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TFTR NEUTRAL BEAM SYSTEMS CONCEPTUAL DESIGN

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ORNL/TM-5227

Contract No. W-7405-eng-26

Thermonuclear Division

TFTR NEUTRAL BEAM SYSTEMS
CONCEPTUAL DESIGN

Inclusive are:

- Part I SDD-71 NEUTRAL BEAM INJECTION
- Part II SDD-72 NEUTRAL BEAM PULSED ENERGY CONVERSION
- Part III SDD-73 NEUTRAL BEAM CONTROL SYSTEM
- Part IV NEUTRAL BEAM PULSED ENERGY CONVERSION AND
CONTROL SYSTEMS REFERENCE BUILDING DESIGN
- Part V DEVELOPMENT AND PROJECT SCHEDULE

MARCH 1976

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This work was performed within the operation of the Plasma Heating Department of the ORNL Thermonuclear Division and more particularly within the High Energy Systems group under the direction of Gerd Schilling. Assisting in the work were Engineering Division personnel under the direction of M. B. Baer and E. H. Bryant, CTR Project Engineering; D. D. Cannon and R. L. Johnson, Experimental Design Engineering; and R. E. Hill and H. F. Dunlap, Experimental Electrical, Instrument and Control Engineering.

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Development and Project Schedule Figures V-1, -1A, -1B, -1C	Part V

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FOREWORD

The material enclosed herein was prepared by the Union Carbide Corporation Nuclear Division and is responsive to:

- a) ERDA-DCTR letter dated April 29, 1975, Nelson Grace (TFTR Technical Project Officer) and James H. Williams (Assistant Director for Development and Technology) to CTR Division Directors at ORNL and LLL/LBL.
- b) Subsequent meetings and memoranda relating to Neutral Beam Conceptual Design.
- c) Suggested system design description (SDD) format as set forth in letter number FPSP 75-127 dated May 12, 1975, T. C. Varljen (Engineering Manager, Westinghouse Electric Corporation) to K. E. Wakefield (Princeton University).
- d) Suggested format for TFTR Conceptual Design Report as set forth in letter dated August 13, 1975, P. J. Reardon (Princeton University) to members of the Neutral Beam Steering Committee.

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ABSTRACT

The following paragraphs summarize the Union Carbide Corporation - Nuclear Division's presentation herein entitled "TFTR NEUTRAL BEAM SYSTEMS - CONCEPTUAL DESIGN."

- A. SDD's - 71, 72, and 73 prepared by UCC-ND provide the functions, design requirements, and design description of the respective systems. Documents will be updated as required to maintain currency.
- B. Conceptual Design Report requirements are met in Section II of the SDD's and the cost summaries discussed below. The design descriptions, with their associated reference drawings, can be used "as is" to provide input to the "TFTR-CONCEPTUAL DESIGN REPORT."
- C. Project Costs were summarized for each system and subsystem. These engineering estimates were prepared by the UCC-ND Cost Engineering Department utilizing data supplied by the Systems Design Groups. Where possible, actual quoted material prices were used. The costs presented are for: 1) materials procurement; and 2) shipping, assembly, and installation at the Princeton site. The estimates do not include an allowance for Architect-Engineering, contingency, or escalation.
- D. Development and Project Schedule milestones are noted below:

<u>Item</u>	<u>Design Start Date</u>	<u>Complete Acceptance Test Date</u>
TFTR Injection System Prototype	October 1, 1975	July 1, 1978
TFTR Injection Systems	September 1, 1976	October 1, 1980

In preparing the estimate, it was assumed that the TFTR Construction Contractor would buy all materials and components and utilize Princeton area crafts to do all assembly and installation. Shipping costs of procured, but fabricated, components were based on a distance of 700 miles.

Engineering and contingency should be applied to the project cost presented. At the present status of design, these factors should be no less than 25 percent for contingency and no less than 20 percent for engineering. Also, all costs should be escalated to the appropriate year utilizing factors as recommended by the ERDA Engineering and Construction Division.

Part I

TOKAMAK FUSION TEST REACTOR PROJECT

SDD-71

NEUTRAL BEAM INJECTION

Prepared by

UCC-ND ENGINEERING

OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee 37830

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UNION CARBIDE CORPORATION

for the

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Part I
ABSTRACT

An experimental tokamak fusion test reactor is being constructed at Princeton Plasma Physics Laboratory to demonstrate the feasibility of producing a "reactor grade" tokamak plasma using neutral beam heating. An essential part of this device is the Neutral Beam Injection System which produces and injects the energetic neutral deuterium particles into the plasma.

As part of the ERDA's Division of Controlled Thermonuclear Research's Development and Technology effort, Oak Ridge National Laboratory is engaged in the development of neutral beam injectors for fusion experiments. The future use of these injectors on the TFTR device requires that a conceptual design of a neutral beam injection system be completed as a part of the conceptual design for the TFTR experiment. In an attempt to utilize the existing neutral beam injection expertise, DCTR requested that ORNL and other beam developers participate in the conceptual design of neutral beam systems for TFTR.

ORNL's approach to the design of a TFTR neutral beam injection system was to design a universal system which could accommodate ion sources which produced neutral beam energies compatible with both modes of operation for the TFTR. The system is designed to meet the more stringent of the operating modes so that only the ion sources and position of the beam line would require changing to convert to a different operating mode.

During the conceptual design effort some design options were studied and selections were made for the conceptual design which will require further evaluation through development programs and further design analysis in the future. These included the selection of cryosorption pumping as the high speed vacuum pumping system, swirl tube type beam targets for handling the high peak power densities to be encountered in the beam calorimeter, and the use of a remotely operable hard seal flange to couple the neutral beam system to the TFTR device. Design

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criteria dictated the use of fixed torus ducts which require replacement to reposition the beam lines, but an alternative was assessed to determine the difficulties and additional cost incurred in developing a more versatile movable neutral beam injection system.

This system design description covers the Neutral Beam Injection System being designed by Oak Ridge National Laboratory for the TFTR.

1.0 FUNCTIONS AND DESIGN REQUIREMENTS

The neutral beam injection system consists of an assembly of beam line components which function collectively to produce deuterium ions, accelerate the ions to a high energy, and neutralize them to produce energetic neutral particles which can penetrate the confining magnetic fields of the tokamak. The system provides the necessary vacuum and gas handling components to avoid excessive leakage of cold gas into the torus or diffusion of tritium into the beam system. Figure 1.1 shows a schematic diagram of the neutral beam system and Fig. 1.2 indicates the required auxiliary subsystems. Tables 1.1 and 1.2 list the functions of the various components and auxiliary systems.

FIG. 1.1 BEAMLINE FUNCTIONAL SCHEMATIC

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Part I

FIG. 1.2 AUXILIARY SUBSYSTEMS SCHEMATIC

Table 1.1 Neutral Beam System Functions

1.1 Functions

1.1.1 Neutral Beam System

The neutral beam system is composed of many components each of which must fulfill a specific function, and in turn must function as a system to:

1. produce 12 beams of neutral deuterium particles each initially consisting of 53 amps of 120-keV, D^+ ions, for a 500 millisecond pulse duration and;
2. inject the 12 beams, 20 MW total power of 120-keV D^+ , into the plasma through 4 openings in the torus using an accelerator power of 80 MW.

Components fulfill the following functions:

1.1.1.1 Ion Source Assembly	1.1.1.2 Neutralizer	1.1.1.3 Bending Magnet	1.1.1.4 Beam Dump	1.1.1.5 Cryosorption Pumping
<ol style="list-style-type: none"> 1. Provide an arc discharge to produce a deuterium plasma. 2. Extract deuterium ions from the source plasma. 3. Accelerate the ions to the specified energy level. 	<ol style="list-style-type: none"> 1. Provide the necessary line density of gas to effect a charge exchange process for energetic ions traversing through the cell. 2. Remove energy deposited on the neutralizer wall by diverging deuterium ions. 	<ol style="list-style-type: none"> 1. Generate a magnetic field to separate the charged fraction of the energetic deuterium beam from the neutral fraction. 2. Direct the charged fraction into a preselected location on the beam dump. 	<ol style="list-style-type: none"> 1. Dissipate the energy of the charged fraction of the energetic deuterium beam which was separated from the neutral fraction by the bending magnet. 2. Measure the total ion beam power output during beam injection into the plasma. 	<ol style="list-style-type: none"> 1. Provide pumping for excess deuterium gas from the beam line during injection into the torus. 2. Provide pumping for tritium which diffuses into the beam line during injection. 3. Provide pumping for additional gas when operation is on the calorimeter rather than into the torus. 4. Provide pumping for any outgassed or inleaked gas.
1.1.1.6 Vacuum Chamber and Valves	1.1.1.7 Calorimeter	1.1.1.8 Fast Valve	1.1.1.9 Support System	1.1.1.10 Radiation Shielding
<ol style="list-style-type: none"> 1. Form the mechanical enclosure which isolates the interior of the beam line from atmosphere. 2. Seal the beam line from air when one or more ion sources are removed. 3. Seal the torus vacuum system when a beam line is removed. 	<ol style="list-style-type: none"> 1. Measure the total neutral beam power output. 2. Dissipate the beam energy when the beam is pulsed at times other than beam injection into the plasma. 	<ol style="list-style-type: none"> 1. Provide a conductance limiting shutter between the torus and a beam line when the absolute valve is open. 2. Limit the amount of cold gas which can diffuse into the torus prior to and following an injection pulse. 3. Minimize the quantity of tritium which diffuses into beam line prior to and following an injection pulse. 	<ol style="list-style-type: none"> 1. Provide support for the neutral beam system. 2. Provide translation motion of the beam system to assure that the sealing surface move normal to each other. 3. Provide support and translation of absolute valve which serves as interface between the beam system and the torus. 	<ol style="list-style-type: none"> 1. Reduce the radiation dose outside beam system to permissible occupancy levels when beam system is completely assembled after a sufficient number of plasma shots have occurred to produce equilibrium radiation fields

Table 1.2 Auxiliary Subsystems Functions

1.1.2 Auxiliary Subsystems				
<p><u>1.1.2.1 Secondary Vacuum</u></p> <ol style="list-style-type: none"> 1. Pump down the beam line from air on start up. 2. Pump the water vapor and other gas evolved from the cryosorption panels during conditioning. 3. Provide a means of moving the gas desorbed during regeneration into a gettering media. 	<p><u>1.1.2.2 Gas Handling</u></p> <ol style="list-style-type: none"> 1. Provide an inlet and distribution system for deuterium to ion sources and neutralizer cells. 2. Provide a way to tie up the tritium contaminated deuterium from cryosorption pumps in solid form. 3. Provide a recycle path to introduce the contaminated deuterium back into the distribution system. 	<p><u>1.1.2.3 Helium Refrigeration</u></p> <ol style="list-style-type: none"> 1. Provide cooling to maintain cryosorption pumping material at the required temperature. 2. Provide cooling for a chevron assembly which thermally shields the cryosorption material. 	<p><u>1.1.2.4 Liquid Nitrogen</u></p> <ol style="list-style-type: none"> 1. Provide cooling for a radiant shield to reduce the heat load on the helium cooled assembly. 2. Reduce the thermal energy of incoming gas particles so they are pumped more efficiently. 3. Cool various traps in the vacuum system to prevent mercury or oil migration. 	<p><u>1.1.2.5 Cooling Water</u></p> <ol style="list-style-type: none"> 1. Provide cooling for calorimeters, dumps, neutralizer cells, ion sources and other locations of pulsed high heat fluxes. 2. Provide cooling to bending magnets, various pumps and other equipment where cooling is needed to prevent thermal damage. 3. Furnish circulation through all water-cooled components exposed to 77 K surfaces inside the beam line to prevent ice formation if main cooling is off.
<p><u>1.1.2.6 Remote Handling Features</u></p> <ol style="list-style-type: none"> 1. Provide necessary remote connections to allow all electrical, cooling, and vacuum system to be disconnected using remote handling equipment provided in the TFR test cell. 2. Provide necessary remotely operable closure bolts and hard seals to allow the main vacuum flanges of the beam system vacuum enclosure to be remotely assembled and disassembled. 3. Provide remote leak detection capability for vacuum flanges. 4. Provide modular component design which allows major components to be removed to the maintenance cell for repair. 5. Provide necessary alignment systems to allow remote relocation of beam system components. 	<p><u>1.1.2.7 Maintenance Cell</u></p> <ol style="list-style-type: none"> 1. Provide space with adequate viewing and remote handling systems to allow major maintenance operations to be performed. 2. Provide facilities for conditioning new injector system components prior to installation on the tokamak. 			

1.2 Design Requirements

1.2.1 General Requirements

Neutral beam injection system shall meet the following design requirements which are based on the functions to be performed, the operating environment and the requirements of interfacing systems. In addition, the design shall meet the applicable requirements of ERDA and industry rules, regulations and standards.

1.2.2 Structural Requirements

1.2.2.1 Materials

Materials of construction shall be consistent with the requirements of the TFTR project guidelines for components operating in the vicinity of high magnetic fields, neutron fluences and vacuums.

- a. Vacuum enclosure materials (except for seals) shall be austenitic stainless steels to avoid excessive outgassing.
- b. Vacuum seals shall be metallic except for the internal seals within the source which may be made of low outgassing elastomers if necessary.
- c. Magnetic materials shall be avoided except for the bending magnet pole pieces and magnetic shields for the neutralizer and injector.
- d. Cryosorption panels shall be coated with a molecular sieve material to provide for pumping hydrogen isotopes at 15 K.
- e. Calorimeter energy absorbing surfaces shall be made of materials compatible with high vacuums and possessing a high thermal conductivity to minimize thermal gradients and thermal recovery time.

1.2.2.2 Stresses and Deflections

Stresses in components will be maintained within the limits of Section VIII, Divisions I and II of the ASME Boiler and Pressure Vessel Code for applicable materials and analyses.

Deflections of structural members will be maintained at less than 50% of those values which would result in functional problems under normal operating conditions and 100% under fault conditions.

1.2.2.3 Loads

<u>Component</u>	<u>Load</u>
Vacuum Chamber	
Pressure load on walls	15 psi (differential)
Lifting Load	50 ton
Calorimeter	
Internal Pressure	150 psi
Heat Load	6.6 MW
Gas Cell	
Cooling Water Press	150 psi

1.2.2.4 Operating Transients

The neutral beam system shall be designed not to fail structurally or produce an explosive gas mixture during the following transients:

- a. Operation of ion source with either the gas cell or beam magnet or both inoperative.
- b. Loss of helium refrigeration.
- c. Loss of liquid nitrogen supply.
- d. Local leak in vacuum chamber.

1.2.2.5 Fault Conditions

Neutral beam components shall be designed to function under operating transients specified for the TFTR device. The neutral beam system will be designed

not to fail during fault conditions specified for the TFTR device which result in shutdown of the device. These faults may require shutdown and regeneration of the cryosorption pumping system.

Vacuum boundary faults will not result in the development of an explosive mixture of hydrogen isotopes within either a single beam line or the TFTR operating or maintenance cells.

Tritium containment within the TFTR tritium boundary will be maintained during all potential fault conditions.

Cooling water systems will be designed with positive automatic shutoff valves which will operate on control signals triggered by water leaks inside the vacuum system.

1.2.3 Operating Requirements

1.2.3.1 Pressures

The line density of gas particles through which the neutral beam must pass from the bending magnet to the torus shall be $\leq 2 \times 10^{-5}$ torr meters. This condition corresponds to a neutral beam loss of approximately 2%.

The pressure in the calorimeter chamber shall be $\leq 1 \times 10^{-4}$ torr with beam on the calorimeter.

1.2.3.2 Temperatures

The temperature of components shall be kept within the material limits to prevent damage during a malfunction event such as loss of beam definition. A malfunction of this nature could deposit large power loads in the neutralizer cells or the torus duct.

The temperature of the cryosorption panels must remain below 20 K to maintain the desired pumping speed.

The calorimeter and beam dump experience the most critical thermal service conditions. Maintaining the temperature within material limits requires special methods of heat removal due to the power densities of 20 to 30 kW/cm².

1.2.3.3 Gas Loads

Gas loads to be pumped in the beam line are divided as shown in Table 1.3 for the 120 and 150-keV cases.

The source pumping region shall handle the un-ionized gas from the sources plus one-half the neutralizer cell gas load. The intermediate pumping region surrounding the bending magnet shall pump the remaining half of the load from the neutralizer cells, the gas generated in the beam dump and some portion of the gas from the calorimeter when it is intercepting the beam. The pumping section around the calorimeter shall be used primarily to lower the pressure in the drift space during injection into the torus.

Table 1.3 Gas Loads

	(Values in torr-liters per second)	
	120-keV	150-keV
Un-ionized Gas from Sources	31.8	26.4
Gas from Neutralizer Cell	60	60
Gas Load to Beam Dump	19.5	19.5
Gas Load to Calorimeter	18.6	12.3
Total Gas	129.9	118.2

Resulting cold gas input to the tokamak torus due to the above gas loads shall be less than 1 torr liter per pulse for four beam lines (12 sources).

