ORNL-TM-4820

Description of a Reference Design Tokamak for the Technology Test Assembly

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $5.45; Microfiche $2.25

ORNL-TM-4820

Contract No. W-7405-eng-26

THERMONUCLEAR DIVISION

DESCRIPTION OF A REFERENCE DESIGN TOKAMAK for the TECHNOLOGY TEST ASSEMBLY

P. N. Haubenreich, editor

OCTOBER 1975

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ABSTRACT

Early conceptual studies for the Technology Test Assembly involved a reference conceptual design for a tokamak with superconducting toroidal field magnets. The TF magnet conductors are NbTi filaments in a copper matrix. The 24 TF coils and associated structure operate at 4–5 K and a maximum field (at the windings) of 75 kG. Principal dimensions of the machine are: TF coil bore, 1.8 x 2.4 m (oval); major radius, 2.25 m; plasma minor radius, 0.6 m. A preliminary but detailed cost estimate for the reference machine was prepared to serve as an anchor point for cost scaling for larger machines in subsequent TTA parameter studies.

Keywords: conceptual design, controlled thermonuclear processes, costs, fusion, plasma, tokamak.

ACKNOWLEDGEMENTS

The studies described here involved contributions from a large number of people in the Thermonuclear Division, other HNL divisions, and the UCCND Engineering organization. M. Roberts is due special recognition for the leadership and supervision of the project. Names at the heads of sections of the report indicate the persons principally responsible for those sections. Others, whose names do not appear, made valuable contributions in nearly every area. These include: T. J. Golson, mechanical design; J. E. Brewer, liner and vessel; A. J. Moorhead, honeycomb fabrication; S. T. Piotrowski, liner replacement; T. C. Domm, thermal analysis; J. W. Yarbrough, cooling water system; K. E. Cook, H. C. Beeson, èt al., cost estimating. G. G. Kelley provided guidance for the concept from its inception and J. T. Hogan, D. G. McAlees, and J. F. Clarke provided physics input that helped to steer the design. H. M. Long and others in his group reviewed portions of the design and made useful suggestions with regard to the toroidal field system. M. H. Kunselman and R. McCarrell performed the design drafting and A. Legg provided the secretarial support.

FOREWORD

The reader of this document should be aware of its background and the purpose for which it is being issued. The information was generated in 1974 and hence does not represent the latest design of a superconducting tokamak. It is reported at this late date because it continues to have utility as a basepoint in cost estimation for various systems employing superconducting toroidal field coils, especially the Technology Test Assembly (TTA).

The concept of the TTA and the TTA with Plasma (TTAP) is still evolving. The TTA is presently visualized as essentially a full toroidal set of superconducting coils similar to but approximately half the size of the TF coils in the tokamak Experimental Power Reactor (EPR). The TTA could accommodate a large, hot plasma, in which case it would be known as TTAP. The EPR will require the development not only of superconducting toroidal magnets but also long-pulse, high-energy neutral beam injectors and other tokamak plasma-related technologies.[1] The recognized advantages of having an operating device as the focus for technological developments has led to the consideration of the benefits that would accrue to the overall CTR program if a tokamak including these technological advances and beginning operation between the TFTR and the EPR were included in the program. This is the role visualized for the TTAP.

Among the early studies leading to the TTAP, we developed the preliminary conceptual design described in this report. One purpose in doing the design of a complete device, operating as a tokamak, was to provide a focus for thinking about the various needs of the technology programs and the concomitant benefits that might be realized in the area of confinement physics. These considerations are fully described in other documents.[2,3] The studies of the technology needs, particularly parametric studies of costs and benefits to the magnet program of toroidal assemblies, have led to consideration of machines larger than the one described here. The comprehensive (albeit preliminary) design and cost estimate have been quite useful, however, as the anchor point for cost scaling in the parameter studies,[4] and it is in this light that they are presented here. Because the design described here was fixed almost a year before the publication of this document, there have been advances in various areas; hence, not every design feature reflects our present thinking.

2. INTRODUCTION

The design described in this report is predicated on the use of toroidal field coils in which the conductors are NbTi filaments in a copper and copper-nickel matrix, operated at a temperature of 4 to 5K. The size of the coils in this reference case was determined by the requirement that the device produce a well-controlled plasma with a circular cross-section of 60-cm radius.[3] (Consideration was also given to non-circular cross-sections, utilizing the extra space available in oval TF coils.) The centerline magnetic field is approximately 4.0 tesla (as high as could be achieved without exceeding 7.5 tesla at the TF conductors). To the maximum possible extent, the design of the reference TF coils was chosen on the basis of relevance to the anticipated EPR design. (The TTA has since been included in DCTR plans for EPR coil development.)

To take advantage of the steady toroidal field provided by the superconducting magnet, a design goal for the TTAP is a plasma pulse 10 seconds in duration with a plasma current corresponding to a safety factor, q_a, of 2.5. In one respect the reference design described in this report fails to meet that goal: The volt-seconds provided by the iron-core transformer may be adequate for only about 3 seconds, depending on plasma resistance. This deficiency does not carry over into the parametric studies; there the allocation of space and the estimated costs are consistent with a 10-second pulse capability.

Many other features of the TTAP, which appear in this reference design contribute to the utility in the investigation and control of plasma impurities. The vacuum is meant to be the best attainable — seals, valves, and pumping equipment are specified accordingly and all parts of the primary system are bakeable at 400—500°C. Neutral beam injection is provided as required for heating, with provisions for subsequent large increases to permit investigations at higher power densities. The internals of the toroidal vacuum vessel include a liner (in this case a honeycomb wall) and a toroidal limiter designed to absorb the particle and energy fluxes out of the plasma with minimum resultant impurity influx. Particular attention is given to facilitating replacement of honeycomb wall panels to permit testing of various wall materials and configurations.

3. DESCRIPTION OF REFERENCE DESIGN

3.1 General Description

P. B. Thompson

The configuration chosen for the reference superconducting TF coil machine is a tokamak with a circular plasma, oval superconducting toroidal field coils, a bakeable single-wall vacuum vessel, a honeycomb first wall, an iron-core transformer driving system, and a neutral-beam heating system. The principal characteristics and dimensions of this design are listed in Table 1. A brief description of the major components and their layout follows. Additional detail and discussions of design choices are included in subsequent sections of this chapter.

Figure 1 is a half-section through the reference design machine, showing the following major elements: the iron transformer core, a toroidal field coil and surrounding cryostat, the toroidal vacuum vessel, the toroidal limiter and honeycomb wall, the ohmic heating, vertical field, and magnetic limiter coils, and part of the support structure.

The iron transformer comprises a cylindrical central core and two symmetrical return yokes that enclose the TF coils and toroidal vacuum vessel. Assembly and disassembly is facilitated by subdividing the transformer into pieces easily manageable by the crane equipment.

The toroidal field coil assembly consists of 24 superconducting TF magnets enclosed in a closely-fitting, interconnected vacuum enclosure which also includes the magnet restraint structure. The conductors are NbTi filaments in a copper matrix, wound in pancake coils with interleaved stainless steel reinforcement and electrical insulation, with liquid helium coolant flowing between pancakes. Restraint of the windings against magnetic loadings is provided by stainless steel hoops, one hoop surrounding each winding. The centering force is carried by a structure around the winding in the nose region of the coils.* Out-of-plane loadings on the coils are resisted by rigidly attached spacer bars between coils and by the wedged noses, which are keyed together.

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*In this regard, the reference design differs from subsequent TTA designs which have an individual dewar around each TF coil to facilitate replacement during the test program.

Table 1. Description of Reference Design Technology Test Assembly with Plasma

Item			
<u>Plasma</u>			
Cross section shape		circular	
Minor radius, a, m		0.6	
Major radius, R_o, m		2.25	
Aspect ratio, R_o/a		3.75	
Volume, $2\pi^2 R_o a^2$, m^3		16	
Plasma current, I, MA		1.3	
Centerline field, B, tesla		4.1	
Safety factor, q_a		2.5	
Neutral injection power,[a] MW		4.0	
Neutral injection energies, keV		40, 20, 13	
<u>Neutral-Beam Injectors</u>			
Number of stations	12 (6 co-, 6 counter-current)		
Number of units (initially)	4 (2 co-, 2 counter-current)		
Power supply current A/unit		50	
Ion species	H_1^+	H_2^+	H_3^+
Ion energy, keV	40	20	13
Fraction of ion beam	0.60	0.30	0.10
Efficiency[b]	0.50	0.64	0.69
Power to plasma, MW/unit	0.60	0.38	0.14
Gas cell length, cm		100	
Gas cell diameter, cm		20(tapered)	
Beam divergence (half angle)		1.2°	

[a]Total actually used initially. See injector data for capability and breakdown among energy groups.

[b]Product of equilibrium fraction from gas cell and beam transport efficiency.

Table 1 (continued)

Item	
<u>Vacuum Vessel</u>	
Inner surface construction	Honeycomb, replaceable
Inner surface material	Niobium (initially)
Vessel wall material	Austenitic stainless steel
Major radius, m	2.25
Vessel wall minor radius, m	0.74
Vessel wall thickness, mm	6
Baking temperature, K	700 to 800
<u>Limiters</u>	
Toroidal (normal)	One 25-cm band on midplane
Poloidal (backup)	14 rings at intervals $\leq 30°$
Plate Material	Tungsten
Heat removal	Radiation to vacuum shell
<u>Toroidal Field System</u>	
Coil shape	Oval
Conductor material	NbTi in Cu and CuNi
Operating temperature, K	4.2
Coolant	Liquid He
Max. field at winding, tesla	7.5
Coil bore, m	1.8 horizontal x 2.4 vertical
Major radius of array, m	2.25
Flat-top time, sec.	Steady
Operating power, MW	Negligible
Stored energy, MJ	480
Restraint	Nested noses, struts, rings
Thermal insulation	Dewar, common in nose region
Number of coils in array	24
Current density in winding, A/cm^2	5000
Winding width x thickness, cm	23.5 x 16.6

Table 1 (continued)

Item	
Toroidal Field System (continued)	
Weight of conductor, kg	4.2×10^4
Hoop width x thickness, cm	28.5 x 12
Hoop material	Type 310 stainless steel
Transformer Core and Yoke	
Material	AISI 1010 carbon steel
Lamination thickness	1 mm (20-gage)
Flux density (max), tesla	1.7
Flux change, volt-sec	7.9
Core radius, m	0.88
Weight of core and yokes, tons	490
Ohmic Heating Coils	
Material	Copper
Coolant	Water
Current, KA	81.3
Number of turns	16
Current density, A/cm^2	4000
Stored energy, MJ	1.5
Power, MW	14
Conductor weight, tons	5
VF Trimming Coils	
Material	Copper
Coolant	Water
Current, KA	11
Number of circuits	4
Number of turns/circuit	4 to 16
Current density, A/cm^2	4000
Power/circuit, MW	1
Conductor weight, tons	7

Table 1 (continued)

Item	
<u>Magnetic Limiter Coils</u>	
Material	Copper
Coolant	Water
Current, KA	130
Number of turns	6
Current density, A/cm^2	4000
Power, MW	9
Conductor weight, tons	2.7
<u>Vacuum Pumping System</u>	
Roughing (760 — 20 torr)	Mechanical/Molecular sieve
Intermediate (20 — 10^{-6} torr)	Turbomolecular
Final (<10^{-6} torr)	17K cryosorption
Attainable liner pressure,[a] torr	3 to 4 x 10^{-10}

[a]After baking.

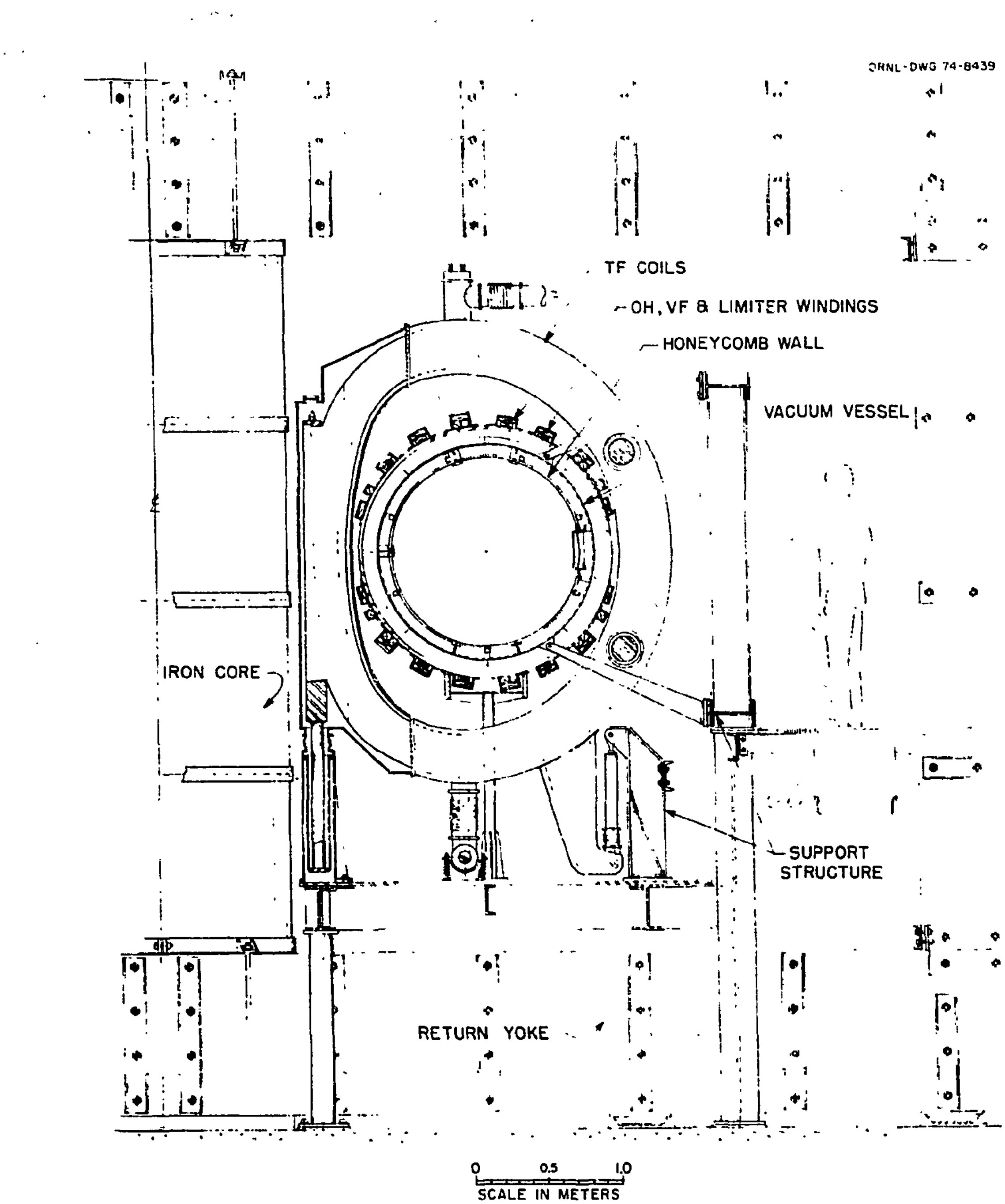

Fig. 1. Typical Cross-Section — Reference Case

(Analysis to determine whether or not an external torque frame is also required was not completed.) The complete TF coil system, which operates at 4.2 K is supported by a set of tension links which are designed to minimize heat leakage into the helium-cooled system. The outer surface of the vacuum enclosure surrounding the TF coil system operates at room temperature.

Components located within the TF coils include the vacuum vessel and contents, thermal insulation, and a structural shell with the plasma driving windings attached to its surface.

These plasma driving windings consist of a set of sixteen ohmic heating windings, sixteen adjacent vertical field windings in which the current can be adjusted to shape the vertical field for plasma position control, and six magnetic limiter windings.

The vacuum vessel support structure consists of an external 12-sided framework surrounding the machine. This framework is made up of two I-beam rings separated by vertical beams. Two support arms connect from the upper and lower rings to the vacuum vessel at 15° intervals. These arms resist the inward directed pressure load and support the weight of the vacuum vessel and its internal elements.

A sub-structure framework is provided to support the weight of the coils and associated equipment. A series of pipe columns locate and support the plasma-driving coil support shell.

The honeycomb wall inside the vacuum vessel consists of small, channel-framed, self-supporting sections, sized for passage through a vacuum pumping port. These honeycomb panels are laid up in a toroidal wall array on permanently installed mounts. This design permits rapid removal and replacement of the honeycomb liner wall. The pumping port size required to achieve the desired base pressure is large enough to allow its use as a man entry port to the inside of the vacuum vessel for honeycomb wall replacement.

Heating provisions are included to allow baking of the vacuum vessel, its contents, and attached ducts. Insulation to protect machine elements not exposed to the high vacuum environment is installed as a blanket around the outside of the vacuum vessel.

Figure 2 is a plan view of the machine, depicting the vacuum vessel construction, neutral beam injection, and vacuum pumping provisions, and a few of the many diagnostic penetrations. Six large ducts penetrate the

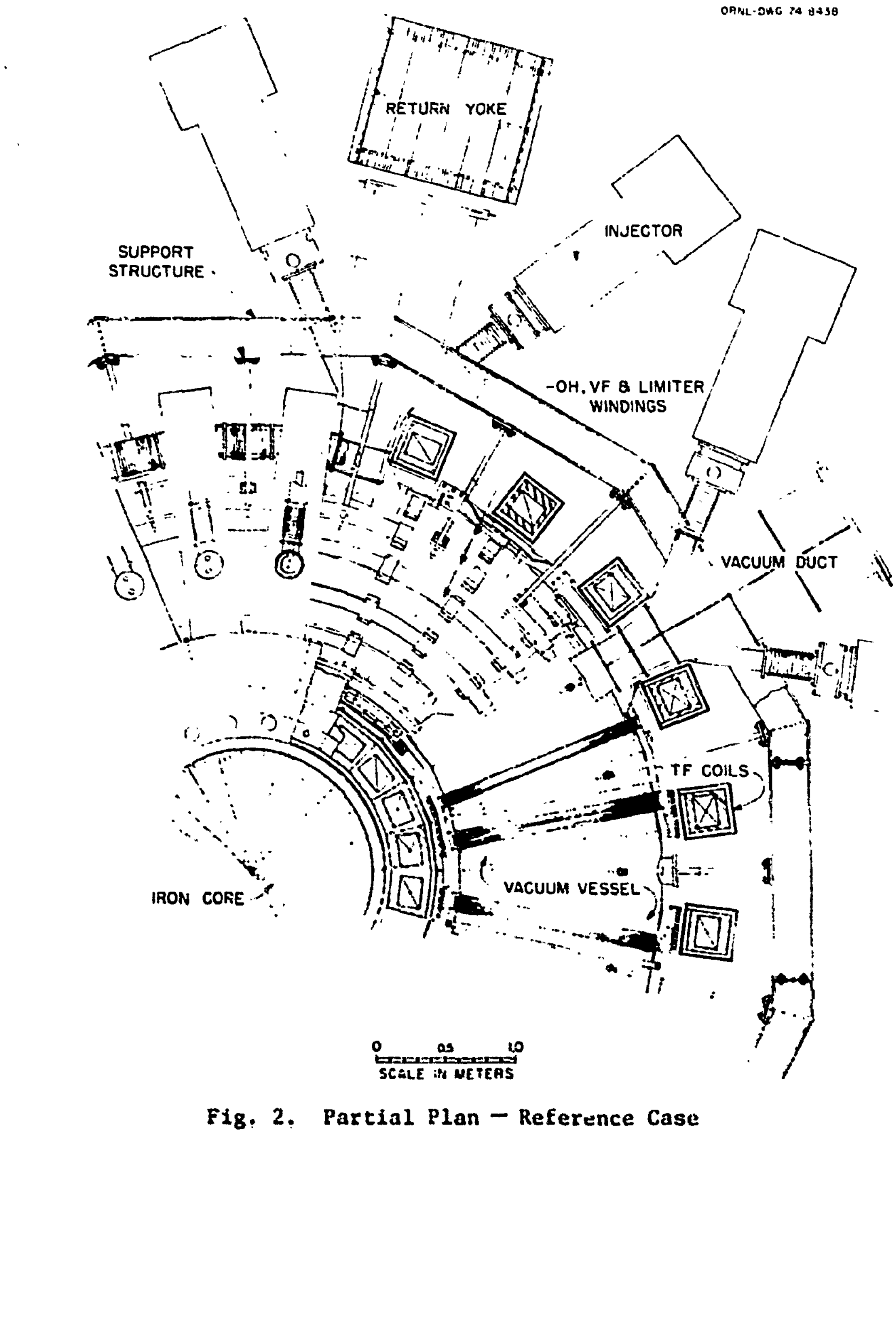

Fig. 2. Partial Plan — Reference Case

vessel and honeycomb wall, providing common ports for injection and vacuum pumping and permitting personnel access. At each station provision is made for two injector units on the plasma horizontal midplane, located as a crossing pair, oriented at an angle of 37 degrees to a radial line. The diagnostic which most perturbs the toroidal assembly is the Thomson scattering system, which requires large penetrations through the vacuum vessel. A total of 110 smaller diagnostic penetrations are provided at various locations around the machine.

The vacuum pumping system is divided into two sections, with roughing and finishing vacuum pumping systems provided to pump the injectors and vacuum vessel separately. To produce a base pressure of 3 to 4 x 10^{-10} torr in the vacuum vessel requires a pumping capability of about 70,000 liter/sec. This is accomplished through the six pumping ports, each equipped with a turbomolecular pump and 17K cryosorption panels. Roughing is provided by dry mechanical and molecular sieve pumps. The injector system pumping is provided by turbomolecular pumps and 17K cryosorption panels to provide a pumping capability of 54,000 liter/sec for each injector enclosure. Roughing is provided by dry mechanical and molecular sieve pumps.

The vacuum vessel is a toroidal chamber consisting of 24 mitered cylindrical sections and 24 bellows sections. The metal bellows sections comprise approximately 30% of the torus and provide a reasonably high electrical resistance to current flowing in the vacuum vessel wall (approximately 5 x 10^{-3} ohms). The total bellows length required is achieved by use of long sections where possible with shorter sections installed where space or access requirements are critical. Two sections, each consisting of two TF coils, a sector of the vacuum vessel, and related internal and external parts, can be removed as units. The removable sections of the vessel are connected to the fixed portions by externally bolted, internally seal-welded flanges.

3.2 Toroidal Vacuum Vessel and Liner

P. B. Thompson

The primary vacuum vessel is an approximate torus with a major diameter of 4.5 m and a minor diameter of 1.5 m. It is constructed of 24 bellows sections alternated with 24 smooth-walled sections and is designed to withstand one atmosphere of external pressure. (There is no secondary vacuum enclosure as in ORMAK-I and the ORMAK-F/BX concept.) The smooth-walled sections, made of mitred cylindrical segments, are fitted with 6 large (35 x 100 cm) ducts for vacuum pumping and injection and 117 diagnostic ports ranging from 5 to 25 cm diameter. The bellows has a wall thickness of 0.75 mm and convolutions with a 50-mm depth and 16-mm pitch. Bellows are used for as much of the periphery as is consistent with the access penetration requirements, to obtain an adequately high electrical resistance around the torus. The resulting resistance, 5×10^{-3} ohms, is sufficiently high to avoid the necessity of an insulating break in the vessel.

As indicated in Fig. 3, the vessel includes two removable segments 180 degrees apart. (Disassembly involves removal of two TF coils along with the segment of vessel and its internals.) The vessel flanges at these locations are externally bolted and internally seal-welded. Access to the interior of the vessel after the removable segments are in place is through any of the six pumping-injection ducts. (Short sections of OH and VF windings penetrating the ducts are removed to provide a manway.)

The vacuum criteria for ORMAK-II require that the vacuum vessel and connected ducts be routinely bakeable at 400 to 500°C. For this purpose strip heaters are located on the outside of the vessel and ceramic fiber insulation is fitted around the outside of the vessel and heaters.

The weight of the vacuum vessel and attached components (11 to 12 tons) is supported by pairs of arms extending inward from the TF coil torque frame at 15-degree intervals. (See Fig. 1.) These arms also resist the inward-directed forces on the vessel due to the external pressure (5 tons on each 15-degree segment) and the forces due to thermal expansion and contraction of the vessel during a baking cycle.

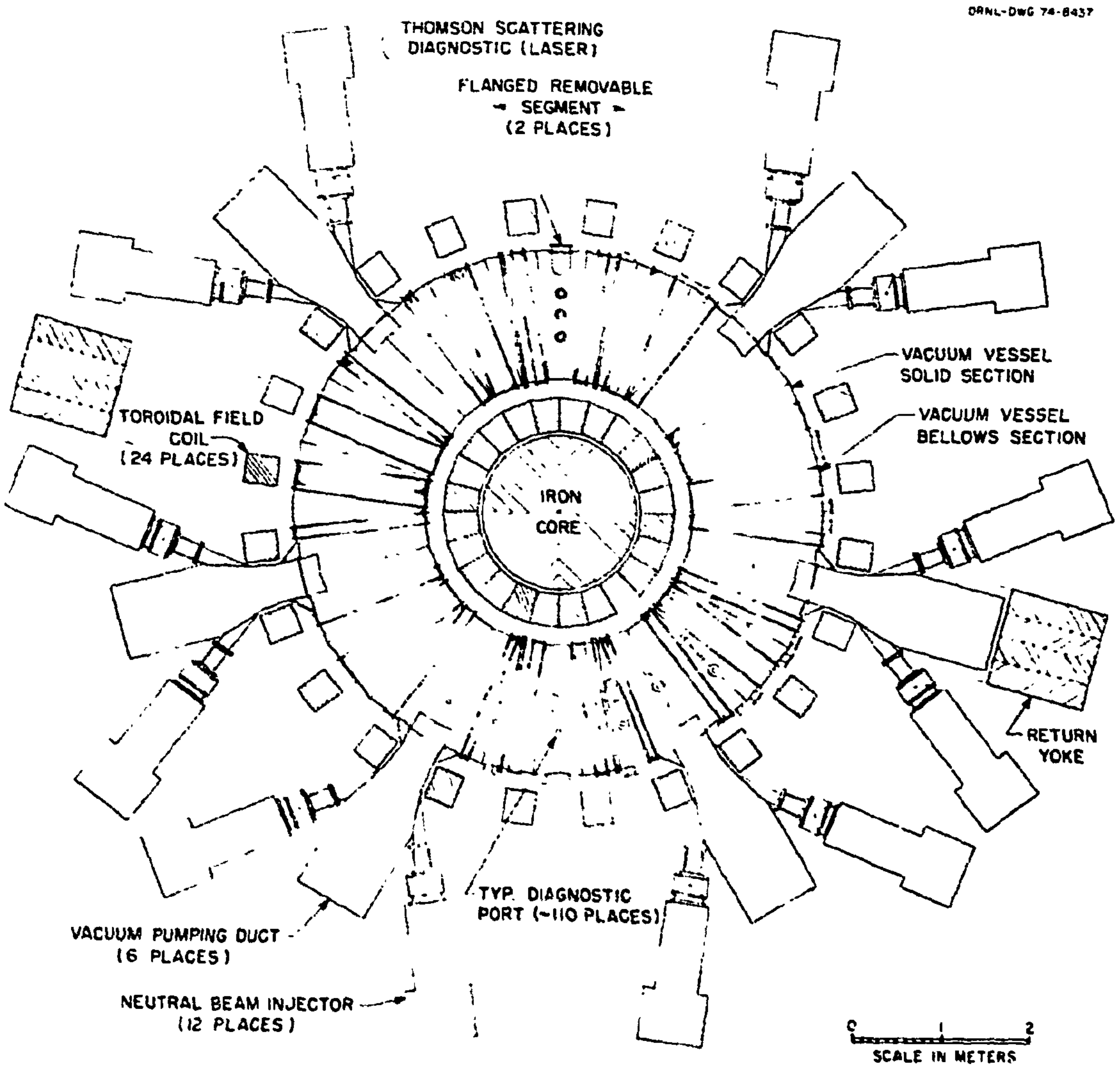

Fig. 3. Plan View — Reference Case

The criterion that TTAP be capable of testing "one-way" walls that minimize the influx of sputtered particles into the plasma is satisfied in concept by providing a first wall composed of replaceable panels. The reference design for these panels is an open honeycomb, fabricated of metal strips 0.13-mm (5 mils) thick and 10-mm wide, run through corrugated rolls and spotwelded to form 10-mm square cells. The honeycomb material is formed into panels, which are framed and braced for rigidity and sized for passage through a vacuum duct. The resulting panels are quite manageable by hand, as they weigh around 5 kg each (about 10 kg if made of tungsten). These panels are laid up to form a toroidal surface on permanent mounting brackets inside the vacuum vessel, designed so that the panels can be slipped in and out and be held in place by gravity. (See Fig. 4.) Since the honeycomb is open, it does not interfere with pumping gas from the space between it and the vacuum vessel wall. Niobium was selected as the first honeycomb material to be tested because of its high melting point (2410°C), good thermal conductivity (0.67 watts/cm°C at 1000°C), low sputtering rate, low atomic number relative to other refractory metals, good availability and fabricability. (Niobium honeycomb structures similar to the TTAP concept have been produced commercially for NASA.)

