DESIGN CONSIDERATIONS FOR ACHIEVING HIGH VACUUM INTEGRITY IN FUSION DEVICES*

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ABSTRACT

Achieving high vacuum integrity in fusion devices requires close attention to both the overall system configuration and the design details of joints and seals. This paper describes the factors in selecting the system configuration, from a vacuum standpoint, for the Princeton Plasma Physics Laboratory (PPPL) DCT-8 Tokamak device. The DCT-8 (driven current tokamak) is the eighth design in a series of tokamak concepts defined to cover the magnetic confinement and development gap between the Tokamak Fusion Test Reactor (TFTR) and the Engineering Test Reactor (ETR). Leak detection concept development is considered a vital activity, as well as the definition of a configuration that minimizes the consequences of leaks. A major part of the vacuum boundaries of the magnet system and the plasma system is common. For the major penetrations, primary and secondary seals are provided with vacuum control over the region between seals. The intent is to instrument these cavities and provide automated recordings of these measurements for leak maintenance.

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INTRODUCTION

A high level of vacuum integrity is mandatory for achieving satisfactory performance in a magnetically confined fusion device. The fusion reactor designer must constantly keep this requirement at the surface in his design definition activities. Vacuum integrity is also a dominant factor in the concept evolution of the tokamak reactor design and must be acknowledged as a high priority goal through the detail design, manufacturing, and quality control activities.

The designer has two basic options in choosing a design approach:

1. Design the system configuration such that a major leak path or a series of leak paths is irrelevant to the maintenance of a high level of vacuum integrity.
2. Design the system configuration such that the leaks, if and when they occur, are immediately detected, are precisely located, and may be rapidly repaired.

One can never achieve the desired results of the first approach; however, one can achieve a design in which the second approach complements the first. Hence, the leaks that do occur are easily detected and are readily accessed and repaired.

This paper addresses these concerns as they are reflected in the design features of the DCT-8 for the Princeton Plasma Physics Laboratory (PPPL). The DCT-8 is the eighth design in a series of tokamak concepts defined to cover the magnetic confinement development gap between the Tokamak Fusion Test Reactor (TFTR) and the Engineering Test Reactor (ETR). The design

resulted largely from previous work accomplished by the Fusion Engineering Design Center (FEDC) at the Oak Ridge National Laboratory (ORNL) on the Fusion Engineering Devices (FED) and on the International Tokamak Reactor (INTOR).

TOKAMAK DESIGN OPTIONS

Tokamak fusion devices that employ superconducting magnet systems have at least two sets of vacuum boundaries. The exact number depends on how the poloidal field (PF) coils are located relative to the toroidal field (TF) coils. One boundary set must be assigned to provide the confinement conditions to the plasma. The other set is assigned to provide the proper environment to the magnets. As will be discussed later in more detail, the magnet system vacuum boundary can be designed such that a significant portion of this boundary is common with the plasma vacuum boundary.

All tokamaks are characterized by a toroidal plasma chamber. This chamber, or torus, is comprised of the first wall systems, the impurity control elements, the bulk shield, a vacuum containment vessel, and certain other auxiliary systems (i.e., heating systems, diagnostic systems, and fueling systems). Direct access to these elements is limited almost exclusively to the outer periphery of the torus. Hence, it is fortunate that those surfaces, where we cannot make leaks irrelevant, are located in the outer periphery of the torus.

In tokamaks, as in other fusion concepts, we have the option of placing the plasma vacuum containment vessel at

several different radial locations. These radial locations are shown in relationship to the magnet vacuum boundaries in Fig. 1.

In Fig. 1(a), the first wall serves also as the vacuum vessel, and the superconducting magnet cryostat is a separate vessel. In Fig. 1(b), the plasma vacuum vessel is at the outer surface of the bulk shield, and the superconducting magnet cryostat is a separate vessel as in (a). In Fig. 1(c), the plasma vacuum boundary is as it was in (b); but this boundary is also employed as the superconducting magnet cryostat inner boundary.

These different approaches to vacuum vessel location are also illustrated in terms of reactor-study configurations presented in Figs. 2-4.

Figure 2 is an elevation view of FED-Resistive Magnet (FED-R) device, which employs all-resistive copper coils for the TF magnet system. One of the driving system requirements is for rapid changeout of test modules, meaning that the plasma chamber must not be brought up to atmosphere for a test module changeout. Hence, the vacuum vessel is at the first wall location.

Because the bulk shield fits snugly against the outer surface of the first wall, it is extremely tedious to access the outer surface of this wall for leak checking. Most of the access must be from the inside. Because of the high heat load requirements, this wall is actively cooled; so vacuum leak checking must contend with water leaks also. After the beginning of deuterium-tritium (D-T) operations, the entire first wall/vacuum vessel becomes activated. Hence, remote techniques must be used throughout all leak maintenance activities.