1.2.3.4 Magnetic Fields

Magnetic materials and deflection magnets shall not produce fields at the center of the plasma greater than:

- a. 50 Gauss from magnetization by the plasma current,
- b. 5 Gauss from their own magnetic fields.

Magnetic shielding shall limit the stray magnetic field within the beam system upstream of the neutralizer exit to less than 5 Gauss.

1.2.3.5 Design Life

Beam system components shall have design lifetimes compatible with the design life of the tokamak (5×10^5 pulses - 4 years of tritium operation) and the maintenance plan for the system, except for those components which are otherwise limited by their unique operating characteristics. Components for which long lifetimes are impractical shall be designed for frequent replacement utilizing remote systems.

1.2.3.6 Duty Cycles

The TFTR neutral beam injectors still must be developed. Their electrical stability and need for conditioning pulses prior to and between TFTR injection pulses in 1980 is therefore unknown.

If the injectors turn out to be extremely stable and no conditioning pulses are needed, then normal operation of the beam system will be at the TFTR rate of one

pulse every five minutes. The beam system should then be capable of operating four beam lines with twelve total sources at full power and pulse length every five minutes. Cooling water and power supply systems would be designed for this rate.

If the injectors turn out to be less stable and conditioning pulses are needed, then normal operation of the beam system might be the five minute TFTR rate plus the maximum conditioning rate allowed by the TFTR electrical net. Cooling water and power supply systems must then be designed for this much higher rate.

The neutral beam system consists of four beam lines each of which shall be capable of operating with three sources at full power and pulse length at a repetition rate of one pulse every thirty seconds. Auxiliary systems shall be capable of normal operation of four beam lines one full power pulse every five minutes for eight hours per day or 96 pulses in any day and 1000 pulses per year.

Since new sources will require conditioning at a greater repetition rate than once every five minutes, a conditioning system must be included which can pulse a single beam line (3 sources) at a repetition rate of once every thirty seconds.

Cooling water and power supply systems for both the five minute repetition rate and the thirty second repetition rate shall be capable of being switched to any of five beam systems (i.e., four active units on the tokamak or one unit on beam test stand located in the maintenance area).

1.2.4 System Configuration

1.2.4.1 Overall Size

The size of the beam line must be maintained within limits dictated by a number of criteria.

The length of the beam line with its associated connections and maintenance space must fit within the cell boundary. This dimension shall be 12 meters or less measured from the torus.

The width of the beam line shall be narrow enough for beam lines to be located in every second torus field coil gap. This will allow four beam lines to be located on the stationary half of the vacuum vessel.

1.2.4.2 Maintenance Access

- a. 1 meter on each side of beam line,
- b. 5 meters aft of forward ion source flange,
- c. 6.5 meters above the neutral beam system.

1.2.4.3 Auxiliary Subsystems Location

The auxiliary subsystems should be located outside the test cell if possible in order to conserve floor space. The gas handling subsystem and vacuum subsystem must be contained within the tritium boundary due to possible contamination of the beam line off gas. Space allocated within the tritium boundary is 9.75 x 5.5 x 2.4 meters high.

The remainder of the auxiliary subsystems can be located outside the biological shield. These subsystems include electrical, cooling water, liquid nitrogen service and helium refrigeration.

1.2.4.4 Component Arrangement

- a. Sources shall be located so that they are aimed into the plasma at a point tangent to a 270 cm or a 220 cm radius from a distance no greater than 9 meters..
- b. The fast valve shall separate the torus and beam line vacuum.
- c. Calorimeter shall intercept the beam after the beam passes through bending magnet. It shall be capable of being retracted out of beam path.
- d. Gas cells are in front of sources, one gas cell is required for each source.
- e. The bending magnet shall be located between the gas cells and the calorimeter.
- f. The beam dump shall be located below the bending magnet in a position to intercept the charged fraction of the beam.
- g. Cryosorption pumping panels shall be located along all available vacuum chamber walls and bulk heads.

1.2.4.5 Component Weight

The total assembled weight of a single neutral beam system shall not exceed 50 tons excluding radiation shielding which may be removed prior to moving the neutral beam system.

1.2.5 Maintenance

The neutral beam system design shall include the necessary features to implement the maintenance plan.

1.2.5.1 Remote Handling Features

Components and service connections for the neutral beam system shall be equipped with the necessary remote handling features to allow remote connection and disconnection of the components and services by the available remote tools specific in the TFTR Remote Maintenance Guide.

Connections and actuators shall be located to be accessible to the remote equipment and to allow direct viewing from the shielded manipulator cab. Where connections or actuators are located in either inaccessible or hidden positions, automated remote systems are required to allow remote operation.

1.2.5.2 Maintenance Access

Space around each beam system shall be maintained for access by the PAR Model 6000 electromechanical manipulator between and behind the beam systems. Adequate space between remote connectors shall be maintained to allow disconnection of any single remote connection without disconnection of surrounding connectors.

Adequate laydown space shall be provided for complete disassembly of a beam line within the maintenance cell.

1.2.5.3 Modular Design

The neutral beam system shall be designed to provide modular components to enhance the remote maintenance operation. Beam line components shall be removable from the TFTR cell as three basic modules:

- a. Source Filament,
- b. Source Assembly,
- c. Complete Beam Line.

These modular components are based on design lifetimes and complexity of the systems.

After removal to the maintenance cell, the beam line shall be capable of disassembly into the following lesser modules:

- a. Fast Valve,
- b. Calorimeter,
- c. Beam Dump,
- d. Bending Magnet,
- e. Cryosorption Assembly,
- f. Neutralizer Assembly.

Each of the above modules shall be capable of being removed and replaced by the remote tooling available in the TFTR plant or the remote tooling which will be included as a part of the neutral beam system.

1.2.5.4 Maintenance Downtimes

Downtimes for maintenance operations are closely tied to the frequency at which a given maintenance operation must be performed. Specified downtimes for operations which must occur in the TFTR cell are as follows.

- a. Removal and replacement of an ion source filament with an available spare unit. < 3 hrs
- b. Removal and replacement of an ion source assembly with an available spare unit. < 24 hrs (excluding source conditioning time)

- c. Removal of neutral beam line to maintenance cell. < 48 hrs
- d. Reinstallation of neutral beam line on TFTR device. < 120 hrs (excluding vacuum boundary leak detection, repair, and source conditioning time)

1.2.6 In-service Inspection

The neutral beam system shall be designed to include sufficient in-service inspection equipment and systems to determine location of vacuum leaks in the vacuum chamber, presence of water leaks in cooling systems, and existence of leaks through the tritium boundary where neutral beam systems penetrate the boundary.

1.2.7 Interfacing Systems

Interfaces between the neutral beam system and other tokamak systems shall be defined and provisions made to maintain interface control.

1.2.7.1 Torus

The neutral beam system interfaces with the torus at the absolute valve situated at the end of the neutral beam duct. Access to the torus is through a 30 x 70 cm clear opening which is defined by the inner dimensions of the torus duct at the intersection of the duct and the torus.

A torus duct can be shaped to accommodate the beam path within the constraints of the tokamak components. Access in the vertical plane is limited to a 70 cm clear opening centered on the equatorial plane at the location of the equilibrium field windings which are located at a 4.7 m radius. Access in the horizontal

plane is determined by the TF coils and is dependent upon the beam aiming point and location of the torus vacuum pump.

Relocation of the beam aiming point requires repositioning of the torus duct.

The size of the absolute valve which serves as the neutral beam system interface and the dimensions of the torus duct will be determined by the neutral beam system design.

1.2.7.2 Torus Vacuum System

A drift space exists for the neutral beam from the last absolute valve on the beam line into the torus vacuum vessel. The size and geometry of this duct is dictated primarily by the contour of the injected beam. It is also directly influenced by the 70 cm x 30 cm injection window into the torus. The end of the duct opposite the injection window must make a hard vacuum seal to the absolute valve which interfaces between the beam line and the torus. Since this duct also serves as a location for part of the torus vacuum system, allowance on the side or bottom of the duct must be made for a suitably sized mercury diffusion pump.

The outlet of this diffusion pump must tie into a tritium scavenging system to store the tritium off gas. This system shall be linked to the beam line cryosorption panel regeneration pump.

1.2.7.3 Cooling Water

The cooling water of the TFTR beam line shall interface with the TFTR process cooling water system in two

places. There will be an interface with the demineralized water system to fill the cooling system and provide makeup water, and an interface with the cooling tower water through the necessary heat exchangers.

1.2.7.4 Remote Maintenance

Interfaces between the neutral beam system and the remote maintenance system are included in the design of beam line components which must be remotely maintained. These include remote vacuum flanges, electrical, coolant and gas connections, and instrumentation leads.

Design of these connections shall be consistent with the available handling equipment in terms of access, type of connections and prime movers. This requires the use of captive bolts, alignment devices, and automated remotely operable devices in locations where either access or viewing is restricted. All remote handling features shall meet the requirements specified in the TFTR Remote Handling Guide.

1.2.7.5 Tritium Handling

The gases adsorbed on the cryosorption panel during operation of the beam line must be removed periodically to restore the panels pumping ability. The gas will be very slightly (max. $\sim .15\%$) tritium contaminated after the first pass through the system. This small tritium content requires that the gas be treated as if it were all tritium.

To fulfill the storage requirement for tritium, the gas must be converted into a stable form. The gas must therefore be reacted in a manner to give a solid product.

1.2.7.6 Fueling Gas Handling

The deuterium gas to the neutralizer cells and to the sources should be supplied at some positive gauge pressure (1 to 25 psig) to insure against electrical discharge and air inleakage. Since the sources operate at greater than 100 kilovolts, the gas supply to each source shall be insulated from ground.

The sources each require approximately 33 standard cubic centimeters of deuterium gas per injection and each neutralizer cell will require 17 standard cc. Total gas requirement for a 500 millisecond injection pulse will be 150 standard cubic centimeters of deuterium by each beam line.

1.2.7.7 Plasma Driving and Confining Coils

Neutral beam components shall be arranged in a configuration which allows positioning of the beam to aim the beam at the prescribed radii without producing interference with the tokamak coils. Access between the coils and outer boundaries are given in SDD-23 and SDD-24 which cover the TF and EF-OH coil assemblies respectively.

1.2.8 Quality Assurance

The quality assurance (QA) requirements for design, construction, test, and operation of the system shall comply with the Quality Assurance Program Plan.

1.2.9 Codes and Standards

A list of codes and standards to be applied to the system design, construction, and operation and to the individual components of that system will be included when complete.

2.0 DESIGN DESCRIPTION

2.1 General

The Neutral Beam Injection System is a part of the Tokamak Fusion Test Reactor (TFTR) being built at Princeton Plasma Physics Laboratory. Other major systems of the TFTR which are directly related to the Neutral Beam System are the Neutral Beam Pulsed Energy Conversion System (SDD-72), which provides the power for the beam system; the Neutral Beam Control System (SDD-73), which provides controls for the neutral beam components; the TF-EF-QH coil assemblies (SDD-23 and 24, respectively), which establish the allowable access for the neutral beam duct; the vacuum vessel (SDD-21), which identifies the beam access to the plasma; auxiliary systems (SDD-43, -47, and -57), which define remote maintenance; and service systems, which provide the required services to the neutral beam injection system.

The neutral beam injection system is based upon the generation of deuterium ions by passing an electric arc discharge through low pressure deuterium gas to form a plasma within the source, extracting the deuterium ions through an electric field, accelerating the ions to the specified energy, and neutralizing a fraction of the ions by providing a suitable gas target line density for charge exchange. This results in a beam of energetic neutral particles which can penetrate the confining magnetic fields of the tokamak.

The system includes the necessary subsystems to provide adequate pumping speeds, gas handling capability, control of the energetic ions and measurement of the beam's energy.

The TFTR device will be equipped with four neutral beam lines each of which is equipped with three sources. Total injected power to the plasma including the half energy component of the beam will be ~ 28 MW.

2.2 Detailed Design Description

2.2.1 System Arrangement

The neutral beam system is composed of four beam lines attached to the fixed half of the tokamak as shown in Fig. 2.1. Each beam is aimed at a point within the plasma tangent to either a 270 cm radius for Mode I or a 220 cm radius for Mode II operation of the TFTR. Reaiming of the beams requires the disconnection of the mating flange between each beam system and the absolute valve on the torus duct. The beam system is then moved away to allow access to the torus duct which must be replaced to provide access to the new aiming point. The beam system can then be reattached to the torus duct.

Each beam line is composed of an arrangement of the beam components within a vacuum enclosure designed for maximum performance by keeping the distance from the ion source to the plasma as short as possible. This is achieved by placing the components in a logical sequence as close to each other as functionally possible and by providing the required cryo-sorption pumping area by increasing the height of the chamber rather than length. The arrangement is shown in schematic form in Fig. 2.2.

The three sources are placed at the rear of the chamber mounted on a flange vertically one above the other. This allows the three beams to be in the same vertical plane, thus tangent to the same radius of the torus.

There is a neutralizing gas cell for each source. The three gas cells are also mounted on a removable flange which fastens to a bulk head within the vacuum chamber. This bulk head is made of stainless steel clad mild steel and forms a magnetically shielded box around the gas cells and the exit of the sources.

FIG. 2.1 PLAN OF FOUR BEAMLINES

FIG. 2.2 ELEVATION OF TFTR BEAMLINE

Such a shield is necessary to permit the ions to travel through the gas cells in a straight line unaffected by the magnetic fields generated by the tokamak. The distance from the source to the entrance of the gas cells has to be sufficient to allow most of the source gas to be pumped away to prevent premature charge exchange of the ion beam within the accelerator structure and to allow the remainder of the vacuum enclosure outside of the magnetic shielded box to be pumped down through the gas cells by a twenty-four inch mercury diffusion pump.

Immediately after the exit of the gas cells, the beams pass through the magnetic field of the iron core bending magnet. This magnet is made in halves and is placed in cavities in the outside of the vacuum enclosure. The magnet return path is inside the vacuum chamber, but the magnet itself is supported by rods in the exterior cavities on each side of the chamber.

The beam dump is directly below the field produced by the bending magnet. It is installed from the same direction as the sources after the cryopanel structure is installed.

The calorimeter is coupled to the vacuum chamber by means of a flange at the top. The calorimeter is movable in the vertical direction so that it can be positioned to intercept the beams or retracted out of the path of the beams. The vacuum integrity is maintained by bellow joints at the interface between the calorimeter and the flange.

The fast valve is located between the calorimeter and the absolute valve which separates the beam vacuum chamber and the duct to the torus.

Each complete beam line is designed to be self-supporting as an integral unit which can be removed to a maintenance cell. It is supported by a structure which allows precise movement of the beam system normal to the mating flange on the absolute valve. This allows the beam system to be positioned for makeup of a hard seal closure on the mating flange or a remote weld joint.

Services to each neutral beam line are provided by a common service module located between each pair of neutral beam lines as shown in Fig. 2.1. Utilities, controls, and gas handling systems are connected directly to the neutral beam lines with connectors designed for remote operation utilizing the remote handling equipment provided in the TFTR cell.

Auxiliary subsystems are located either in the basement below the TFTR cell or in adjoining equipment bays within the TFTR plant. Penetrations through the tritium confinement boundary require the use of sealed service lines. Fluid service lines must be provided with valves to allow sealing during maintenance periods when services must be disconnected from the beam system.

2.2.2 Operating Sequence

The partially assembled beam line is transferred from the maintenance cell to the proper location in the operational cell. The front flange seal is then remotely made up. Other water, vacuum, and electrical remote connections necessary to pump down the beam line are then connected.

The mechanical pumps and associated traps are made operational. The diffusion pump assembly is pumped down and started after leak checking.

The mechanical pump is used to rough the beam line down from air. The diffusion pump is used to reduce the pressure to a level where the beam line can be verified leak tight by proper leak checks.

Remote connections to all other locations are made after leak checks have been made.

Hot helium gas ($\sim 300^{\circ}\text{C}$) is circulated through the cryosorption panels to condition them, and diffusion pumping continues to $\sim 5 \times 10^{-6}$ torr. The hot gas flow is then stopped.

Water cooling to all locations in the beam line exposed to liquid nitrogen surfaces should now be turned on. This will prevent ice formation in cooling passages.

Liquid nitrogen flow into all thermal shields and chevrons now commences. After cooling to ~ 100 K, the diffusion pump is valved off. The helium refrigeration is then started to the chevron assembly. When the chevron temperature reaches ~ 20 K, the cryosorption panel is also cooled and both should reach ~ 15 K.

The bending magnet is energized and the supply of deuterium to the ion source and neutralizer cell pulse valves is turned on. The beam line is now ready for source operation.

With the calorimeter in place, the ion sources are conditioned. After the sources are operating at the proper voltage, current and pulse length, injection into the torus is possible.

The absolute valve between the beam line and the torus is opened. The calorimeter is retracted out of the beam path. The fast valve is pulsed to open at the time the source injects into the torus and close afterward. The absolute valve is

closed and the calorimeter is moved into position if any tuning pulses of the sources are required.

2.2.3 Operating Data

During normal operation, the operating data for the neutral beam system are as given in Table 2.1.