Alternate first walls have been considered from the standpoints of the primary "one-way" function and compatibility with the panel replacement scheme. Tungsten honeycomb is more difficult to fabricate than niobium and much heavier, but the mounts are designed to accommodate the greater weight. Other candidate materials include tantalum and molybdenum. As an alternative to the welded honeycomb configuration, panels consisting of sheet metal with the exposed surface virtually covered with grooves or pits produced by mechanical or chemical means are being considered.

The procedure for replacement of the first wall has been laid out and the time and manpower requirements estimated as described in Sect. 3.4.

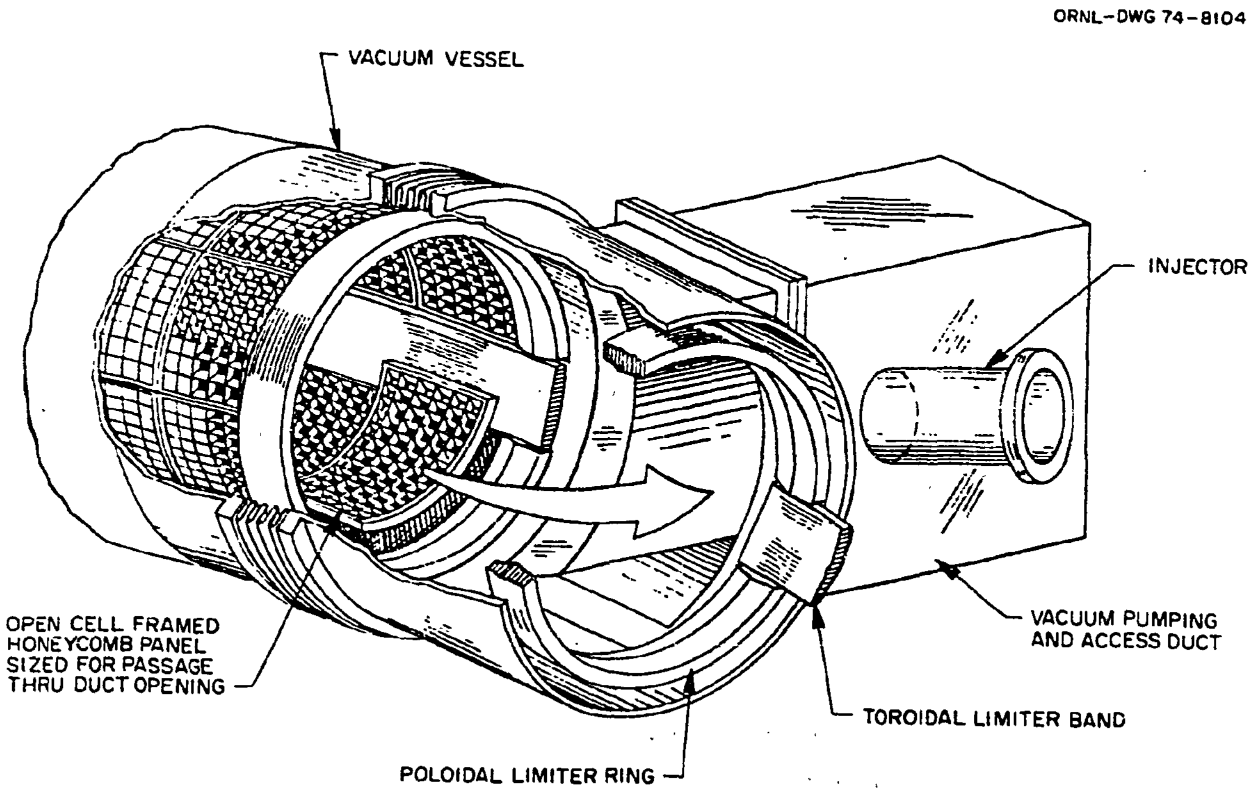

Fig. 4. Honeycomb Wall Removal

3.3 Limiters

G. G. Kelley

In a tokamak the size of TTAP we expect much of the plasma energy to come out in the form of radiation and charge-exchange neutrals, but a significant portion of the power transport is likely to be in the energy flux of charged particles from the plasma. In TTAP the limiter is designed to distribute the surface flux of charged particles over as large an area as possible. We discuss below the considerations involved in arriving at the design chosen.

In any practical situation there is one first drift surface which just touches the limiter and, because of inevitable asymmetry, it touches at only one point. Not all particles arriving at this surface strike this point, however, because of the diffusion which takes place during the time required for a particle to find the limiter. The thickness of the "scrape-off" region (the annular region of contact between particles and limiter) scales as

$$\delta \propto \sqrt{D\tau}$$

where D is the appropriate diffusion coefficient and τ is the lifetime of a particle in the region. The ideal limiter is one which intercepts this region in such a way that the power flux to it is uniform.

A toroidal limiter is potentially better than a poloidal ring limiter in that the time required for a particle to find the limiter (τ) is longer, δ is greater, and the energy deposition is spread over a larger area. Diffusion coefficient values inferred from results in ST[5] and in ORMAK, and rough estimates of τ yield expected scrape-off thicknesses of from less than one to several cm (depending on the functional form for D) when a toroidal limiter is used. A reasonable design then is a vertical band on the midplane at the outer radius of the plasma. This band should be shaped so that its mid-region is tangent to a plasma flux surface while flaring outward at top and bottom to intercept a shell of flux surfaces several cm thick.

It should be recognized that any estimate of the thickness of the scrape-off region is necessarily very crude. The mean lifetime of a particle depends on the size of the region intercepted, which is a function of depth in the scrape-off region, and the appropriate diffusion coefficient is not known. Also the surface temperature and density are uncertain and even the functional form of the diffusion coefficient cannot be predicted.

In a normal situation only one toroidal limiter band is necessary. In fact, having more might not even be desirable because more would reduce the time necessary for a particle to find its way out and thus would increase the density gradient across the flux surfaces.

Fault conditions present a different problem and one that is particularly difficult because very high instantaneous power flux densities can be involved, even though the total energy deposited during a fault probably can be kept small by external protective measures. Protection is needed also against enhanced transport, such as that which might occur during a disruptive instability, which could carry charged particles past the toroidal limiter to the wall. The TTAP design includes 14 poloidal ring limiters located at intervals of not more than 30° in major azimuth to protect the honeycomb wall against this eventuality.

The concepts just described are illustrated in Fig. 4. The toroidal limiter surface is located at the smallest minor radius (60 cm) at the midplane, flaring to 61 cm at top and bottom edges of the 25-cm wide band. The inner edges of the poloidal limiters are at 61 cm and the surface of the honeycomb is at 65 cm. There are 24° interruptions in the toroidal limiter at each of the six equatorial penetrations for injection and diagnostics.

Both the toroidal and poloidal limiters consist of rows of tungsten links mounted so as to permit thermal expansion. Heat is dissipated by radiation to the vacuum shell behind the limiters.

3.4 Neutral Beam Injection

T. C. Jernigan

The requirements imposed by plasma physics considerations on the neutral beam injectors in TTAP are discussed in reference 3. A particle energy of 40 keV was specified on the basis of penetration and trapping. About 3 to 5 MW of power into the plasma was calculated to be necessary to achieve the desired temperatures; 4 MW was specified for the reference design.

Neutral beam injectors in the size range from 0.5 to 1.0 MW seem best for meeting the TTAP requirements. Injectors of this size can realistically be expected to be available and are large enough to meet the minimum and anticipated needs with reasonable numbers of units. The reference design includes four 1-MW injectors, with access provisions for a total of twelve similar units.

To obtain the injectors proposed for TTAP, the present ORMAK duoPIGatron-II injectors must be scaled up in current and pulse length. Present ORMAK injectors typically operate at 10 A of power supply current at 25 kV, delivering 150 kW of neutral power to the entrance aperture. Pulse length of greater than 0.5 sec and power supply voltage and current of 30 kV and 10 A have been achieved. For shorter pulses 12.5 A of power supply current at 40 kV has been achieved.

Current should scale directly as extraction electrode area. Electrodes in the present ORMAK injectors are 10 cm in diameter, so scaling up to 20 to 25 cm in diameter should produce more than 1.0 MW of usable neutral power. Increasing the pulse length to 2 seconds or longer will require better cooling of the multiaperture extraction grids and a new filament in the plasma source.

Problems of scaleup include plasma uniformity across the extraction grids and neutral gas load. The duoPIGatron seems scaleable from 7 cm to 25 cm in diameter with no loss of plasma uniformity. However, should it fail to reach the necessary size at the necessary uniformity, alternate routes to the desired goal seem available. The present injectors are 50% gas efficient (i.e., 50% of input gas comes out as beam, the rest as neutral gas). This is primarily a function of the source pressure required for best operation and the conductance of the lower parts of the source, the extraction grids, and the gas cell. The conductance increases as the diameter increases so the gas efficiency would be expected to fall. However, by using a converging gas cell and perhaps increasing its length hopefully 50% gas efficiency can again be approached.

In calculating sizes and costs of injectors the following assumptions are made:

1. A present injector (10-cm diam) is capable of 10 to 12.5 A of extraction current.
2. More than 80% of the ion beam can pass through the TTAP injector geometry into the liner using aperture displacement focusing.
3. More than 60% of the ion beam at 40 kV is neutralized (varies depending upon ion species distributions).
4. The injector modules can be made 50% gas efficient (5A of gas = 1 torr liter/second).
5. None of the hardware, mechanical or electrical, is any more complicated (except for the addition of an accelerating supply regulator) than the present ORMAK injectors, only bigger.

To produce 1 MW of neutral power at 40 kV using the above assumptions requires a source 20 cm in diameter with an extraction current of 50 A and a gas load of 10 torr liters/second. A power supply capable of 50 kV at 60 A seems most reasonable. Table 2 compares the dimensions of the TTAP injectors with those presently in use on ORMAK.

It is expected that to produce minimum impurity levels and maximum reliability of the injector during a shot, about 30 seconds of operation at 10% duty cycle just before a machine shot will be necessary.* Enough cooling water must be supplied to dissipate the maximum supply power plus the auxiliary supplies, operating on a 10% duty dycle. (The auxiliary supplies amount to about 100 kW per injector.)

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*After a new injector is installed on the machine, several hours of operation at 10% duty cycle is necessary. Also if an injector is left idle for several days even under vacuum, up to an hour of 10% duty cycle operation will be required for optimum operation.

Table 2. Comparison of Neutral Injection in ORMAK and TTAP

	ORMAK			TTAP		
Number of units	2			4		
Power supply current, A/unit	6			50		
Ion species	H_1^+	H_2^+	H_3^+	H_1^+	H_2^+	H_3^+
Ion energy, keV	25	12.5	8.3	40	20	13
Fraction of ion beam	0.6	0.3	0.1	0.6	0.3	0.1
Efficiency[a]	0.60	0.69	0.71	0.50	0.64	0.69
Power to plasma, MW/unit	0.090	0.051	0.018	0.60	0.38	0.14
Total to plasma, MW/unit	0.160			1.12		
Gas cell length, cm	50			100		
Gas cell diameter, cm	7			20 (tapered)		
Beam divergence (half angle)	1.2°			1.2°		
Cooling requirements, MW/unit	0.2			2.2		

[a]Product of equilibrium fraction from gas cell and beam transport efficiency.

3.5 Vacuum Pumping Systems

J. S. Culver

3.5.1 Requirements

Two components of the TTAP device require vacuum pumping systems: the systems: the toroidal plasma containing vessel and the neutral beam injectors. The desired characteristics of these systems which provided the basis for the conceptual design are as follows.

1. The toroidal envelope surrounding the plasma is a single-wall, bakeable vessel with an open honeycomb liner. The desired base pressure is in the low 10^{-10} torr range to minimize low-Z gas contaminants.
2. Immediately before each shot the pressure will be raised to 10^{-3}–10^{-4} torr by admission of hydrogen gas.
3. After each shot it must be possible to pump out most of the gas to remove undesirable species and again backfill with hydrogen to permit repetition of shots at 3-minute intervals.
4. After maintenance that requires opening the system to air and entry of personnel, it must be possible to pump down, bake, and reach operating conditions in one week or less.
5. Each injector shall be provided with adequate pumping and storage capacity to allow injection for 10 sec at 3-minute intervals and test firing into a target (for 30 sec at 10% duty cycle) between shots for a full 8-hour day.
6. The cryosorption panels in the injector assemblies shall have sufficient capacity for a full day's operation and be capable of regeneration in the off shifts.

3.5.2 Toroidal Vacuum Vessel Pumping Systems

The desire to produce a base pressure of $\sim 3 \times 10^{-10}$ torr in a vessel with an outgassing area of $2.2 \times 10^{6} cm^{2}$ (including the honeycomb wall) requires a very clean, bakeable vessel with a pumping system capability of about 70,000 liter/sec. This is accomplished through six pumping ports, each equipped with a turbomolecular pump and 17K cryosorption panels. (See Fig. 5.)

The six turbomolecular pumps serve to remove the large amount (∿ 36 torr-liter) of hydrogen introduced before and during each shot. After the pressure has dropped to 10^{-5} torr (in about one minute) the fast valve is opened, allowing the cryosorption pumps to reduce further the pressure three or four decades before the next shot. Each cryosorption panel has a pumping speed of 35,000 liter/sec and a capacity of 10,000 torr-liters. If the fast valves can be made sufficiently tight to reduce the conductance to a fraction of 1% the cryosorption panels will only need to be regenerated after several weeks of operation.

When it becomes necessary to regenerate these panels the condensibles (H_2O and CO_2) can be retained on the LN_2-cooled radiation shield, if desired, while the H_2, N_2, He, Ar, and Ne are removed by the turbomolecular pumps as the cryopanel temperature is raised above 17K.

The roughing system is intended for use during pumpdown after the system has been let up to atmospheric pressure, quickly removing the gross amounts of gas (possibly air) contained in the vessel without any danger of contamination. The dry mechanical pump has Teflon piston rings and piston sleeves that require no lubrication. After this pump has reduced the pressure from atmospheric to 50 torr, the molecular sieve pump will take the system down to 10^{-4} torr in less than two hours.

During the baking process the turbomolecular pumps, with a combined speed of about 2400 liter/sec, continue to remove the gas as it is evolved. The forepressure with these pumps alone, after baking, should be 10^{-8} torr. The cryosorption panels can then be cooled as soon as the manifolds reach room temperature.

3.5.3 Injector Vacuum System

Each of the four neutral-beam injectors has its own vacuum system. The estimated gas load for a 1-MW, 40-keV injector is 12 torr-liter/sec at a pressure of 2 x 10^{-4} torr. If the flow into the plasma region is limited to 10% of this gas load by the drift tube, the pumping speed on

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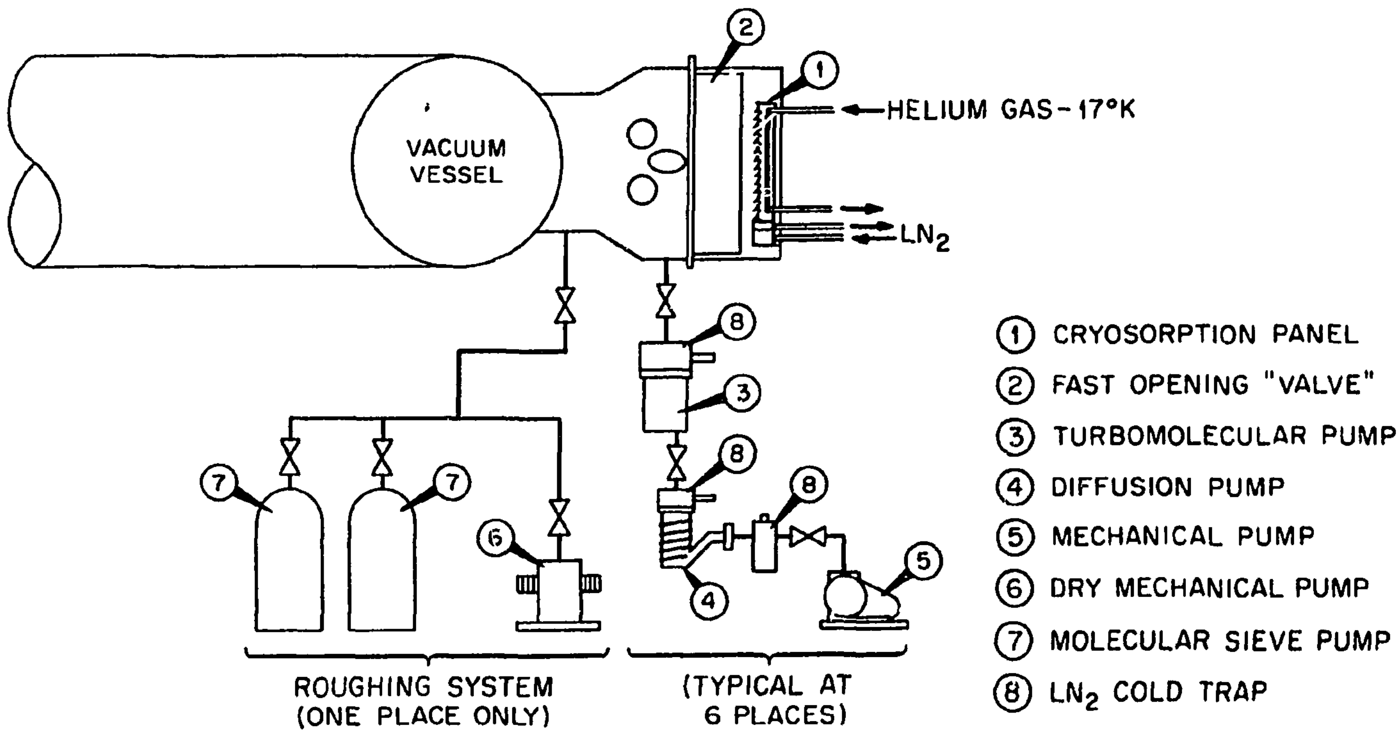

Fig. 5. Vacuum Vessel Pumping Schematic

the injector enclosure must be 54,000 liter/sec. The pumping speed of a cryosorption panel cooled to 17K is about 5 liter/sec/cm^2, hence, the net area required is 1.1 m^2. The storage capacity of this type of panel is 20,000 torr liter/m^2, so a 1.1 m^2 panel is just about able to store the total gas pumped during an eight-hour period of operation (2100 sec total operation at 11 torr-liter/sec). A panel of this area can easily be installed in the 1 x 1 x 1/2 m enclosure provided for the gas cell, target, and fast valve.

The system also includes a turbomolecular pump (see Fig. 6). These LN_2-trapped pumps have a net speed of 400 liter/sec and are used only during regeneration of the cryosorption panels and during roughdown after maintenance. The pump has adequate capacity to remove the gas accumulated on the cryosorption panel as it is warmed up. This operation should take about eight hours.

A small (8-lb) molecular sieve pump is provided to remove the air from the injector enclosure during roughdown after maintenance.

3.5.4 Magnet Vacuum System

Elimination of the gas conductance heat transfer in the dewar surrounding the superconducting toroidal field coils requires that the pressure in this space be pumped down to 10^{-5} torr or less. To accomplish this two 50-cfm mechanical pumps are provided to remove the initial charge of air and rough pump the interconnected vacuum jacket system down to 10^{-2} torr. At this point four six-inch diffusion pumps are valved in to reduce the pressure to 10^{-5} torr or below. Because of outgassing from the large, unbaked, stainless steel surfaces and the numerous layers of aluminized Mylar insulation, this operation will take about two days. Once the jackets have been pumped down to a satisfactory pressure by this means, the cooling of the coils can begin. Thereafter the surfaces of the liquid-helium-cooled magnets will pump most of the gas released in the insulating space.

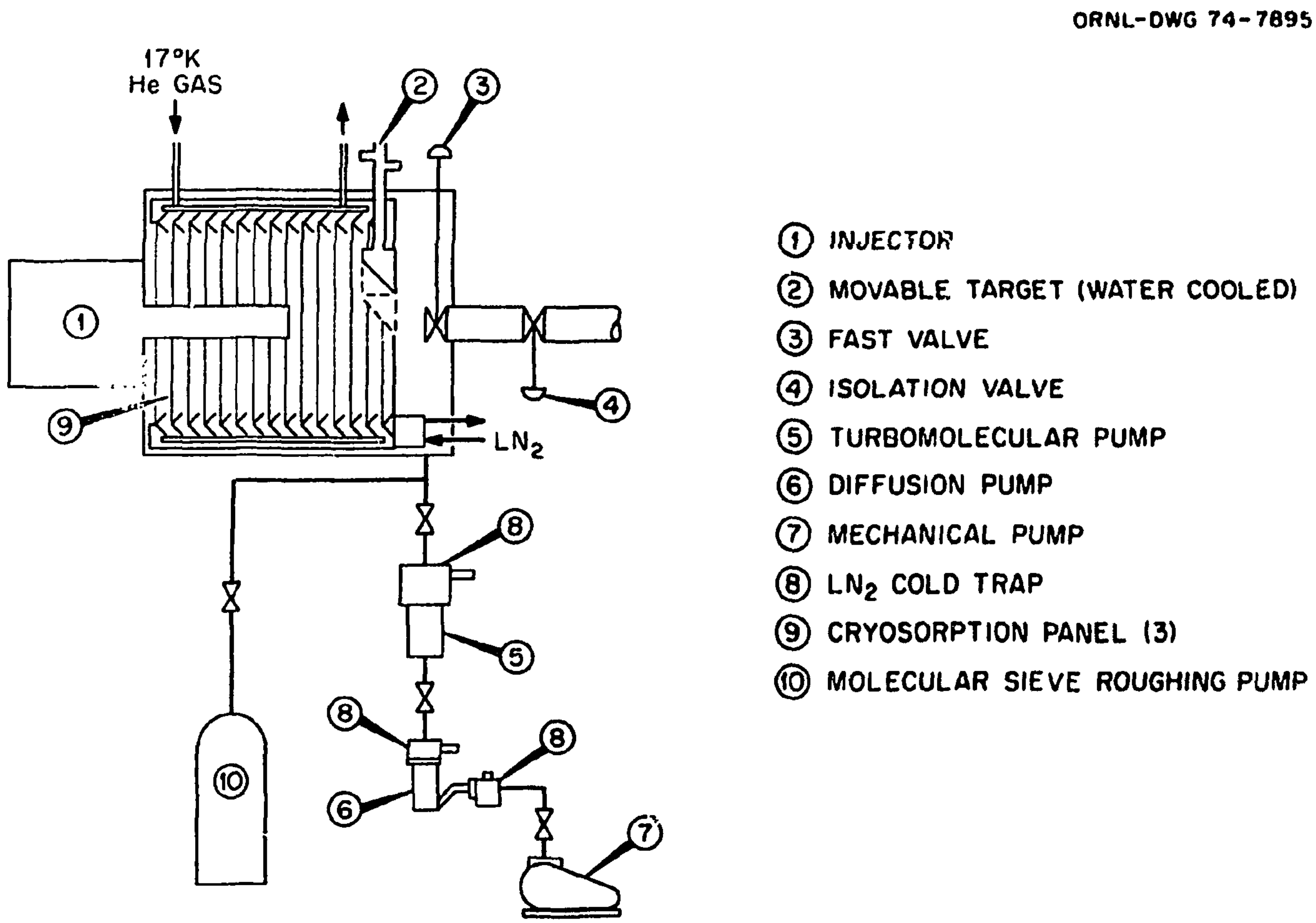

Fig. 6. Injector Vacuum Pumping Schematic

3.6 Plasma Driving System

R. S. Lord

3.6.1 General

The plasma driving system comprises several subsystems of coils, controls, and power supplies that have independent functions but are closely related because of their interactions with each other. These subsystems are as follows.

(1) The ohmic heating (OH) system supplies the major driving force for maintaining the plasma current, and because of the distribution of currents, it also supplies a portion of the plasma shaping force in the form of a vertical magnetic field. This subsystem includes the primary coils, the current sensing and control elements, the multirange power supply, and the iron core of the transformer which improves the efficiency of the magnetic circuit including the primary ohmic heating coils and the secondary current ring (in the plasma).

(2) The vertical field (VF) trimming system supplies the portion of the vertical field which must vary with time to control the plasma shape and position. The control system provides an adjustable programmed profile of current vs time, with a superimposed demand from a feedback signal proportional to lateral plasma displacement. The position of the plasma will be computed from magnetic probe signals and measurements of the poloidal field intensity and the vertical field current will be adjusted during the pulse to minimize position shifts as is being done now in ORMAK.

(3) The magnetic limiter system causes the plasma to form initially in a small area, and then expand to its full cross section while minimizing skin-effects.

The locations of the various coils, all of water-cooled copper, are shown in Fig. 7. Other principal characteristics of the plasma driving system are summarized in Table 3. The usefulness of the expanding magnetic limiter is unproven and will require further study and development.