TYPICAL CROSS SECTION

ORNL-DWG 81-17378A8 FED

0 1 2 3 4 5
METERS

An elevation view of the FED baseline (Fig. 3) presents the same approach as that in Fig. 1(b). The vacuum vessel has been brought to the outside of the shield, except for some regions at the top and bottom. Because of electrical requirements, the construction of the plasma vacuum vessel (the spool structure) is a thin-gage, double wall with internal corrugations. The inner wall, while separate from the magnet vacuum vessel, is very close to it, making access very difficult.

Figure 4 shows INTOR, which has a common vacuum boundary with the magnet cryostat. The INTOR is a somewhat larger device than FED baseline, and it incorporates a tritium-producing blanket. The plasma vacuum boundary is common with the magnet vacuum boundary over the top, inner, and bottom walls. Both the FED baseline and the INTOR are similar at the outer wall of the plasma chamber.

OPERATING CONDITIONS AND REQUIREMENTS

Vacuum pumping system performance requirements of the DCT-8 device are listed in Table 1 for both the plasma and magnet chambers. This table shows the pressure requirements and potential leak concerns associated with each operational event. Table 1 applies to both the separate boundary configuration and a combined plasma and magnet chamber boundary.

During assembly and checkout of the magnet chamber, the pressure in the magnet chamber is required to be less than 10^{-5} torr with the plasma chamber open to the atmosphere, which

Table 1. Vacuum leak problems – separate vacuum boundaries

Operational event	Vacuum quality (torr)		Leak problem	
	Plasma chamber	Magnet chamber	Separate boundaries	Common boundaries
Assembly checkout magnet chamber	Atmos.	10^{-5}	●Air leaks from surroundings – all surfaces of magnet cryostat	●Air leaks from plasma chamber & surroundings to magnet chamber
Assembly checkout plasma chamber	10^{-7}	Atmos.	●Air leaks from surroundings – all surfaces of plasma spool	●Air leaks from magnet chamber & surroundings to plasma chamber
Startup	10^{-7}	10^{-5}	●Air leaks from surroundings to either chamber – all surfaces of either chamber	●Air leaks from surroundings to either chamber
Equilibrium burn	10^{-5}	10^{-4}	●Air leaks from surroundings to either chamber ●Tritium leaks to surroundings	●Air leaks from surroundings to either chamber ●Tritium leakage from plasma chamber to surroundings & to magnet chamber
Maintenance in plasma chamber	Atmos.	10^{-4}	●No effect on magnet chamber	●Air leaks from plasma chamber & surroundings to magnet chamber
Maintenance in magnet chamber	Atmos.	Atmos.	●No leak problem	●No leak problem

ensures that the cryogenic surfaces will have adequate thermal isolation from the warm vacuum boundary surfaces and that the buildup of condensate on the cryogenic surfaces is sufficiently slow. For either the common magnet/plasma vacuum vessel configuration or the separate magnet/plasma vacuum vessel configuration, air leaks to the magnet vacuum system can occur through any region of the vessel.

During assembly checkout of the plasma chamber, the pressure in the plasma chamber must be reduced to 10^{-7} torr or lower with the magnet chamber open to the atmosphere, ensuring that impurity levels in the chamber will not affect plasma performance. Air leaks from any portion of the plasma vacuum vessel are a concern during this operational event for either vessel configuration.

For startup of the device, both the plasma and magnet vacuum pumping systems are operating, and the required pressures are less than 10^{-7} torr in the plasma chamber and less than 10^{-5} torr in the magnet chamber for the reasons mentioned. Air leaks from the surroundings to either chamber are a concern during this operation. Leaks between the magnet and plasma chambers are inconsequential for the combined boundary configuration.

During operation of the device, the plasma chamber (before adding the D-T fuel to the chamber) must be 10^{-5} torr. This pressure ensures that the number of impurity atoms in the chamber is below 1% of the D-T fuel atoms in the plasma during the burn. The magnet chamber pressure must be maintained below

10^{-4} torr. For the combined boundary configuration, leaks between the two chambers that were inconsequential during operation may now be unacceptable; therefore, detection and repair are required.

Maintenance of the magnet system is expected to be infrequent. If the magnet vacuum system must be deactivated and exposed to the surroundings, then the plasma chamber will also be opened to the surroundings. Therefore, since neither vacuum system is operating, there are no potential leak problems.

ASSESSMENT/CONCEPT SELECTION

The three vacuum vessel concepts described in the "Design Options" section were compared based on their vacuum system performance and impact on total device cost. Vacuum system performance was characterized by relative leak probability and accessibility to repair potential leaks.

Since it was felt that a smaller area exposed to the surroundings should lead to a lower probability of leaks, the surface area distributions were compared for the two concepts. Results of this comparison are presented in Table 2. A common boundary reduces the total surface area subject to leaks by 32.5%, compared to the separate boundary configuration. Furthermore, the surface area exposed to the surroundings is reduced by 85% for the plasma chamber and by 50% for the magnet chamber.