Table 2.1 Operating Data

	120-keV	150-keV
Ion Current Per Source (Amperes)	55	44.0
D ⁺ Per Source	44	35.2
D ₂ ⁺ Per Source	11	8.8
D ⁰ at Rated Energy (As Amperes)	17.6	10.1
D ⁰ at Half Energy	14.5	10.3
Total D ⁰ to Torus (Calorimeter)	25.3	20.44
D ⁺ to Dump at Rated Energy	26.4	25.1
D ⁺ to Dump at Half Energy	7.5	7.3
Gas Loads Per Source (torr-liters)		
Un-ionized Gas	10.6	8.8
Gas to Neutralizer Cell	20.0	20.0
Gas to Beam Dump	6.5	6.5
Gas to Torus (Calorimeter)	6.2	4.1
Total Gas Per Source	43.3	39.4
Pressure in the Pumping Regions (torr)		
Source Region	2.5×10^{-4}	2.3×10^{-4}
Beam Dump Region	2.5×10^{-5}	2.5×10^{-5}
Calorimeter Region		
Beam on Calorimeter	3.1×10^{-5}	2.1×10^{-5}
Beam into Torus	5×10^{-6}	5×10^{-6}
Water Flow Through Calorimeter	2000 gpm	2550 gpm
Water Pressure Drop Through Calorimeter	~ 50 psi	50 psi
Peak Power Density of Neutral Beam in Plasma (at 9 m from source)	2.761 kW/cm ²	2.683 kW/cm ²
Peak Power Density of Total Beam at Calorimeter	27.5 kW/cm ²	27.5 kW/cm ²
Effective Power Density at Calorimeter (Taking geometry of calorimeter into account)	0.96 kW/cm ²	0.96 kW/cm ²

2.2.4 Performance Characteristics

2.2.4.1 Vacuum System

The operational performance characteristics¹ for the vacuum pumping system are described by the gas load and pumping speed in each compartment and the conductances between them. The partial pressure of each gas species and total pressure in each compartment vs time is presented for pulsed operation. Figure 2.3 is a simplified schematic identifying the gas loads and pumping speeds in each system compartment.

During pulsed operation, the fast valve and ion source gas valve are cycled open and the neutralizer gas source is turned on prior to pulsing the beam. The ion source is electronically turned off to terminate the beam pulse. The fast valve and ion source valve are closed and the neutralizer gas source turned off. A typical time sequence for pulsed operation is given in Fig. 2.4.

To check out the neutral beam injector, a calorimeter is positioned in front of the fast valve in Chamber 2 to stop the beam. When the beam is pulsed, a gas load due to the neutral beam is produced in Chamber 2 and a gas load due to the deflection ions appears in Chamber 3. Figure 2.5 gives the pressure-time variations for each gas species in each injector compartment for the operating sequence in Fig. 2.4.

When the neutral beam is injected into the torus, the pressure time variation in each injector compartment is given in Fig. 2.6. There are 2.15×10^{18} (~ 0.06 torr-liters) molecules of tritium that "backstream" into the injection system.

FIG. 2.3 VACUUM SCHEMATIC OF TFTR BEAMLINE

FIG. 2.4 TFTR BEAMLINE VALVE SEQUENCE

FIG. 2.5 PRESSURE RESPONSES FOR 0.5-SECOND INJECTION PULSE ON CALORIMETER

FIG. 2.6 PRESSURE RESPONSE FOR 0.5-SECOND INJECTION PULSE WITH CALORIMETER RETRACTED

2.2.4.2 Regeneration of Cryosorption Surfaces

The volume of gas collected on the cryosorption panels before regeneration is controlled by two criteria: (1) the maximum amount of gas allowed to be stored on the panels and (2) the time allocated for regeneration.

In order to avoid the potential for development of an explosive concentration of hydrogen isotopes⁸ should a vacuum failure occur, the maximum volume of gas adsorbed on the panels is 1.1×10^6 torr-liters. This represents $\sim 14,000$ pulses of the beam line or 140 hours of normal operation. Using the secondary vacuum system it would require ~ 5 days to pump out this gas volume.

A more reasonable approach might be to regenerate the pumping surfaces over a 48 hour weekend. Normal operation for ~ 80 hours could be pumped away in this regeneration period.

To accomplish this regeneration, the secondary vacuum system must be started. The fore vacuum pump must evacuate the foreline, the diffusion pump and other piping to the getter assemblies or the gas recycle system.

When the diffusion pump is pumped down to an acceptably low level ($\sim 5 \times 10^{-6}$ torr) and all the associated liquid nitrogen traps are cold, the mechanical pump is valved out and the proper gettering assembly is valved into the system. Then the gate valve into the beam line is opened and the cryosorption panel temperature is raised slowly. Evolved gases are pumped into the gettering material by action of the diffusion pump.

The cryosorption material should be sufficiently regenerated after its temperature has reached ~ 50 K under 5×10^{-6} torr conditions. The gate valve will then be closed and the panels cooled to 15 K once again.

The diffusion pump will be allowed to run and the getter continue to pump until the pressure in the fore line piping reaches 5×10^{-6} torr. The tritium content of the desorbed gas is expected to be .15% maximum on the first recycle. If one assumes the volume of the pumps, traps, and piping in the system to be ~ 1000 liters, then the total tritium contained at 5×10^{-6} torr would be

$$\begin{aligned} V_{TR} &= (5 \times 10^{-6} \text{ torr})(1000 \text{ liters})(0.15\% \text{ tritium}) \\ &= 7.5 \times 10^{-6} \text{ torr liters} \end{aligned}$$

The pressure in the foreline is then raised to 1×10^{-4} torr by introduction of deuterium; getter pumped again to 5×10^{-6} and the sequence repeated a second time. The tritium content of the system is now 1.9×10^{-8} torr-liters. This represents a tritium activity of $6 \times 10^{-2} \mu\text{Ci}$. If the system is let up to atmospheric pressure with nitrogen, the volumetric activity is $6 \times 10^{-8} \mu\text{Ci/Ml}$. The system could then be mechanically pumped back down and the pump exhausted into the off gas stream from ventilation fans.

2.2.4.3 Recycle of Tritiated Deuterium Gas

Recycle of gas from a beam line is initiated by regeneration of the cryosorption pumps as described in Section 2.2.4.2.

The gas pumped from the beam line is introduced into the uranium gettering trap shown in schematic form in Fig. 2.17. The gas is allowed to react at optimum temperature ($< 100^{\circ}\text{C}$) and come to equilibrium. The uranium in the trap will be two to four times the stoichiometric quantity to react the gas volume being recycled. When equilibrium is reached, the trap is isolated from the pumping system. Any gas remaining in the foreline is pumped by high vacuum getters as previously described.

Valves are opened to connect the trap to the previously evacuated gas storage tank which is maintained at 77 K. The uranium is dehydrided by heating to $\sim 500^{\circ}\text{C}$ and the gas driven into the tank. When equilibrium is reached, the valves between storage tank and the uranium trap are closed. Any gas remaining over the uranium will re-react as the temperature is lowered.

The storage tank is warmed from 77 K to increase the deuterium pressure sufficient for use by the gas handling system for sources and neutralizer cells.

2.2.4.4 Calorimeter

The calorimeter is designed to withstand the heat load of the total beam. Normally only the neutral portion of the beam would reach the calorimeter, but there may be instances when the beam would be pulsed without the bending magnet being in operation. The beam power at the source is 6.6 MW with an approximately uniform distribution of about 13.4 kW/cm^2 . Based on an assumed $\pm 1^{\circ}$ divergence and a peak power density at any distance "x" from the source equal to

$$\frac{I_0}{R^2(1 - \frac{x}{f})^2} \left[1 - \exp(-R^2(1 - \frac{x}{f})^2/a(x)^2) \right]$$

where I_0 is the total beam power, R is the radius of the beam, f is the focal distance of the beam, and $a(x)$ is the $\frac{1}{e}$ half width of the beam, with the focal point located at 5.85 meters from the source the peak power density at the calorimeter, which is located at 5 meters from the source, is 27.5 kW/cm^2 . If for some reason, either intentional or due to some unforeseen operating conditions, the focal point should change, the power density at the calorimeter would change. The power density varies from 27.5 kW/cm^2 to 22.5 kW/cm^2 as the focal point goes from 5.85 m to 9 m. The calorimeter is designed to dissipate the heat from the beam focused within this range. The peak power density of the beam also varies substantially as a function of the distance from the source with the beam focused as a given point. The beam peak power density for a focal distance of 5.85 meters reaches a maximum value of 41.9 kW/cm^2 at a distance of 3.2 meters from the source. The location of the calorimeter in such a region of high power density would have required a cooling water flow rate of approximately 5000 gpm.

The calorimeter is designed using copper swirl tubes at an incident angle of 2° to the beam at the center of the target, which increases near the fringes where the power density decreases. This increases the area the beam acts on, thus reducing the power density of the total beam to an effective value of approximately 1 kW/cm^2 with the beam focal point at 5.85 meters from the source.

The design is based on experimental heat transfer, burnout, and pressure drop data for water in swirl tubes presented in ORNL-2911.³

Using these data and the 27.5 kW/cm^2 power density, the calorimeter requires 3000 gallons of water per minute during each beam pulse. The surface temperature of the copper swirl tubes reaches 300°C .

The temperature rise for a water flow of 3000 gallons per minute during the .5 second pulse of 6.6 MW beam is 8.4°C .

The erosion of the copper tubes due to sputtering limits the life of the calorimeter to $.0565/S$ years where S is a function of the product of the peak flux density and the incident angle.⁴ If the product S goes to a maximum of 5×10^{-3} , the life of the copper tubes would be 11.3 years with a duty cycle of .5 seconds out of every 5 minutes.

2.3 Component Design Description

2.3.1 Ion Source Assembly

The DuoPIGatron ion source was developed at ORNL for use in neutral beam injection plasma heating. The 120-kV version shown in Fig. 2.7 will be developed on the 150-kV beam test stand now under construction. This source is an extension of the one developed for use on ORMAK which has been proven highly reliable.

The source is divided into three subassemblies to make the system more accessible and easier to assemble. The top assembly contains the cathode, which consists of a tantalum wire heater with emission carbonates coated on a support gauze. The tantalum filament will be removable as a unit with a remote manipulator. The deuterium gas feed to the source is also connected into the filament support flange.

FIG. 2.7 ION SOURCE ASSEMBLY

The second subassembly contains the intermediate electrode, magnet coil, and anode. The intermediate electrode is ferro-magnetic. This electrode shields the cathode region of the source from a magnetic field and shapes the magnetic field produced by the coil in the discharge region, compressing the arc discharge for greater ionization. The anode is water-cooled copper which terminates the ionizing arc discharge.

The third subassembly contains the four electrode acceleration system. The anode and target cathode operate slightly positive with respect to the intermediate electrode and is optically aligned with the accelerating electrodes. The electrodes are copper, water-cooled around the periphery and also across the electrode. They are drilled in a programmed offset hole pattern of about 50% transparency and steer all individual beamlets to a common focal point.* The insulators are fluted Al_2O_3 with metal terminations. The assembly is welded or brazed together to avoid elastomer seals.

The entire source assembly may be remotely disconnected and removed from the beam line.

2.3.2 Neutralizer

The neutralizer cell is a water-cooled copper tube two meters long. The tube is OFHC copper 30 cm inside diameter with approximately 10 mm wall thickness. The tube is cooled by a 1/2 inch O.D. copper cooling line brazed on it. The heat capacity of the tube is adequate for short incidence of 3 MW which is half the source output power. The cooling is sized for a steady-state load of 1.2 MW corresponding to 80% transmission of the 6 MW beam through the gas cell.

The neutralizer cells are individually mounted on an assembly flange which is installed in the beam line. This is done for ease of remote assembly and maintenance.

*The exact voltages applied to each electrode as well as the total number of electrodes remain to be determined in the source development program.

The purpose of the neutralizer cell is to furnish a high pressure region in which the energetic ions can charge exchange and form high energy neutral particles. To accomplish this, neutral gas is injected in the center of the gas cell and allowed to drift out the extreme ends. Twenty torr liters per second of gas will be injected into the cell.

2.3.3 Ion Removal System

The ion removal system is composed of the bending magnet and a beam dump.

The design parameters for the bending magnet are shown in Table 2.2. The magnetic field is generated by copper tape wound coils interleaved with fiberglass insulation. Six of these 250 turn coils are used to create the 90,000 ampere turns required for the 3 kilogauss field needed for 150-keV D^+ beams. Water cooling paths are placed between coil pancakes to dissipate the ~ 25 kilowatts of heat generated when the magnet is energized. An adjustable power supply makes it possible to deflect either 150-keV or 120-keV deuterium ions into the same location in the beam dump. The field produces a parallel beam of charged particles.

Table 2.2

Bending Magnet Parameters	
Deflection Angle	
Full Energy D^+	70°
Half Energy D^+	105°
Entrance and Exit Angles	$45^\circ \pm 4^\circ$
Pole Gap	35 cm
Pole Width	20 cm
Pole Length	200 cm
Field Strength for 120-keV D^+	~ 2.7 kG
Nominal Bending Radius	
Full Energy D^+	35 cm
Half Energy D^+	25 cm

The beam dump consists of four parallel tube arrays of a type similar to that shown in Fig. 2.10 for the calorimeter. The design parameters for the beam dump are summarized in Table 2.3. The primary beam dumps are sized for a fault condition by which the total beam is deflected to the dump. The three half energy beams are accepted on one tube array.

The beam dump is removable as an assembly after removal of the mercury diffusion pump.

Table 2.3

Beam Dump Parameters	
Tube Array	1/2 inch I.D. copper swirl tubes
Tubes per Array	42
Total Tubes	168
Nominal Water Flow per Tube	17.5 gpm
Total Water Flow	3000 gpm
Pressure Drop across Tubes	100 psi
Temperature Rise in Water	< 10°C

2.3.4 Cryosorption Pumping

The requirements for pumping speeds approaching 3×10^6 liters per second indicated a choice of either cryosorption or cryogenic pumping. Cryosorption was the choice for the reference design because of three principle factors. First, the apparent ease of regeneration by warming the panel slightly to ~ 50 K. There is no problem from storage or awaiting boil-off of liquid helium when regenerating. Second was the reduced refrigeration requirement. The refrigerator size requirement and operating cost at 4.2 K is three to four times that required at 15 K using equivalent pumping arrangements. The third is possible evolution of pumped gas due to neutron heating of panels during a pulse.

The geometry for the pumping panels is shown in Fig. 2.8. The array consists of two chevrons of Clausing factor⁹ 0.25 cooled to 77 K and 15 K, the cryosorption panel at 15 K and a 77 K thermal shield between the panel and the outside wall. A conservative pumping speed of 5 liters per second per square centimeter of incident area was calculated for this array.

The liquid nitrogen cooled chevron serves as a radiant heat shield and as a mechanism for cooling down the gas particles before they reach the cryosorption panels. The accommodation coefficient⁵ for hydrogen on a 77 K surface is 0.5 which indicates a molecule will statistically lose half of its energy in a single collision with the surface. A molecule will bounce several times while migrating through this chevron and therefore should essentially reach an equilibrium with the temperature of the chevron array.

A second chevron assembly between the cryosorption panel and the liquid nitrogen chevron is cooled to 15 K. The accommodation coefficient for hydrogen on a 15 K surface is ~ 1 so all molecules leaving the 15 K chevron that will reach the cryosorption panel are at panel temperature. The sticking coefficient of the particles on the molecular sieve panels will then be essentially unity.⁶

Based on the foregoing estimates, the pumping requirements for the three regions of the beam line are shown in Table 2.4. The expected pressures generated during an injection into the torus are also tabulated.

FIG. 2.8 TYPICAL SECTION THRU CRYOSORPTION PANELS

Table 2.4 Pumping Requirements

Region	Pumping Speed	Pump Area	Pressure
Source	2.5×10^5 l/sec	5 sq meters	2.4×10^{-4} torr
Beam Dump	2×10^6 l/sec	40 sq meters	2.3×10^{-5} torr
Calorimeter	6×10^5 l/sec	12 sq meters	5×10^{-6} torr

2.3.5 Vacuum Enclosure

The vacuum enclosure consists of the vacuum chamber, two absolute valves, and all component mounting or access flanges that penetrate the vacuum chamber.

The vacuum chamber itself is a box 5 meters x 5.35 meters x 1.5 meters fabricated out of 19 mm thick 304 L stainless steel plate and reinforced with type 304 L stainless "T" section ribs. This box is the primary structure for the beam line. All the components mount to this box. The chamber withstands the atmosphere pressure load outside the box with a maximum deflection of 10 mm.

The vacuum chamber is divided into two distinct sections by a bulk head of mild steel clad with stainless steel. The smaller section of the chamber will be called the source compartment since this is the area of the enclosure to which the sources attach. The stainless steel clad mild steel bulk head provides a mounting surface for a flange containing the three neutralizing gas cells. These gas cells are installed from the rear using remotely operable hardware. The bulk head serves as a magnetic shield. A support structure for cryopanel is installed in the source chamber on a series of roundway bearings. The coolant connections for the cryopanel and coolant plus gas connection for the gas cell are arranged on flanges which mate with the flange supporting the sources. The source flange containing all three sources is installed next. Since this flange and the coolant flanges which mate

to it form boundaries for the vacuum environment, the seal must be a hard seal. The remaining opening of this chamber is for a 24-inch absolute valve. This valve provides a hard seal between the vacuum chamber and a mercury diffusion pump.