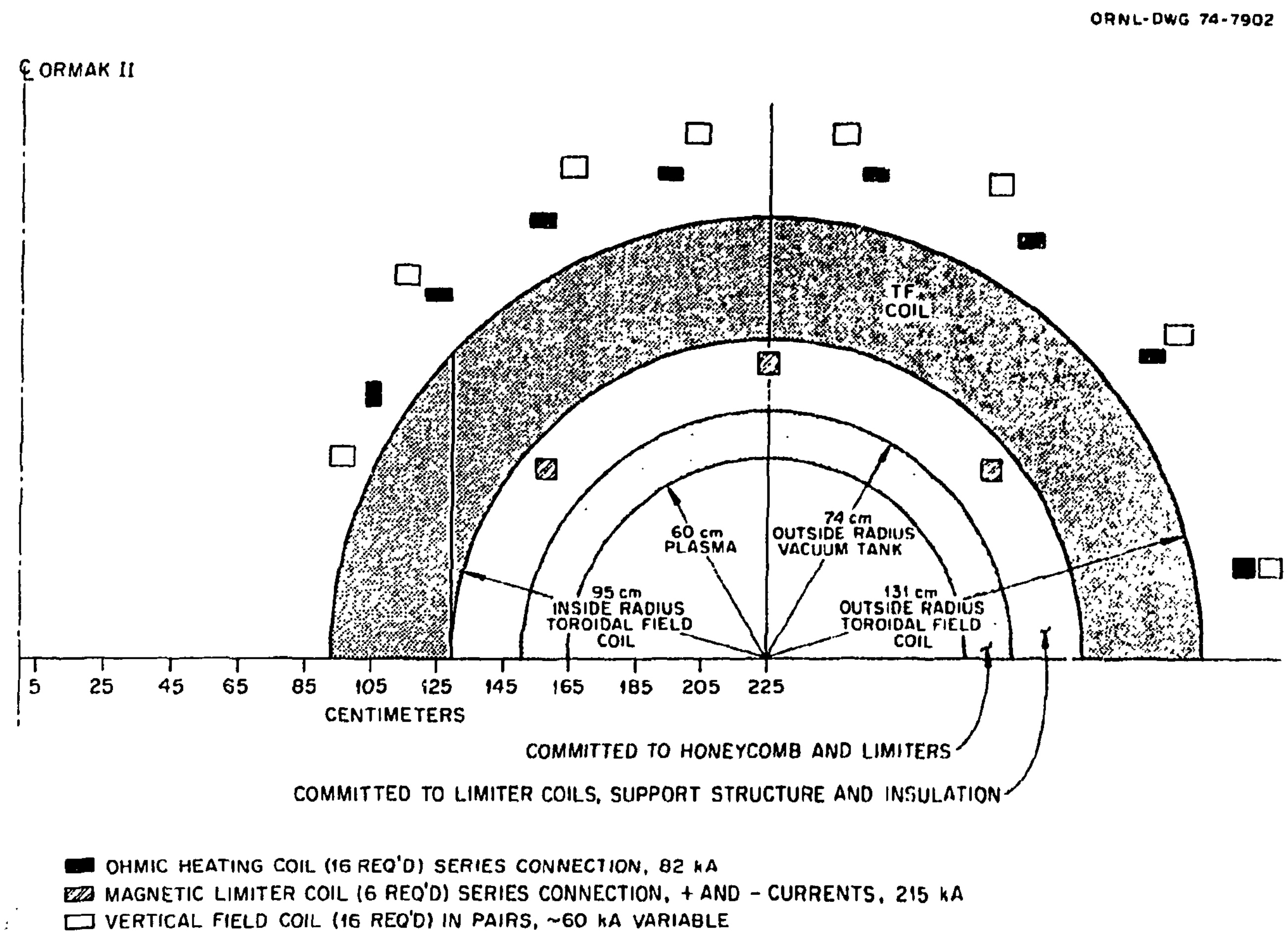

Fig. 7. Plasma Driving System Coil Locations — Reference Case

Table 3. Principal Features of the Plasma Driving System

<u>Core and Yoke</u>	
Material	20-gage AISI 1010 carbon steel
Core radius	0.88 meter
Number of return yokes	2
Weight of core and yokes	490 tons
Flux density (max.)	1.7 tesla
Flux change	7.9 volt-sec.
<u>Ohmic Heating Coils</u>	
Material	water-cooled copper
Current	81.3 KA
Number of turns	16
Conductor weight	5 tons
Current density	4000 A/cm^2
Stored energy	1.5 MJ
Power	14 MW
<u>VF Trimming Coils</u>	
Material	water-cooled copper
Current	11 KA
Number of circuits	4
Number of turns/circuit	4 to 16
Conductor weight	7 tons
Current density	4000 A/cm^2
Power/circuit	$\sim$ 1 MW
<u>Magnetic Limiter Coils</u>	
Material	water-cooled copper
Current	130 KA
Number of turns	6
Conductor weight	2.7 tons
Current density	4000 A/cm^2
Power	9 MW

3.6.2 Transformer Core

At the beginning of the design process, it is necessary to consider the choice between an air-core and an iron-core magnetic circuit. For the TTF an iron core was chosen after an assessment of the various factors involved including the relative advantages and disadvantages of air and iron for each problem area. In particular, the iron core was chosen principally for the following arguments: when compared to the air core, it is considerably easier

1) to minimize the effects of stray fields at the diagnostics and injectors,
2) to supply the power requirements for the ohmic heating system, (both the switching and control requirements during buildup and the energy storage for the running condition) since the current change required in the OH windings for an air-core system would be many (∿8) times larger than for the iron core system, and
3) to minimize the adverse effects on the TF coil superconductors from the changing flux due to the OH windings.

Because of the rapidly changing flux during the plasma buildup phase, the transformer core must be laminated to limit eddy-current effects. Calculations of the thickness of lamination required to permit the flux to penetrate the core during plasma buildup give results in the range of a few millimeters, depending on the strategy assumed in initiating the discharge. Based on this we chose to use AISI 1010 steel in sheets about 1-mm thick. Sheets of this thickness can be readily punched and are sufficiently thin to limit eddy currents to acceptably low values for the highest rates of flux change. The core will operate at a maximum flux density of 1.7 tesla, a conservative value consistent with our desire to minimize stray fields. It will be back-biased before each pulse to provide a total swing of 3.4 tesla.

A total of 7.9 volt-seconds is available with this flux density. Approximately 1.5 volt-seconds are required to store the energy of the magnetic field. The remaining 6.4 volt-seconds are available for plasma breakdown and ohmic heating. At the expense of additional ohmic heating power and larger stray magnetic fields, the core could be operated at somewhat higher flux density, yielding perhaps an additional 1/2 volt-second.

The transformer has two return legs and a central core. The proposed method of construction generally is the same as was successfully used in the 1940's to construct 2 large betatrons. The central core is composed of circular sectors nested together and clamped. Each sector is fabricated by bonding under pressure punched steel sheets of graded widths with epoxy. After curing, these sectors can be handled with the overhead crane for final assembly. The horizontal and vertical yokes are fabricated by building up subassembly "planks" from epoxy-bonded sheets. These planks will be fastened together with insulated bolts to form the large units. Butt joints are used at each of the corners and several places in the central core. At each of these joints the lower surface will be ground and etched to assure a flat, smooth surface with no interlaminar short circuits. Electrical insulation (∿ 3/4 mm) will be used at each of these butt joints. The use of butt joints greatly simplifies the fabrication (as opposed to lapped joints customarily used in power transformers) and in TTF increases the primary current less than 1%.

3.6.3 Plasma Driving System Coils

In selecting the number of turns and location of the plasma driving system windings, the following principal factors were considered:

1) effect of location of OH coils on total volt-second requirements (stored energy),
2) access to the plasma for beam injection, pumping, and diagnostics,
3) practicality of making connections during initial assembly and maintenance,
4) effect of localized fields near windings on the shape of the flux surfaces, and
5) the effects of rapidly changing magnetic fields at the superconducting windings.

The location of the magnetic limiter coils must be as close to the plasma as practical. Factors 2, 3, and 4 favor location of the OH and VF coils outside the TF coils; factors 1 and 5, inside. The decision for the TTF reference design was to locate them inside, as shown in Fig. 7.

The forces on the individual conductors are in most cases modest (100–150 pounds/inch on the OH coils due to the vertical field) however, in the crossover regions of the OH coils — or wherever the current flows at right angles to the toroidal field — the forces are very large. The maximum force expected on a conductor is about one ton/inch. The direction can be either tending to separate or to compress the crossovers, depending on the current direction with respect to the toroidal field.

Each OH winding has associated with it a vertical field winding. The current in the vertical field windings will be distributed so as to achieve an approximately uniform vertical field in the plasma region. The presence of iron in the magnetic circuit makes the computation of the vertical field more complex than in the air-core case but methods are being developed to study this problem in detail. The vertical field windings will be separated into 4 circuits for control of the field shape and intensity. The coils will be wound and connected so that they are decoupled from the flux of the OH coils and the plasma.

Adjacent conductors of the six magnetic limiter windings carry current in opposite directions, forming a sextupole field in the plasma region. The coils are also wound without linking the iron core so as to minimize interaction with the OH windings. They are driven by a single power supply.

The coil systems described here have not been optimized with respect to either cost or peak power. The peak pulse power for the system could be lowered substantially by reducing the current density in the OH, VF, and limiter coils by a factor of two, and combining the functions of the OH and VF systems into one system consisting of 8 circuits with programmable power supplies. Although combining the functions of the VF and OH systems into a single system makes a more complex control problem, it could be solved by software changes in a computer-control system. These design changes would probably not significantly change the cost of the facility.

3.6.4 Power Supplies

For the purpose of cost estimating, all the plasma driving system power supplies have been assumed to be solid-state and to operate directly from the power line with no intermediate energy storage. A preliminary cost comparison study of possible power sources made by Sargent & Lundy, Engineers, indicates that this assumption is probably optimum from an economic stantpoint; however, studies of possible power sources are continuing.

The ohmic heating power supply system must supply not only the resistive power of the plasma and the primary windings, but also the energy stored in the magnetic field associated with the plasma and primary currents. This stored energy amounts to about 1.5 megajoules. It is anticipated that the starting voltage for the plasma will be $\sim$ 130 volts/turn (or $\sim$ 2000 volts across the primary winding). The resistive drop in the OH coils at full current will be $\sim$ 165 volts. The plasma voltage as seen by the power supply should fall to 5 volts or less at full current.

It appears to be more practical and more economical to accommodate this wide range of voltages and currents with multiple power supplies. The proposed system consists of two power supplies connected in a crossover network as shown in Fig. 8. Both supplies can be energized simultaneously. The "short pulse" power supply, having a higher voltage, supplies energy to the load first. Since it also has a high internal impedance the terminal voltage drops as the current builds up. The blocking diodes prevent the starting voltage from appearing across the internal rectifiers of the "sustaining" supply. When the voltage drops to the output voltage of the "sustaining" supply the load will shift to the "sustaining" supply. In this system the "short pulse" supply provides the necessary high voltage for initiating the plasma plus some of the inductively stored energy. The "short pulse" supply is rated 2500 volts open circuit and 8000 amps short circuit. It can remain connected to the load during the entire pulse and is much less expensive than a capacitor bank. It could be made by a series-parallel arrangement of modules similar to those now being acquired for the higher field operation of ORMAK. The "sustaining" power supply is rated 400V open circuit and 200V at 82 KA. The voltage and current waveforms of the ohmic heating power supplies are shown in Fig. 9.

When the plasma current decays, the stored energy must be disposed of in some manner. A portion of this energy will be dissipated in heating the liner and mechanical limiter but much of it will be dissipated in resistive elements of the ohmic heating windings and their power supply. A portion of the inductively stored energy in the OH system will be returned to the power grid.

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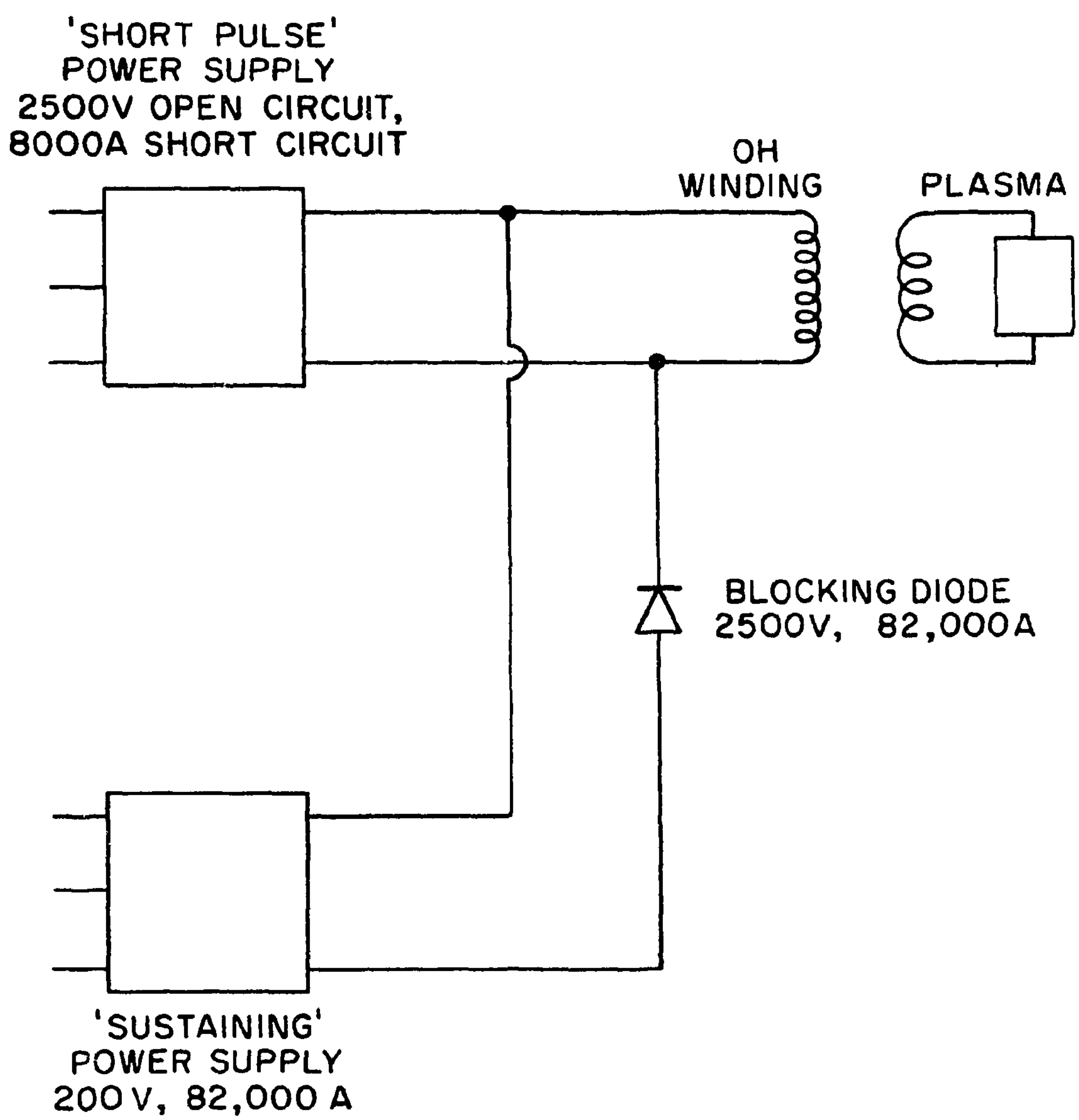

Fig. 8. Ohmic Heating Power Supply — Black Diagram

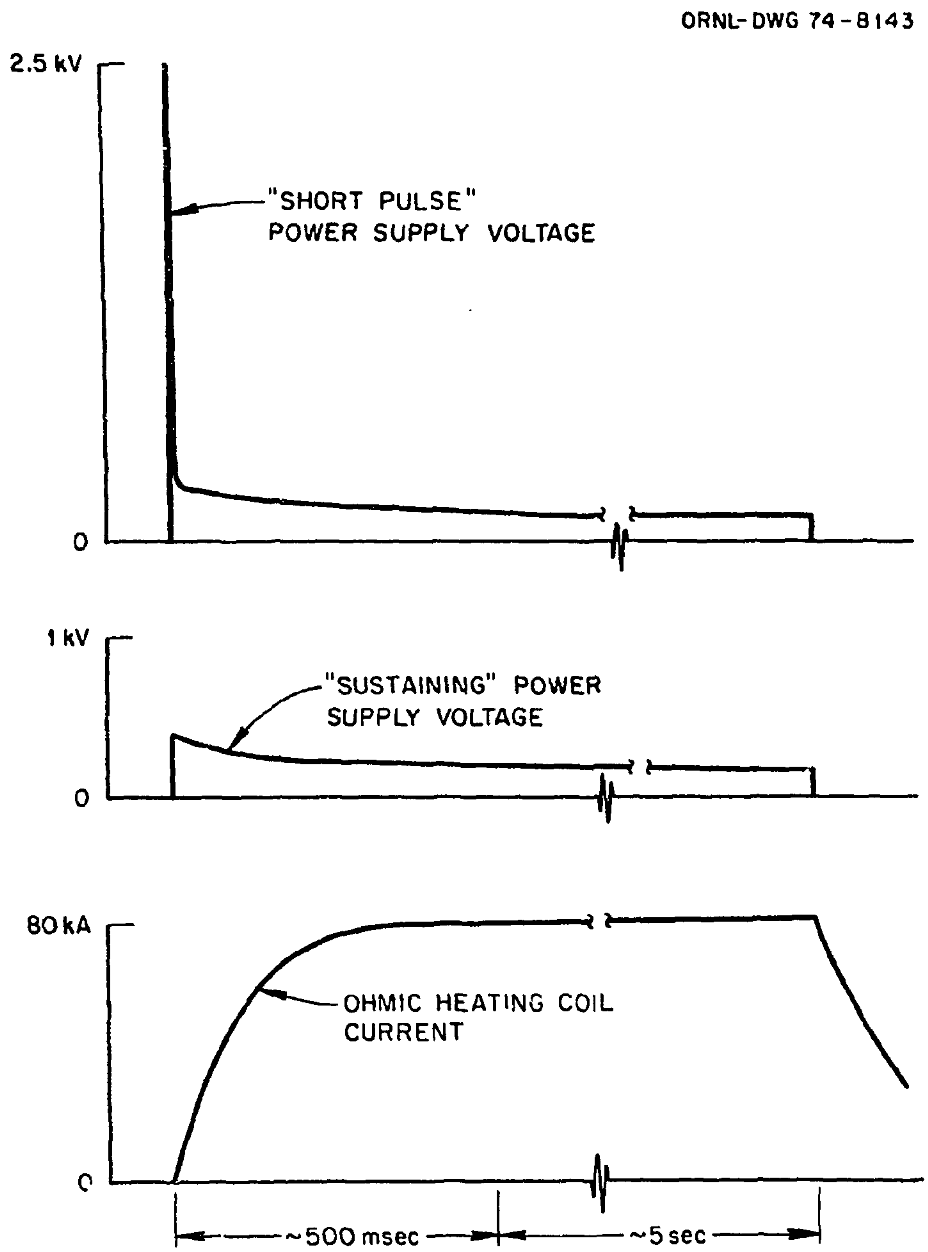

Fig. 9. OH and VF Power Supply Voltage and Current Waveforms

The requirements for the power supplies for the vertical field trimming windings and magnetic limiter windings are much less severe than for the OH system. The power supplies will also be solid-state. All of these coils will be wound without linking the iron core so that they have a minimum of interaction with the OH windings and with each other. There will be four separate circuits for the VF coils. The nominal rating of the power supplies is 75V at 11 KA.

The limiter current of 130 KA can be applied just before the OH current starts and then be reduced to zero in a controlled program as the plasma current rises. (See Sect. 3.8.) The design "on-time" is about a second but it can be programmed for much shorter rise-time.

3.7 Toroidal Field System

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M. S. Lubell J. L. Anderson

3.7.1 General

The best choice of conductor materials for the TF coils for this first superconducting tokamak is rather clear: ductile NbTi in the form of multiple filaments imbedded in a rectangular matrix of copper and copper-nickel with the operating temperature, current density, and magnetic field intensity limited so that the NbTi operates in the superconducting mode under all operating conditions. Beyond this basic choice, there are many design decisions that require more extensive analysis. For the purposes of this initial study of feasibility and costs, a set of parameters was chosen that may not be optimum, but does appear to be workable and reasonable. The following description is presented in that light.

The number of coils was set at 24 by considerations of assembly, access, and field ripple at the plasma. The coil shape that we chose for initial consideration is oval, about midway between a circle and the "pure-tension-D" shape. The coils are pancake-wound, with only a small amount of stainless steel interleaved with conductors and interturn insulation. Cooling is by forced circulation of liquid helium through passages between pancakes. The coils are wound on U-shaped bobbins, with a heavy stainless steel ring around the outside. (In the preliminary design this ring was sized on the approximation that the windings did not contribute any strength to the assembly, so that the full load would be taken by the ring.) The shape of the coils and the method of resisting the toroidal centering forces lead to quite moderate bending stresses. The centering forces are resisted by stainless steel wedges between adjacent coils, bearing against each other to form a complete ring wedged around the space for the iron core. Torques on the TF coils due to the interaction of the coil currents with the vertical field are resisted by a system of braces that are attached rigidly to the top and bottom of every coil.

3.7.2 Windings

The toroidal field requirements for the TTAP plasma fall well within the range that can be obtained with the ductile alloys of Nb and Ti. For the conceptual design, we therefore assumed critical current density and critical field values appropriate for the various alloy compositions that are commercially available at the present time.

In order to obtain optimum performance of the NbTi superconductor, it is advantageous and economical to employ different superconductor for the different field ranges. The exact number of different superconductors to employ depends on stability as well as cost considerations. In general, one uses a high-Ti composition for low fields and vice versa. Also, although we speak of NbTi as the superconductor, we may in fact use a ternary with a little Ta replacing some Nb or a little Zr added as a dopant to optimize the current density. In the present concept we use two different superconductors in the windings (one for the inner or high-field region and one for the outer or low-field region). The low-field region is where the superconducting instabilities are likely to occur and thus this conductor has a higher copper-to-superconducting ratio than the conductor employed in the high field region. (It may be that subdividing the windings still further will save additional money but the added complexity for the winding operation makes too many subdivisions unattractive. An optimization study has not yet been made.)

We note that the operating current is less than half the critical current of the conductor. This is done for two reasons. First, local heat input due to pulsed fields and plasma current instabilities could raise the temperature of the superconductor as much as 1 K and thus reduce the critical current by some 33%. In addition, the operating current also has to be higher during the possible quench of a coil since the ones adjacent will have currents induced in them in an effort to maintain the flux constant. The sum of both these effects means that there must be a wide spread between the critical current (design current) and the operating current at steady state operation at T = 4.2 K.

Stabilization

An important consideration in the design of any superconducting magnet is the method of stabilization employed. When the volume of a magnet is not a critical consideration and long-term operation without any interruption is needed, and if in addition no rapidly varying fields are present, the best choice is a design employing cryostatic stabilization. However, the recent advances in the manufacture of NbTi wire and magnet construction offer a viable alternative, at least so far as an experimental device of the nature of a tokamak is concerned. Adiabatically stabilized NbTi originally developed at Rutherford Laboratories has been extensively used in many small and intermediate sized magnets operating at high overall current density (>30,000 A/cm^2) with great success and there is no reason not to consider this stabilization technique for extrapolation to the size needed for TTAP. A single coil for the W7-Stellarator in Garching with a bore of 80 cm and using adiabatically stabilized NbTi was successfully built and tested by Siemens. Briefly, the technique involves breaking the superconductor up into many fine strands both to increase the surface to volume ratio and to allow penetration of the magnetic field before exceeding a critical flux jump value. In addition, the filaments are twisted to help cancel induced emf resulting from changing magnetic fields. While it is true that an adiabatically stabilized magnet is more likely to suffer a quench (or sudden loss of stored energy) than a cryostatically stabilized magnet during charging, it should be noted that in either case adequate protection must be provided to prevent permanent damage. An adiabatically stabilized magnet not only would be smaller and lighter than a cryostatically stabilized one (due to higher current density), but since less high conductivity normal metal matrix (copper or aluminum) is used, the losses due to the eddy currents induced by the pulsed ohmic heating and vertical field coils would be significantly less. It is also easier to stabilize against rapidly varying fields. In addition, the adiabatically stabilized conductor has a much higher yield strength than copper, which is the value one must use when employing cryostatically stabilized windings. In fact, a careful study of these problems may render a cryostatically stabilized coil exceedingly expensive in terms of the refrigeration power required.

In the present study for TTAP, we employ adiabatically stabilized NbTi. Since the toroidal field coils are not themselves pulsed but merely see a pulsed field, there is no need in the first instance to consider either fully transposed flat braid or cables composed of many small wires. We will consider only rectangular conductor with aspect ratios (width to thickness) up to 15 and normal metal-to-superconducting ratios in the range of 3:1 to 5:1 containing many fine strands (2 mils or less in diameter) of NbTi superconductor with some small amount of twisting. The filament diameter and twist necessary will depend on the magnitude and rate of rise of the pulsed fields sweeping over the toroidal magnet. If manufacturing limitations should prevent an ideal conductor from being made in one piece, then two or more conductors could be bonded to a substrate and operated as a single conductor. Alternately, one could fabricate a rectangular conductor from a flat braid or cable which has been fully impregnated with a solder and rolled flat. This will be the preferred conductor (comprised of strands with mixed matrix normal metal) if the pulsed ohmic windings turn out to be energized more rapidly than initially anticipated.

Alternative Designs

There are a number of alternative designs to consider for the winding configuration of a large magnet using adiabatically stabilized NbTi. The conductor can be wound in either pancake (spiral) or layer configurations, potted or unpotted. Complete potting in epoxy with fiberglass insulation as has been done, for example, with the levitated coils at Culham is a viable alternative. The cooling is done by conduction and hence thick windings are not advisable. However, this type of construction can be sectionalized to avoid local heating. Another possibility which has not been utilized yet is a potted coil internally cooled with tubes embedded in the proper geometry to assure adequate cooling of all turns of the superconductor. One could also envision using hollow conductor cooled internally by forced circulation of supercritical helium as is the case with the large 20-kG Omega magnet at CERN. With hollow conductor the superconducting filaments are preferably embedded in the walls (but strands can be wrapped about a copper tube), but whether manufacturing techniques can produce th.s type of conductor for high field application with the necessary tolerances and lengths has to be determined. Finally, one considers pancake winding of large rectangular conductor with some edge cooling by helium. Although direct contact to liquid helium is not necessary for adiabatically stabilized conductor, it seems prudent for the initial design of such a large system to consider this technique to provide another margin of reliability. Most of the large magnets built to date used this method for the winding and cooling configuration. In these cases cryostatic stability was employed and so it was necessary to have the intimate contact with helium. Because of the size and toroidal geometry of the TTAP magnets, we will also initially assume forced circulation of the liquid helium. Detailed calculations and experiments will be needed before a proper determination of the cooling channels and helium mass flow can be specified. The insulation between pancakes can be grooved in such a manner that the helium will be able to flow upward to the top of the coil and prevent vapor locks from forming.

Interleaved Reinforcement

For the general design of these coils, we will assume that some stainless steel will be interleaved or bonded to the superconductor and that we will employ both lumped and distributed structural reinforcement. On purely structural considerations, arguments can be given for omitting any structure internal to the windings and designing the coil so that all the electromagnetic forces will be transmitted to an external reinforcement ring, which will likely be needed in any event to provide rigidity. In our preliminary considerations, we decided not to adopt this approach, but to take a somewhat more conservative design philosophy and include stainless interleaving with the superconductor.

The stainless interleaving serves four functions. First, it provides strength at the highest field region where it is most needed. Second, it reduces the differential thermal contraction between the windings and the steel reinforcement ring since the superconductor bonded in copper (or in copper plus cupro-nickel) has a higher thermal contraction on cooldown than stainless steel. Third, it prevents the axial compression forces between pancakes (during normal operation and fault conditions) from damaging the edge of the superconductor since the latter is unlikely to be available in as close a tolerance as the stainless steel. This also means that a higher fraction of the exposed superconducting surface can be in contact with helium. Finally, the stainless steel can be grooved if need be at the inner and outer radii of the pancakes to permit the liquid helium coolant to flow axially for easier removal from the coil. It is also assumed that the superconductor will be bonded to the stainless steel and insulated in some manner — perhaps by vacuum impregnating in epoxy. The electrical insulation between turns may be fiberglass, Kapton, or a metal oxide.

Another important factor that favors distributed reinforcement is the possibility of using a coil protection method in which the energy is dumped throughout the windings. In this case the temperature differential between the copper and the low thermal conductivity stainless steel could become unacceptably large unless the stainless steel is distributed.

The first conceptual design of the superconducting toroidal field coils for TTAP is characterized by the design data listed in Table 4.

Table 4. Toroidal Field Coil Winding Data

Conductor Material	NbTi in Cu and CuNi
High field composition	Nb – 45 wt% Ti
Low field composition	Nb – 55 wt% Ti
Stabilization	Adiabatic and transient cryostatic
Operating temperature[a]	4–5K
Maximum operating field, tesla	7.5
Winding bore dimensions, m	2.0 x 2.67 (oval)
Toroidal array major radius, m	2.25
Central field, tesla	4.1
Stored magnetic energy, MJ	480
Total ampere-turns (in 24 coils)	47×10^6
Ampere-turns per coil	2.0×10^6
Winding cross section area, cm^2	390
Winding axial length, cm	23.5
Winding radial width, cm	16.6
Average current density,[b] A/cm^2	5000
Critical current per conductor (4.K), A	6900
Critical current per conductor (5.K), A	4600
Operating current per conductor, A	2780
Turns per coil	704
Pancakes per coil	16
Total turns per pancake	44
Conductor width, mm	11.5
Insulation width between pancakes, mm	3
Conductor thickness in inner turns, mm	4.2
Conductor thickness in outer turns, mm	2.1

[a]Forced flow of helium is assumed.

