritium Handling
Charles Ward	Auxiliary Systems
Bob Daniels	Auxiliary Systems
Jack Bundy	Remote Handling
Ken Young	Diagnostics

7.2 Task Force Participants

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