The larger compartment of the vacuum chamber encloses the beam dump, a large cryopanel structure, calorimeter and a fast valve.

The large cryopanel support structure is installed from the opposite end of the chamber from the sources. This end of the chamber is open. The cryopanel support structure is supported on roundway bearings. The coolant connections for the cryopanel mate with the back surface of the box on a flange which must make a hard seal. The beam dump is installed next through an opening beneath the 24-inch absolute valve for the mercury diffusion pump. The beam dump flange must provide a hard seal with the vacuum chamber. The calorimeter actuators are mounted on the outside of the box. The fast valve mounts directly to the cryopanel support structure.

The open end of the chamber is closed with a large remote flange. This flange has the ability to be removed by utilizing a remotely operated set of impact wrenches (shown in Fig. 2.9) traveling on a track located on the flange itself. The interface between the vacuum chamber and the remote flange must provide a hard seal.

The final opening in the vacuum chamber is located on the remote flange. This opening is closed with an absolute valve which protects the vacuum in the torus from the atmosphere in the beam line during the pump down time or at any time the beam line must be removed or replaced or during regeneration of the cryopanel.

FIG. 2.9 REMOTE FLANGE AND TOOL

The vacuum chamber has four mounting rods for the bending magnet halves to be mounted on. The bending magnet halves fit into pockets located in the side of the chamber which do not penetrate the vacuum.

The vacuum chamber is structured so that it may be lifted from above using a crane.

2.3.6 Calorimeter

The calorimeter consists of three beam targets, one for each source. These targets are made into one assembly and the cooling water flows through all three in a parallel flow circuit. The entire assembly is supported by two actuators which lift the targets out of the path of the beam during injection.

Each target is made up of 42 copper swirl tubes arranged in two double row banks shown in Fig. 2.10. Each bank forms a panel which intercepts the beam at a 2° incident angle. The two panels intersect near the center of the beam so that when viewed from the side the target looks like a "V" laying on its side with the beam going into the open part of the "V". The geometry of the target is such that no part of the tubes is ever perpendicular to the beam. This allows the beam to be spread over as large an area as possible, which reduces the power density to $\sim 1 \text{ kW/cm}^2$.

The panels of swirl tubes are manifolded into a 3-inch diameter pipe at one end which bridges two supply pipes 5-inches in diameter, and into another 3-inch diameter pipe which bridges two 5-inch diameter discharge pipes at the other end. The flow in each target is from the apex of the "V" outward.

The two supply and discharge pipes are made of 304 L stainless steel. The supply pipes are welded into a single eight inch

FIG. 2.10 TYPICAL TARGET SECTION OF CALORIMETER ASSEMBLY

stainless pipe which penetrates the vacuum chamber. The discharge pipes weld to a similar eight-inch pipe which returns the water to the auxiliary cooling water system.

When the beam is pulsed on to the calorimeter, the heat is absorbed by the water flowing through the tubes. The temperature rise caused by this heat input is detected and converted to beam power data.

2.3.7 Fast Valve

The fast valve is a focal plane shutter type of device which is intended to limit the conductance between the vacuum in the beam line vacuum chamber and the vacuum in the torus and is shown in Fig. 2.11.

The fast valve consists of a .25 mm thick stainless steel belt with two rectangular openings, 82 centimeters by 65 centimeters. This belt is wrapped around two drums which are free to rotate. One drum is driven in order to align the two openings in the belt during injection and rotate the openings out of phase to close the conductance path. There are two idler drums or rollers which serve to hold the belt away from the calorimeter. The entire fast valve assembly with the exception of the vacuum chamber "feedthrough" and drive motor is mounted on a frame which can be attached and removed from the cryopanel support structure using manipulators and remote tooling.

2.3.8 Beam Line Support System

The beam line support system consists of a motor driven tow which allows a neutral beam system to be accurately positioned along a fixed set of rails which provide the necessary alignment for aiming the beam into the plasma. Repositioning the beam to aim at a different point within the plasma requires relocating the fixed track, which can be accomplished easily using only

FIG. 2.11 FAST VALVE ASSEMBLY

the overhead crane and manipulator. Alignment devices located in the floor will allow the tracks to be positioned accurately to the two predetermined aiming radii of 270 and 220 cm.

The tracks are hardened cylindrical rails upon which roundway linear bearings attached to the lower frame of the beam line vacuum enclosure operate. Alignment guides on the beam vacuum enclosure serve to position the linear bearings over the rails when the beam system is returned to the TFTR cell after maintenance. They also serve as stationary supports for the beam system when it is removed from the TFTR device in order to protect the linear bearings. Figure 2.12 shows the beam line support system. Design data for the support system are given in Table 2.5.

Table 2.5 Support System Data

Load	50 tons
Travel	1.75 m
Operating Speed	24 cm/min
Type of Drive	Ball screw powered by electric motor
Power	600 Watts

Engagement of the beam system with the motor driven tow is accomplished by lowering the tow attachment on the beam system onto a tapered drive lug on the support system. The drive lug is driven by a ball screw powered by an electric motor. Power requirements are such that positioning could be accomplished by the electromechanical manipulator, except that the manipulator is too valuable to devote to this operation when major maintenance operations are in progress.

An alignment system is required for positioning the beam system accurately for the physics experiments. Incorporation

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FIG. 2.12 BEAMLINE SUPPORT SYSTEM

of a driven positioning system is brought about by the requirement to make up a hard sealed or remotely welded joint between the beam line system and the absolute valve on the torus duct. Use of a hard seal requires that the beam system move normal to the flange on the absolute valve. Use of a remotely weldable flange requires both accurate alignment and normal motion which can be obtained with the beam support system.

Although it is not a part of the neutral beam system, a support system for the torus duct and absolute valve can operate on a similar set of rails supported from the same framework. The duct must be similarly accurately positioned to allow remote welding of the internal joint which couples the duct to the torus.

2.3.9 Radiation Shielding

Three facets of radiation shielding were investigated for the neutral beam injection system. These were shielding requirements to protect personnel from radiation resulting from neutron activation of beam line components, potential for radiation damage to beam line components from neutron irradiation and heat generation within cryosorption panels from radioactive decay.

One-dimensional radiation transport calculations have been made to estimate the effects of 14-MeV and 2.6-MeV radiation on the operation and maintenance of the neutral beam injector for the TFTR. Since only one-dimensional methods were employed, the results must be considered to be very approximate, but they should serve to enumerate the various problem areas and the magnitude of the radiation effects. A detailed discussion of these calculations is given in ORNL-TM-5068,⁷ and the approximate results are given below.

2.3.9.1 Unshielded TF Coil Heating and Activation

The time-averaged, volume-integrated energy deposition rate in the unshielded TF coils adjacent to the injector port will be in the range $851 \text{ W} \lesssim H_t \lesssim 5710 \text{ W}$.

The unshielded dose rate at one meter from the TF coil from the activated copper windings will be ~ 87.3 rem/hr. Four inches of lead reduces the dose rate to 0.16 rem/hr. This is the dose rate following 100-D-T pulses at time of shutdown.

2.3.9.2 Injector Structure Activation

The injector structure will be activated by 14-MeV neutrons. For a uniform wall thickness of 1.91 cm, the dose rate at 1.4 M from the front corner of the structure after 100-DT pulses and at zero time after shutdown will be ~ 218 millirem/hr. At 8 hours after shutdown the dose rate is 100 times lower due to the decay of ^{56}Mn ($T_{1/2} = 2.58 \text{ h}$).

To minimize the activation, it is recommended that the front surface of the injector be shielded from the 14-MeV neutrons by inserting or stacking as much neutron shielding material (borated-polyethylene plus lead) as possible. In addition, lining the surface of the injector with 25 mm of lead will reduce the dose rate at 1.4 M to ~ 0.5 millirem/hr. To limit the radiation dose to maintenance personnel working around the neutral beam system, the 25 mm thick lead shield will be provided on the exterior of the vacuum enclosure.

Design of the lead shielding will allow removal of all shield blocks on the top and sides of the vacuum enclosure prior to removing the neutral beam system

for maintenance. Total weight of the lead shielding on each neutral beam line amounts to approximately eleven tons.

2.3.9.3 Dose Rate to Injector Components

The dose rate from neutrons at the injector mechanism at 7 m from the port will be $\sim 4 \times 10^5$ mrad/pulse. For 2000 pulses, the total dose to the injector components will be $\sim 8 \times 10^8$ mrad. There is no damage anticipated for ceramic insulators.

2.3.9.4 Cryopanel Heating

Heat generation within the cryosorption panels from neutron bombardment amounts to 0.127 watts/cc from the 14-MeV neutrons and only 6.4×10^{-7} Watts/cc from the 2.6-MeV neutrons. Assuming an aluminum structure gives a 3.8 K temperature rise in the cryopanel for a 500 millisecond pulse. Since only the 2.6-MeV neutrons are present during conditioning pulses and plasma pulses occur only once every five minutes, heat generation within the cryosorption panel is not a problem.

2.3.10 Auxiliary Subsystems

2.3.10.1 Secondary Vacuum Subsystem

The secondary vacuum subsystem is shown schematically in Fig. 2.13. It consists of a set of mechanical pumps, Item 11, a diffusion pump, Item 8, getter assemblies, Items 10, and various traps and valves.

The mechanical pumps are pump-blower packages with rated speed of 130 CFM from air to 10 torr and 660 CFM from 10 torr to 10^{-1} torr. A typical pumpdown curve is presented in Fig. 2.14.

FIG. 2.13 SECONDARY VACUUM SUBSYSTEM

FIG. 2.14 TYPICAL PUMPDOWN CURVE

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The 24-inch mercury diffusion pump has a speed of 12,000 liters per second. The water-cooled baffle and liquid nitrogen baffle reduce the speed from the beam line to ~ 3000 liters per second. If a total outgassing rate of the order of 10^{-3} torr-liters per second is assumed then the beam line would pump down to the 10^{-6} torr range.

The getter assemblies are used to collect, in solid form, any tritium contaminated deuterium which is pumped from the beam line. These assemblies may be commercial zirconium-aluminum alloy getters or a uranium getter proposed for gas recycle. The getters are expected to pump the tritium contaminated gas in the vacuum piping to a level where any residual activity may be flushed into the facility offgas stream. The pumping speed of these assemblies is ~ 1400 l/s for hydrogen and 200 l/s for air. The foreline system exposed to pumping by the getters is bakeable so pumping to 1×10^{-6} torr is not unreasonable.

All pump inlets are trapped with liquid nitrogen to prevent migration of mercury or oil into the beam line or foreline piping. The outlet of the diffusion pump is trapped with liquid nitrogen to prevent mercury from migrating into the piping when getters reduce foreline pressure to 1×10^{-4} torr or less.

All valves in the foreline have metallic seats and seals. This prevents radiation damage and also guards against introduction of hydrogen into the gas stream from elastomers.

All piping assemblies are welded stainless steel or metal gasketed flanges. The piping is suitable

for ultra high vacuum service and will be pumped to $\sim 1 \times 10^{-6}$ torr by the getter assemblies.

2.3.10.2 Demineralized Water Subsystem

The demineralized water subsystem is shown schematically in Fig. 2.15. It is designed to take out the high heat loads input in pulse form at a repetition rate of one pulse of .5 seconds duration every five minutes (normal rate) or one pulse of .5 seconds every thirty seconds (conditioning rate). The cooling water flow rate required to prevent damage to the beam line components is high due to the high peak power densities. To provide the required flow rates continuously would require enormous pumping equipment, therefore, the subsystem is designed to provide pulsed flow at the same rates as the beam is pulsed.

The conditioning pulse rate will only be used on one beam line at a time. A separate pumping system is required to provide the flow rates at the thirty-second frequency, but since it will be used in only one beam line at a time the components can be smaller than if it had to provide the flow to four beam lines simultaneously. The pumping scheme shown in Fig. 2.15 is the system required for the half-second pulse every five minutes. The system for the thirty-second frequency is similar except for component sizes. The thirty-second pulse repetition system is capable of being valved to any one of the four beam lines on the tokamak or one unit on the test stand located in the maintenance area.

Both systems provide continuous flow as well as the pulsed flow. This is necessary to prevent the formation of ice in the cooling tubes of components exposed to

FIG. 2.15 DEMINERALIZED WATER
SUBSYSTEM SCHEMATIC

77 K cryosurfaces between pulses and to accommodate the thermal inertia of the neutral beam system.

The pumping system for the five-minute repetition pulse rate provides 32,092 gpm during each pulse to four beam lines and 8023 gpm continuous flow to four beam lines. The pumping system for the thirty-second repetition pulse rate provides 8023 gpm during each pulse to one beam line and 2000 gpm continuous flow to the same beam line.

The entire demineralized water subsystem is a closed loop arrangement. It is connected to the TFTR process cooling-water system through four heat exchangers, two 660,000 Btu(h) and two 680,000 Btu(h) units requiring a total of 825 gpm of water at 85°F.

The demineralized water is pumped through these heat exchangers to a pressure vessel charged with gaseous nitrogen. At the beam pulse the water stored in the pressure vessel is released and allowed to flow through the beam lines at a high flow rate. From the beam lines the water flows to a reservoir then back through the heat exchanger. The continuous flow is provided by a circuit which has its own pump and no pressure vessels.

2.3.10.3 Liquid Nitrogen Subsystem

Heat radiation shields and chevron baffles for the cryosorption panels must be supplied with liquid nitrogen cooling. Operation of four beam lines will require ~ 8300 gallons per day. The projected cost and the uncertainty of a supply of this quantity of liquid nitrogen requires the installation of a recondenser to allow recirculation of the liquid

nitrogen. The cost of the recondenser will be offset by savings on purchased liquid in approximately two years.

The nitrogen recondenser makes use of the Philips-Stirling refrigeration cycle which has been used for many years in a wide range of cryogenic equipment. The machine has an efficiency of 42% relative to the Carnot cycle at 77 K. The recondenser has a capacity of ~ 345 gal/hour with input power of 610 kW.

Liquid nitrogen will be supplied from a remote storage tank through vacuum jacketed lines to a manifold inside the test cell. Metering valves control flow to the various panels. Gas is then returned back to the recondenser.

2.3.10.4 Helium Refrigeration Subsystem

The cryosorption pumping panels and the adjacent chevron assembly in the four beam lines are cooled to 15 K. The total heat load for these assemblies is expected to be ~ 1000 watts each.

A 2000-watt gaseous-helium refrigerator is shown schematically in Fig. 2.16. An auxiliary heater is included so that 300°C helium may be circulated through the cryosorption panels to condition them.

Transfer of the 15 K gas from the refrigerator is through 1-1/2" vacuum jacketed superinsulated lines. Manifolding to individual 1/2" lines is done inside the test cells with valves in each of the lines.

Power requirements for the refrigerator is ~ 290 kilowatts.

FIG. 2.16 HELIUM REFRIGERATION SUBSYSTEM SCHEMATIC

2.3.10.5 Gas Recycle Subsystem

During the conditioning of new ion sources, there will be a required high repetition rate for pulsing of the sources with a correspondingly large volume of gas to be handled. Although the neutral beam system would be operated during this phase as a closed system separated from the torus by the absolute valve, there will be some minute amount of residual tritium within the neutral beam system. Therefore, it may be necessary to trap all of the gas generated during the source conditioning phase as tritium.

Use of Zr-Al getters to trap the gas would require a substantial number of cannisters (~ 8) for 1000 source conditioning pulses. The added difficulties associated with remote replacement of these cannisters leads to the desirability of having a separate gas recycle system for the source conditioning phase. Since normally only one beam line would require conditioning at any time, the gas recycle system can be sized for a single beam line and the necessary valving provided to allow use on any of the four operating beam lines or on the beam test stand. An additional advantage of such a system would be that the normal operation injection system gas which is trapped in Zr-Al cannisters could also be recycled to avoid replacement of the getter cannisters. This section describes such a system.

The gas recycle module is connected directly to a beam line vacuum system and is used during the conditioning of an ion injector source. The system consists of a uranium trap to getter a deuterium-tritium gas mixture, a recycled gas holdup tank,

and the appropriate piping, monitors, valving, and instrumentation required to deliver measured quantities of gas back to the ion sources for the conditioning pulses. The system is illustrated in Fig. 2.17 and the equipment items are described in detail below. The D-T mixture gettered by the uranium trap contains trace quantities of tritium and can be recycled until the main line concentration approaches 5000 ppm maximum. An enclosure housing the D-T uranium trap contains an inert argon atmosphere to preclude the formation of explosive mixtures. The argon bleed flow from the enclosure will be piped to the TFTR Cell Treatment System prior to exhausting to the building stack. Where feasible, deuterium-tritium handling equipment will be designed, manufactured, and installed in accordance with ASME Section III, Class 3.