[b]Average over conductor, interleaved stainless steel, radial and axial insulation. Neither the bobbin nor the reinforcement ring of stainless steel is included.

Table 4. (continued)

Matrix to superconductor ratio (inner)	3/1
Matrix to superconductor ratio (outer)	5/1
Current density in conductor (inner), A/cm^2	5760
Current density in conductor (outer), A/cm^2	11,520
Insulation thickness per turn, mm	0.127
Stainless steel per turn, mm	0.5
Total radial thickness per turn (inner), mm	4.82
Total radial thickness per turn (outer), mm	2.72
Inner turns per pancake	22
Outer turns per pancake	22
Length of 4.2 x 12 conductor per pancake, m	168
Length of 2.1 x 12 conductor per pancake, m	179
Total length of 4.2 x 12 conductor per coil, m	2690
Total length of 2.1 x 12 conductor per coil, m	2870
Volume fraction conductor in coil	0.67
Volume fraction stainless steel in coil	0.11
Volume fraction coolant and insulation in coil	0.22
Bobbin cross section per coil, cm^2	225.5
Conductor weight per coil, kg	1,635
Interleaved stainless steel per coil, kg	260
Insulation weight per coil, kg	75
Bobbin weight per coil, kg	1375
Total weight per coil (without structure), kg	3400

3.7.3 Structure

The toroidal field coil restraining structure must resist the electromagnetic forces developed in the winding due to the Lorentz force between the current and the magnetic field. Criteria for the design of the TF coil structure consist of a stress criterion for both the conductor material and the restraint structure, a deflection criterion for the conductor material based on the amount of movement permitted by the characteristics of the superconductor, and a heat conduction criterion based on the operating temperature of the conductor and the refrigeration system design.

The concept for the toroidal field coil restraining structure is based on the precept of maintaining the entire structure at or near the operating temperature of the superconducting winding.* The principal element of the structure consists of a hoop restraint which surrounds each winding and resists the electromagnetic forces on the winding. Each hoop has tapered surfaces which transmit the net centering force on each coil to the two adjacent coils. A set of two spacer bars between coils acts in conjunction with the wedged noses to resist the out-of-plane loads on each coil. Each TF coil is supported by an inner support ring and a gravity support on the outer side. The inner support ring is supported by several gravity supports. The entire TF coil system, the wedged coils, support ring, and spacer bars are enclosed in an interconnected series of cryostats which provide the thermal insulation for the coil system. Construction of the cryostats is accomplished using basic cylindrical geometries with the necessary bellows and seal-weld flanges to allow assembly of the cryostat interconnections. A common cylindrical cryostat around the wedged-nose region requires use of a vertical seal weld between the cryostats enclosing the outer parts of the coils.

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*Consideration of alternatives in the course of the ORMAK-F/BX study[5] indicated that this was clearly the most practical approach.

3.7.4 Loadings and Stresses

The predominant forces acting on the TF coil system are the electromagnetic forces developed in the winding due to the interaction of the current and the magnetic field. Variation in the magnetic field, which is inversely porportional to the major radius within the toroid, results in a magnetic pressure load on the winding which is asymmetric (i.e., the magnetic field varies both radially and azimuthally about the central axis of one minor cross section). The differential magnetic pressure at the centerline of the winding varies approximately from 1700 psi at the outer winding location to 4800 psi at the inner winding location. Resulting hoop tension, bending moments and shears are resisted by the hoop restraint which surrounds the coil winding and is integrally attached to the bobbin.

A net radial centering force on each coil of approximately 55 million pounds results from the vector summation of the magnetic pressures on the winding. This force is resisted by the compression of the wedged coils acting against each other. In an oval TF coil the resulting bending moments are substantially less than those in circular coils and the required structure is consequently less.

The overturning moment which results from the interaction of the TF coil current and the vertical field is about 2 million ft-lb. This is resisted by rigidly attached spacer bars between coils, by the wedged noses which are keyed to one another, and possibly by external structure. Rigorous, detailed analysis of the out-of-plane loadings and the restraint structure has not been completed; it may be that additional restraints which transmit part of the out-of-plane loads to a room-temperature structure will prove necessary. If so, the structure in this case will also serve to support the toroidal vacuum vessel.

A different pattern of electromagnetic forces develops in case of a fault condition in which the current in one coil decreases relative to that in the other coils. Under these conditions, fault loads acting perpendicular to the planes of the coils develop in the coils adjacent to the low-current coil. For a complete loss of current in one coil, the load on adjacent coils has a magnitude approximately equal to the centering force. Simultaneously there is a change in the centering forces on the other coils; on some it is higher, on others lower. The out-of-plane fault loads must be resisted by the same structure which resists the torque load.

The TF coil structure was initially sized to limit the stresses in the structure to a maximum allowable value of 60,000 psi. The selection of this allowable stress for the structure was based on limiting the stress to less than 2/3 of the yield stress at temperature for typical austenitic stainless steels. In a study of candidate materials, Type 310 stainless steel was selected as the structural material. The yield stress of Type 310 stainless steel at 4K is 110,000 psi.

The structures required to resist the electromagnetic forces become quite massive and in turn present significant loads which must be transferred to ambient surroundings while minimizing the heat conducted to the toroidal field coil. (A weight of around 170 tons must be carried through gravity supports that limit the heat conduction to the 4K system to a few tens of watts.) The concept for supporting this load consists of providing pure tension supports of extended length and with a high strength-to-thermal conductivity ratio. As can be seen in Fig. A.2, the weight of each TF coil is carried to ground through a stainless steel tension hanger rod on the outer side and a support ring on the inner side that in turn is supported on hangers. These hangers are approximately one meter long and are designed to support 1-1/2 times the load at a stress of approximately 20,000 psi which results in a heat leak through the gravity supports of approximately 1 watt per toroidal field coil.

3.7.5 TF Coil Fabrication and Assembly

As a part of the conceptual design of the ORMAK-F/BX, a study was made of the fabrication and assembly problems associated with TF coils similar to those proposed for TTAP.[5] The following is a brief description of major facilities needed, with some comments on handling problems. This study was limited to unique problems, particularly to the coil assembly; many conventional processes and techniques needed for complete assembly are therefore not discussed below.

Bobbin — The bobbin is required to have a thick inside coating of oxygen-free copper on a structural base material of non-magnetic stainless steel. Stainless steel plate is commercially available with one side clad with copper. By proper joint design, one may weld these cladded plates into the basic bobbin configuration. The bobbin must then be stress-relieved and overall machined to provide dimensional integrity. Machining of 120-inch diameter oval parts is a capability not normally included in the repertoire of UCCND shops; however, a large capacity (10-ton, 120 in.) rotary table and a good milling head with controllable x,y,z motions probably can do the job.

The copper on the bobbin serves as a heat transfer shunt to remove the heat from the bobbin and will be sufficiently thick to allow the machining of spiral starting grooves for the superconductor winding. This groove will provide space for the superconductor to form the crossover between pancakes. The last few centimeters of each groove will be ramped up to provide zero depth at the starting point of the next turn. This requires the use of tape-controlled equipment on the depth of feed axis of the milling head.

Coil Winding — The winding operation requires several preliminary steps. In addition to workpiece and winding equipment alignment, the crossover strips, which connect the conductor stacks in series, must be affixed in their machined grooves. Also, the coil spacers must be affixed to the bottom inside surface of the bobbin. The end of the first conductor could be spliced to a crossover strip at the start of the bottom groove next to the coil spacer. The conductor may be wound by rotating the entire coil at a very slow speed. A guiding system which locates off the outer edges of the spool will position the conductor to provide a precise radial stack. A constant tension control system will also be required. This system may be very massive and will require closed-loop control systems in order to wind a consistent size coil with a prescribed amount of pretension in the conductor.

Another system is needed at this winding station to make the conductor "sandwich." This system may include epoxy application, individual tension, and guiding mechanisms to supply each component of the sandwich properly.

Each conductor stack must be wound in the opposite direction from its neighbors; therefore, much of the above described equipment must operate for both clockwise and counterclockwise wrapping.

An alternate approach to coil winding is to hold the bobbin stationary and move the winding equipment around it. The principal advantage of this method for very large coils is that the energy required to stop the winding operation is less. For the TTAP coils, the kinetic energy of the rotating table and bobbin is small (a few joules) and it is much easier to design a system to dissipate this energy than to provide the equipment mobility required to wind with a stationary bobbin.

As each pancake is wound, it will be soldered to a generous area of a crossover superconductor and this will be fastened on the last turn in alignment with the spiral groove on the bobbin. After all the pancakes have been wound and connected to crossovers, the copper-clad outside closing ring will be shrink-fitted over the pancake-filled bobbin and positioned to place the two coil leads in alignment with the spiral groove on the bobbin. That is, the closing ring is to be machined with a matching spiral groove that will coincide with all the crossovers and nullify their stray field with the leads. The result is a closing ring that contains both leads pressed tightly against the outer crossovers and the O.D. of insulating spacers as well as fully pre-compressing the O.D. of each pancake.

Restraint Ring. The idea that the restraint ring be maintained at temperatures near 4K has led to the assumption that more structural integrity and material homogeneity will be achieved by using monolithic (i.e., non-welded) hoops for its construction. Consequently, Fig. 10 shows two forgings tied laterally with long bolts to prevent buckling. These forgings are drilled out with cooling channels symmetrically about the vertical midplane of the coil. They will be seal-welded together and structurally fastened and seal-welded to the bobbin to form the helium reservoir for the coil. Machining of the joint between the two forgings and the bobbin cover is critical since most of the strength required to hold the coil together is in this interface. To reduce the wedge reactions' tendency to

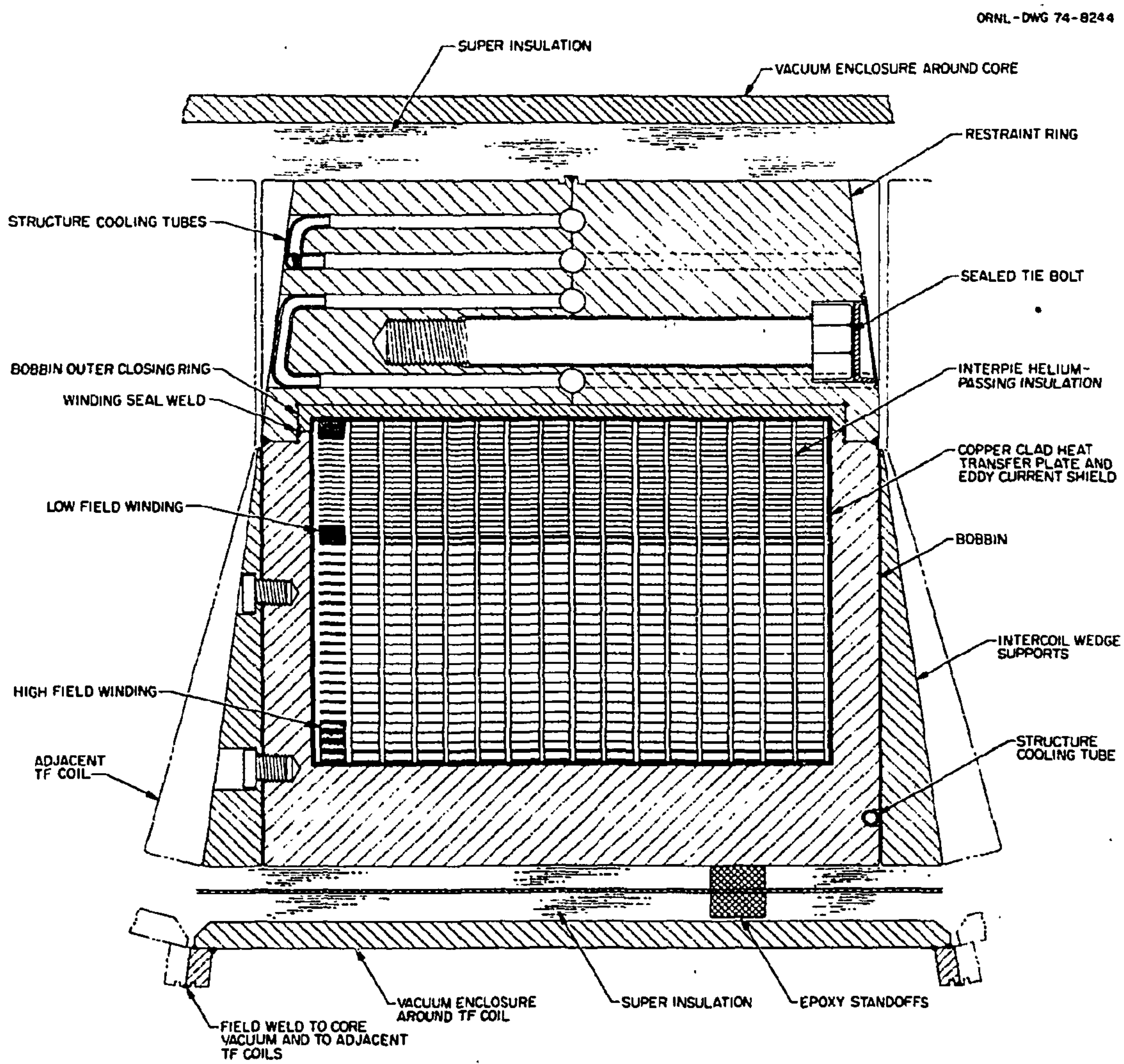

Fig. 10. TF Coil Cross-Section — Reference Case

shear the seal welds, the intercoil wedges will be separate forged pieces that will transmit the centering force to the restraint ring so that the weld is not loaded. Similarly, the extensions of the ring to the gravity links will protect the seal weld. To reduce the bending imposed by the lateral couple, the connections for the spacer bars between coils will bridge the sealed interface of the bobbin-restraint ring to employ the stiffness of the ring at these high moment connections.

The restraint ring subassembly must provide a compressive preload on the outer diameter of the conductor stacks. It is reasonable to assume that each stack will have a slightly different outer diameter and that there will be small variations around the circumference of individual stacks. To allow for this variation, there are two possible methods. First, material may be added between the top of the coils and the spool cap. One method involves signature castings of the coil contour and has been done on smaller coils. The second method involves inspecting the contour of each stack and creating a machining tape for signature cutting grooves in the copper cladding of the restraint ring.

Shrink Fit Press — The restraint ring subassembly must be fitted snugly over the conductor stacks. If a temperature difference of 180°C were achieved, then the clearance between the two would be more than a centimeter on the diameter. If a large press were employed and the two parts aligned to each other while on the platens of that press, then one would only need to heat the backing ring subassembly with blankets or some other convenient method and lower it in place over the conductors. Admittedly this scheme requires one large precision-guided press, and the heating of the backing ring may take many days. The press does not, however, need to apply force; but only to support and precisely guide.

Cryostat — The coil structure will be surrounded by many layers of NRC-2 metalized mylar reflective insulation. This insulation, mounted to sheets of aluminum, will occupy the annular space between the coil structure and a stainless steel vacuum vessel that also surrounds the coil. This vacuum vessel wall will be supported by epoxy standoffs on 26-in. centers so that the low coil temperature can be maintained. The standoffs are sized to prevent compression of the reflective insulation by the deflection of the coil dewar wall. Construction of the vacuum enclosure is such that the coil structure is fitted with the superinsulation and placed inside an open-sided vacuum enclosure. The enclosure is completed by attaching a closure flange at this point which is seal-welded in place. Openings remain in the enclosure through which the spacer bars and compression jacks are installed. These openings are ultimately closed at assembly by the bellows and closure flanges which constitute the interconnections of the cryostat system which houses the entire TF coil support system. The only conductive heat paths into the coil system are the epoxy standoffs, the electrical and helium leads and the gravity support links.

Vapor-Cooled Leads — The function of the helium vapor-cooled leads is to introduce 3000 amps from the room-temperature bus to the 4K liquid-helium cooled superconductor with a minimum coolant loss or refrigerator cost. A minimum lead length of one meter will be provided using a stainless steel tube filled with fine cable wires.

The copper-to-superconductor joint will have generous length of solder to insure reliably-low resistance connections. For ease of handling and to improve the contact pressure of this joint, consideration is being given to a collet chuck type clamp to aid the solder joint. The reference design employs a scheme that will provide full bearing support of the superconductor leads and the O.D. of the pancakes that pass under the opening for the helium conduits. The intent of providing this support is to reduce stress raising condition on the outer windings. The necessity for electrically isolating the leads has suggested ceramic feedthroughs and spacers of the quality used for ultra-high vacuum applications. Bellows have been used to provide leak-tight sealing and thermal and differential pressure compensation.

Special Equipment — Fabrication and assembly of the TF coil system requires special equipment not only for the winding of the coil but also for other functions as well. The handling of the assembled coils requires special equipment. The stainless dewar is not strong enough to support the weight of the coil. The complete coil must, therefore, be handled through the openings in the dewar for the stabilization spacers. This handling fixture must clamp the coil from both sides in such a way that the coil may be handled in an upright position.

There are within the coil two spaces that form leak-tight systems. One space is the parts to be bathed in helium. This includes all the leak-tight welds on the bobbin and restraint rings. The second is the space occupied by the super insulation starting at the coil structure and extending to the closures on the dewar. Both of these systems require integrated leak-checking. Integrated leak-checking is done by putting the system to be checked under a hard vacuum and surrounding the system with gas (normally helium) or surrounding the system with a hard vacuum and backfilling the system with gas. The discharge from the vacuum pumps in either case is sampled for helium concentration. The dewar will not be as hard to pump down to a hard vacuum as the coil area will be. The coil area may leak trapped gasses for weeks. Large pumps will help the time problem only partially. Only proper coil design will make the problem manageable.

It would be naive to try to manufacture these coils and expect the parts to all fit together without careful independent checking of certain critical dimensions. This is not to say we need a 150-inch inspection machine. We do need, however, a special area with equipment specifically developed for the kind of dimensional control the design itself requires. These dimensions may well be met by rotary tables with good flatness and runout characteristics, properly instrumented.

3.7.6 Coil Protection

A protective scheme must be devised to prevent damage to the toroidal field coils, their associated structure, and auxiliary systems when any credible fault event occurs. In addition, the design should incorporate features to minimize the occurrence of such faults and minimize the consequences of their occurrence. The requirement for extraordinary protective features arises from the extremely large amount of energy stored in the magnetic field. When the coils are equally energized the magnetic forces tend to compress the coils axially and result in a centering force towards the torus major axis which can be restrained by large bucking rings or tension members. When the coils are unequally energized, as when one or more coils has quenched, the axial compressive forces become asymmetric and the bending moments exerted on the coils become large near the fault. In addition the coils must be protected against internal damage which might result from quenching. Passive external resistive shunts will provide the principal protective means, but some active protection may be necessary such as fast acting valves, switches, or heaters. (The detailed requirements for coil protection are being addressed in the DCTR program for development of toroidal superconducting magnets for fusion research.)

The protective requirements for the toroidal field system fall into three principal categories:

1) the prevention of mechanical damage due to the high magnetic forces. Considerations include the internal coil structure and the external support and restraint structure;
2) the prevention of local internal temperature rises which might damage the windings or connections;
3) the prevention of damage to the dewar system by overpressure caused by large energy release (quench), and the associated economic consideration of avoiding loss of helium and refrigeration energy by venting liquid as well as gaseous helium when quench occurs.

Potential accidents which lead to the protective requirements also fall into three general categories; mechanical, thermal, and electrical. When mechanical failures of the coils or restraints occur or stress yield causes breakage of the superconductor filaments, little can be done to protect the failed coil, but measures may be necessary to prevent propagation of the failure to other coils or structure. Quenching of the failed coil brings about asymmetrical axial magnetic forces and the deposition of a large amount of heat in the coil internals. Quench may also be initiated by leaking or plugging in the helium refrigeration system. Thermal failures leading to quenching may be caused by a variety of failures in the refrigeration systems, the vacuum systems, or the complex insulation of the coils. Potential electrical failures similarly are many fold. The loss of power to almost any of the numerous vital active systems would lead to the necessity of dumping the energy stored in the field. Individual failures to coil charging supplies, refrigeration units, vacuum pumps, switch gear, etc., would require steps to avoid the effects of the asymmetrical forces which result when the coils are not equally energized.

Magnetic field anomalies may also lead to undesirable quenching. The magnetic interaction of other fields such as the vertical and trimmer fields may lead to spontaneous quenching if the flux exceeds the critical value in the superconductors. Similarly, current decay in one coil may lead to a quench condition in an adjacent coil due to mutual coupling.

The specification of required protective functions cannot be completed until the detailed design of the coils is further advanced. Some of the possible functions will be discussed along with their effects on system design. A very desirable basic philosophy of protection is to dissipate the stored energy of the system external to the low temperature environment. While desirable, this concept may not always be possible as will be discussed later. Some external dump will be necessary in any event to limit the coil voltage on discharge and protect the electrical insulation. It is probable that individual charging supplies will be necessary for each coil in order to avoid the accumulation of voltage which results from series operation. The external resistance in parallel with each coil should be made as high as possible (within the limits of maximum coil voltage) so that as much energy as possible is dumped external to the coils when quench occurs. Because of the amount of energy involved, the dump resistance may require forced cooling. Two operating techniques are possible which affect the way in which protective action (external dump) is initiated. A common technique with large coils is to keep the energized charging supply connected to a coil during normal operation. In this case the dump resistor may be permanently connected in parallel with the coil. At the charging voltage the power loss in the dump resistor is small and is readily supplied by the charging supply along with the coil losses, with no switching necessary. To initiate dump the supply is disengaged either with a conventional circuit breaker or, if a blocking diode is used, by de-energizing the supply primary. Alternatively, the coils after being energized may be short-circuited with superconducting switches so that the charging supplies may be de-energized. The complete superconducting loops are self-sustaining except for very slow decay due to small losses from internal joints. Obviously, to effect a dump in this case it is necessary to quench the superconducting switch to get the dump resistance into the magnet circuit. This scheme, while more conservative of energy, is more complicated and less reliable in initiating protective action. If the external energy dump is used to avoid prolonged or excessive asymmetric forces when one or more coils quench due to local perturbations or failures, then all coils must dump reliably on demand, whichever technique is used. It is probably tolerable for one or two coils to fail to dump, because the forces in this event will be much less than if only one or two dump, although detailed calculations of this situation have not been made. Transient asymmetric forces will have to be tolerated regardless of technique, because when quench occurs the total loop resistance changes markedly and the energy decay time constant will be different for quenched and unquenched coils.

Somewhat contrary to the principle of external energy dump is the possible requirement for forced uniform quenching of coils for protection against internal damage. Very localized quenching may occur which could lead to excessive local temperature rise and damage unless positive means are employed for forcing the quench of a much larger volume of the coil to dissipate the stored energy more uniformly. A uniform quench is calculated to raise a coil's temperature by 50 to 100K depending upon the particulars of design and refrigeration capacity. Once quench is initiated the temperature would rise very rapidly, because the copper resistance rises rapidly with temperature and as the resistance rises more of the total energy is deposited internally rather than externally. Two methods are envisioned for rapid quenching. The first would valve off the liquid-helium flow and allow the developing pressure due to heating to drive off the remaining fluid from the windings, or perhaps purge the fluid by admitting additional high pressure gas. The second method would require heaters to be imbedded in the windings which when energized, would rapidly heat the windings above the critical temperature. Either method would require rapid sensing of initial quench and rapid, reliable actuation of valves or switches.

Complete coil protection may require a combination of external dump and forced quench. Rapid sensing of coil quench is an important part of the protective schemes. Several detection techniques are possible, the simplest probably being the measurement of coil terminal voltage. The coil resistance increases sharply when quench occurs and the voltage will surge accordingly since the current cannot change rapidly because of the large inductance. Magnetic probes could also be used effectively to sense the rapid change in flux. Sensitive detection might also be possible by monitoring helium pressure and liquid-helium level. Thermometry is possible but probably much slower than the other methods and less likely to detect localized quenching. In addition to quench detectors, monitors will likely be required on the charging supplies, refrigeration and vacuum systems so that uniform external energy dumping can be initiated if required when the dumping of one or more coils is initiated or imminent. Some effective redundancy of these systems may be a reasonable design objective since generally much larger capacities are required to achieve steady state conditions than are necessary to maintain them. If the extra startup capacity is provided by essentially independent systems, the failure of one or more of these auxiliary systems may be tolerable without interrupting operation. Redundancy and diversity of quench sensing with the different methods available is also feasible. Detection of incipient mechanical failures may be possible using displacement detectors to monitor vital points in the restraining and supporting structures.

Conflicting objectives arise from the desire to provide a high degree of protection by use of redundant and independent supply lines and signal on the one hand, and the need to keep penetrations of the secondary vacuum enclosure surrounding the coils to a minimum on the other. For example, it is desirable to locate the manifolding and orificing for proper flow distribution of the helium inside the vacuum enclosure to minimize the complicated, insulated penetrations. However, the common coupling between coils without valving of the helium supply may lead to quenching of all coils supplied by the same plumbing complex through loss of coolant since the increased pressure would drive the liquid helium from all coupled coils. With this arrangement the mechanical restraints would need to be sized for the load of several quenched coils, rather than just one or two.

When fully charged each coil stores 20 megajoules. When a quench occurs, much of this energy could be deposited in the coil where it must ultimately be removed by the helium refrigeration system. The helium system must also accommodate the consequent rapid temperature rise and pressure increase without substantial loss of helium. In order to accomplish this, it may be necessary to use fast-acting valves to isolate quenched coils from the remainder of the system.

The detailed protective requirements can only be determined when the coil design and development have progressed and the effects on and interactions with other systems are better established. The most significant factors affecting the complexity of protection system design, and to a similar degree the system reliability, are the ability of the coil support and restraint structure to withstand asymmetric loading and the degree to which the coils will be self-protecting against internal damage by rapid propagation of a quench throughout the volume of the coil. Both of these factors involve design trade-offs of both performance and economy.

3.8 Electrical Power

E. W. Pipes T. W. Reddoch* S. W. Mosko

This section describes the electrical power system, including the primary and secondary power distribution systems, power utilization centers, special purpose power supplies, and major electrical loads.

3.8.1 General

The electrical loads in the TTAP will mainly consist of special purpose power supplies for the experiment, process utilities electrical loads, and the usual building services and auxiliary services associated with an R&D complex of such magnitude. The average electrical power load of the TTAP facility is about 6 MW, but the peak load during an operating pulse ranges up to about 30 MW. Each pulse lasts nominally from 5 to 10 sec and pulses can be repeated at intervals as short as 3 minutes. Special consideration must be given to preventing this pulsed electrical load from degrading the quality of the electrical source networks, including those power systems having interties with the source power system.

Power for the facility will be supplied at the 161-kV level through the Oak Ridge Area (ORA) power transmission net from the Tennessee Valley Authority power system. Inter connected generating capacity of the TVA system is presently greater than 20,000 MVA, much of it provided by fast-responding hydroelectric generators. The system stiffness factor, a measure of capability to withstand sudden load changes, is approximately 240 MW/0.1 Hz, making the system adequate for supplying the TTAP cyclic load. Power supply phase-shifting arrangements, delta circuit transformer connections, and transmissions line harmonic filters will be utilized at the TTAP facility as required to prevent experiment-generated power system frequency harmonics from being fed back into the power net.

Electrical connection of the TTAP to the ORA transmission net will be at the ORA Elza-1 substation located in the east end of the Y-12 plant. The Elza-1 substation is supplied by four incoming 161-kV lines having a

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total transmission capacity of 1100 MVA. On an average, less than 20 percent of this capacity is presently being utilized. Therefore, supplying the TTAP from the Elza-1 substation will require use of only a minor portion of the available transmission capacity into the substation. Figure 11 is a map of the Y-12 Plant 161-kV transmission system showing how power will be delivered to the facility in Bldg 9204-1 from the Elza-1 substation. Figure 12 shows the conceptual arrangement of the TTAP Facility at Bldg. 9204-1.