D-T Gas Recycle Subsystem Operation. The recycling of D-T gas mixtures begins by opening the valve between a beam line diffusion pump and the uranium trap, where gas mixtures will collect on the uranium trap. The temperature of the trap is varied to obtain the best combination of rapid absorption with minimum vapor pressure of hydrogen isotopes above the uranium at the end of the absorption period. The valves in the line connecting the uranium trap and the recycled gas holdup tank are then opened and the trap is heated to drive off the D-T gas mixture into the liquid-nitrogen cooled tanks. When 95 to 99% of the D-T mixture has been transferred, the trap is again isolated. The holdup tank is then heated to a temperature where the gas pressure is sufficient for return and reuse of the gas at an ion source. The uranium trap will be replaced when it collects too much O_2 and N_2 .

FIG. 2.17 GAS RECYCLE SYSTEM

When necessary, it will be valved off and removed from the glove-box enclosure. Automatic valves and monitors permit gas cycling operations to be conducted from a remotely located control room.

Uranium Trap and Enclosure. The uranium trap, or getter cannister, contains an agglomeration of powder prepared by heating depleted uranium hydride. The trap is enclosed in a glove box containing an inert argon atmosphere to preclude air inleakage into the trap and prevent the formation of explosive mixtures. Oxygen analyzers with appropriate alarms will be used to monitor the D-T gas and the glove box atmosphere for oxygen buildup which should be kept below 1%. In addition, automatic valves will be actuated to isolate the trap from a beam line and backfill with argon if oxygen is detected in the D-T gas mixture. Argon is piped to the glove box through a pressure controller maintaining the glove box at slightly above atmospheric pressure. A small flow of argon is bled from the glove box through an orifice to preclude oxygen buildup, and pressure buildup and surges are relieved through an automatic valve actuated by a pressure switch. A resistance-type bayonet or Calrod heater equipped with temperature control will be used to heat the trap to arrive at the proper hydriding and dehydriding temperatures. The trap cooling cycle following dehydriding can be shortened by lowering a furnace with electrically operated jacks installed in the box. Entry into the dry-box enclosure is through a vacuum air-lock. The use of a vacuum air-lock and vacuum pump serves to conserve argon by reducing the quantity of inert gas required to purge oxygen from the system.

2.4 System Interfaces

The neutral beam injection system interfaces with the TFTR device and plant in several areas. Interfaces of the Neutral Beam Pulsed Energy Conversion System and Instrumentation and Control System will be covered in SDD-72 and -73, respectively. Only mechanical interfaces with the TFTR device and plant along with power requirements for auxiliary systems will be covered in this section. Auxiliary systems will require a utility building as shown in Fig. 2.18.

2.4.1 TFTR Device

The neutral beam injection system's interface with the TFTR device is an adapter flange attached to the absolute valve on the torus duct. The torus duct and absolute valve are part of the vacuum vessel.

Absolute valve requirements are that it must provide a clear opening of 90 cm diameter to allow passage of the neutral beam from three ion sources when aimed at either the 270 or the 220 cm radius. The valve must provide a sealing surface for the front closure plate of the beam line and be capable of remote connection.

2.4.2 Remote Handling

Components and service connections for the beam line are designed to interface with the PAR Model 6000 electromechanical manipulator and remote tools specified in the TFTR Remote Maintenance Guide. The beam line itself interfaces with an overhead crane capable of lifting the beam line and moving it to the maintenance cell.

2.4.3 Tritium Handling

There will be gas desorbed from the beam line cryosorption pumps periodically. This gas will be recirculated back to the beam line if the recycle system is available for it.

He & LN₂ SYSTEMS

- A1 HELIUM COMPRESSOR
- A2 HELIUM COLD BOX
- A3 NITROGEN RECONDENSER
- A4 GHe STORAGE TANK
- A5 LN₂ STORAGE TANK

FOUR INJECTORS COOLING SYSTEM

- B1 CONTINUOUS FLOW PUMP
- B2 RETURN SURGE TANK
- B3 HEAT EXCHANGER PUMP
- B4 HEAT EXCHANGERS
- B5 BOOSTER PUMP
- B6 SUPPLY SURGE TANKS

SINGLE INJECTOR COOLING SYSTEM

- C1 CONTINUOUS FLOW PUMP
- C2 RETURN SURGE TANK
- C3 HEAT EXCHANGER PUMP
- C4 HEAT EXCHANGERS
- C5 BOOSTER PUMP
- C6 SUPPLY SURGE TANK

FIG. 2.18 BEAM LINE UTILITY BUILDING

If the recycle system is unavailable or if the tritium content is too high ($> 0.5\%$) the gas must be gettered for processing off-site. These getter cannisters should be processed with others from the torus pumping system.

A more acceptable interface will be a cross connection between the secondary vacuum system foreline and the foreline from torus pumps. This would allow the TFTR tritium handling system to getter the off-gas from a beam line. Redundancy for both gas handling systems would then be accomplished.

2.4.4 Demineralized Water

The beam line cooling system interfaces with the TFTR demineralized water system at two surge tanks. The total demineralized water required is 12,600 gallons for the surge tanks and pressure vessels plus the quantity to fill the plumbing and components. There will also be a continuous requirement for makeup water.

2.4.5 Cooling Water

Beam line cooling water interfaces with TFTR cooling tower water system at four heat exchangers two 660,000 Btu(h) and two 680,000 Btu(h) requiring a total of 825 gpm of water from the cooling tower.

2.4.6 Electrical

Table 2.6

Power Requirements of Auxiliary Subsystems Four Beam Line Operation	
Cooling Water	1460 kW
Liquid Nitrogen Recondenser	610 kW
Helium Refrigerator	290 kW
Secondary Vacuum System	120 kW
Gas Recycle	10 kW

2.5 Design Options

Conceptual design of any advanced system almost always results in design alternatives which must be further considered in the next design phase. Typically, design choices must be made without sufficient data or analyses. The situation is no different in the conceptual design of the TFTR neutral beam injection system. Several design options have been identified on which the final choice must await further data, analyses, funding limitations or results of development activities. Other options must be evaluated through the analysis of system reliability and maintenance operations. Some of the significant design options are:

2.5.1 Repositioning of Beam System

Use of an articulated beam line which would allow repositioning of the beam to aim at either a 270 or a 220 cm radii without requiring disconnection of the beam line. This option has the advantage of avoiding the long down times associated with the disconnection and reattachment of both the beam line and the torus duct and the associated downtime required to perform leak checks and repair vacuum leaks.

This option will require somewhat more space between OH/EF windings to the extent that no winding structure could be positioned on the equator side of the windings in their present location. A bellows would be required in the torus duct to allow it to articulate sufficiently to aim the beam at the desired radii. Similarly additional support system equipment is required to provide the angular motion of the beam system. The required torus duct design is shown in Fig. 2.19 and the support system is shown in Fig. 2.20.

The advantage of this design option is the increased flexibility of the TFTR device which allows a more efficient utilization of the device for physics research as opposed to testing remote systems.

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FIG. 2.19 FLEXIBLE TORUS DUCT

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FIG. 2.20 ARTICULATED BEAMLINE SUPPORT SYSTEM

2.5.2 Primary Vacuum Pumping System

High pumping speed requirements require the use of some type of cryogenic or getter pumping. The decision to use cryosorption pumping was based upon the ease of regeneration and less refrigeration load. However, the final choice between cryosorption and cryocondensing pumping system must await the results of cryopumping experiments being conducted by LBL, BNL, and ORNL.

Fortunately, the pumping speed selected for each of these types of pumps is almost identical $\sim 5 \text{ liters/sec cm}^2$, therefore the area provided within the neutral beam system will not change. There will be differences in the detail design of the cryopanel, helium transfer lines and the helium refrigeration system. With the present degree of detail in the conceptual design, it is difficult to speculate on differential cost between the two types of systems.

A third option for pumping the beam line might be SAES getter type pumping. Although introduction of the number of individual pumps required to approximate the $3 \times 10^6 \text{ liters/sec}$ needed appears unrealistic, panels of this type material might be fabricated and installed in the beam line. Large quantities of liquid nitrogen for thermal shielding and trapping would not be necessary nor would helium refrigeration. It should be pointed out that rather large power loads would be required to maintain pumping temperature ($250^\circ - 400^\circ\text{C}$ for hydrogen) or for regeneration ($\sim 750^\circ\text{C}$).

2.5.3 Calorimeter System

Since previous experience in the cooling of ion beam targets has been with forced cooling of the target directly, it was decided that the initial design should utilize a target which dissipates the energy of the beam directly on water-cooled swirl tubes. Another approach would be to design a target

which allows the beam to impinge upon a refractory material such as tungsten during the pulse. The tungsten would heat up during the pulse, then radiate to water-cooled tubes during the time between pulses. A target of this type would require an extensive development program.

Some advantages to a thermal inertia system as described above would possibly be a reduction in the required water flow rate. The water flow would, however, be continuous instead of pulsed as it is with the present system.

Without a more detailed study of both systems it is impossible to estimate the economic advantage of either system over the other.

2.5.4 Remote Flange

The conceptual design of the vacuum chamber employs a remotely operable hard seal flange between the absolute valve on the torus duct and the beam enclosure. Included with the remote flange are the required remotely operable impact wrenches to assemble and disassemble the flange. Remotely operable and positioned impact wrenches are required because the lower portion of the flange is inaccessible to the electromechanical manipulator. Inclusion of a hard seal flange of this type requires a development program to assure success.

An alternative would be to use a remotely operable welding machine which would complete a weld joint between the vacuum chamber and a flange on the absolute valve. This would require equipment similar to that presently provided for the makeup of a hard seal joint and would also require some development.

The differential cost between the two options cannot be determined without significantly more design effort but the complexity, number and type of components is comparable.

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Therefore, it is believed that the cost is also comparable. It is recommended that any development program aimed at developing a large vacuum flange for this system include both the hard seal and welded flange option.

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7. ORNL-TM-5068, "Neutraonics Calculations for the TFTR Neutral Beam Injectors," R. T. Santoro and R. G. Alsmiller, Jr.
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Appendix A. TFTR Neutral Beam Injection Drawings

DRAWINGS

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2. Typical Plan - Neutral Beam Line	M-E-14630-ET-002
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5. Ion Source Assembly	M-E-14630-ET-005
6. Neutralizing Cell	M-E-14630-ET-006
7. Cryosorption Panel Arrangement	M-E-14630-ET-007
8. Cryosorption Panel Support Frame	M-E-14630-ET-008
9. Calorimeter Assembly	M-E-14630-ET-009
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20. Beam Line Support System - Sheet 2	M-E-14630-ET-022
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22. Articulated Beam Line Support - Sheet 1	M-E-14630-ET-024
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25. Articulated Beam Line Support - Sheet 2	M-E-14630-ET-027

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Part I

PRELIMINARY QUALITY ASSURANCE
FOR FABRICITY AND COST EVALUATION
ONLY. DESIGN AND CONSTRUCTION WILL
BE IN ACCORDANCE WITH PROCEDURES
SPECIFIED IN THE THERMONUCLEAR
SYSTEM QUALITY ASSURANCE PROCEDURES
MANUAL.

TOLERANCES UNLESS OTHERWISE SPECIFIED		DES	UNION CARBIDE CORPORATION - NUCLEAR DIVISION	
FRACTIONS	1/16	DATE	ION SOURCE ASSEMBLY	
DECIMALS	0.001	CHK	TFTR NEUTRAL BEAM SYSTEM	
ANGLES	1/2	SEC	125 KV ION INJECTOR	
BREAK SHARP EDGES MAX.	0.005	DEPT & PLANT	TYPE	
A.S.		SCALE		1
UCC NO.		ID		REV
ENGR		DATE		M-E-14630-ET-005

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REFERENCE DRAWINGS	NUMBER
OAK RIDGE NEUTRONAL LABORATORY OPERATED BY UNION CARBIDE CORPORATION OAK RIDGE, TENNESSEE	
TETR NEUTRAL INJECTION SYS. 9-20	

ION SOURCE			
REMOTE CONNECTIONS			
START	STOP	APPROX	
M E 14630	ET 015		REV

PARTS LIST			
PART	QTY	NO.	RECD
DESCRIPTION			
STOCK SIZE			
MATERIAL			

PERMANENT QUALITY ASSURANCE
 THE MANUFACTURER AND THE INSTALLER
 SHALL BE RESPONSIBLE FOR THE QUALITY OF THE
 WORK AND THE CONSTRUCTION SHALL
 BE IN ACCORDANCE WITH THE MANUFACTURER'S
 SPECIFICATIONS AND THE INSTALLER'S
 SPECIFICATIONS.

REFERENCE DRAWINGS		NUMBER			
THE BUREAU OF METROLOGY OPERATED BY BUREAU OF METROLOGY CORPORATION ONE BUREAU, TOWNSHIP					
TFR 6000 SECTION 515					
SOURCE MANIFOLD					
M 21480 ST 010					

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PARTS LIST				
PART	DWG NO.	REQD	DESCRIPTION	STOCK SIZE MATERIAL

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REFERENCE CHANGES		NUMBER
Oak Ridge National Laboratory OPERATED BY ORNL-CORPORATION ONE OAK RIDGE, TENNESSEE		
TETR NEUTRAL INJECTION SYS		
BEAM LINE REMOTE SERVICE SCHEMATIC		
M. E. 14630	ET 017	

GENERAL SPECIFICATIONS		TOLERANCES		FINISHES		NO.		REVIEWS		DATE / APPD		APPRO	
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2. TOLERANCES ARE TO BE GIVEN BY DECIMALS		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
3. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
4. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
5. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
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7. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
8. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
9. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
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13. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	
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24. UNLESS OTHERWISE SPECIFIED		FRACTIONS		DECIMALS		INCHES		BY		DATE		DATE	

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BOLT SPACING	
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REFERENCE DRAWINGS		NUMBER	
Oak Ridge National Laboratory OPERATED BY Union Carbide Corporation OAK RIDGE, TENNESSEE			
TFTR NEUTRAL BEAM INJECTOR SYSTEM			PLATE NO.
VACUUM ENCLOSURE REMOTE FLANGE TOOL			
SUBMITTER		APPROVER	DATE
M E-14630 E T		OIB	8 NOV 68

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FERROGRANT QUALITY ASSURANCE
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DIVISION QUALITY ASSURANCE PROCEDURES
MANUAL.

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SK-JRN-081475

SN² / or /

PRELIMINARY QUALITY ASSURANCE
FOR FEASIBILITY AND COST EVALUATION
ONLY. BIDDING AND CONSTRUCTION WILL
BE IN ACCORDANCE WITH PERFORMANCE
SPECIFIED IN THE THUNDERBOLT/CLAS
GROUND QUALITY ASSURANCE PROGRAM
MANUAL.

PARTS LIST					
PART	DWG NO.	REQD	DESCRIPTION	STOCK SIZE	MATERIAL

	REFERENCE DRAWINGS	MUNSTER
	ONE RIDGE NATIONAL LABORATORY OPERATED BY UNION CARBIDE CORPORATION ONE RIDGE, TENNESSEE	
	TFTR NEUTRAL INJECTION SYS	BLIND NO.
	TORUS DUCT AND VALVE SUPPORT	
WFO REV		
DATE	DESIGNED	APPROVED
REV	ME 4630 ET 023	REV

PARTS LIST			
PART	DWG NO.	REQD	
DESCRIPTION			
STOCK SIZE			MATERIAL

PERMANENT QUALITY ASSURANCE
FOR PERMANENT AND BEST EVALUATION
ONLY. NO OTHER INSPECTION, ETC.
IS TO BE CONSIDERED AS A
SUBSTITUTE FOR THE PERMANENT
QUALITY ASSURANCE PROGRAM
PARTIAL

SKJRN-081275
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NOZZLE SUPPORT
BELLONS CONCEPT

REFERENCE DRAWINGS		NUMBER
ONE HUNDRED EIGHTY-ONE UNION CARBIDE CORPORATION ONE HUNDRED EIGHTY-ONE ONE HUNDRED EIGHTY-ONE		
TYPICAL INJECTION SYS		
ARTICULATED TORUS DUCT AND VALVE SUPPORT		
ME	14630	ET 025

UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN INCHES. ALL DIMENSIONS ARE TO FACE UNLESS OTHERWISE SPECIFIED. ALL DIMENSIONS ARE TO CENTER
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PARTIAL SECTION A-A

PARTIAL SECTION B-B

BELLOWS & FLANGE ARRANGEMENT (TCT)
SCALE 1:1
J. R. NICHOLSON 7-16-75

PROBABILITY QUANTITY ASSURANCE
AND PROBABILITY AND COST ANALYSIS
AND A. HANSEN AND ASSOCIATES, INC.
AN INTERNATIONAL FIRM
SPECIALIZING IN THE DESIGN AND ANALYSIS
OF STRUCTURAL AND MECHANICAL SYSTEMS
AND THE DESIGN AND ANALYSIS OF
STRUCTURAL AND MECHANICAL SYSTEMS

REFERENCE DRAWINGS		NUMBER
GAS TUBE NATIONAL LABORATORY		
OPERATED BY		
UNION CARBIDE CORPORATION		
ONE MOORE, YONKERS		
TCTE NEUTRAL INJECTION SYS.		100
ARTICULATED TORUS DUCT BELLOWS		
DESIGNED	APPROVED	DATE
J. R. NICHOLSON	J. R. NICHOLSON	7-16-75
ME 14630	ET 026	

GENERAL SPECIFICATIONS		REVISIONS	DATE	APPROVED	DATE
1. BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		1	7-16-75	J. R. NICHOLSON	
2. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		2	7-16-75	J. R. NICHOLSON	
3. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		3	7-16-75	J. R. NICHOLSON	
4. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		4	7-16-75	J. R. NICHOLSON	
5. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		5	7-16-75	J. R. NICHOLSON	
6. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		6	7-16-75	J. R. NICHOLSON	
7. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		7	7-16-75	J. R. NICHOLSON	
8. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		8	7-16-75	J. R. NICHOLSON	
9. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		9	7-16-75	J. R. NICHOLSON	
10. THE BELLOWS SHALL BE DESIGNED TO WITHSTAND THE FULL RANGE OF OPERATING PRESSURES AND TEMPERATURES.		10	7-16-75	J. R. NICHOLSON	

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Part I

TOKAMAK FUSION TEST REACTOR PROJECT

SDD-72

NEUTRAL BEAM PULSED ENERGY CONVERSION

SECTIONS I and II

SEPTEMBER 1975

Prepared by

UCC-ND Engineering

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ABSTRACT

The neutral beam pulsed Energy Conversion System (ECS) will take energy from a generator-flywheel distribution system at 13.8 kv, 3 phase, 60 Hz, and convert it to pulsed 120kv direct current to drive twelve (12) neutral beam sources.