3.8.2 Primary Power Distribution

The nonpulsed loads for TTAP will be supplied from an existing regulated 161-kV transmission line in Y-12. If the 30-MW pulsed load were supplied from one of two existing voltage-regulated lines, however, the power pulses could cause a 1 percent voltage drop at the regulator output for about 5 seconds. The operating sensitivity of the regulators is 0.5 percent of 161 kV and the regulators have some time delay. However, the 5-second time interval of voltage drop would be long enough to allow the voltage regulators to cycle up and down with the power pulses. Since this continuous action of the regulator would be detrimental to its operating mechanism, power for the pulsed loads will be drawn from the unregulated line.

To implement this arrangement, Y-12 line No. 2 will be reconnected to Elza-1 substation through 161-kV circuit breakers and disconnect switches as shown in Fig. 11. The line will be separated south of 9204-1 and the east section from Elza-1 substation will be extended to a new 20-MVA. 161—13.8-kV outdoor substation south of 9204-1. The 161-kV radial line to 9201-2 will be disconnected from Y-12 line No. 2 south of 9201-1 and will be extended by a new 0.3-mile section of 161-kV line to the west section of Y-12 line No. 2 south of 9204-1. A new 161-kV sectionalizing switch will be connected between the new section of line and Y-12 No. 1 line, at a location south of 9204-1. Revenue metering, protective relaying and telemetry facilities will be installed in Elza-1 substation as required for operation of the TTAP 161-kV line in a manner that is compatible with ORA-TVA power net operation. An existing 161-kV radial line to 9204-1 will be reconnected to the west section of Y-12 No. 2 line south

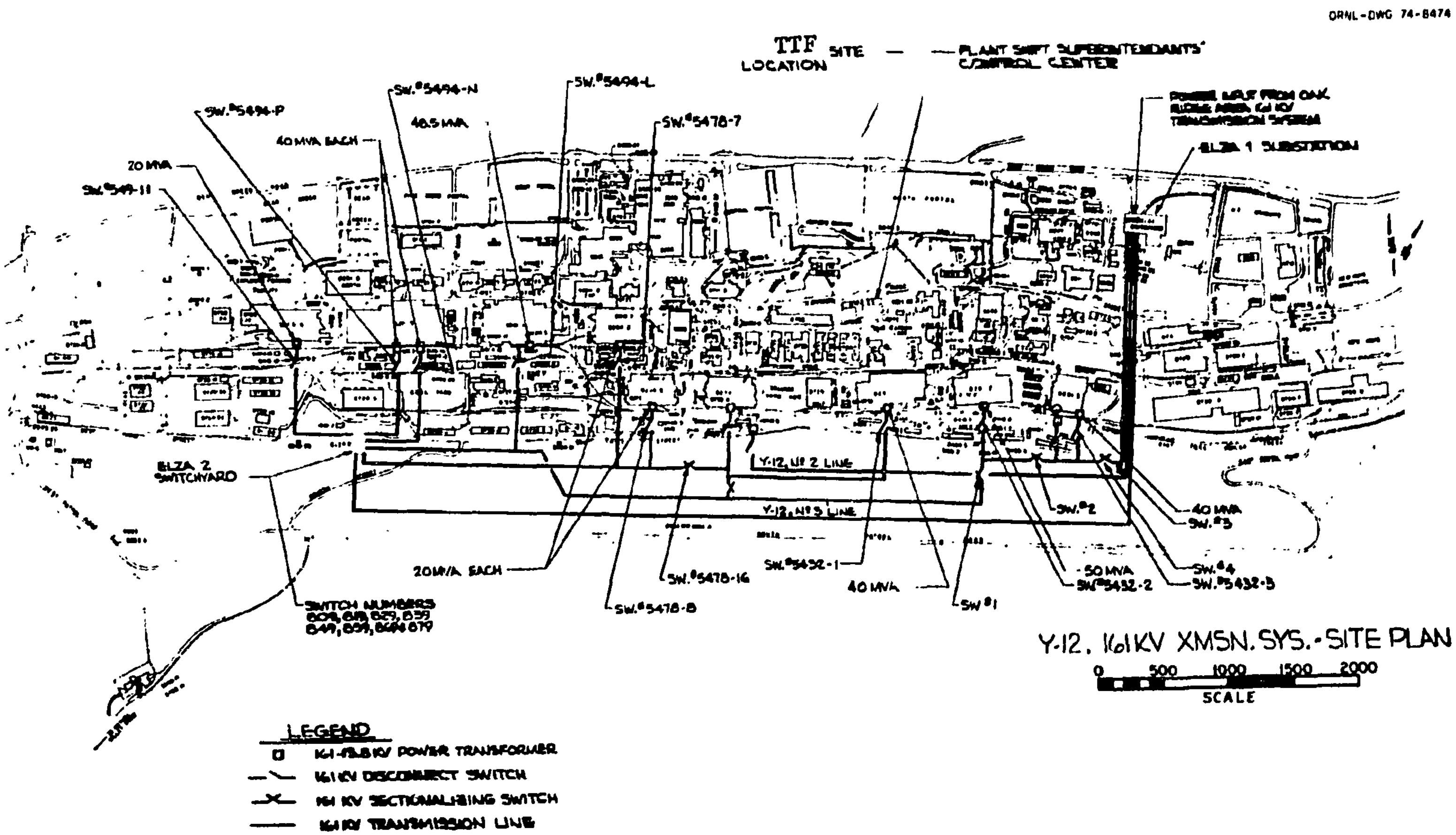
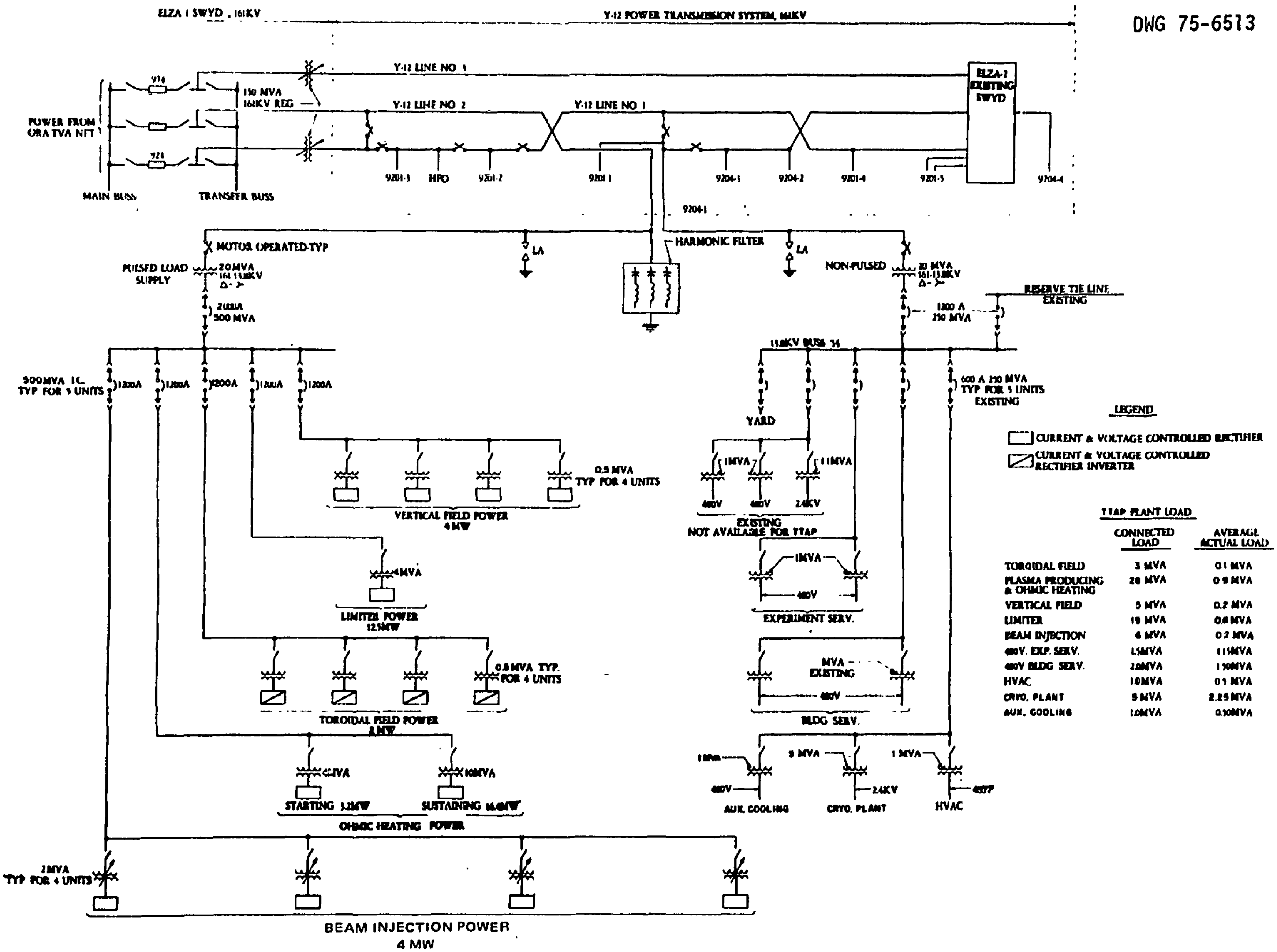


Fig. 11. Site Plan — 161-kV Transmission System



TTAP PLANT LOAD

	CONNECTED LOAD	AVERAGE ACTUAL LOAD
TOROIDAL FIELD	3 MVA	0.5 MVA
PLASMA PRODUCING & OHMIC HEATING	20 MVA	0.9 MVA
VERTICAL FIELD	5 MVA	0.2 MVA
LIMITER	10 MVA	0.6 MVA
BEAM INJECTION	6 MVA	0.2 MVA
480V. EXP. SERV.	1.5MVA	1.15MVA
480V BLDG SERV.	2.0MVA	1.50MVA
HVAC	1.0MVA	0.5 MVA
CRYO. PLANT	5 MVA	2.25 MVA
AUX. COOLING	1.0MVA	0.10MVA

Fig. 12. Electrical System One-Line Diagram

of 9204-1. The radial line will be connected to another new 20-MVA 161—13.8-kV outdoor substation at an existing substation site at the south side of 9204-1.

The two new 20-MVA outdoor substations will include 161—13.8-kV power transformers, 161-kV motor-operated disconnect switches with magnetizing current interrupters, substation monitoring and control equipment, associated auxiliary power services, and personnel protective devices. One 20-MVA transformer will be required to withstand and supply about 200 percent of its continuous MVA rating during pulses. The other 20-MVA substation will supply the remaining portion of the TTAP electrical system in addition to other plant operations in Bldg 9204-1.

3.8.3 Secondary Power Distribution

A new secondary power distribution system will be installed to supply the TTAP pulsed loads. It will include 13.8-kV metal-clad indoor switchgear which will be fed from one of the 20-MVA substations and will be installed in 9204-1 in a vault-type enclosure, per National Electrical Code requirements. The switchgear will include air or vacuum circuit breakers, and associated protective relaying, control and metering equipment. It will be used to control 13.8-kV radial feeders, consisting of cross-linked polyethylene cables in conduit, directly connected to the rectifier transformers of the pulsed power supplies for the experiment. Cable and bus will be installed as required to transmit power from the transformer-rectifier modules to the pulsed loads. The transformer-rectifier modules will be installed as near the experiment loads as is practicable.

Part of an existing 13.8-kV secondary distribution system in 9204-1, presently fed by way of an overhead 13.8-kV reserve tie line from 9204-3, will be used to supply some of the nonpulsed load. It includes 13.8-kV switchgear, 13.8-kV cable in conduit and 13.8—0.48 kV unit substation power distribution centers. The required 13.8-kV switchgear units are existing and two of the five required unit substations are existing. The additional unit substations will be installed in existing vault-type enclosures, per National Electrical Code requirements. Some reworking and reconnecting of the equipment will be required. This secondary power distribution system will normally be supplied from one of the new 20-MVA substations, but will have an alternate supply from 9204-3 by way of the existing reserve tie line.

The unit substations supplied by the same 20-MVA substation will, in turn, supply utilization loads, e.g., motors, lighting centers, experiment and shop equipment. Large motors will be supplied at the 2400-volt level by way of 5000-volt cable in conduit. Smaller motors, lighting centers and experiment equipment on the system will generally be supplied at the 480-volt level by way of bus duct and 600-volt cable in conduit. Lighting and low voltage receptacle loads will be fed by way of 600-volt wiring in conduit from 480-120/240-volt or 480-120/208-volt load centers. An extensive system of lighting and low voltage receptacle circuits already exists in 9204-1. It will be augmented as required for the TTAP offices and experiment.

3.8.4 Special-Purpose Power Supplies

The general layout of all power supplies developed for TTAP is a solid state 12-phase thyristor bridge rectifier (Fig. 13). By placing two 3-phase, full-wave bridge circuits in series or parallel and adjusting the transformer phasing, a twelve-phase equivalent is obtained. The twelve-phase configuration provides low ripple dc power and minimal harmonic interference on the primary power net work. In Fig. 13, each thyristor symbol may represent several devices in series and/or parallel in order to achieve appropriate voltage and/or current capabilities. Delta-wye connections on the transformers provide natural filtering of even harmonics. Supplementary line filtering may be required for odd harmonic suppression. Phase angle control of the thyristor gates permits dc output variation over a wide range. A programmable automatic process controller generates gate firing signals in an appropriate sequence and interval for specific dc current levels as a function of time. Power supply currents are monitored and digital performance data is fed back to the process controller for closed loop current regulation.

All of the power supplies will operate in a pulsed mode as previously described. Rectifier transformers will have continuous KVA ratings of 20 to 30 percent of their peak pulse load. The thyristors are typically

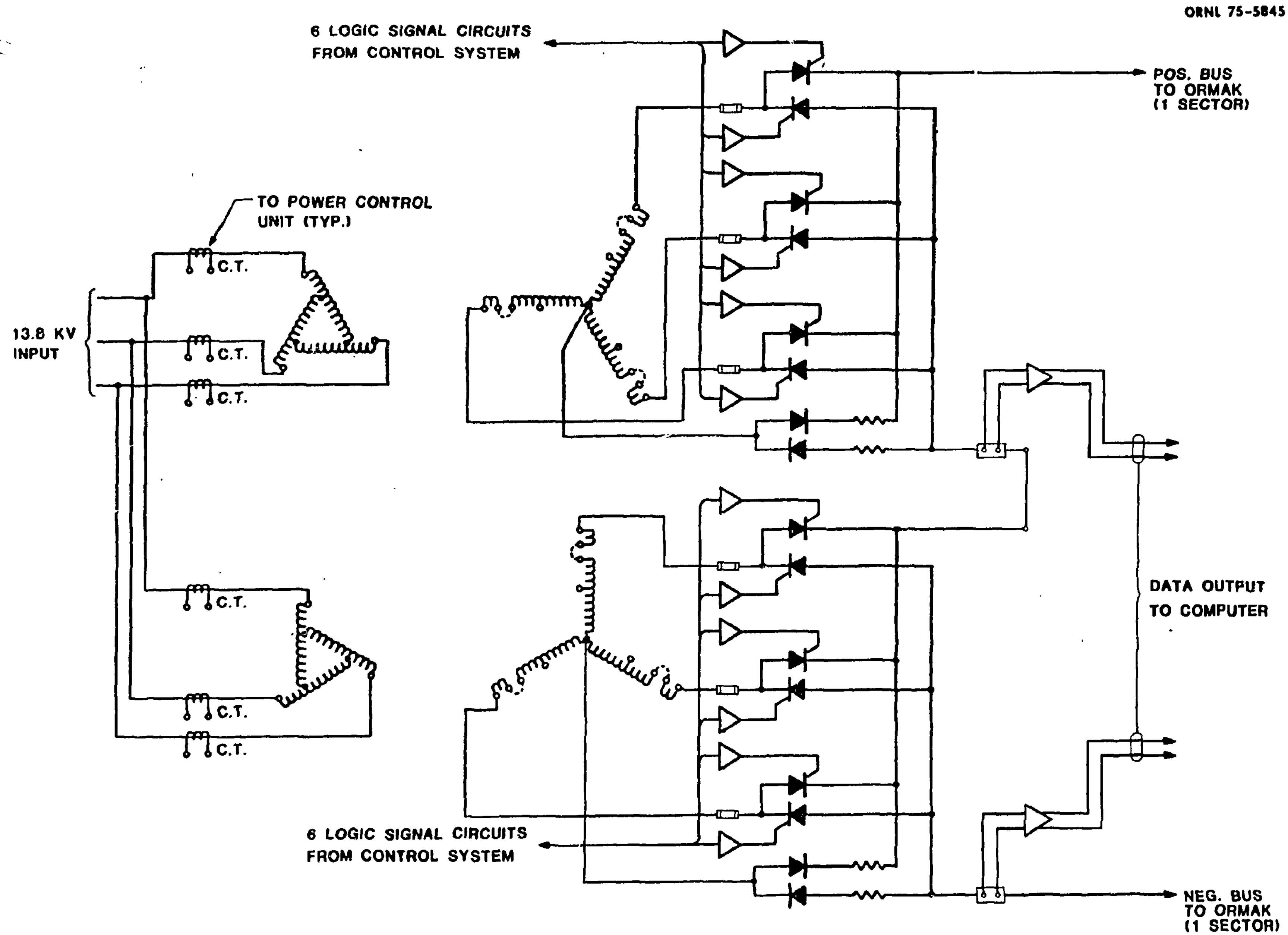


Fig. 13. Typical Power Supply Module Schematic

rated for continuous duty at the peak current. A description of specific power supplies and their loads follows. (More information regarding them is given in sections which describe the various TTAP subsystems.)

Toroidal Field — For cost estimating purposes, it is considered that the TF magnets themselves require only the power dissipated in the leads (a few kW). Refrigeration power required for superconducting coils is about 2 MW.

Ohmic Heating — The plasma current of about 1.3×10^6 amperes constitutes the secondary winding of a transformer. The transformer primary or ohmic heating coils has 16 turns in series. The peak primary current is about 82,000 amps. About 200 volts is required for sustaining the plasma current, but a potential of about 2500 volts is required for striking an arc.

The power supply configuration uses two units — a high-voltage, high-impedance striker, or "short pulse" unit, rated at 2500 volts open circuit — 8000 amps short circuit, and a sustaining unit rated at about 400 volts open circuit and 82,000 amperes at about 200 volts. The two power supplies are separated by a diode network which shifts the load to the high-current unit as the plasma potential falls to its minimum value. Peak power ratings are 3.2 MW and 16.4 MW respectively.

Vertical Field — The function of the vertical field coils is to provide a magnetic field of the proper intensity and shape to keep the plasma approximately centered in the liner, and to control the shape of its cross-section. This function could conceivably be performed by changing the distribution of current in the OH coils as a function of time (holding the sum of the currents always equal in magnitude to the plasma current). However, the configuration with separate vertical field coils was chosen for conceptual design.

Sixteen windings are required with 4 individual power supplies and 4 windings per power supply. Each winding may have several turns as needed to obtain a reasonable load impedance. Each power supply is nominally rated at 75 volts and 11,000 amps. The total power for the vertical field power supplies is about 4 MW.

Magnetic Limiter — The limiter winding contains six axial turns which are phased to produce a sextapole field configuration. The field is required during plasma formation but it must be unloaded in about 500 msec after the plasma is formed. A single power supply is required to produce 130 KA of excitation current at about 100 volts. Power input is about 13 MW; however, the limiter field is unloaded simultaneously as the OH field is loaded. Consequently peak limiter power and OH power do not contribute simultaneously to the total system power.

Neutral Beam Injectors — During initial experiments will require total injected beam power of 4 MW which will be supplied by 4 neutral beam injectors operating simultaneously. (Future experiments envision up to 16 MW of beam power delivered by 12 injectors.) A rectifier rated 40 kV at 60 amps will supply the power for each injector. The rectifiers will have output variable from zero to 100 percent. The rectifiers will be arranged in 3 groups, 4 rectifiers per group. Each group of rectifiers will be supplied by a 3-phase, 2-MVA transformer, having a multiwinding secondary connected to facilitate phase shifting for peak load distribution.

3.8.5 Cryogenic Plant

Two 2.5-MVA 13.8–2.4-kV unit substations, including transformer and switchgear, will be added to supply a cryogenic plant for the superconducting coils.

3.8.6 Other Electrical Loads

Cooling Water — The TTAP major electrical loads, e.g., plasma-driving coils, neutral-beam injectors, power supplies and other water-cooled devices, will be cooled by pumping demineralized water through heat exchangers then pumping process water through the heat exchangers and cooling towers which will include cooling fans. Metal-clad 5-kV and 600 volt switchgear will be installed in an existing pumphouse for feeding motors that will circulate the demineralized water and cooling tower water. The demineralized water pumps will require about 150 horsepower total of 2400-volt motors. A 1-MVA 13.8–0.48-kV transformer will also be installed in or near the pumphouse to supply 460-volt cooling tower pump motors, cooling tower fan motors, and other 480-volt utilities. Both the 2400-volt and 600-volt switchgear will incorporate protective relaying, metering and control devices as required for satisfactory operation of the load centers.

Experiment Services — Two 1-MVA unit substations will be installed in existing enclosures, per National Electric Code requirements, for supplying 480-volt power and services to low voltage experimental equipment other than the pulsed power load previously described. The unit substations will consist of 13.8–0.48-kV transformers, metal-clad 600-volt switchgear, and protective relaying, metering and control devices as required. Busduct or 600-volt cable in conduit will be installed from switchgear to experiment equipment.

Ventilation, Air Conditioning and Auxiliary Equipment Cooling — A 1-MVA unit substation will be installed to provide power for ventilation and air conditioning of offices and work spaces. In addition, the unit substation will supply ventilation for cooling the unit substations previously described and some cooling of the pulsed load rectifiers and power transformers previously described. The unit substation will include power transformer, metal-clad switchgear, and protective relaying, metering and controls as required.

Building Services — Two existing 1-MVA indoor unit substations, rated 13.8–0.48 kV, will supply small motor control centers and 480-volt, 3-phase busduct which in turn will supply fabrication and maintenance shops, building cranes, lighting and receptable load centers, and other 480-volt loads. Some reconditioning and reconnection of the unit substations will be required to adapt them for TTAP use. Existing systems of busduct and 600-volt cable in conduit will be modified and expanded as required.

3.8.7 Auxiliary Electrical Service

Clean Power and Emergency Power Supplies — An uninterruptable power supply will be installed to provide power for critical control and computer circuits. A gasoline or diesel engine driven generator will be provided as an alternate power source for equipment which can tolerate momentary power outage, but must not be without power for an appreciable length of time.

Plant Monitoring System — Data gathering panels will be installed to collect data from power substations, switchgear monitoring centers, and other devices which are to be monitored by the Y-12 Plant Shift Superintendent. The data will be transmitted to an existing Y-12 plant monitoring center.

Fire Protection System — A Gamewell fire protection system is already installed in Bldg. 9204-1 and is connected into the Y-12 plant fire protection system. Additional manual fire alarm boxes, automatic sprinkler systems, heat detectors and other fire protection devices will be installed at the TTAP experiment and associated facilities as required.

Public Address and Telephone Systems — The existing public address and telephone systems in Bldg. 9204-1 will be modified as required for the TTAP facility.

Lighting — The existing lighting system in 9204-1 will be modified as required for TTAP operation. Supplemental high bay fixtures will be installed in the experimental and assembly areas. Additional exit lights, emergency egress lights, etc., will be installed as needed and in accordance with code and OSHA requirements.

3.8.8 Application of Codes, Standards and Specifications

The design and installation of the electrical power system for TTAP will comply with industry codes, standards, and specifications for electrical safety and reliability. The main guide for application of the codes, standards, and specifications will be General Design Criteria, AEC Appendix 6301; General Design Criteria, UCC-ND document Y-EF-538; Electrical Construction Specification, UCC-ND document E-2.1.

3.9 Cooling and Cryogenic Systems

W. H. Fleischman J. P. Kois

3.9.1 Cooling Water System

The TTAP cooling water system is required to remove the heat generated in the neutral beam injectors, the TF, OH, and VF coils, and other equipment during experimental operation. The conceptual design is based on production of 320 MJ of heat in a few seconds at 3-minute intervals (1.8 MW average). Cooling is provided continuously to limit equipment temperatures and to reduce the coil temperatures to an acceptable range before the initiation of another shot.

Major components of the system include a 500-gpm demineralized water circulation system (piping and pumps), three 250-ton cooling towers, a 2,750-gpm cooling tower water circulation system (piping and pumps), 4 heat exchangers, and a demineralizer system. An existing building (9404-7) located just across the creek south of 9204-1, will be renovated to house the demineralized water circulation pumps, tower water pumps, demineralizer equipment, and electrical switch gear. The cooling towers are to be located about 50 ft south of Bldg 9404-7. Tower water pipes (12-in. dia.) will be run under the road that passes between Bldg 9404-7 and the towers.

3.9.2 Cryogenic System Requirements and Description

The loads on the TTAP cryogenic system are primarily from heat leakage into the superconducting toroidal field magnet system and operation of the cryosorption panels in the vacuum system; resistance heating in the joints of the superconducting TF windings accounts for roughly 10% as much. Based on requirements of the NbTi windings, the refrigeration system is based on removing heat from the TF system between 3.5 and 4.2 K. System loads are summarized in Table 5.

The refrigeration and liquefier systems are represented schematically in Figs. 14 and 15. (Detailed flowsheets are given later.) Some of the features shown are included in order to increase the reliability of the total system. The units will use liquid-nitrogen forecooling and have redundant compressors, expansion engines, and adsorbers. The amount of redundancy provided will depend on the size of the individual compressors and

Table 5. Summary of Loads on Cryogenic System

Component	Heat Load (watts)
TF coil cryostat with 124 layers of super insulation, 2-in. thick	300 at 3.5K
Vacuum jacketed piping for refrigerator	275 at 3.5K
Vacuum jacketed piping for liquefier	82 liters/hour
Internal heating (superconductor joints)	75 at 3.5K
Cold gas shielding from 300 to 3.5K	
Gravity supports	15 liters/hour
Electrical feedthroughs	100 liters/hour
Cryosorption panels	250 at 17K

expansion engines. If a single compressor is used for full capacity, a second full-size compressor will be furnished to give 100% redundancy. If, on the other hand, two half-size compressors are used, only one additional compressor will be furnished to give 50% redundancy.

Dry teflon ring or labyrinth-piston type helium compressors will be used to eliminate oil contamination. Experience indicates a ring life of from 90 days to about one year for the dry teflon ring type. The labyrinth-piston type may only require annual rod packing changes.

The expansion engines may be reciprocating, gas-bearing turbine, or oil-bearing turbine types. The oil-bearing expansion engine is the most reliable and expensive, and probably the best choice at this time. Experience indicates a mean-time-between-failure (of about six months for the reciprocating expanders and about one year for the turbine types. For properly designed expanders, the most significant factor contributing to failure is contamination, either oil, wear particles from compressor rings, or frozen contaminants in the process stream.

In addition to increasing the system reliability the redundant expanders will provide extra capacity during cooldown.