Each of the neutral beam injection systems will consist of the following:

One reactor, one 13.8 kv circuit breaker, one variable transformer, one step-start vacuum interrupter, three identical transformer-rectifier assemblies, protective surge capacitors, series current limiting resistors, crowbar assemblies, three modulators, one source table, one decel supply, and one ion source.

Equipment is provided for controls and instrumentation as required for startup, normal operation, off-normal operation, infrequent operating modes, fault protection, overloads, and shutdown of each ion source.

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1.0 FUNCTIONS AND DESIGN REQUIREMENTS

1.1 Functions

The overall function of the Energy Conversion System (ECS) is to supply 80 MW total grid #1 power for TFTR injectors. This injection power will be distributed between twelve (12) neutral beam systems, each of which will consist of the following components with the listed specific functions.

1.1.1 Reactor

A reactor will be installed in the 13.8 kv line ahead of the circuit breaker to reduce the short-circuit current, allowing a 750 MVA breaker to be used.

1.1.2 13.8 kv Circuit Breaker

The circuit breaker will provide overload protection for the variable transformer, short circuit interrupting duty for faults ahead of the vacuum interrupter, and isolation from the 13.8 kv system.

1.1.3 Variable Transformer

The transformer will provide a means of varying the supply voltage to the ion source over a wide range allowing pre-conditioning pulses to be started at low voltage levels and gradually increased to the selected injection voltage.

1.1.4 Vacuum Interrupter

The interrupter will be a step-start type with the first step designed to limit the inrush current of the rectifier transformers through a series resistor. Overload protection and fault interrupting service for the high voltage power supply will be provided by the vacuum interrupter.

1.1.5 Transformer-Rectifier

Three identical transformer-rectifier assemblies will convert the ac output of the variable transformer into high voltage dc (66 amps, 45 kvdc). The three units will be connected in series to produce 135 kvdc, 66 amps with taps to provide the voltages and currents required by the second and third accelerating grids.

1.1.6 Surge Capacitors

The surge capacitors will limit voltage transients during normal pulsed operation and fault conditions.

1.1.7 Current Limiting Resistors

The resistors will limit the current during a fault condition, provide transient dampening in conjunction with the surge capacitors and serve as an energy dump.

1.1.8 Crowbar Assemblies

The crowbar as connected between ground and the 45 kv, 90 kv, and 135 kv levels will divert the output of the HVPS away from the modulator and source to ground during a fault condition.

1.1.9 Modulators

The modulator serves as an interface between the high voltage power supply (HVPS) and the accelerating grids to perform the following functions:

- a. Electronic switching, provides high voltage switching between the HVPS and the ion source.
- b. Regulation of voltage to compensate for power supply transients and to provide ripple reduction.
- c. Fault energy limitation to avoid internal source damage as well as overload interruption of the HVPS.
- d. Automatic restoration of high voltage to the source after a finite delay which allows the source arc to extinguish.

- e. Fault interruption counting during each pulse with a selectable number from one to ten. The modulator output will be inhibited after a preselected number of trips has been exceeded.
- f. Automatic reset of the fault counter between pulses if selected number of trips is not exceeded.
- g. Triggers a crowbar circuit which directs the HVPS energy away from the modulator and source to ground.

1.1.10 Source Table

The source table supports and insulates from ground all of the equipment necessary for operation of the ion source and must float at the same voltage as the source itself. Equipment located on the source table will include:

- a. One filament power supply
- b. One arc power supply
- c. One magnet power supply
- d. One gas bottle
- e. One auxiliary magnet power supply
- f. Controls for one gas valve, one motor driven gas leak, and one vacuum readout.

1.1.11 Decel Supply

The decel supply will apply a negative potential of -1 to -10 kv with respect to ground on grid #4 providing a barrier to back streaming electrons.

1.1.12 Ion Source

The ion source generates an arc discharge in the intermediate electrode and anode chamber which is initiated and maintained by the primary electrons emitted from the filament. The resulting ions of this discharge are extracted from the plasma, accelerated, neutralized and injected into the TFTR plasma.

1.2 Design Requirements

1.2.1 General Requirements

Equipment shall be designed to occupy a minimum of floor space and be enclosed in grounded metal enclosures with high voltage bushings as required.

The exception being components which are required to float above ground such as the source table, surge capacitors, current limiting resistors and crowbar assemblies. All enclosures shall be NEMA I, or better, suitable for installation in a sheltered area. All control equipment, accessories, wiring and cable to make a complete installation shall be provided.

1.2.2 Structural Requirements

1.2.2.1 Electrical Design Condition

The Energy Conversion System (ECS) shall be designed and constructed in accordance with present-day electrical standards and codes using commercially available equipment and components.

1.2.2.2 Design Life

A service life of 15 years shall be used as a basis for the design. Components that cannot reasonably be expected to have a life of 20 years shall be designed and installed to permit replacement.

1.2.2.3 Material Requirements

All material for use in fabrication and installation of the ECS shall be approved for the use intended. If adequate information is not available to justify approval, a testing program shall be initiated to determine the characteristics necessary for approval.

1.2.3 System Configuration

The electrical equipment required for twelve sources shall be arranged to allow the modulators and source tables to be located as near as possible to the ion source to minimize the stored energy in the system which would be dissipated in the source during a fault condition. Consequently, the modulator and source table for six (6) ion sources shall be located at the same elevation as the TFTR machine, immediately outside the barrier wall and six (6) more shall be located directly above on a second floor.

1.2.3.1 Overall Configuration and Features

Refer to Figures 2.3-1, 2.3-2, and 2.3-3 which show the overall configuration of the ECS and the neutral beam control room. All equipment is arranged to occupy a minimum of floor space with maintenance access provided by overhead cranes.

1.2.4 Safety and Reliability Requirement

1.2.4.1 Safety

The design shall provide safe access for operating personnel, maintenance personnel and their tools and handling equipment. The design shall assure the safety of the maintenance personnel and equipment and prevent access to energized equipment by unauthorized personnel.

1.2.4.2 Reliability

The ECS shall be designed to obtain maximum reliability of components and assemblies. Standard, tested, and proven components shall be used where applicable. Assemblies will be tested to ensure that the design requirements are met.

1.2.5 Maintenance and Surveillance Requirements

1.2.5.1 Maintenance

The ECS shall be designed to permit repair or replacement of equipment. In the event of failure of major components, which may require repair or replacement at the manufacturer's factory, the equipment shall be designed and constructed to permit removal and reinstallation following factory repair.

All equipment shall be designed for service by overhead crane. Lifting eyes shall be provided on all components or assemblies weighing more than 150 lbs.

1.2.5.2 Surveillance

The design shall include monitoring of all critical components and provide annunciation and identification in the event of failure. Such equipment shall be designed to permit testing and repair with a minimum of down time.

1.2.6 System Interfaces

The ECS interfaces with a number of other TFTR systems as indicated in Table 1.2.6-1.

TABLE 1.2.6-1
SYSTEMS WITH WHICH SDD-72 INTERFACES

<u>SDD No.</u>	<u>SDD Designation</u>	<u>Paragraph Number</u>
10	Overall Facility	2.5.1
31	Energy Supply & Distribution System	2.5.2
33	TF Pulsed Energy Conversion	2.5.3 TBD
36	Central Instrumentation & Control	2.5.4 TBD
43	Remote Maintenance	2.5.5 TBD
46	Tritium Cleanup	2.5.6 TBD
47	Electrical Equipment Water Cooling	2.5.7 TBD
71	Neutral Beam Injection	2.5.8

Table 1.7-1 shows the complete listing of all system interfaces.

TABLE 1.7-1 - SYSTEMS INTERFACE MATRIX BY SDD

SDD	10	21	22	23	24	31	32	33	34	36	41	42	43	44	45	46	47	51	52	53	54	55	56	57	58	71	72	73
10		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
21			x	x	x					x	x	x	x	x	x	x										x		
22		x		x	x						x	x	x				x	x								x		
23		x	x					x			x		x															
24		x	x				x		x		x		x				x											
31							x	x	x	x			x	x	x	x	x			x							x	x
32					x	x				x			x				x		x									
33	x			x		x			x	x			x				x		x								x	
34	x				x	x	x			x			x				x		x								x	
36		x				x	x	x	x				x	x	x	x			x								x	x
41		x	x	x	x							x	x															
42	x		x								x		x	x												x	x	
43	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x		x	x	
44	x	x				x				x			x						x									
45	x	x				x				x			x						x									
46	x	x				x				x			x	x					x				x	x		x		
47	x			x	x	x	x	x	x				x						x	x	x							
51			x										x	x		x	x				x							
52								x	x									x										
53	x					x								x		x	x	x	x							x		
54													x															
55													x	x		x												
56													x	x		x												
57	x											x		x														
58																					x							
71	x	x	x										x												x		x	
72	x					x		x		x			x			x	x									x	x	x
73	x					x				x													x			x	x	x

1.2.7 Quality Assurance

Quality assurance requirements shall be based on the applicable paragraphs of TBD "Quality Assurance Program Requirements."

TBD "Quality Verification Program Requirements," supplemented by suitable reliability tests, may be used for "off-the-shelf" equipment procurements, or for equipment that does not involve "in-house" design effort.

1.2.8 Codes and Standards

Design, materials, fabrication, installation, inspection, and testing shall conform to applicable sections of the following codes and standards.

National Electrical Manufacturer's
Association Standards (Applicable Sections TBD)
National Electrical Code - NFPA No. 70-1975

2.0 DESIGN DESCRIPTION

2.1 Detailed Design Description

A power supply system designed to drive an ion source with parameters as listed in Table 2.1-1 will be described. Each supply will consist of one reactor, one 13.8 kv circuit breaker, one step-start vacuum interrupter, one variable transformer, three identical rectifier assemblies (containing high voltage transformers and rectifier components), three modulators, one source table, protective surge capacitors and crowbar assemblies.

The three dc output units when connected in series as shown in Figure 2.1-2 will provide a variable output for extracting ions from a multi-gap high current ion source. The source may have four grids each supplied as follows:

- Grid #1, 0-120 kv at 55 amps;
- Grid #2, 0- 80 kv at 5.5 amps;
- Grid #3, 0- 40 kv at 5.5 amps; and
- Grid #4, 0-(-10kv) at 11 amps.

Grid #4 will be supplied from a separate power supply and modulator system providing 2% voltage regulation.

The high voltage power supply outputs will be voltage regulated to 1% and switched on and off with series high voltage tetrode vacuum tubes. Capacitor surge and crowbar protection for the vacuum tubes and ion source will be provided.

2.2 System Performance

2.2.1 Normal Operation

With all sources pre-conditioned and ready for an injection pulse the power supply will be turned on at a preset level of output voltage. The modulators will hold the voltage off of the source until turned on by a programmed signal. Injection will be accomplished during an operating pulse width of 500 msec with modulator cutoff at the end. During the operating pulse, the modulators will voltage regulate within $\pm 1\%$. Should any

TABLE 2.1-1
NEUTRAL BEAM SOURCE ELECTRICAL SPECIFICATIONS

<u>Ion Source Parameters</u>		<u>Unit</u>
Number of Sources per Beam Line x Beam Lines	3 x 4	
Grid #1 Voltage	120	kv
Grid #1 Current	55	A
Grid #1 Regulation	± 1	%
Total Grid #1 Current	660	A
Total Grid #1 Power	80	MW
Pulse Separation Between 1A, 1B		msec
Pulse Width (Operating)	500	msec
Pulse Width (Preconditioning)	500	msec
Pulse Rise Time to 90%	20	μ sec
Pulse Fall Time to 10%	20	μ sec
Repetition Period (Operating)	5	min
Repetition Period (Preconditioning)	30	sec
Grid #2 Voltage (Nominal)	80	kv
Grid #2 Voltage (Selection)	200V steps, ± 5 kv	
Grid #2 Current	5.5	A
Grid #2 Regulation (<u>Slaved to Grid #1</u>)	± 1	%
Grid #3 Voltage (Nominal)	40	kv
Grid #3 Voltage (Selection)	200V steps, ± 5 kv	
Grid #3 Current	5.5	A
Grid #3 Regulation (<u>Slaved to Grid #2</u>)	± 1	%
Grid #4 Voltage (Nominal)	-1 to -10 (Variable)	kv
Grid #4 Current	11	A
Grid #4 Regulation	± 2	%

(Continued)

NEUTRAL BEAM SOURCE ELECTRICAL SPECIFICATIONS (Continued)

<u>Parameter</u>	<u>HNL</u>	<u>Unit</u>
Filament		
Voltage	0-10 Vdc	V
Current	300A	A
Rated Pulse Length	Cont.	
Max. Rise time to steady state		
Max. bus length		ft.
Ripple (no inductive filter)		
Arc Supply		
Voltage (open circuit)	150	V
Voltage (Operating)	90	V
Current per Ion Source	1000 - 20	A
Regulation	5	%
Rated Pulse Length	CW	
Transient Compensation		
Magnet Supply		
Voltage	0-10	V
Current	300	A
Arcing Protection		
Max. energy per Arc (All Grids)	<50	J

source spark-over, the modulator will remove the voltage for approximately 20 μ sec and then turn on again a number of pre-set times (TBD). Continued spark-over would initiate a system shut down.

FIG. 2.1-2

2.2.2 Off-Normal

At the end of an operating pulse of 500 msec, the modulators will remove the voltage from the source and remain in stand-by awaiting the next operating pulse in approximately five minutes.

2.2.3 Infrequent Operating Modes

Normal operating procedures require that main sources be pre-conditioned on a test stand to full operating voltage and current. Subsequent conditioning will be done with the source on the machine and firing into a target. Each beam line will be fired once every 30 seconds during preconditioning and standby periods. The power will be derived, during these periods, either from the motor-generator set or an auxiliary power source such as a 20 MVA, 130 kv to 13.8 kv transformer substation with appropriate switching to connect and disconnect the beam line power supplies into the system.

2.3 System Arrangement

The electrical equipment required for twelve sources with provisions for addition of six (6) future sources will be arranged as shown on Figure 2.3-1, Figure 2.3-2, and Figure 2.3-3. The primary switchgear, reactors, variable transformers, vacuum interrupters, high voltage tanks, resistor banks, surge capacitors and crowbars will be housed in a temporary type building on the first floor level. The decel supplies, modulators, isolation transformers, source tables and voltage divider stacks will be located on the first and second floors as near the sources as practicable.

All equipment is arranged to occupy a minimum of floor space with maintenance access provided by overhead cranes.

Figure 2.3-3 indicates the method by which access for electrical leads from the source table to the ion sources will be accomplished.

2-139
Part II

FIG. 2.3-2

SECTION - A-A

PART	DWG NO.	RECD	DESCRIPTION	STOCK SIZE	MATERIAL
------	---------	------	-------------	------------	----------

[illegible]

TFTR BEAM LINES
SECT. A-A'

FIG. 2.3-3

Figure 2.3-3 also indicates an arrangement to provide a control room for the ion sources. The control room floor will be raised to permit wiring underneath.

All primary power wiring will be routed under the floor slab or in ducts with control wiring and high voltage interconnections being carried in cable trays or insulating pipe (PVC). Clearance will be maintained overhead to allow removal for service of all equipment.

2.4. Component Design Description

2.4.1 DC Supply Subsystems

2.4.1.1 Reactors

A reactor, [.16 ohms impedance, 400 amps pulsed for 500 msec every 1/2 minute (preconditioning pulse) with a 10 cycle rating of 35,000 amps], inserted in the 13.8 kv line ahead of the circuit breaker supplying each source will allow a 750 MVA circuit breaker to be used for each source.

2.4.1.2 AC Circuit Breaker

Each source power supply will be protected by a 15 kv class metalclad switchgear unit rated 1200 amps continuously. All breakers will have 750 MVA interrupting capacity, a 5 cycle interrupting time, with (TBD) accessories for control, operation, maintenance, relaying and metering. Connections between breakers and their loads will be cables (size, number per phase, type of construction, TBD).

2.4.1.3 Variable Primary Power Source

The variable primary source will have a range of 30 - 100% with maximum steps of 200 volts that can be changed under load from a remote location. It will be rated 5 MVA, 13.8 kv, 3 Ø, 60 Hz, for a duty cycle of 1/2 second every 1/2 minute. The device will be subjected

to currents and transients resulting from ion source and switch tube breakdown and crowbaring as indicated in Figure 2.1-2 and will be designed for such service.

2.4.1.4 Vacuum Interrupter

Each source power supply will be protected by a 15 kv class metalclad step-start vacuum type interrupter to provide overload and short circuit protection. It will be designed to withstand the excessive and numerous operations to which it will be subjected due to load application. Trip and interrupt time shall be less than 1 1/2 cycles.

2.4.1.5 Transformer & Rectifier Assemblies

This portion of the power supply will consist of three units with each having delta primaries and delta/gye secondaries so designed and connected that they form a 6-phase series bridge rectifier output. Each of these three units shall consist of two sub-units, (one with delta secondary, the other with wye secondary) which will be connected in series for a total output of 66 amps, 45 kv dc. Taps shall be provided between each unit and between each delta and wye for the second and third accelerating grid voltage. The duty factor for these units will be 1/2 second every 30 seconds.

2.4.1.6 Surge Capacitors

Each capacitor bank (three required) will be composed of ten (10) 0.5 μ f, 70 kv, capacitors in parallel to limit voltage transients during normal pulsed operation and fault conditions.

2.4.1.7 Crowbars and Protective Devices

Each crowbar will be connected to the midpoint of a series current limiting resistor at the 135 kv, 90 kv,

and 45 kv levels and connected in series to ground. The crowbars will consist of krytron triggered ignitrons to provide fault protection between the high voltage rectifier outputs and the modulator output.

2.4.1.8 Load Instrumentation/Controls/Interlocks

All sensors, limit switches and auxiliary control items (TBD) necessary for remote monitoring and control of system components will be installed with the necessary interconnecting wiring to a power beam line and auxiliary control room.

2.4.1.9 DC Cables

The high voltage leads from the source table and modulator at the 120 kv level will be standard 600 V insulated cables installed together in 4" Sch. 80 PVC pipe (one for each source). The PVC pipe will provide isolation to operate at 120 kv above ground potential and will contain the following:

- a. Filament - 2-1/C # 2/0 welding cables
- b. Arc Supply - 2-1/C # 4/0 welding cables
- c. Magnet Supply - 2-1/C # 2/0 welding cables
- d. Gas Valve - 2/C # 14 RHW
- e. Thermocouple - Iron Constantan
- f. Gas Line - 1/8" Stainless Steel
- g. Motor driven gas leak 3/C # 14

The leads for Grid #2, Grid #3, and Grid #4 will be RG17/U coaxial cable installed together in 3" Sch. 80 PVC pipe (one for each source) as follows:

- A. Grid #2 - 1 - RG 17/U
- B. Grid #3 - 1 - RG 17/U
- C. Grid #4 - 1 - RG 17/U

A low inductance ground return will be fabricated from 6" wide x 1/32" thick copper strips.

2.4.1.10 Enclosures

All equipment hazardous to personnel will be isolated behind fenced enclosures or in fire rated vaults with access only through locked doors controlled by a key interlock system. All systems will be de-energized automatically when a key is obtained to open a door. A redundant system will also be utilized to de-energize all systems automatically using limit switches on all doors.

2.4.2 Modulator & Auxiliary Supply Subsystem

2.4.2.1 Modulators (For Grids 1, 2, and 3)

A high voltage tetrode will be connected in series with each grid. All modulators will provide voltage regulation of $\pm 1\%$ and electronic switching to connect and disconnect the grids at their respective voltage levels. High frequency switching during source sparkover will allow the sparkover arc to extinguish and the source to return to an injection mode a pre-selected number of times during a pulse before modulator lockout.

2.4.2.2 Local Instrumentation/Controls/Interlocks

Current monitoring of the source input, vacuum monitoring of the ion source and control of a pulse valve, with a variable leak rate, will be provided on the source gas feed system. The filament supplies, arc supplies, ion source filament supplies and magnet power supplies will be electrically isolated and remotely controlled. All remote monitoring and controls will be accomplished by an optical telemetry system utilizing solid state sensors and drivers.

2.4.2.3 Crowbars/Spark Gaps

Spark gap protection will be provided between the screen and filament and between the control grid and filament of each tetrode modulator. An ultraviolet sensor will detect breakdown between the anode and the screen and trigger the crowbar system. Another ultraviolet sensor will detect a discharge across the spark gap between the control grid and the filament and turn off the bias supply.

2.4.2.4 Filament Supplies

Each modulator filament will be powered by a 10 KVA supply which will be remotely controlled through a 10 KVA isolation transformer. A variable transformer primary will be remotely controlled to vary the filament voltage.

2.4.2.5 Grid #4 Power Supplies

Grid #4 of each source will derive its power from a transformer-rectifier solid state supply. The output will be variable from -1 to -10 kv dc at 11 amps. $\pm 2\%$ regulation will be provided by a series high voltage tetrode. Input voltage will be 480 V, 3 $\emptyset$, 60 Hz.

2.4.2.6 Arc Power Supplies

The source arc supply will be a transformer-rectifier solid state supply, rated at 90 KVA, controlled by a saturable reactor to achieve 5% regulation and current variation of 20 - 1000 amps. The supply will provide 1000 amps @ 90 V dc, with an open circuit voltage of 150 volts. SCR's in the rectifier assembly will provide pulse capabilities for the supply. Input voltage will be 480 volts, 3 $\emptyset$, 60 Hz.

2.4.2.7 Ion Source Filament Supplies

Each source filament will be powered by a 3 KVA, solid state transformer-rectifier supply. Voltage control will be obtained by a remotely controlled saturable reactor. The power supply input will be 480 volts, 3 $\emptyset$, 60 Hz, with a rated output of 0 to 10 volts, 300 amps, dc.

2.4.2.8 Magnet Power Supplies

Each magnet will be powered by a 3 KVA, solid state, transformer-rectifier supply. Voltage control will be obtained by a remotely controlled saturable reactor. The power supply input will be 480 volts, 3 $\emptyset$, 60 Hz, with a rated output of 0 to 10 volts, 300 amps, dc.

2.4.2.9 Isolation Transformers

The modulator for grid #1 will require two isolation transformers each insulated for 225 kv. The tube filament transformer will be rated 10 KVA, 480/120/240 V, 1 $\emptyset$, 60 Hz. The tube control grid and screen transformer will be rated 20 KVA, 480/120/240 V, 3 $\emptyset$, 60 Hz. The modulator for grid #2 will require two isolation transformers each insulated for 150 kv. The tube filament transformer will be rated 10 KVA, 480/120/240 V, 1 $\emptyset$, 60 Hz. The tube control grid and screen transformer will be rated 10 KVA, 480/120/240 V., 3 $\emptyset$, 60 Hz. The modulator for grid #3 will require one isolation transformer insulated for 150 kv. The transformer will be rated 480/120/240 V, 1 $\emptyset$, 60 Hz.

2.4.2.10 Enclosures

All equipment hazardous to personnel will be isolated behind fenced enclosures or in fire rated vaults with

access only through locked doors controlled by a key interlock system. All systems will be de-energized and grounded with vacuum switches automatically when a key is obtained to open a door. A redundant system will also be utilized to de-energize and ground all systems automatically using limit switches on all doors.

2.5 System Interfaces

2.5.1 Interface Parameters Between the ECS and the Overall Facility

a. Beam Line Equipment Building

A building as shown on Figure 2.5-1 and Figure 2.5-2 will be required to house the equipment for the neutral beam injection system.

b. Crane Facilities

Shown on Figure 2.5-1 and Figure 2.5-2

c. Others (TBD)

2.5.2 Interface Parameters Between the ECS and the ESDS

a. Voltage	13.8 kv $\pm$ 5% rms line-line
b. Frequency	90-60 Hz.
c. Power	10.3 MW per Ion Source (At the 13.8 kv circuit breaker for each ion source)
d. MW (TBD)	Preconditioning & standby periods
e. Pulse period	500 msec every 30 seconds
f. Location and termination of ac buses	(TBD)
g. 480 V, 3 $\emptyset$, 60 Hz. Auxiliary Power	90 KW per ion source
h. Auxiliary Control	120/240 volts $\pm$ 10% rms, 1 $\emptyset$, 60 Hz., (TBD) amperes rms
i. Location of system ground	TBD
j. Others	TBD

FIG. 2.5-2

2.5.3 TBD

2.5.4 TBD

2.5.5 TBD

2.5.6 TBD

2.5.7 TBD

2.5.8 Interface Parameters Between the ECS and Neutral Beam Injection

a. All the parameters as listed in Table 2.1-1.

2.6 Design Options

Operation of the neutral beam sources at the 150 kv level as well as the 120 kv level has received much consideration. Consequently, it would be advisable to include the higher voltage requirement in the specifications for the variable transformer, the transformer-rectifier, the surge capacitors, the source table isolation transformer, and the isolation transformers for the grid modulators. The estimated additional cost of this equipment is included in reference Table VI-5.

TOKAMAK FUSION TEST REACTOR PROJECT
SDD - 73

NEUTRAL BEAM CONTROL SYSTEM

SEPTEMBER 1975

Prepared by
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for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ABSTRACT

The Neutral Beam Control System (NBCS) controls the injection of neutral particles into the plasma. Information from the Central Instrumentation and Control System (CICS) is transmitted to the NBCS which uses this data to regulate the amount of neutral beam power to be transferred into the plasma and then initiates injection start and stop signals.

The NBCS adjusts the output power level of the various power supplies and turns them on and off via modulators at the proper time. The NBCS also monitors and controls vacuum levels, valve positions, coolant flows and temperatures and prevents beam firing if a fault condition exists.

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1.0 FUNCTIONS AND DESIGN REQUIREMENTS

1.1 Functions

The function of the Neutral Beam Control System (NBCS) is to monitor and control the Neutral Beam Lines on the Tokamak Fusion Test Reactor (TFTR).

The NBCS receives data from the CICS regarding neutral beam power levels, pulse length, and pulse timing. A host computer in the NBCS distributes these commands to each source in each beam line. Diagnostic information is in turn fed back to the CICS.

1.2 Design Requirements

1.2.1 General Design Requirements

1.2.1.1 Structural Requirements

The NBCS shall be designed and constructed in accordance with present day electrical standards and codes using commercially available equipment and components.

1.2.1.2 Design Life

A service life of 15 years shall be used as a basis.

1.2.1.3 Maintenance Requirements

The NBCS shall be designed to permit the location and replacement of failed components. Where feasible and economical, self checking circuits shall be incorporated in the design. Interlocks shall be provided to protect personnel and equipment during performance of maintenance procedures.

1.2.1.4 Quality Assurance

The NBCS shall be designed, built and factory tested in accordance with applicable standards and test codes for commercial electrical and electronic equipment.

Installation and test procedures shall be in accordance with national and local electrical and electronic equipment standards and safety codes.

1.2.1.5 Codes and Standards

Design, materials, fabrication, installation, inspection and testing shall conform to applicable sections of the following codes and standards:

National Electrical Manufacturers Association
Standards

National Electric Safety Code, C2-1973 Edition.

1.2.2 System Design Requirements

- 1.2.2.1 Activate the neutral beam line system when requested by the Central Control System.
- 1.2.2.2 Provide the required logic circuits and interlocks for sequential and safe startup, operation and shutdown of the neutral beam system.
- 1.2.2.3 Monitor and control the beam line vacuum system.
- 1.2.2.4 Monitor and control the operation of all system valves.
- 1.2.2.5 Monitor and control the operation of system coolants.
- 1.2.2.6 Monitor and control the neutral beam line diagnostic system.
- 1.2.2.7 Monitor and control the operation of source modulators and source table electronics.
- 1.2.2.8 Provide alarms for out-of-limits conditions on all critical measurements.
- 1.2.2.9 Provide the controls required for operating the beam lines from the CICS, beam line computer system, or from local cabinets.
- 1.2.2.10 Provide the circuitry required to input all system measurements to the beam line computer system.
- 1.2.2.11 Provide a digital computer system for data collection, control and calculations.

- 1.2.2.12 Provide diagnostic instrumentation for determining beam power and efficiency.

1.2.3 Computer System

- 1.2.3.1 The computer system shall be made up of central processing units and interfaces as required to operate 15 remote devices with future expansion to 24.
- 1.2.3.2 A central console shall be provided from which the 15 remote devices can be controlled and from which the system can be programmed.
- 1.2.3.3 Input-output devices shall be provided at or near the central console which allow system programming by punched paper tape and cassette tape.
- 1.2.3.4 Output devices shall be provided for hard copy output and video display.
- 1.2.3.5 A communication link shall be provided to the CICS.

1.2.4 Vacuum Control System

- 1.2.4.1 The vacuum system shall provide the vacuum level required for proper operation of the neutral beam line.
- 1.2.4.2 The vacuum system controls shall provide inputs to the system logic for sequential operation of the neutral beam line system.

1.2.5 Coolant Control System

- 1.2.5.1 The coolant system controls shall monitor all cooling water flows and temperatures as necessary for safe operation of the neutral beam line.

1.2.6 Diagnostic Instrumentation

- 1.2.6.1 The diagnostic instrumentation shall provide the information necessary for determining beam power and efficiency.

- 1.2.6.2 The diagnostic instrumentation shall provide inputs to the system logic for proper operation of the neutral beam line.

1.2.7 Power Control System (Ion Source and Modulator Controls)

- 1.2.7.1 The power system controls shall provide adjustments for the high voltage supplies, modulators, and source table voltage supplies.
- 1.2.7.2 The power system controls shall provide the electronics required for monitoring the complete power system.
- 1.2.7.3 The power system controls shall provide the electronics for pulsing the ion source and gas supplies.
- 1.2.7.4 The power system controls shall be interlocked with all the other controls for safe operation of the neutral beam line.

1.2.8 Tritium Recycle Control System

- 1.2.8.1 The tritium recycle controls shall provide the instrumentation required for monitoring and controlling the tritium facility.
- 1.2.8.2 The tritium facility instrumentation shall provide alarms for all out-of-limits critical functions.

1.2.9 Remote Handling Controls

The remote handling controls shall provide for remote assembly and disassembly of the beam line flanges.

1.3 Interfacing Requirements with Other Systems

The NBCS interfaces with a number of other TFTR systems as indicated in Table 1.3-1

TABLE 1.3-1
SYSTEMS WITH WHICH SDD-73 INTERFACES

<u>SDD No.</u>		<u>Paragraph No.</u>
10	Overall Facility	1.3-1 TBD
31	Energy Supplies and Distribution System	1.3-2 TBD
36	Central Instrumentation and Control System	1.3-3 TBD
56	Facility Heating and Ventilation	1.3-4 TBD
71	Neutral Beam	1.3-5 TBD
72	Neutral Beam Pulsed Energy Conversion	1.3-6 TBD

1.3.1 Overall Facility System (SDD-10)

The overall system facility shall provide floor space of TBD square feet for housing the NBCS, offices and electronic maintenance area.

1.3.2 Energy Supplied and Distribution System (SDD 31)

TBD 115 volt, 60 Hz, 20 amp circuits, and TBD 208/240 Vac, 60 Hz circuits shall be supplied to the NBCS room and offices.

1.3.3 Central Instrumentation and Control System (SDD 36)

1.3.3.1 The NBCS shall supply instrument signals to the CICS comprising the following:

- Operative conditions in the NB Lines
- Power levels generated in the NB lines.

1.3.3.2 The CICS shall supply signals to the NBCS as follows:

- Beam pulsing signals
- Beam pulse length signals
- Beam power level signals

1.3.4 Facility Heating and Ventilation (SDD 56)

Heating and air conditioning shall be supplied for the NBCS control room and adjacent offices. TBD Watts heat load will be dissipated. TBD temperature limits must be maintained.

1.3.5 Neutral Beams (SDD 71)

1.3.5.1 Digital signals shall be supplied by each NB line as follows:

- TBD valve open contacts
- TBD valve closed contacts
- TBD water flow switches
- TBD pressure switches
- TBD temperature switches

1.3.5.2 Analog signals shall be supplied by each NB line as follows:

- TBD high vacuum pressures
- TBD low vacuum pressures
- TBD temperatures
- TBD flows

1.3.5.3 Digital signals shall be supplied to each NB line as follows:

- TBD valve close
- TBD valve open
- TBD calorimeter in
- TBD calorimeter out
- TBD pump power signals

1.3.5.4 Analog signals shall be supplied to each NB line as follows:

- TBD

1.3.6 Neutral Beam Pulsed Energy Conversion (SDD 72)

1.3.6.1 Digital signals shall be supplied to each NB PEC system as follows:

- TBD

1.3.6.2 Analog signals shall be supplied to each NB PEC as follows:

- TBD to power supplies to program the output voltage.