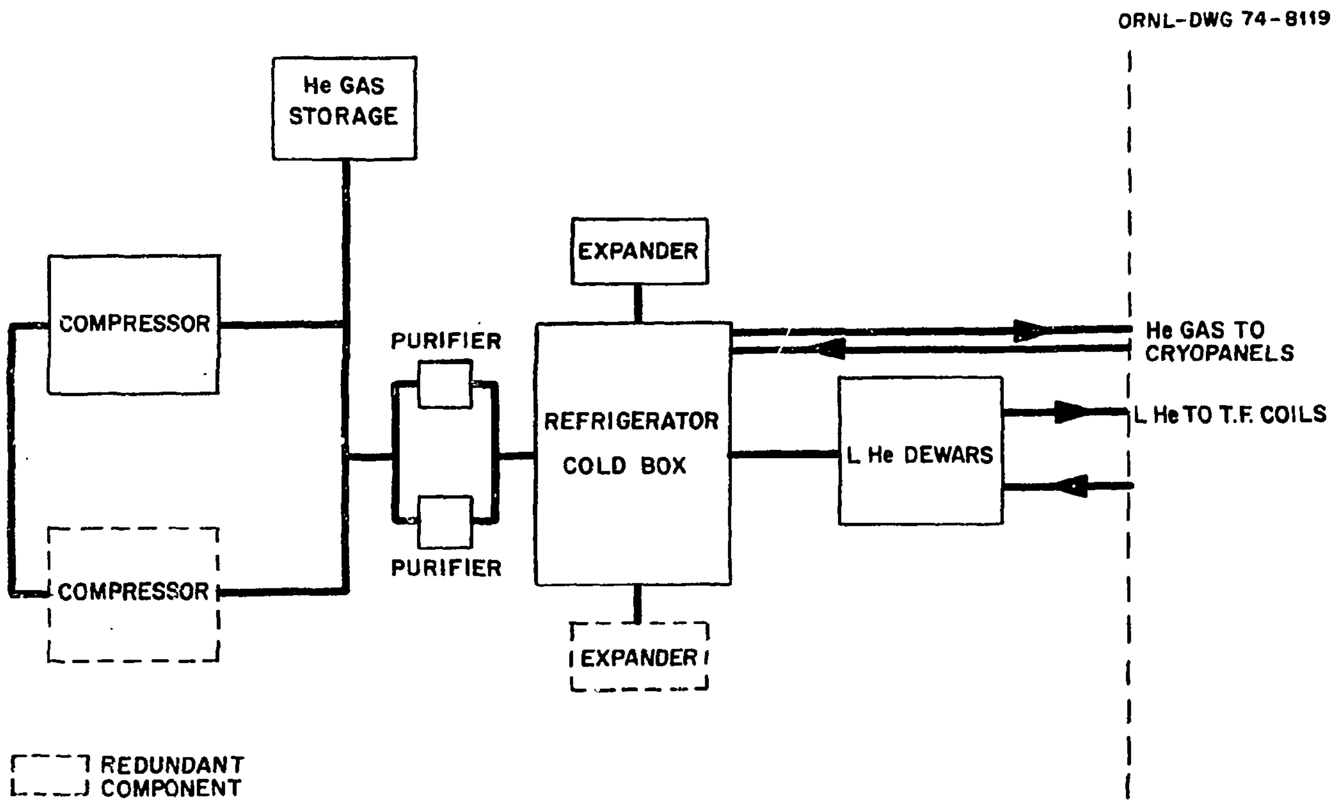


Fig. 14. Refrigeration System Schematic

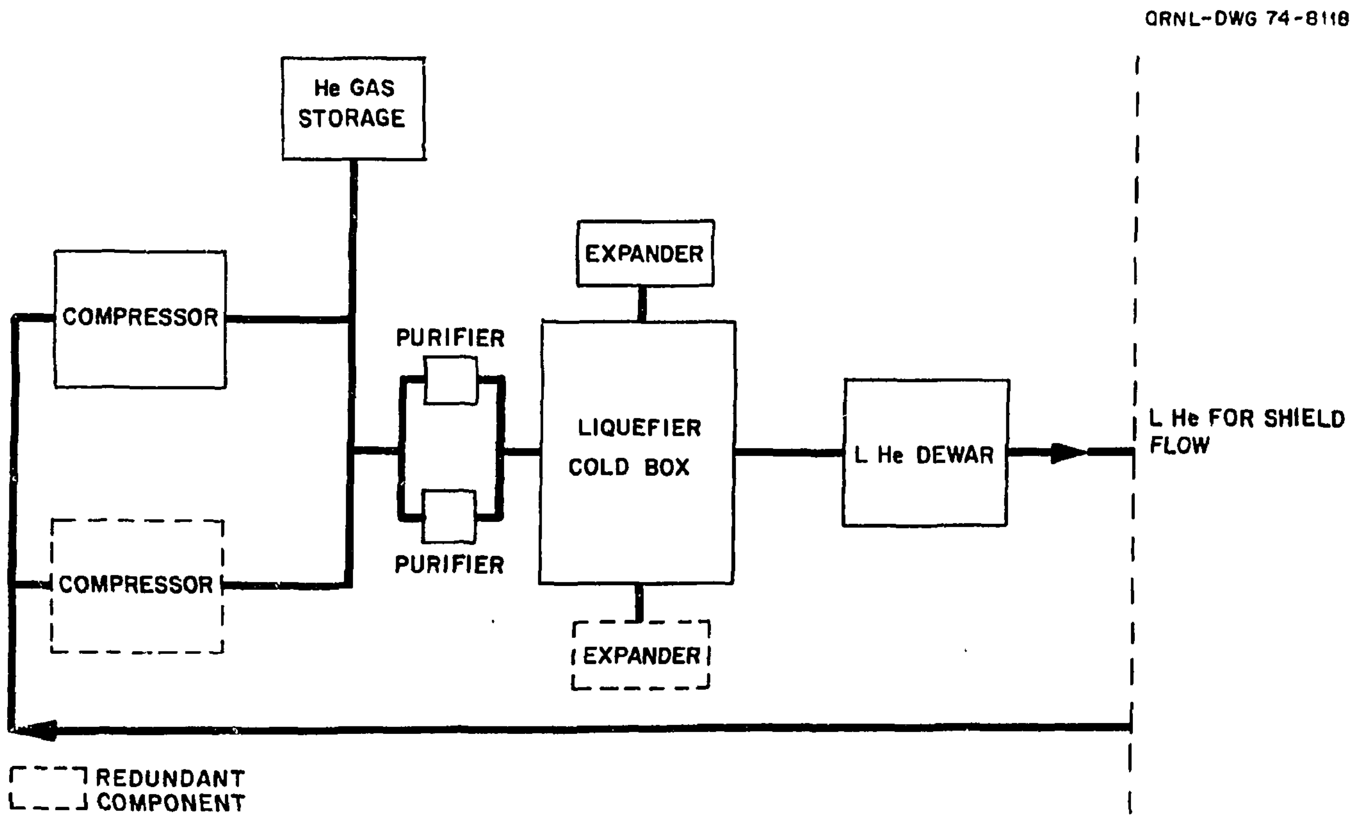


Fig. 15. Liquefier System Schematic

The vacuum jacketed liquid-helium and liquid-nitrogen piping will be prefabricated, insulated, evacuated, and sealed in individual spool sections. The insulation used will be of the multilayer radiant shield type with the use of "adsorbents" and "getters" as required to maintain satisfactory vacuum levels.

The primary mode of helium storage is in the form of liquid in two 5000-gallon storage tanks. Secondary storage consists of 9000 standard cubic feet of gas storage at atmospheric pressure and 6000 standard cubic feet of gas storage at 235 psia. Helium gas will be supplied to the system from the Y-12 Plant distribution system. Provisions shall be made to supply liquid helium to the system from trucks and by rail. Dual full flow purifiers with valves, regeneration controls, purity monitor, and dew point monitor will be provided in each refrigerator and liquefier.

3.9.3 Refrigerator Process Cycle

The process cycle for the refrigeration system adopted for this study, shown in Fig. 16 is of conventional design.

At design conditions, 1080 scfm of helium gas, initially at ambient temperature and a pressure of 15.2 psia, is compressed to 265 psia in a three-stage, non-lubricated compressor with interstage cooling and aftercooling to bring the temperature of the gas to ambient. The compressed gas first passes through one of the dual molecular sieve purifiers where moisture is removed, then enters the first heat exchanger. Here it is cooled by the return low-pressure gas, and by use of liquid-nitrogen precooling. The flow of liquid-nitrogen to precool the incoming gas is approximately 35 liters per hour as equivalent refrigeration.

After the gas passes through the nitrogen exchanger, it enters one of the dual charcoal purifiers, where the air impurities are removed. The gas then enters the next exchanger and is cooled from 80K to approximately 20K. After passing through the exchanger, the gas stream is divided; approximately 450 scfm flows to the expansion engine, while 630 scfm flows to the third exchanger.

The gas entering the expansion engine is isentropically expanded to a lower pressure, exhausting at one atmosphere and a temperature of 7.5K.

The high-pressure gas, at approximately 17 atmospheres and 6K after passing through the third exchanger is divided into two streams. One

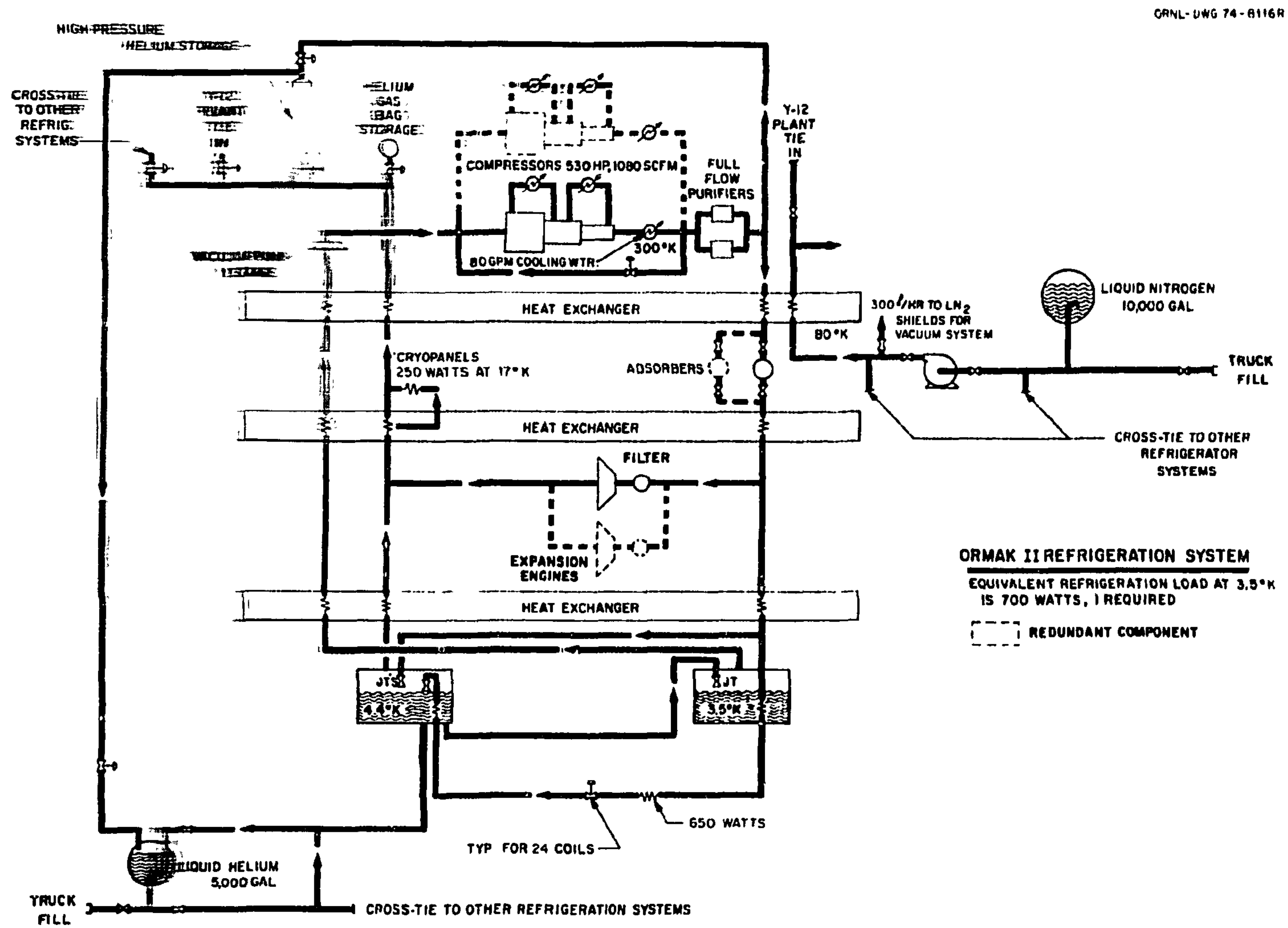


Fig. 16. Refrigeration System Flowsheet

high-pressure gas stream enters the Joule-Thomson valve where it expands to low pressure, and partial condensation takes place in the storage dewar where the liquid and gas are separated. The gas portion is returned to the refrigerator to cool the incoming gas.

The low-pressure return gas passes through the third exchanger where it is joined with the gas exhausting from the expansion engine, and enters the second exchanger. As the gas passes through the exchangers, it exchanges heat with the incoming gas and leaves the first heat exchanger at approximately 290K. The gas then enters the suction side of the compressor and is recompressed again.

The second high-pressure gas stream enters a heat exchanger in a second storage dewar at 3.5K. Once cooled to 3.5K, the pressurized liquid stream is circulated through the TF coils to pick up the heating load, and it is then expanded through a second J-T valve in the 4.4K storage dewar. This gas is then returned to the suction side of the compressor with the other gas.

The 3.5K liquid is obtained by pulling a vacuum on the dewar that is expanding some of the 4.4K liquid through a third J-T valve. The gas from this second dewar is returned through the heat exchangers to the compressor suction as shown in Fig. 16. The 3.5K liquid may also be obtained by using an ejector instead of a vacuum pump. This scheme would have the advantage of eliminating one of the return gas passages in the heat exchangers and also one of the J-T valves.

Refrigeration for the cryopanels is obtained from the second heat exchanger at the 17K temperature level.

3.9.4 Liquefier Process Cycle

The process cycle for the liquefier is shown in Fig. 17. As in the refrigerator cycle, the first step is compression of gas initially at ambient temperature and at a pressure of 15.2 psia. A stream of approximately 1000 scfm is compressed to 265 psia in a three-stage, non-lubricated compressor with interstage cooling and aftercooling to bring the temperature of the compressed gas back to ambient. The compressed helium gas first passes through one of the dual molecular sieve purifiers, where the moisture is removed from the gas, then enters the first heat exchanger. As

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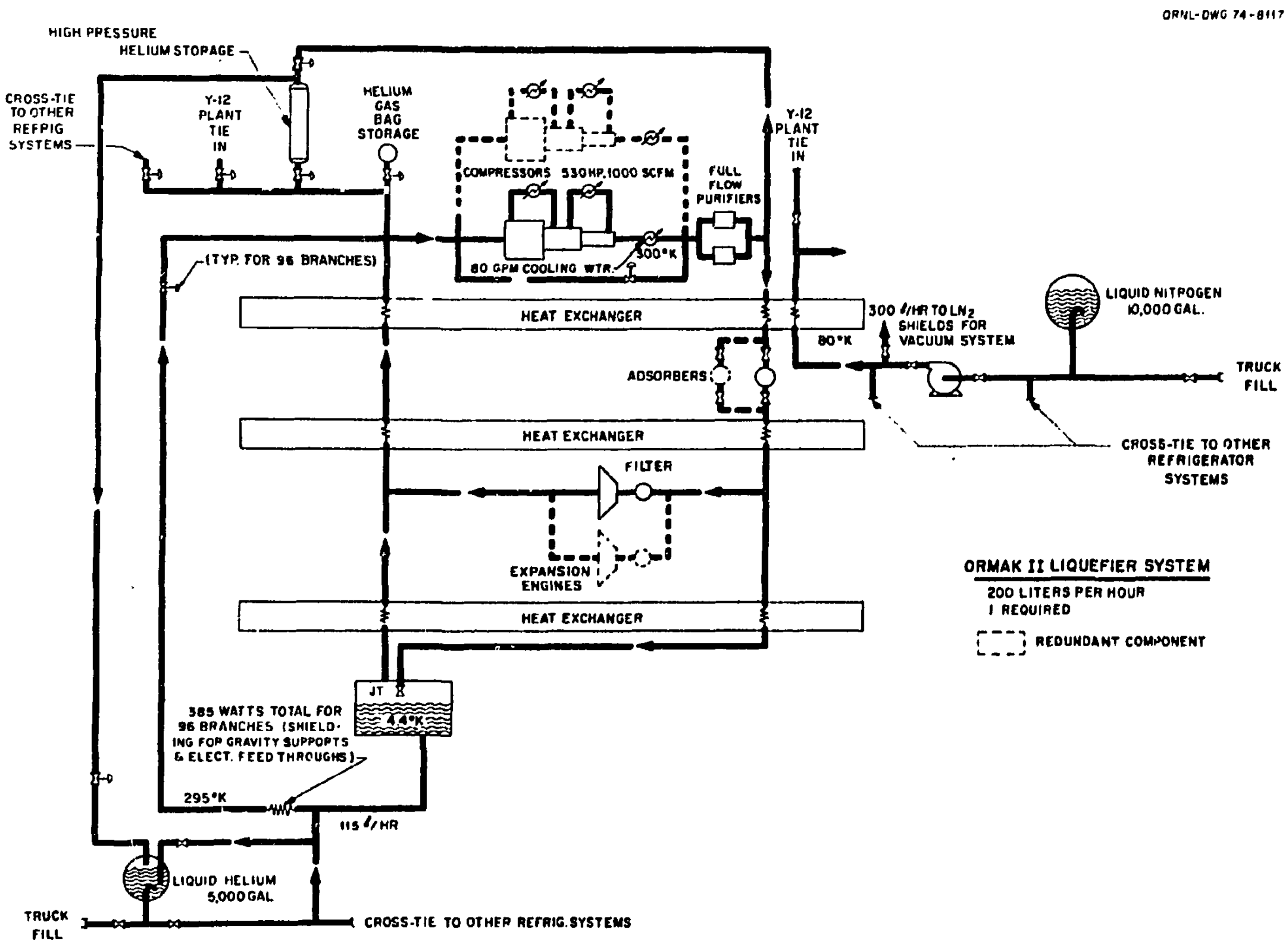

Fig. 17. Liquefier System Flowsheet

the gas passes through the heat exchanger, it is cooled by the return low pressure gas, and by use of liquid-nitrogen precooling. The flow of liquid-nitrogen to precool the incoming gas is approximately 100 liters per hour as equivalent refrigeration. After passing through the nitrogen exchanger, the gas enters one of the dual charcoal purifiers, where the air impurities are removed. The gas then enters the next exchanger and is cooled from 80K to approximately 20K. After passing through this exchanger, the gas is divided; one portion, approximately 735 scfm, flows to the expansion engine, while the other portion, 265 scfm, flows to the next exchanger where it is cooled to approximately 6K.

The gas entering the expansion engine is isentropically expanded to a lower pressure, and exhausts out of the engine at one atmosphere and a temperature of 9.6K.

The high pressure gas enters the Joule-Thomson valve where it expands to low pressure, and partial condensation takes place in the storage dewar where the liquid and gas are separated. The gas portion is returned to the liquefier to cool the incoming gas.

The low pressure return gas passes through the third exchanger where it is joined with the gas exhausting from the expansion engine, and enters the second exchanger. As the gas passes through the exchanger, it exchanges heat with the incoming gas, and leaves the first heat exchanger at approximately 290K. The gas then enters the suction side of the compressor, and is recompressed again.

3.9.5 Helium Management

Ideally, one would charge the complete refrigeration/coil network once, and keep the helium in that system perpetually; that is, liquid helium in the coils and the liquid storage dewars, and gaseous helium in the refrigerator and room-temperature gas storage. It would be necessary to add purified gas to the network to make up for gas lost during maintenance and leakage from compressor seals (about 0.1% of flow for ring-type compressor).

Each refrigeration system would have a liquid-helium storage sufficient to maintain the coils in the maintenance mode for a period of time if the refrigerator were not working. That time could be up to 21 hours with a 5000-gallon storage capacity. Such a liquid-helium storage capacity would permit most minor malfunctions to be detected and corrected without any major interruption, and thereby greatly enhance the reliability of the system.

If the refrigeration capacity is not matched perfectly to the load, there will be, over time, a loss or gain of liquid helium in the storage vessel, which will necessitate a supply or storage of gaseous helium. To achieve this, a 15- to 20-atm storage vessel will be a part of each unit. If the low-pressure intake to the compressor increases, the discharge pressure will increase and the excess gas will be pumped into the storage vessel. If the low pressure intake decreases, gas will be released from storage into the intake line. Two sensitive pressure regulators will affect this performance.

If one refrigerator is out of commission because of an unscheduled failure, up to 21 hours of reduced operation would be possible, but the helium boiling off would be 880 liters per hour. This boil-off would automatically be diverted through an air-to-helium heat exchanger to warm it up to ambient temperature before entering the low-pressure line. If the low-pressure line linked all compressors in the system, then, as the low pressure increases, all other compressors would be putting excess helium into their storage vessels. This would happen automatically and there would be no loss of helium in the system.

At any refrigerator/liquefier, if the liquid level were low, the redundant compressors and expanders could be operated to provide excess liquefaction of gas that would automatically be released from the storage vessels. So the liquid lost from the unit could automatically be stored as gas or as liquid wherever needed. Similarly, in the event of a scheduled routine maintenance, the helium from the unit or units under maintenance can be stored elsewhere as gas and/or liquid.

Such an approach makes possible an almost zero loss helium system and would go a long way to overcome what is probably the most common cause of refrigeration system malfunction, i.e., contamination. Once the system is cleaned up, no further contamination should enter the system, except by improper maintenance procedures.

With all the compressors linked through the common low-pressure line, it is possible to have only one makeup point in the system where helium gas could be introduced through a purifier on a scheduled basis from the Y-12 Plant. For unscheduled events, helium lost would be made up from the storage vessels.

3.10 Diagnostics

J. L. Dunlap

The diagnostics consist of the equipment for measuring those signals from which the principal parameters of the plasma are determined. In general, signals from this equipment are routed to data acquisition computers (Sect. 3.12) for storage and processing.

In our review of diagnostics for TTAP, we have selected those diagnostic subsystems which we feel are required to fulfill the scientific potential of the experiment, with special attention to the investigation of impurities. Continuing effort is required to define the full range of diagnostics necessary for other particular plasma technology studies (e.g. high beam power handling, fueling, etc.). We have estimated the number of individual diagnostic channels and the accesses needed to permit spatial and temporal profiling of plasma parameters during a single machine pulse (or at most a few pulses). We have also considered implications of the TTAP criteria of a single vacuum wall, high temperature bakeout, and low permissible contaminant level.

Table 6 details the selected subsystems. These are "conventional" diagnostics in the sense that the basic techniques have been developed and already applied to tokamak plasmas. Item 1 represents a considerable extension beyond current laser diagnostics in that receiving optics are to be arranged to view a number of spatial points for a single laser pulse, thus speeding up the rate of data acquisition. Item 7 is special in that the nature of this poloidal field diagnostic is not specified. A number of possibilities exist (e.g., electron gyrofrequency modulation of Thomson-scattered laser light, harmonic generation at the upper hybrid, and heavy ion beam probes); but this is a rapidly developing area and the merits of the different approaches for specific application to TTAP will have to be examined carefully at the time a choice is necessary.

Access for those diagnostics requiring views of the plasma through the vacuum wall is geometrically more simple with the proposed single wall than with a double vacuum enclosure. Most of these diagnostics will be accommodated by flanged penetrations of a few standard sizes on solid sections of the wall between bellows sections. These solid sections appear between each pair of coils and ample diagnostic access is available from

Table 6. *Diagnostic Subsystems*

Diagnostic	Purpose	Basic Requirements	Layout Details
1. 90° Thomson Scattering	Generate spatial and temporal profiles of T_e and n_e from point measurements at a number of positions and times during a single plasma pulse.	Single laser but multiple receiving optics and a choice of laser paths along 3 different chords through the plasma.	See Fig. C.13.
2. Charge-Exchange	Measure, as a function of time, the charge-exchange reaction rates and the energy distributions of charge-exchanged neutrals directed at the diagnostic from along chords through the plasma. These measurements can be related to T_i, n_i, and n_o.	2 detector systems (with electron channel multiplier detectors) each capable of simultaneous measurements along 3 chords. 3 detector systems (with surface barrier detectors) each capable of such measurements along 4 chords.	Access for perpendicular analysis along numerous chords from both top and side. Access for parallel analysis along numerous chords from side.
3. Optical and UV	Evaluate line radiation for impurity identification and measurement of ionization rates. Doppler shifts for evaluation of rotational asymmetries. Fast photography to identify major plasma perturbations.	3 Czerny-Turner spectrometers; 3 grazing incidence spectrometers; 1 vacuum UV monchromator/spectrograph; monitors: 3 visible, 3 UV, 3 VUV; fast framing camera.	Multiple access ports.
4. X-Rays a. soft	Obtain T_e profiles from bremsstrahlung and recombination radiation. Obtain $Z_{effective}$ from bremsstrahlung count rates. Identify impurity species from line radiation	10 partially instrumented and and 10 fully instrumented channels of ratio detectors + intensity monitors. 2 fully instrumented channels for high-resolution spectra.	Access ports for developing profiles by viewing along both horizontal and vertical chords.
b. hard	Identify the presence of a runaway component of the electron distribution.	4 monitors	All gear outside the machine

Table 6. (continued)

Diagnostic	Purpose	Basic Requirements	Layout Details
5. Interferometry (2 mm)	Obtain n_e profiles (time dependent) by inversion of electron line density measurements along a number chords.	16 channels, 8 partially instrumented and 8 fully instrumented.	Access ports for developing profiles by viewing along both horizontal and vertical chords.
6. Electron Synchrotron	Obtain the spectral distribution and power contained in synchrotron radiation (and any other electron cyclotron modes).	2 microwave systems at different wavelengths in the mm range, and a scanning far IR system.	Multiple access ports.
7. B_p Measurement	Obtain a relatively direct measurement of the spatial and temporal variation of the poloidal component of magnetic field. To obtain from this the J(r,t) profiles, which are available only in a more inferential sense from other diagnostics.	Unspecified at this time.	Unspecified at this time.
8. Fast $\dot{B}$ Probes	Measure the total discharge current, track displacement of the current column as input to the vertical field control, identify periodic distortions of the current column (MHD modes).	6–8 Rogowsky loops with several different m windings. Numerous point sensors.	Mounted between the plasma wall and the vacuum wall
9. Power Measurements	With Items 2, 3, 4, and 6, to measure components of the power balance equation.	Several radiometer probes, filters, electronics, etc. Numerous thermocouples.	Multiple access ports; most thermocouples wired in place.
10. Residual Gas Analyzer	Determine base pressure constituents and partial pressures.	RF mass analyzer	Single access port.
11. Auger Spectroscopy	Analysis of the composition of the plasma wall.	Auger spectrometer, arranged for uncontaminated sample transfer.	Spectrometer connects to plasma chamber by vacuum lock, with manipulators for transfer of wall samples to spectrometer.

above, below, and from the outer perimeter of the torus. For cost estimation we consider that these flanged penetrations consist of 75 2-in.-dia., 25 4-in.-dia., and 8 10-in.-dia. ports. Later phases of design will detail the specific sizes and arrangements about the torus.

The 90° scattering laser diagnostic requires the most complicated access. Figure 18 shows a conceptual arrangement which appears compatible with the present winding layouts. Consideration is also being given to an even more desirable arrangement in which the laser path is horizontal, in the equatorial plane. This scheme is better suited for examination of plasma shifts, which are primarily in-out rather than up-down. However, the laser-path components at the inner radius are cramped for space as are the viewing optics for plasma inside the major radius. The practicality of this second arrangement rests on details not yet in hand.

The absence of a second vacuum wall and emphasis on low contaminant level (with the concomitant high temperature bakeout) are strongly determinant factors in mounting and packaging the diagnostics. The TTAP criteria will be met by application of ultra-high vacuum techniques: by using bakeable high-vacuum seals (metal-to-metal flanges or seal welds) for attachments through the wall, by requiring items such as "glass"-to-metal windows and vacuum valves to be of high quality and also bakeable, by careful design of each diagnostic package that represents an extension of the plasma vacuum chamber, and by careful handling of components exposed to the vacuum. Detailed resolutions are specific to each diagnostic, and the development of appropriate designs will be an essential part of later design phases.