1.3.6.3 Digital signals shall be supplied by each NB PEC system as follows:

- TBD

1.3.6.4 Analog signals shall be supplied by each NB PEC system as follows:

- TBD

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2.0 DESIGN DESCRIPTION

2.1 Detailed Design Description

A computer controlled system designed to control the Neutral Beam (NB) injectors for TFTR will be described. The control system will furnish automatic control for NB system pump-down and beam pulsing. Calculations of beam power will be made both during beam calibration and tune up and during normal firing into the Tokamak. Constant checks will be made of coolant flows, pressures, temperatures and component positions to assure operation that is safe to both equipment and personnel. Beam pulsing may be originated at the Central Instrumentation and Control System, at the NBCS console or manually at the source equipment cabinets. All other functions may be originated at the NBCS console or manually at the source equipment cabinets. (See Figures 2.1-1 and 2.1-2).

2.1.1 Computer System

The computer system consists of a host central processing unit with input-output peripherals and intermediate CPU's as required to interface to 15 remote devices and allow future expansion to 24 remote devices.

2.1.1.1 The host CPU shall be a 16 bit machine with 28 K words of core memory and a cycle time of 1 microsecond or less.

2.1.1.2 Output devices shall consist of three hard copy units, (two 30 character per second units and one 60 lines of 132 columns per minute), paper tape punch, cassette tape recorder, and video display CRT.

2.1.1.3 Input devices shall consist of two keyboards, paper tape reader, cassette tape reader, light pen and console switches.

2.1.1.4 A 1.2 million word disk system shall be interfaced to the CPU.

FIG. 2.1-1

NOTE: EACH BEAM LINE HAS 3 SOURCES, ONLY ONE SHOWN HERE FOR SIMPLICITY.

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- 2.1.1.5 Intermediate CPU's (between host CPU and remote interfaces) shall be 16 bit machines with TBD words of memory.
- 2.1.1.6 A high speed bi-directional communication link shall be provided to interface with the Central Instrumentation and Control System.
- 2.1.1.7 Fifteen remote interfaces shall be supplied capable of operating up to 2000 ft. from the CPU and connected to the CPU by one coaxial cable. Each remote device shall accommodate a minimum of 256 digital signals. Each remote interface device shall have connections for a keyboard hard copy device.
- 2.1.1.8 The system shall operate from 115 V, 60 Hz power or 220 V, 60 Hz power.
- 2.1.1.9 All computer peripherals, including remote interfaces, shall be fully supported by software supplied with the system.

2.1.2 Vacuum Control System Design Requirements

- 2.1.2.1 The vacuum system controls shall consist of the instrumentation to monitor and control the operation of mechanical pumps, diffusion pumps and cryosorption panels. Each neutral beam line shall be equipped with a separate, but identical vacuum control system.
- 2.1.2.2 The vacuum system controls shall be thermocouple vacuum gages and controllers with ranges of 0 - 1000 microns Hg and 0 - 100 microns Hg, and ion gauge controllers with a range of 2×10^{-3} - 2×10^{-11} torr. The vacuum gauges shall be protected from overpressure both internally, and by sequencing into the system at the proper vacuum levels.
- 2.1.2.3 The vacuum controllers shall have front-settable setpoints. The setpoints shall act as inputs to the system logic, and provide sequential control of the beam line vacuum system. In addition, each setpoint

actuation shall be logged in the computer, and registered as the value equal to the setpoint. Should any setpoint be exceeded during operation, an alarm shall sound and orderly shut down of the neutral beam line will proceed. The vacuum system controls shall be interlocked with other system controls to guarantee that ion source firing cannot proceed until the neutral beam line is ready.

- 2.1.2.4 The thermocouple gauge controllers shall be used to sequence the mechanical pumps, diffusion pumps and associated valving. In addition, a thermocouple gauge shall be mounted in the source to verify source vacuum before firing. The ion gauges shall sequence the cryo-sorption pumping panels and associated valving on line, and verify that proper vacuum exists in the neutral beam line prior to source firing. In conjunction with the vacuum gauges, temperature indicator controllers shall be used to control the operation of the cryo-panels. The exact configuration and ranges of the temperature controllers are TBD.

2.1.3 Coolant Control System Details

- 2.1.3.1 The water cooling flows shall be monitored for safe operation of the neutral beam line system. The flows shall be monitored by a combination of flowswitches and flowmeters mounted in each line requiring cooling water flow. The control of the main header water supply and return valves, is TBD, but each portion of the beam line requiring cooling shall be monitored.
- 2.1.3.2 The setpoints from the flowswitches and flowmeters shall act as inputs to the system logic and prevent source operation without the water flows being present.

2.1.4 Diagnostic Instrumentation

- 2.1.4.1 The diagnostic instrumentation shall monitor the

temperatures and flows necessary for the calorimetric determination of beam power and efficiency. The instrumentation shall be provided on the calorimeter for determination of neutral beam power, and on the beam dump for determination of ion power.

- 2.1.4.2 The temperatures shall be monitored by a thermopile type differential temperature transducer. The transducer shall monitor the temperature difference in the cooling water inlet and outlet lines. The signal shall be recorded on one pen of a two-pen analog recorder, and also be analog to digitally converted and inputted to the computer system.
- 2.1.4.3 The flows shall be monitored by turbine type flowmeters, and their outputs fed in digital form to the computer. In addition, the appropriate frequency to voltage converters shall be provided to record the signal on the second pen of the two-pen recorder.
- 2.1.4.4 The temperature and flow data obtained shall be used by the computer in a heat flux calculation for determining the beam energy to the calorimeter, and ion energy to the beam dump. In the event the computer system is down, the data from the recorder may be used to manually perform the calculations.
- 2.1.4.5 Setpoints on the flow instrumentation shall be input to the coolant system logic to guarantee safe operation of the beam line.

2.1.5 Ion Source and Modulator Controls

- 2.1.5.1 The modulators and ion source high voltage supplies shall be controlled from controllers mounted locally at each source console. The locally mounted controllers shall provide adjustment for the Filament, Arc, Magnet, and Auxiliary Magnet supplies, and provide the timing and pulsing of the source and neutral gas cell supplies. A separate controller shall control the

modulators providing pulse inputs, lockout reset, interlocking functions, and fault-sensing.

- 2.1.5.2 Adjustments to the source parameters and the actual pulsing of a neutral beam may either be generated from the local control panels or from the digital computer system via the interfaces located at each source remote control console.

2.1.6 Tritium Recycle Controls

- 2.1.6.1 The tritium recycle controls shall monitor and control uranium getter preparation, and tritium recycle operations.
- 2.1.6.2 The instrumentation shall measure and control temperature, pressure, vacuum level, and percent oxygen in the system. The operating parameters are TBD, but standard process instrumentation shall be utilized.

2.1.7 Remote Handling Controls

- 2.1.7.1 The remote handling controls shall be utilized to remotely mount the beam line flanges.
- 2.1.7.2 The instrumentation shall consist of optical encoders, digital counters with the required presets, and the interfacing required to control the operation.

2.2 System Operational and Performance Characteristics

2.2.1. Time Sequence of Events

- 2.2.1.1 Normally, upon receipt of a fire signal from the CICS, the NBCS steps through a fixed sequence of checking pressures, applying coolant, applying voltages, valving gas into the source, applying arc current, monitoring for malfunctions, and then removing all the above after having maintained the beam for the required length of time.

2.2.2 Operating Modes

- 2.2.2.1 Normally the above sequence is followed for each operating source when a fire signal is received from the CICS.
- 2.2.2.2 The firing sequence may also be originated from the NBCS computer console or from the source control panels. The calorimeter may also be lowered into the beam from these locations for calibration.
- 2.2.2.3 The system shall be programmed for automatic source conditioning. This consists of firing the source into the calorimeter at regular intervals and gradually raising the operating potentials until normal operating points are reached.
- 2.2.2.4 Source failures shall be annunciated at the source control cabinets, the NBCS console and at the CICS console. Recovery from some types of failure is possible and may be programmed for automatic sequencing. Others are not and must result in source shut down. This too shall be programmed to occur automatically.

2.3 System Arrangement

2.3.1 Equipment Size and Weight

- 2.3.1.1 The NBCS will occupy 100 standard relay racks and may require 35 more relay racks if two more beam lines are added. Each relay rack will weigh approximately 300 lbs. Thirty-six hundred square feet of floor area will be required to house these panels. Offices and an electronic shop should also be adjacent to or part of this control room.

2.3.2 Facility Location

- 2.3.2.1 Most of the wires and cables from this control room go to the Neutral Beam Power System. Several cables also go to the beam lines in the test cell. Therefore this control room should be located as near to both as possible.

2.4 System Interfaces

2.4.1 Interface from Neutral Beam System (See Figure 2.4-1)

<u>Signal</u>	<u>Number Required</u>	<u>Parameter Monitored</u>
Absolute Source Valve	12	Valves open
Position Switch Contact Closure	12	Valves closed
Absolute Output Valve	4	Valves open
Position Switch Contact Closure	4	Valves closed
Fast Valve Position	4	Valves open
Switch Contact Closure	4	Valves closed
Calorimeter Position Switch	4	Calorimeter in beam
Contact Closure	4	Calorimeter out of beam
Water Flow Switch Contact Closure	12	Source cooling water flow
	12	Gas cell cooling water flow
	4	Vacuum system cooling water flow
	4	Bending magnet cooling water flow
	4	Beam dump cooling water flow
	4	Calorimeter cooling water flow
Analog Signal	4	Calorimeter differential temperature transducer output
	4	Beam dump differential temperature transducer
Pulse Signals	4	Calorimeter flowmeter
	4	Beam dump flowmeter
Analog Signal	4	Bending magnet gaussmeters
Vacuum System Setpoint	12	Thermocouple gauge controllers on sources
Switch Closures	16	Thermocouple gauge controllers in vacuum system rough down
	12	Ion gauge controllers on gas cells
	12	Ion gauge controllers in vacuum system headers

PROCESS INSTRUMENTATION

FIG. 2.4-1

<u>Signal</u>	<u>Number Required</u>	<u>Parameter Monitored</u>
Analog Signal from Cryogenic Temperature Monitors	16	Liquid nitrogen chevrons temp.
	16	15°K Helium chevron temperature
	16	15°K Helium pumping panel temperature

2.4.2 Interface from Neutral Beam Pulsed Energy Conversion System

<u>Signal</u>	<u>Number Required</u>	<u>Parameter Monitored</u>
Analog Signal from Power Supply Voltage Outputs	12	Filament power supply voltage
	12	Arc power supply voltage
	12	Magnet power supply voltage
	12	Auxiliary magnet supply voltage
Analog Signal Gas Bottle Pressure	12	Source table gas bottles pressure
Analog Signal Source Vacuum Gauge	12	Thermocouple gauge in source
Analog Signal from Power Supply Current Outputs	12	Filament power supply current
	12	Arc power supply current
	12	Magnet power supply current
	12	Auxiliary magnet supply current
Analog Signal, Grid 1 Modulator Output	12	160 kv Modulators output
Analog Signal, Grid 2 Modulator Output	12	105 kv Modulators output
Analog Signal, Grid 3 Modulator Output	12	55 kv Modulators output
Analog Signal, Grid 4 Modulator Output	12	10 kv Modulators output
Pulse Signal, Fault Sensing	36	Grid 1 Modulator fault
	36	Grid 2 Modulator fault
	36	Grid 3 Modulator fault

<u>Signal</u>	<u>Number Required</u>	<u>Parameter Monitored</u>
Contact Make or Break for Alarm Condition	600	High voltage supply alarms
Analog Signal for Phase Voltage Measurements	36	High voltage supply system inputs
Control Cable to Inductrol Motor	12	Voltage control

2.4.3 Interface From Overall Facility

Control Room Space Required	(See Figure 2.4-2)
Interface Cabinet Space Required at Source Table	TBD
Cable Trays and Conduit	TBD (Requirements to be furnished to Electrical)

2.4.4 Interface From Central Instrumentation and Control System

Interface from CICS Computer to Host Computer in NBCS	TBD
Neutral Beam Power Level Requirement	1 per Source per Test
Neutral Beam Pulse Width Requirement	1 per Source per Test
Neutral Beam Pulse Timing Requirement	1 per Source per Test
Diagnostic Information from NRCS to CICS	4 each Calorimeter and beam dump power levels and any other information required by CICS

2.4.5 Interface From Facility Heating and Ventilation

Heating Required	TBD (See Figure 2.4-2)
Air Conditioning Required	TBD (See Figure 2.4-2)

Equipment operating temperature requirements are +10 - +50°C and operating humidity 20% to 95% without condensation. Equipment heat loads and required number of operating personnel are TBD.

2.4.6 Interface From Energy Supplies and Distribution System

115 Volt, 60 Hz	TBD
208/240 Volt, 60 Hz	TBD

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FIG. 2.4-2

See Figure 2.4-2 for approximate location requirement. Exact locations are TBD. Instrument power requirements at the source table are TBD.

2.4.7 Interface to Neutral Beam Pulsed Energy Conversion System

<u>Signal</u>	<u>Number Required</u>	<u>Function</u>
Analog Signal from Ion Source Controller (Fiber Optic Transmission)	12	Adjust filament power supply output
	12	Adjust arc power supply output
	12	Adjust magnet power supply output
	12	Adjust auxiliary magnet power supply output
	12	Spare circuit ran 1 per each source table
	12	Adjust calibrated gas leak, or Piezoelectric valve power supply
Pulse Signal (Fiber Optic Transmission)	12	Pulse the arc power supply
Pulse Signal (Fiber Optic Transmission)	12	Pulse the gas supply
Pulse Signal (Fiber Optic Transmission)	12	Adjust Grid 1 Modulator fault counter
	12	Adjust Grid 2 Modulator fault counter
	12	Adjust Grid 3 Modulator fault counter
Analog Signal (Fiber Optic Transmission)	12	Adjust Grid 1 Modulator current setting
	12	Adjust Grid 2 Modulator current setting
	12	Adjust Grid 3 Modulator current setting
Analog Signal (Fiber Optic Transmission)	12	Adjust Grid 1 Modulator voltage setting
	12	Adjust Grid 2 Modulator voltage setting
	12	Adjust Grid 3 Modulator voltage setting
Pulse Signal (Fiber Optic Transmission)	12	Pulse the Grid 1 Modulator
	12	Pulse the Grid 2 Modulator
	12	Pulse the Grid 3 Modulator
	12	Pulse the Decel Modulator

NEUTRAL BEAM PULSED ENERGY CONVERSION AND CONTROL SYSTEMS
REFERENCE BUILDING DESIGN

The energy and control systems for the Princeton/Westinghouse TFTR experiment should be housed in a building 200 feet long by 160 feet wide immediately adjacent to the experiment building (Ref. Part II, Fig. 2.5-1 and 2.5-2). The building is separated into two sections by a 12-inch block fire wall, one section being two story containing the Beam Modulator Equipment, offices, control room, etc., and the other section being one story containing the High Voltage power supplies.

The building frame is of structural steel with curtain walls of concrete block. The first floor is constructed with a concrete floor slab on-grade, and second floor of concrete on steel decking. Roof construction is of insulated metal decking on bar joists with built-up roofing. A pre-engineered rigid frame building will be considered as an alternate to the structural system shown.

All structural steel is exposed except for that supporting the second floor in the Beam Modular Equipment area, where two hour fireproofing is required for both the beams and columns. The second floor of this area includes a masonry fire partition between the equipment room and the control room, offices and rest rooms. Eight foot high masonry partitions isolate groups of both modulating and power units to concentrate sprinkler fire control systems and to limit fire spread. Smoke vents are provided in the roofs.

The control room, rest rooms, and offices are constructed with masonry partition walls, vinyl asbestos tile floors and suspended ceilings. The control room is furnished with an elevated panel floor as a cable chase under instrument cabinets.

Equipment areas are provided with a clean air ventilation system by using high efficiency filters. The control room and offices are temperature and humidity controlled.

The Beam Modular Equipment area is serviced with five-ton cranes, two for the first floor and one for the second floor. Only one hoist and trolley is provided for the first floor crane bridges which are interlocked so that the one hoist provides full equipment and service area coverage. The second floor crane can lower and raise equipment through a floor hatch in the building service area.

The High Voltage Power Supply portion is serviced with two ten-ton cranes.

FIG. V-1
PART V

TFTR NEUTRAL BEAM INJECTION SYSTEM
PROTOTYPE AND PRODUCTION
PLANNING SCHEDULE

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Part V

FIG. V-1A
PART V

TFTR NEUTRAL BEAM INJECTION SYSTEM
PROTOTYPE AND PRODUCTION
PLANNING SCHEDULE

SYSTEM CONTROLS

CONTROL & INSTR. DEFINITIONS
SOURCE & MODULATOR ELECTRONICS
INSTRUMENTATION PANELS
PROCESS CONTROL
DATA PROCESS
SOFTWARE
HARDWARE
INSTALLATION
INSTALLATION / SYSTEMS INTEGRATION

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Part V

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FIG. V-1C
PART V

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