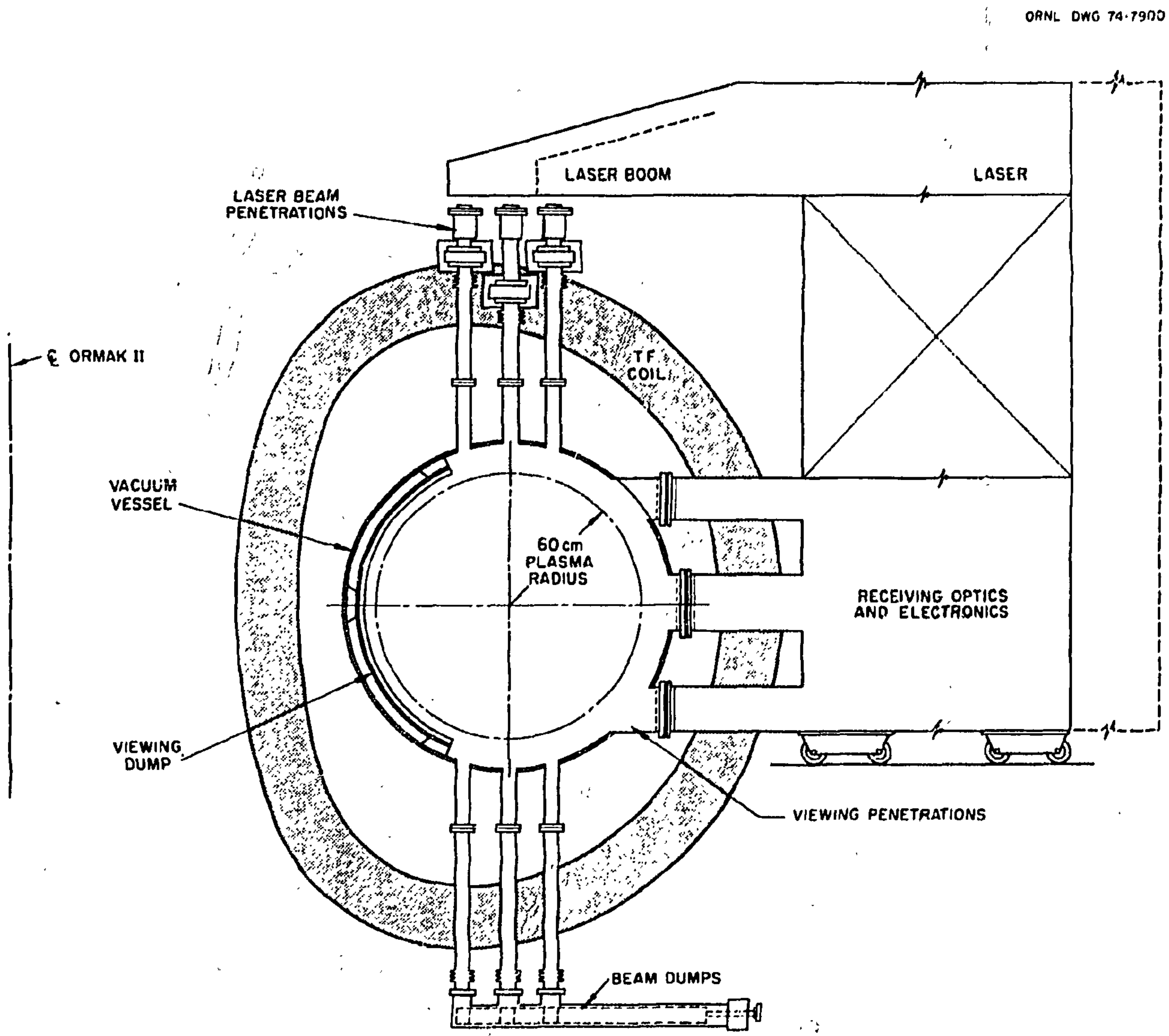

Fig. 18. Laser Diagnostic Cross-Section

3.11 Instrumentation and Control

B. E. Cooper E. E. Dunn

The basic I&C design concept for TTAP makes use of monitoring and control components of modular, interchanging construction that are prepackaged, prewired, and pretested as a system at the Seller's facility before shipment. The overall system is computer-controlled, with analog controller and monitor backups. There will be an operating control console, of the semigraphical display type, with controls arranged to minimize the chance of human error. Indicating lights for valve positions and other system conditions will be integrated with the graphics on the control panels.

The field transducers — which of necessity vary in design — sense and provide output signals to standardized input buffers which have been prepackaged and located in a nest configuration with common power supplies and accessories. The outputs from all input buffers are 0–10 V, and all control and monitoring equipment is identical, thus simplifying fabrication and packaging. The 0–10 volt signal is compatible with both analog input modules and computer control modules, thus providing selection of front-of-panel or computer forms of control. The machine control computer has the capability to adjust, track, or program setpoints and to monitor out-of-limit conditions on the miniaturized controllers.

The numbers of control loops and points monitored were estimated as indicated in the paragraphs which follow and are summarized in Table 7 (A control loop is defined as those components required to accomplish automatic control of a variable, i.e., sensor, input buffer, output buffer, alarms, control module, analog indicator or recorder, final control element such as a valve, computer interface, power supplies and other common equipment such as cabinetry which is prorated on a point basis.) In most cases, the details of the sensing elements in the channel or loop are not specified. For the purposes of cost estimating, the proposed control concept is based on the Foxboro Company's combination of "SPEC" and "INTERSPEC" instrumentation; it should be noted, however, that similar systems are available and competitively offered by other manufacturers.

Table 7. Requirements for Monitoring, Interlocks, and Control Loops in TTAP[a]

System	Numbers Required		
	Monitor Points	Interlocks	Control Loops
Ohmic Heating System	5	30	1
Vertical Field System	5	85	2
Magnetic Limiter	10	66	6
Toroidal Field Systems	248	192	4
Neutral Beam Injectors	40	60	50
Vessel Vacuum System	6	51	6
Cooling Water System	20	12	7
Cryogenic System	5	5	1
Total of above	339	501	77

[a]The special monitors and other I and C equipment for radiological safety, life safety and environment, and diagnostics packages are not included.

Ohmic Heating System

Control of the ohmic heating system described in Sect. 3.6 will require the measurement of one current and five temperatures. Provisions are made for selection of any one of these for control. Temperature will be controlled when the ohmic heating coils are used as inductive heaters for baking the vacuum shell. Water flows and temperatures on each of the twelve coils and at other points in the system are monitored and interlocked.

Vertical Field System

The vertical field system involves feedback control. In the reference design there is one circuit in the vertical field system. The current will be programmed according to a calculated profile and modified by sensing plasma position and shape during the experiment. This will require a field sensor with a control loop. Temperatures of conductors and water flows will be monitored and interlocked.

Magnetic Limiter

The current in the magnetic limiter windings that determine the size and location of the plasma during the initiation and growth of the plasma current will be controlled according to a predetermined time profile. In reference design, there are six separate circuits in the magnetic limiter system. In addition, the coil system will be provided with temperature and water flow monitors with interlocks.

Toroidal Field System

The special instrumentation and controls for this system involve monitoring and controlling the current in each group of 6 coils for a total of four control loops. The magnetic field is also monitored at two points on each coil. The temperature in the coils are monitored and interlocked at 5 points in each coil. Also, the voltage of each coil and each set of coil leads will be monitored and interlocked. The pressure in the interconnected vacuum jacket surrounding the TF coils and structure is monitored and interlocked at 24 points. In order to gather information on the stresses in the coils and the associated structure, a total of 200 strain gages are provided and monitored.

Neutral Beam Injectors

On each of the 4 neutral beam injectors, 10 temperatures are monitored and interlocked. These include points on the accelerator grids, target valve, beam tube, and cooling water inlet and outlet. Currents in the filament, arc, source magnet, and auxiliary coil are monitored and controlled. The voltages that are monitored on each injector include filament, arc, power table, intermediate electrode, anode, and extractor. Also, one accelerating power supply voltage and current and one decelerating power supply voltage and current will be monitored. Because voltages are biased some 80 kV above ground, special provisions, such as isolating transformers or perhaps optical detection, are required which result in a higher than normal cost per point. Vacuum pressure and temperature are monitored on each injector, and provisions are made for interlocking the vacuum, source current, power table voltage, gas flow, and cooling water flow. Each injector will be equipped with a vacuum manifold containing a cryopanel backed by a turbomolecular pump and each set of two injectors will be connected to a molecular sieve roughing pump. Discharge of the molecular sieve pumps will be connected to individual mechanical pumps. A vacuum monitoring point with necessary interlocks will be provided on the vacuum manifold of each injector. Temperature control will be provided on the cryosorption and molecular sieve pumps. For use in baking, the injectors are provided with programmed temperature control for each of five zones; that is 5 temperature control loops for each injector, or 20 loops for 4 injectors.

Vessel Vacuum System

Six vacuum pumping ports will be provided on the toroidal vessel and a fine vacuum manifold will be provided at each port. Each manifold will be provided with a cryosorption panel and a turbomolecular pump backed by a diffusion pump and a mechanical pump. A common roughing system will pump down the vessel and all six manifolds initially. Instrumentation will include high and low vacuum sensors for the cryosorption pumps, low vacuum sensor for the mechanical pump, and temperature sensors for control of the cryosorption pump. Cooling water flow, temperature and vacuum interlocks will be provided at each manifold.

Cooling Water

We anticipate that the demineralized cooling water supply will require instrumentation on tank levels, flows, and pressure. We estimate that five control loops and 20 monitor points are adequate for this system. For the cooling tower it is estimated that two control loops are required. In addition, the following variables are monitored: pH, conductivity, chromate concentration, temperature, and corrosivity.

Radiological Safety

Provisions are made for continuously monitoring for X-rays produced by the machine. These monitors are located at strategic points in the vicinity of the machine. Personal radiation monitors will be used extensively to insure that no one is exposed unknowingly to X-radiation.

Life Safety and Environment

Because inert gases (nitrogen and helium) are to be utilized in the facility, oxygen depletion in operating areas is conceivable and it is anticipated that one fixed oxygen analyzer with associated indication and alarm features to meet OSHA standards will be required. In addition, portable oxygen meters will be provided.

3.12 Data Handling System

R. A. Dory   B. Kuperstock   T. W. Bookhart

3.12.1 Functions

The data handling system for TTAP will input information from the process control system and the diagnostic instrumentation described in preceding sections as digital values, store and process the information, and display results for the operators and experimenters. A portion of the data handling system is dedicated to machine control in order to carry out properly the functions of sequencing, accurate timing and rapid response to abnormal situations. The functions of the data handling system can be enumerated as follows.

1. To allow the operators to check the status of all system components for readiness before a shot.
2. On command of the chief operator, to initiate the shot and control the sequence of operation of the subsystems.
3. To acquire data from the diagnostic experiments and the machine controls throughout the shot.
4. To process some of these data, interpret them and respond with automatic and rapid (time scale of $\sim$1 msec) feedback control.
5. To terminate the shot in a safe way if conditions violate prescribed limits.
6. To monitor machine systems during intervals between experimental operation.
7. To store selected data for later analysis.
8. To analyze certain data in real time in order to aid the experimenters in prescribing parameters for subsequent shots.
9. To transmit the data to a remote data analysis computer for analysis of individual shots and sequences of shots.

3.12.2 General Description

The system to handle these tasks will comprise a number of interconnected digital computers, systems of electronic circuitry required for tasks that must be done faster than permitted by digital techniques, interfacing, and various kinds of information display. This is shown schematically in Fig. 19. It should be noted that the data analysis functions will be isolated from the control functions so that input or feedback from the analysis portions of the network cannot compromise the safe, orderly operation of the machine.

In Fig. 19, the lines coming from the plasma represent the acquisition, limited analysis and storage, and transmission by the diagnostic instrumentation (primary sensors, sample and hold circuits, multichannel analyzers, transient recorders, spectrum analyzers, etc.) of the experimental data. For purposes of cost breakdown, the data handling system is defined as beginning with the interfacing of these to the data acquisition computers. Similarly, the lines to and from the 'machine' in Fig. 19 are part of the process control systems. The data handling system begins at their interface with the machine control computer.

Some of the facility staff are represented schematically in Fig. The 'operators' are the supervisors and crews that are responsible for the safe, orderly operation of the facility. The 'experimenters' are those who outline the overall experimental program, prescribe experiment conditions, analyze, and report results. Not shown in the figure, but a key element in the data handling function are the staff members who will be engaged in programming and handling the data management system. Considering the amount of equipment and the continuing necessity of reprogramming to meet changing needs, we expect that the equivalent of 4 to 6 persons will be required for programming and software maintenance of the system.

The equipment list in Table 8 indicates the classes of computers and other equipment that would be utilized if the data handling equipment for TTAP were being procured today. As described in the paragraphs which follow, details of specific computer systems were worked out in order to resolve questions of feasibility and space requirements, and to provide a well-defined basis for cost estimation. A subsequent review of ADP capability that will already exist in the Thermonuclear Division has shown that most, if not all, of the TTAP needs could be met by adaptation of this equipment. The actual TTAP data handling system will, therefore, likely differ in detail from that which is described below. The basic functions are less likely to change, however.

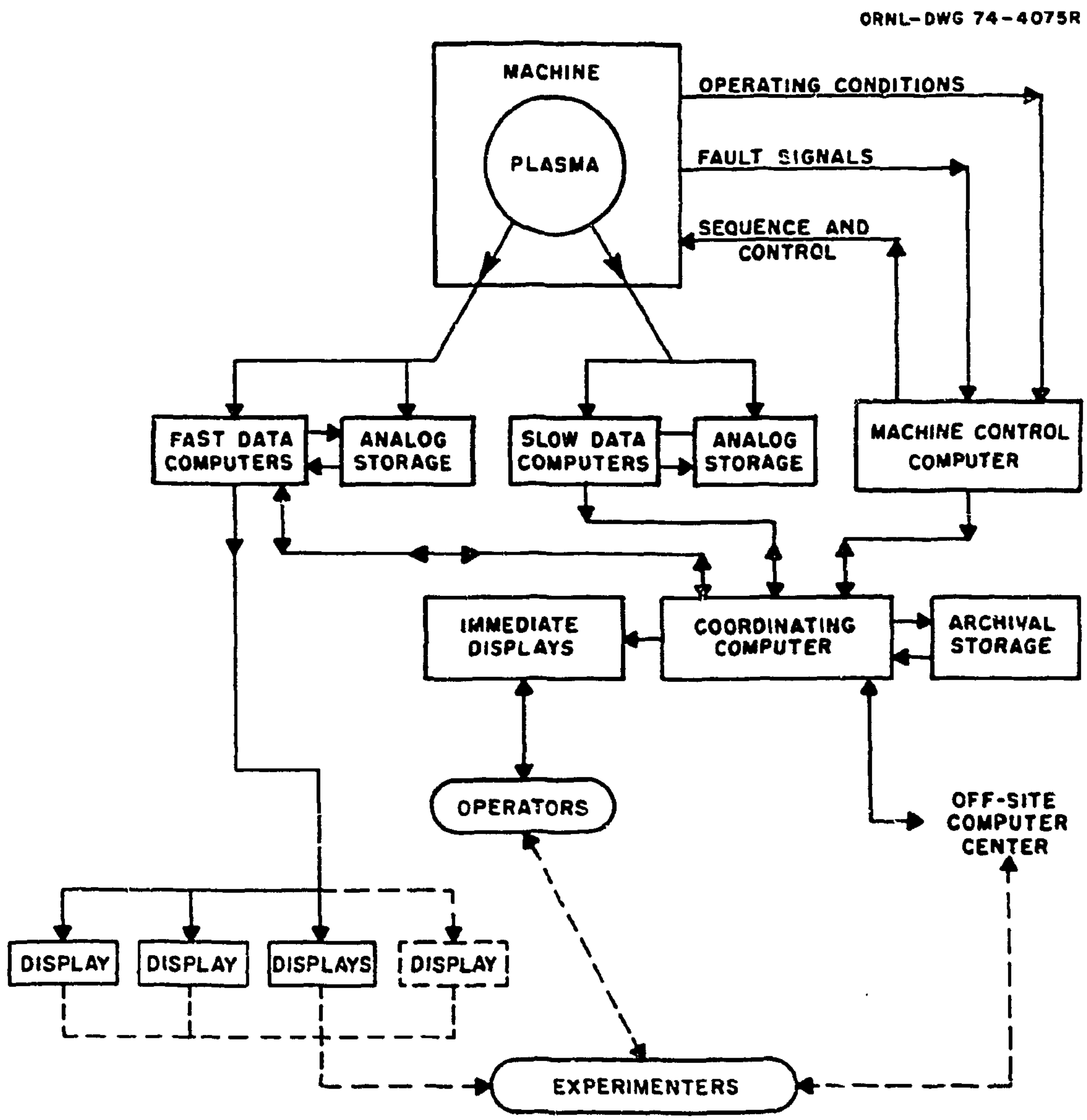

Fig. 19. Data Handling Schematic

Table 8. Equipment in Data Handling System

Function	Equipment[a]
Data Acquisition Computers	5 PDP-11/10 4 PDP-8/A
Machine Control Computer	1 PDP-11/40
Coordinating Computer	1 PDP-11/45
Displays (CRT, light pen)	6 DEC GT-40
Analog Storage (high speed)	unspecified
Interfacing	unspecified

[a]The indicated equipment was assumed in estimating costs. In every case, other equipment with equivalent capability could be used.

3.12.3 Data Acquisition (Diagnostic) Computers

There are five medium sized minicomputers, PDP-11/10 or equivalent, configured for use with the major diagnostic experiments. Four smaller microcomputers, PDP-8/A or equivalent, are used with the lesser diagnostics. Typical configurations are shown in Figs. 20 and 21. As the diagnostic computers will be able to gather data faster than it can be transmitted during the portions of the shot of interest, it will be necessary to buffer the data locally at times. To ease the programming requirements, which could be a great operating expense, these computers are configured to run under a bulk storage operating system. Thus, each microcomputer will be equipped with a dual cassette tape system, and the computers for the major diagnostics will be equipped with 1.2-million word moving head disks. The computers for the major diagnostics will be equipped with an average of 32k words of memory. The microcomputers will have 4k words of memory.

The major diagnostic computers will be connected to the coordinating computer by high speed duplex data transfer channels. These can operate

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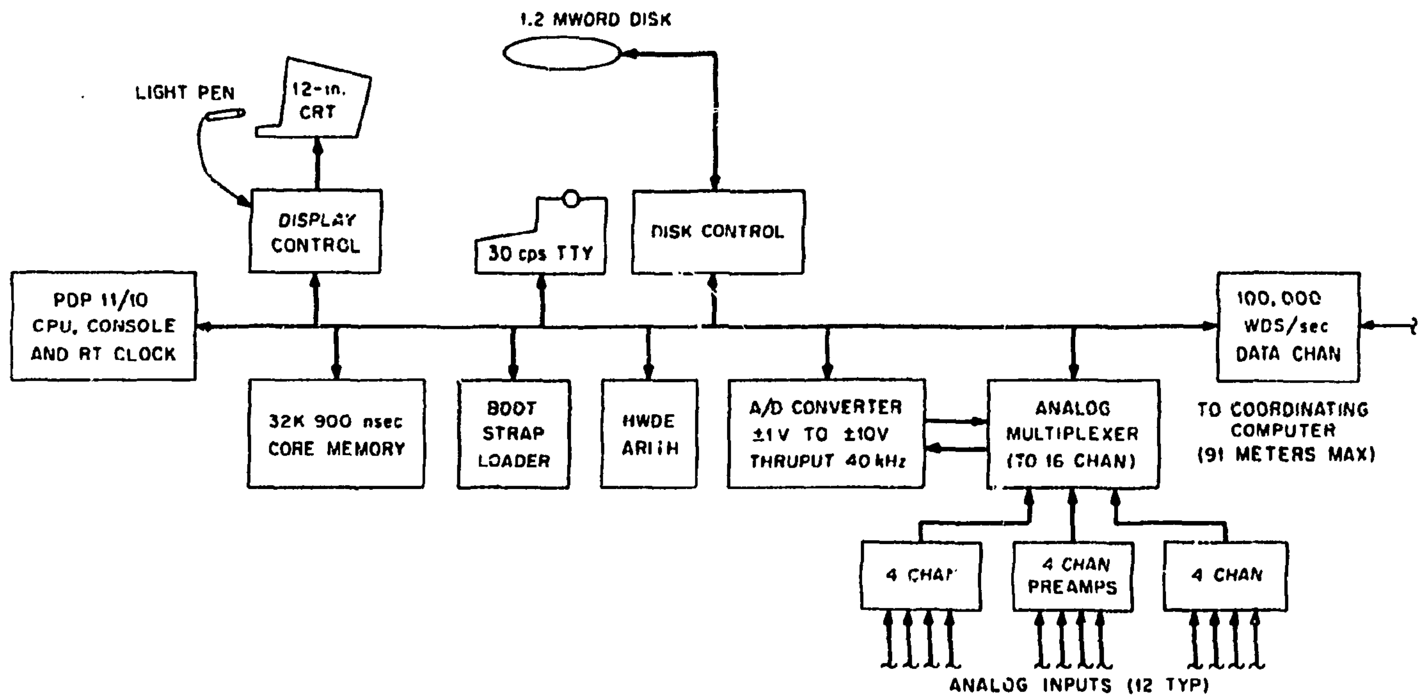

Fig. 20. Typical Major Diagnostic Computer

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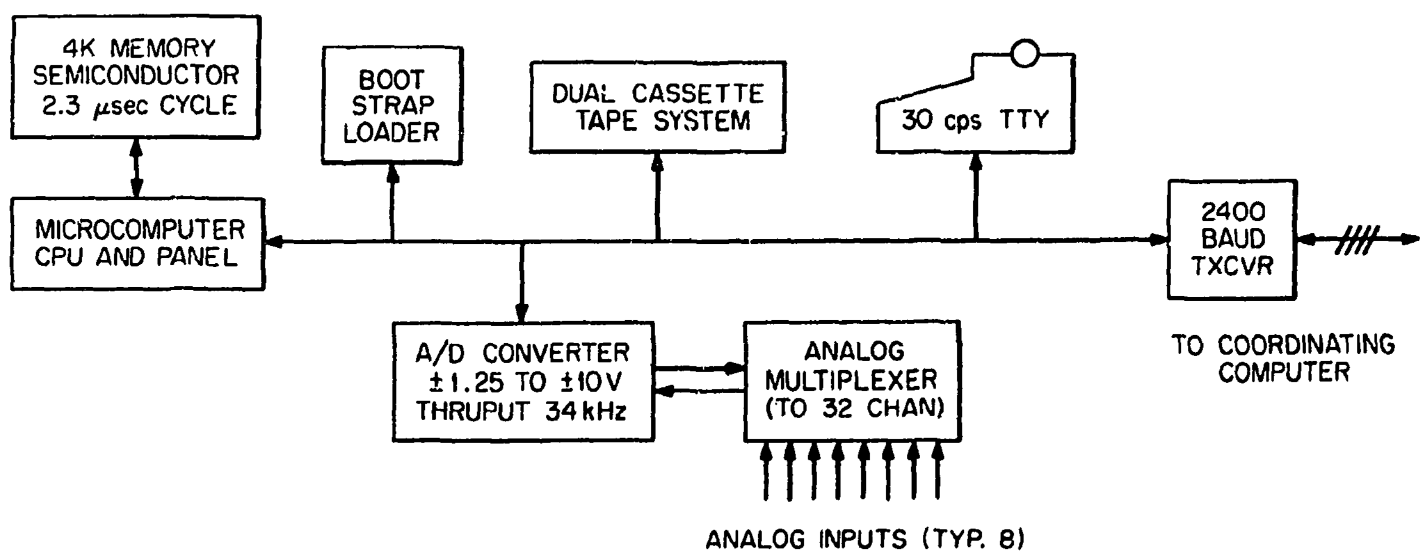

Fig. 21. Typical Smaller Diagnostic Computer

at a maximum speed of 100,000 words per second over a maximum distance of 91 meters. The computers for the smaller diagnostics, which handle orders of magnitude less data, will be connected to the coordinating computer by means of 2400-baud asychronous serial transceivers.

Input-output equipment will be plugged into each computer as required for the particular experiment. This will include such items as an analog-to-digital converter and multiplexer, digital levels in and out and digital-to-analog converters. A number of high-speed analog disk recorders will be used to keep up with high-frequency plasma phenomena of interest.

Due to the extremely fast data rates and criticality of time during the pulses, much of the programming of the diagnostic computers will be done in assembly language. Common routines will be used in more than one computer wherever possible, but the diagnostic techniques and instrumentation are quite different between systems, requiring some individually written programs for each.

3.12.4 Machine Control Computer

The machine control computer monitors the machine and process variables and controls some of them. It also controls the sequence of operation of the subsystems, interprets data and responds by changing system parameters or operating sequences if necessary, and aborts the operation safely if a fault condition is detected. The machine control computer will be a PDP-11/40 or equivalent as shown in Fig. 22. This computer must support the control system vendor's process control language, which is presumed to be equivalent to a disk operating system plus a Fortran IV system. For support of this type of program, the computer is equipped with 32k words of core memory, and a 1.2-million word cartridge type disk. A real-time clock is furnished to facilitate real-time control. The process control vendor will furnish his equipment wih an interface designed to plug into the I/O bus. The control computer will be connected to the coordinating computer by a 100,000-word per second half duplex data channel. This will operate over a maximum distance of 91 meters.

The software for the machine control computer will use the vendor's process control language programs to the maximum extent possible and

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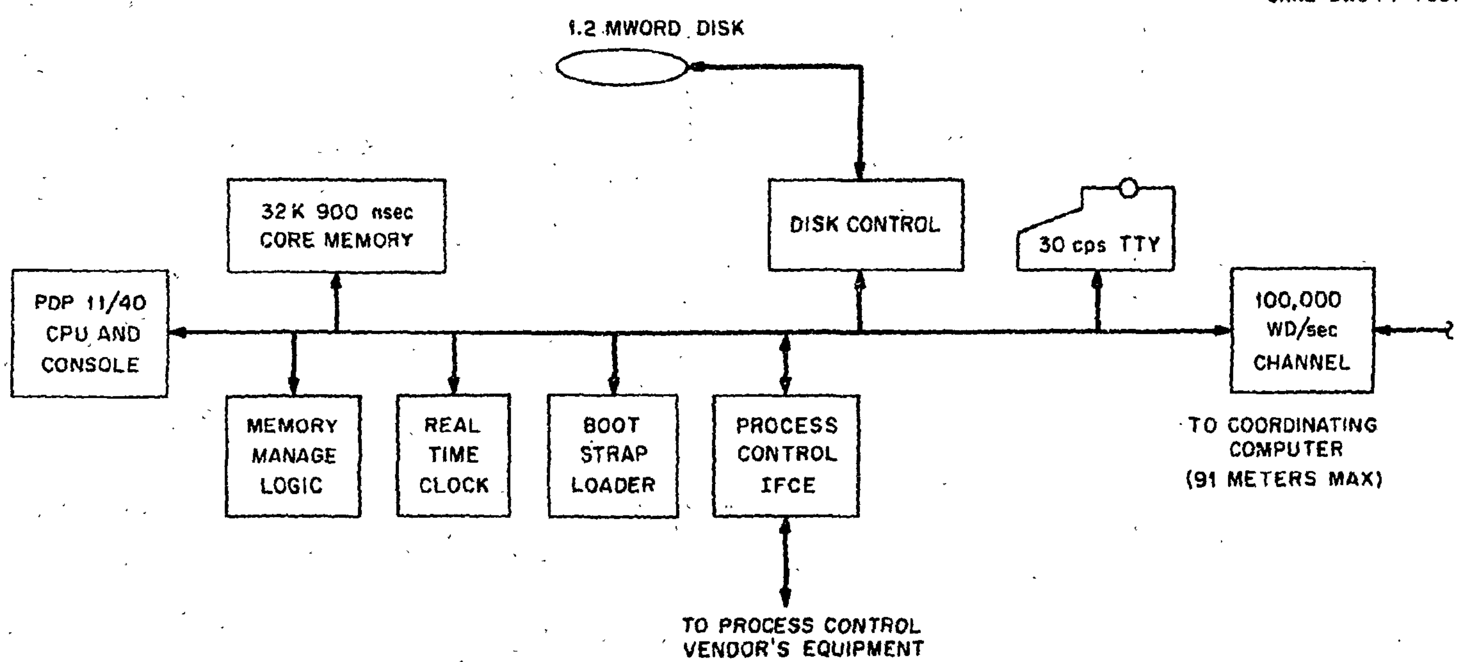

Fig. 22. Machine Control Computer

Fortran or other higher level languages. The process control language will be of the fill-in-the-blanks table driven type.

3.12.5 Coordinating Computer

The coordinating computer functions as a data concentrator and coordinator for data transmission dialog with the diagnostic computers and the machine control computer. It also maintains archival data files, provides small to medium scale data analysis and monitors the operation of various front end devices. The coordinating computer maintains a data link with a remote large analysis computer, at the 9201-2 User Service Center. This analysis computer is also tied to a very large 'number cruncher' at Livermore. The coordinating computer will be a PDP-11/45 or equivalent, with 48k words of core and 16k words of faster semiconductor memory. The operating programs will be run in the semiconductor memory while the data buffering of the input from the other computers will be done in the core memory. As the semiconductor memory has two ports, and the intercomputer transfers from the data channels will be done on a direct memory access basis, the processor will be able to run at nearly full speed, even when the peripheral data traffic almost saturates the normal I/O bus. The configuration of the computer is shown in Fig. 23.

Magnetic tape transports are provided for maintenance of archival files of past runs. Three disk files are provided for programming purposes. Programs for the major diagnostic computers can be written on a disk and carried to the target computer. Programming of the minor diagnostic computers will be done on a PDP-8/E cassette system at another location. In both cases, some programs can be sent over the interprocessor connections. The disks will also be used during runs for spooling, or organizing files to be passed on to other computers or peripherals. A line printer is included for data output and to use while programming.

There are 11 interprocessor connections at the coordinating computer. Four of these, 2400 baud serial asynchronous full duplex transceivers, are connected to the minor diagnostic computers. There are six half duplex data channels to the major diagnostic computers and the machine control computer. These are capable of operating at a speed of up to 100,000 words

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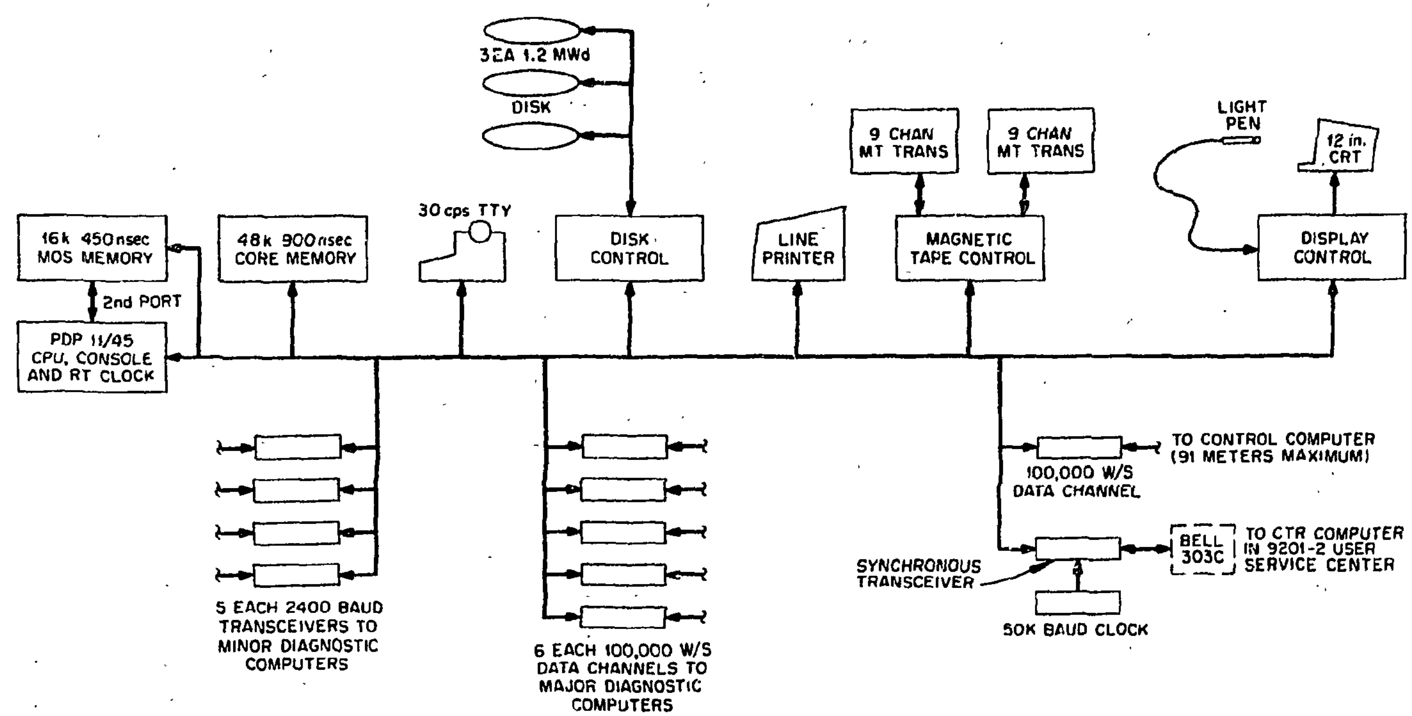

Fig. 23. Coordinating Computer

per second over distances of up to 91 meters. There is one 50,000-baud full duplex synchronous transceiver which connects to the remote data analysis machine at the User Service Center. This connection will be about 920 meters long, and will be made via a Bell 303C modem.

Vendor-supplied communication and data management software will be used to the maximum extent possible in programming the coordinating computer.

3.13 Civil and Architectural

:. T. Huffaker

The site of the reference design TTAP toroidal assembly is Building 9204-1, a concrete and masonry building in the south-central part of the Oak Ridge Y-12 Plant. This building has a total floor area of about 220,000 square feet on two floors (some limited mezzanine and basement area also exists). It was constructed in 1944 to house electromagnetic isotopes separation systems, but was withdrawn from this use in 1947. In 1954 the electromagnetic separations equipment was removed to provide space for ORNL research and reactor component testing facilities. No major additions have been made to the building, but extensive modifications and equipment installations have been made over the years.

Because of adjustments in ORNL operations plans, it has become feasible to convert approximately the western half of the building to CTR uses. A part of this space, contiguous with the reference TTAP location, has been designated as a laboratory for superconducting magnet development and testing (part of the DCTR program for development of superconducting toroidal magnets that is being conducted by ORNL). The physical characteristics of the building and the arrangement of its site well adapt it to magnet development and to limited TTAP use. As shown in Figs. 24 and 25, the location for the reference TTAP device is in a high crane bay over an extremely massive column and footing system which previously supported a heavy (thousands of tons) electromagnetic separation unit.

Location of the TTAP toroidal device on the second floor of the crane bay of Bldg. 9204-1 will require the following structural modifications. The area indicated in Fig. 24 will be stripped of existing experimental equipment (no longer in use) and removable plate, grating and supporting steel will be dismantled and removed. About 2500 sq ft of new reinforced concrete floor with a design live load capacity of 500 pounds per square foot will be constructed in this rea. Additional beams, columns, and foundations will be provided to provide adequate support for the TTAP device, which will weigh approximately 1000 tons complete. Additional structural steel will be installed to strengthen portions of the second floor crane bay (about 2100 sq ft) to provide a suitable capacity for an assembly area.

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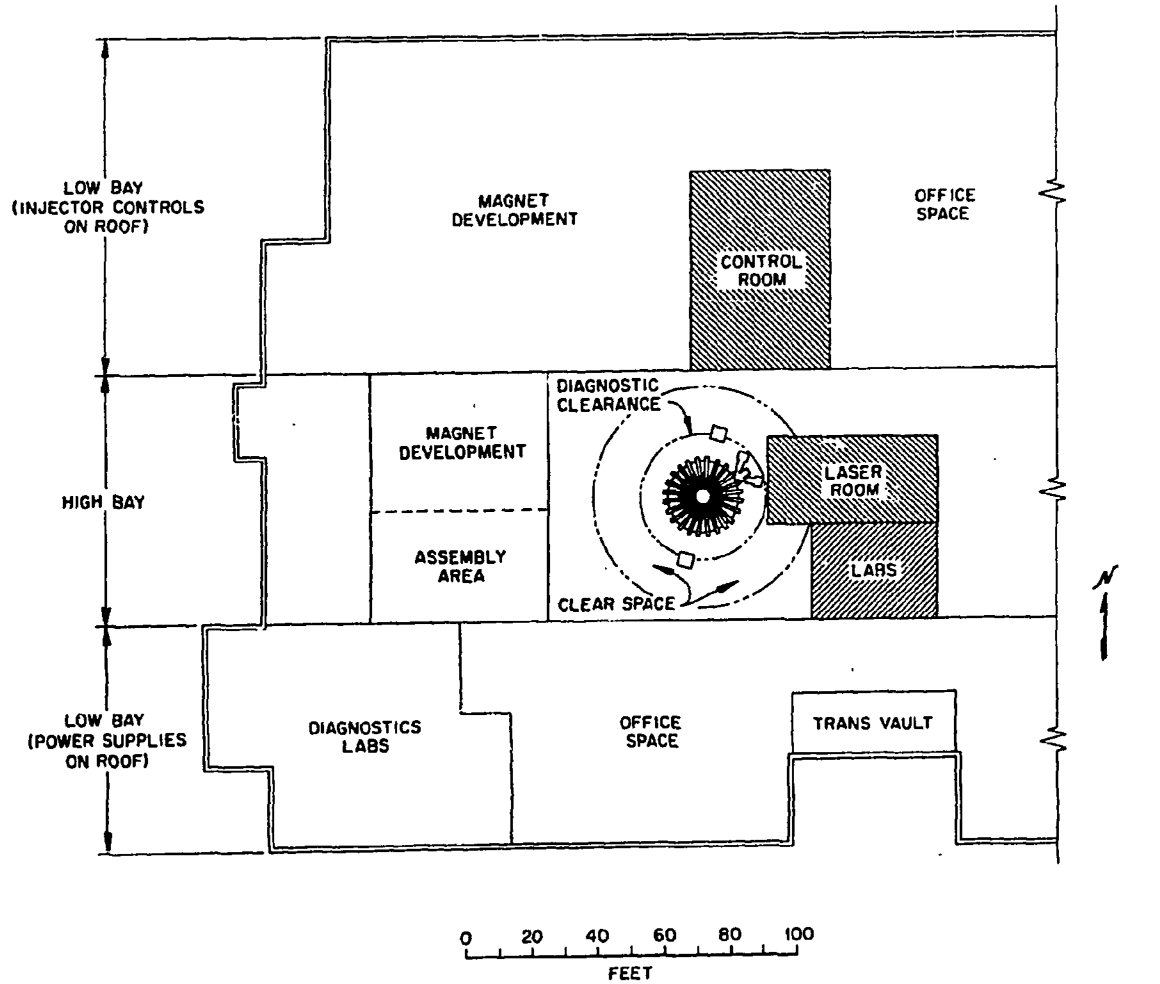

Fig. 24. Building 9204-1 Plan Showing Reference TTA Location

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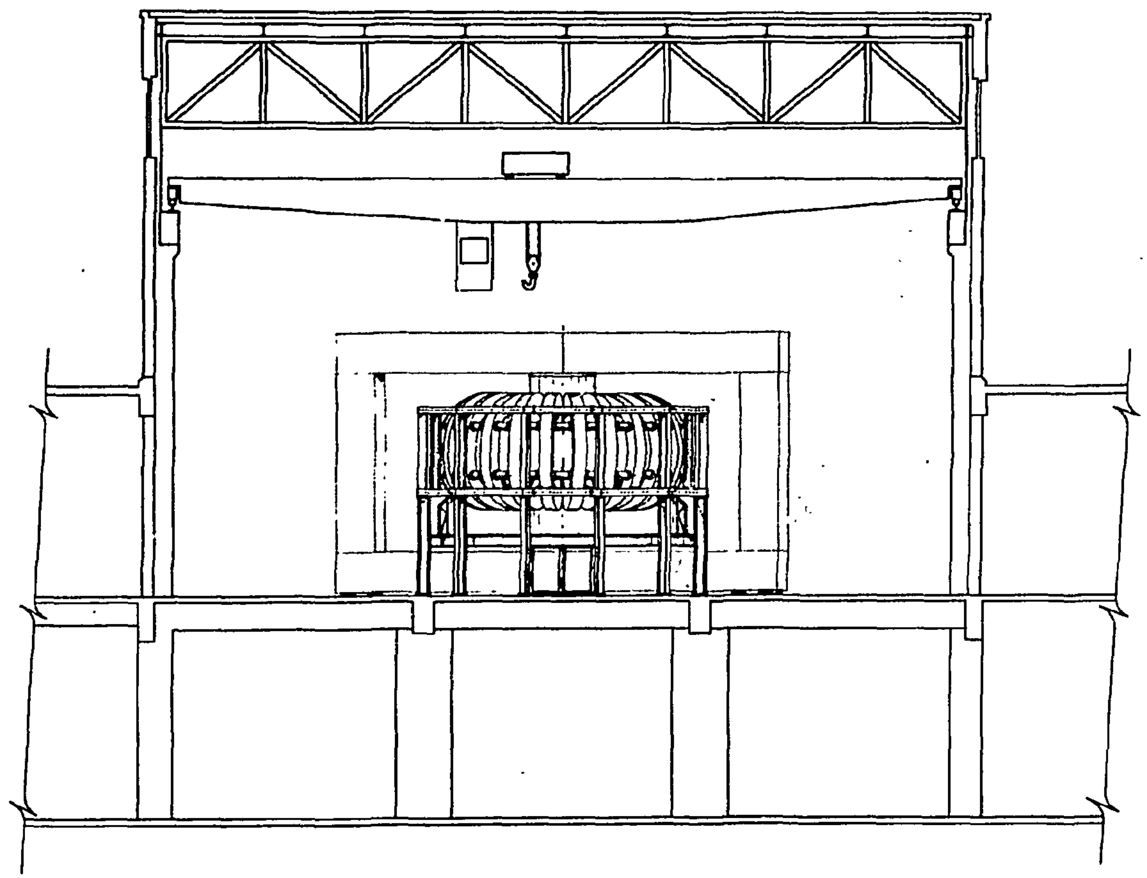

Fig. 25. Building 9204-1 Section Showing Reference TTA Location

A bridge crane of 40-tons capacity with a 10-ton auxiliary hoist is to be procured and installed in place of the existing 20-ton with 5-ton auxiliary, 70-ft span crane. (The runway supports and the existing 60-lb ASCE crane rails are adequate for the higher load.) New 4-conductor feed rail is to be provided for the full length of the building (approximately 370 feet).

As shown in Fig. 24, an enclosed control room, having a total area of 2200 sq ft, will be constructed on the second floor of the building near the device. Also on the second floor adjacent to the device will be an enclosed space of about 1000 sq ft for a laser service laboratory.

The first-floor crane bay space will be stripped of existing equipment to provide space for utilities (12,500 sq ft) and a laboratory (4,000 sq ft). The existing slab will undergo miscellaneous repairs and equipment foundations as required will be provided. The laboratory space will be enclosed and air-conditioned. The first- and second-floor "Diagnostics" areas (13,000 sq ft) the "Magnet Development" area on the second floor (16,000 sq ft) and the "Shop" area on the first floor (16,000 sq ft) will undergo general refurbishing. Some existing masonry partitions will be removed; new partitions will be constructed where required.

The low-bay roof extending from the west end to near the center of the building (about 10,000 sq ft) is to be the location for the power supplies. The existing built-up roof in this area will be removed and a prefabricated metal structure with a 12-foot eave height will be erected to provide shelter for the electrical equipment to be installed on the existing roof slab. Structural steel beams will be provided where necessary to support the loads imposed by this equipment.

The cooling water system will require a concrete basin for three 250-ton capacity cooling tower south of Third Street, concrete foundations for the pumps in 9404-7, and a concrete slab and concrete foundations north of 9404-7 for the heat exchangers. Excavation and backfill for underground piping and steel pipe supports for overhead piping associated with the cooling tower and exchangers will be provided.

For the purposes of cost estimation it was assumed that the cryogenic equipment would be housed in a new building south of 9204-1. A prefabricated metal building approximately 120 ft x 70 ft with a 30-ft eave height and a 4200 ft^2 mezzanine floor, erected on a concrete slab-on-grade between Bldg. 9404-7 and the creek is envisioned.

4. COST ESTIMATES

4.1 Summary

The estimated costs specific to the basic reference design TTAP facility in Building 9204-1 are listed in Table 9 in the format prescribed in AEC Appendix 6101 Annex C. A real effort was made to include every identifiable item and to make the estimate on the basis of detailed analysis of the proposed design, including procurement, fabrication, assembly, and engineering. These estimates were made by an interdisciplinary team from the UCCND Estimating Engineering organization by standard procedures, using drawings and bills of materials for basic machine elements produced by UCCND and ORNL engineers and specialists. The design itself was, of course, quite preliminary. Costs conceivably could be reduced by design iterations that consider both technical performance and costs; on the other hand, because the design effort expanded before the cost estimate constitutes a small fraction of the total design effort that will be required, the estimates are necessarily uncertain. For this reason a contingency allowance of 30% has been added to the project costs.

The costs listed in Table 9 do not include the necessary prior and concomitant costs for development, for support of the operating staff, and other costs of testing and experimental operation. Furthermore, although all parts of the fully equipped facility were considered in the cost estimation process, not all are reflected in the costs in Table 9 because we have assumed that, in keeping with practices in other CTR projects, some plasma-related equipment will be provided as part of the costs of experimental operation while other items that will have been procured in the normal course of already existent programs will be available for exclusive or shared use by TTAP.

Equipment provided from operating funds conventionally includes neutral beam injection systems and a large part of the diagnostics. The costs of such additional equipment that we assumed would be procured for the reference design device, listed in Table 10, amounts to $8.0 million. Adding this to the $45.1 million for the basic facility gives a total of $53.1 million that

Table 9. Summary of Preliminary Cost Estimates
For Basic Reference Design TTAP Facility[a] in Oak Ridge Y-12 Area

Item	Estimated Cost: \$ Million[b]	Estimated Cost: Percentage of Construction Costs
Limiters	0.31	1.1
Liner (honeycomb)	0.16	0.6
Toroidal vacuum vessel	0.36	1.3
Toroidal field coils	12.33	45.4
Other coils	0.31	1.2
Iron core and yokes	1.35	5.0
Support structures	1.06	3.9
Power supplies	2.04	7.5
Vacuum pumping systems	0.36	1.3
Cryogenic systems	1.04	3.8
Electrical (special facilities)	0.44	1.6
Civil and architectural (sp'l fac.)	0.39	1.4
Instrumentation and controls	1.30	4.8
Maintenance equipment	0.10	0.4
Assembly	3.10	11.4
Total special facilities	24.66	90.9
Building modifications	1.37	5.1
Auxiliary building	0.11	0.4
Other structures (cooling towers)	0.03	0.1
Utilities	0.91	3.4
Improvements to land	0.03	0.1
Total construction costs	27.12	100.0
Engineering, design, and inspection	7.51	27.7
Standard equipment	0.10	
Total of above	34.73	
Contingency allowance (30%)	10.42	
Total project cost	45.15	

[a]See text for distinction between basic and full-equipped facility and dependence on other programs.

[b]FY-1975 equivalent.

Table 10. Incremental Costs of Equipping Reference Design Facility[a]

Item	Cost ($ thousand)
Injection systems[b]	1821
Diagnostic systems	1748
Diagnostic access valves	275
Data handling	100
Subtotal	3944
Assembly	592
Engineering and Inspection[c]	1582
Total of above	6118
Contingency allowance[d]	1835
Total	7953

[a]Representing funds in addition to those required for the basic facility (Table 9) and which are not specifically in existing budget projections for associated CTR programs (Table 11).

[b]Three systems, including power supplies, vacuum, I&C, at 1 MW each.

[c]This includes nothing for injectors (which will have already been engineered), 30% of the cost of diagnostics and data handling, and $849 thousand for Title III engineering (Q.A., inspection, etc.) on the entire facility.

[d]This is 30% of the total above, and represents the pres-eng uncertainty in costs. By the time operating funds are appropriated there will be little uncertainty in injection system costs.

must be provided for the fully equipped reference design facility. The items that we expect to come from existent programs, if they had to be procured specifically for the reference design, would cost another $7.4 million as shown in Table 11. This would make a grand total of $60.5 million for the facility if there were no benefit from other CTR programs. (A completely free-standing facility would cost even more since the foregoing estimates count on using an existing building and other facilities in the Y-12 plant.)

4.2 Estimates by Subsystem or Function

4.2.1 Vacuum Vessel, Liner, and Limiters

The indicated cost for the vacuum vessel includes the attached vacuum pumping ducts and the diagnostic penetrations to the first flange. The cost of the liner includes the supports and one set of replaceable honeycomb panels. The cost of the latter is based on the use of niobium. Stainless steel honeycomb would cost about the same; tungsten, being more difficult to fabricate, would cost substantially more. Limiter costs cover the toroidal band and 14 poloidal rings, each consisting of tungsten links or plates assembled on stainless steel rods.

4.2.2 Toroidal Field System

In the case of the superconducting TF coils, the cost of the conductor is $3.92 million or 32% of the total (49,900 lb of high-field material at $50/lb and 35,500 lb of low-field material at $40/lb). The balance covers other materials and all fabrication costs. Tooling costs are not included; the assumption here is that tooling used earlier to produce test coils of similar size for the superconducting magnet development program will be available and adequate for producing the TTA coils.

Additional costs associated with or affected by the toroidal field system are included under power supplies and utilities. Power supplies for the superconducting TF coils cost $0.47 million. A major item under utilities is a 40-MVA transformer; here we assume that a unit that will be available following high-field operation of ORMAK can be used. This

Table 11. Anticipated Benefits to Reference Design TTAP from Other CTR Programs at Oak Ridge

Program and Item[a]	Equivalent Cost ($ thousand)
Confinement Systems	
ORMAK	
diagnostics	437
data handling	538
power supplies	280
transformer substation (40 MVA)	1000
maintenance equipment	150
Development and Technology	
Beam Development	
one prototypical injector, complete	606
Magnet Development (full-scale)	
refrigeration system (shared)	1154
Subtotal	4165
Assembly	436
Engineering	1058
Total of above	5659
Contingency allowance	1699
Total	7358

[a]These items are either existing pieces of equipment (e.g., diagnostic analyzers and oscilloscopes) or presently programmed in the respective budgets (e.g., the planned refrigeration in the magnet development program). If these items become unavilable by virtue of other use or altered schedules or directions, then these funds would be required directly in the TTAP program.

transformer substation is valued at about $1.0 million. Including assembly, engineering and contingency this represents a $1.8 million savings.

4.2.3 Plasma Driving System

The costs for "other coils" in Table 9 cover the ohmic heating, vertical field, and magnetic limiter windings. The figures shown, which cover materials, tooling, and fabrication, amount to $10.80/lb. (This is 10 percent above the actual PLT costs.)

The power supplies for the VF and limiter coils are estimated at $473 thousand and $371 thousand, respectively. The estimated costs of power supplies for the OH coils are $727 thousand. It is assumed that the rectifiers used in the ORMAK TF power supply will be moved to 9204-1 to serve as part of the TTA OH supply. These rectifiers have a base value of $280 thousand. Including assembly, engineering and contingency, $490 thousand can be saved.

4.2.4 Injectors

Injectors are not listed in Table 9 because the design and part of the equipment to be used initially is presumed to be available from the injector development program and subsequent additions are regarded as operating costs. The estimated costs do include the injector connections to the vacuum vessel and the provision of space for the injector and their associated equipment. A prototype injector system, including power supply, vacuum pumping system, and I&C, is expected to be available from the development program. The base cost of this system is estimated to be $606 thousand; assembly, engineering, and contingency allowance bring the total estimated cost to $1.18 million. Three other similar systems would be procured specifically for TTAP initial experiments at a cost of $2.7 million.

4.2.5 Vacuum Pumping Systems

Equipment in these systems is presently commercially available, and estimates are based on actual prices. It is to be noted that as explained above, the cost of the pumping equipment for the injectors is not included in the tabulated estimate.

4.2.6 Cryogenic Systems

The cryogenic system costs listed ($1.04 million) are half of the estimated cost of the systems described in Sect. 3.9. The basis for this allocation is the assumption of dual use of the cryogenic plant by TTA and other elements of the superconducting magnet development program, where similar equipment will be required for the testing of larger coils. The base cost of these shared items is $1.15 million including auxiliary buildings required. Assembly, engineering and contingency costs result in a total savings of $2.1 million.

4.2.7 Diagnostics

As mentioned above, the cost of the vacuum vessel includes provision of access for diagnostics. As is conventional, however, funds for new diagnostic equipment are not included in the fabrication budget. The costs of the isolation valves, the diagnostic subsystems themselves, and the supporting calibration and maintenance facilities are considered to be part of the operating costs of experiments to be done in the facility. These are estimated at a base cost of $2.02 million with assembly, engineering and contingency bringing the total to $3.93 million. Some equipment is expected to be available from other HNL programs and use of this equipment would save an estimated $0.44 million in base cost or a total of $0.85 million including assembly, engineering and contingency. This cost is in addition to the new equipment required.

4.2.8 Instrumentation and Controls

The basic machine process instrumentation and control are all included in the costs listed in Table 9. I&C associated with the injectors and diagnostics are not, as explained above.

4.2.9 Data Handling

No cost for data handling is listed in Table 9 for the following reasons. Review of the existing and projected ADP capabilities in the Thermonuclear Division in relation to the functions of the system described in Sect. 3.12 led to the tentative conclusion that they will be adequate to handle the TTAP needs. Included in this capability is a local computer that will be provided to serve as the HNL TD terminal with the CTR computer in California. The proposal for expansion of the CTR-USC computer system includes $290 thousand of peripheral equipment which would enable this system to handle the processing of experimental data; this will presumably be available for TTAP use. Use of additional existing equipment would result in a base cost savings of $0.54 million with assembly, engineering, and contingency costs bringing the total to $1.05 million. Additional new equipment would be procured specifically for TTAP initial experiments at a cost of $0.2 million.

4.2.10 Buildings

The auxiliary building cost is half of the cost of a building that could house the cryogenic systems that serve both TTA and the proposed full-size magnet testing program. Building modifications include new floors and walls in Building 9204-1. Civil and architectural costs under special facilities are for foundations, etc., specifically for TTA equipment.

4.2.11 Standard Equipment

As defined in AEC Appendix 6101, Annex C, this category includes office and laboratory furniture and equipment, hoists, and machine tools that can be procured with only a nominal engineering effort. Much of this type quipment will be available from previous use in the Thermonuclear Division. Maintenance equipment that must be engineered specifically for TTA, as for example special optics and other attachments to laser cutting and welding equipment, is not included here but under special facilities. Some equipment is assumed to be available from other HNL programs and result in a base cost savings of $0.15 million with assembly, engineering and contingency costs bringing the total to $0.23 million.

4.2.12 Assembly

The substantial costs for assembly listed in Table 9 include the assembly of primary machine elements and connection of electrical, cooling, vacuum, and utility services to the machine. (Installation costs for supporting systems are included among the costs of those systems.) Machine assembly costs were first estimated on the basis of detailed analyses of all identifiable assembly tasks for the major items. These estimated costs amounted to 10.3% of the cost of the items themselves. On the basis of previous UCCND experience with a wide variety of large programs, a figure of 15% was chosen for TTA, to be applied to those items that comprise the basic machine (not to supporting systems, utilities, buildings, etc.).

4.2.13 Engineering, Design, and Inspection

A detailed review of the engineering required for the major machine elements and associated equipment and facilities was conducted and estimates made for each item. Weighted average percentages were derived, compared with actual experience with previous programs, and factors selected for use in TTA. Engineering costs were calculated by applying these factors to the basic machine costs. Engineering costs for complex experimental equipment were calculated at 30%; engineering for facilities, conventional equipment design, and procurement specifications, were figured at 20%.

Additional engineering costs to support Title III efforts subsequent to initial design and assembly were estimated but are not listed in Table 9 because they are considered to be part of the operating costs of the start-up testing to be done on the machine.

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