Table 2. Distribution of leak surface areas^a

Surface type	Area (m ²)	Percentage of total
Plasma chamber to surroundings	130 (882)	8.3 (38.2)
Magnet chamber to surroundings	676 (1428)	43.4 (61.8)
Plasma chamber to magnet chamber	<u>752 (0)</u>	<u>48.3 (0)</u>
	1558 (2310)	100 (100)

^aNumbers in parentheses are for separate plasma chamber and magnet chamber boundaries. These correspond to either 1(a) or 1(b) of Fig. 1.

The contiguous area of the magnet and plasma chambers is an essentially inaccessible region. Leaks in a separate magnet boundary configuration must be repaired after removing the shield sectors and plasma chamber vacuum vessel. For the combined boundary configuration, leaks in these same regions would also be difficult to repair; however, leaks could potentially be repaired from the inside of the plasma chamber vessel after removing the shield sectors. Also, leaks in these regions would be inconsequential during operation of both vacuum pumping systems for the common boundary configuration, although as pointed out previously, these leaks may still need to be repaired for the common boundary approach during other operations such as plasma chamber maintenance.

A cost comparison for fusion devices with either the separate boundary configurations [(a) and (b) of Fig. 1] or the common boundary configuration [(c) of Fig. 1] has been documented [1] as part of the FED studies. The total system cost is reduced by 6% for the common vacuum boundary configuration because of its smaller major radius. (The major radius was reduced from 4.84 m for the separate vacuum boundary configuration to 4.56 m for the combined vacuum boundary approach.) A device with a smaller major radius results in a reduced cost because it has less total volume of bulk shielding and smaller TF and PF coils.

Based on its favorable impact on vacuum system performance and device cost, the combined vacuum boundary configuration was selected for DCT-8.

LIMITING LEAK RATES

The DCT-8 plasma chamber vacuum pumping system makes use of turbomolecular pumps ($8\text{--}5\text{ m}^3/\text{s}$) which, together with the ducts and valves, results in a total effective pump speed of $19\text{ m}^3/\text{s}$ for the plasma chamber. The magnet chamber vacuum pumping system consists of turbomolecular pumps of the $2\text{--}5\text{ m}^3/\text{s}$ type (effective pump speed estimated at $5\text{ m}^3/\text{s}$) that are used for the initial pumpdown to 10^{-5} torr. After achieving this pressure, the cryogenic system is activated and the magnet surfaces are brought down to a liquid helium temperature of 4.2 K. The total surface area at 4.2 K is about 1000 m^2 , resulting in an effective pump speed of about $10^5\text{ m}^3/\text{s}$ for air in the magnet chamber.

Maximum permissible leak rates were determined, based on these pump speeds and the pressure requirements listed in Table 1. Results are presented in Table 3 for leaks from the surroundings to the plasma chamber, from the surroundings to the magnet chamber, and between the plasma chamber and magnet chamber.

Air in-leakage to the plasma chamber of less than 1.9×10^{-3} torr-L/s is required to achieve the 10^{-7} torr pressure required for plasma chamber assembly checkout and startup. This leak rate corresponds to a leak through an aperture of less than $21\text{ }\mu\text{m}^2$.

Table 3. Maximum permissible leak rates

Operational event	Maximum tolerable (air) leak rate to achieve desired vacuum quality (torr-L/s)		
	Type of boundary		
	Plasma chamber -surroundings-	Magnet chamber -surroundings-	Plasma chamber -magnet chamber
Assembly checkout - magnet chamber	NA ^a	5×10^{-2}	5×10^{-2}
Assembly checkout - plasma chamber	1.9×10^{-3}	NA	1.9×10^{-3}
Startup initialization	1.9×10^{-3}	5×10^{-2}	b
Equilibrium burn	2.5×10^{-3}	0.5	b
Maintenance in plasma chamber	NA	0.5	0.5
Maintenance in magnet chamber	NA	NA	NA

^aNA = Not applicable.

^bLeaks are inconsequential.

A larger leak could develop during device operation. The air in-leakage and its subsequent effect on plasma contamination sets a limit on the maximum permissible leak size that can be tolerated during device operation. Contamination of the plasma with high atomic number (relative to hydrogen) impurities (air in this case) leads to an increase in the power lost by radiation from the plasma. For DCT-8, calculations indicate that an air leak greater than 2.5×10^{-3} torr-L/s will result in excessive radiated power (corresponds to an aperture size of $28 \mu\text{m}^2$).

Out-leakage of tritium from the plasma chamber during normal conditions (not accident conditions) to the surroundings was investigated as a safety issue. Leakage rates of less than 1×10^{-3} Ci/d (3×10^{-16} kg/s) of tritium were calculated for leaks corresponding to the sizes mentioned in the previous paragraphs. Because the maximum permissible release to the environment is on the order of 10 Ci/d, we concluded that tritium leakage from the plasma chamber to the reactor room during normal operation is not a safety concern and, therefore, does not add any further restriction to permissible leakage rates.

Leakage of air into the magnet chamber was also investigated. Leak rates as high as 0.05 torr-L/s can be tolerated in the magnet system without exceeding a pressure of 10^{-5} torr during assembly checkout and startup initialization. During device operation and plasma chamber maintenance, leak rates can be an order of magnitude higher.

These leaks correspond to leaks through apertures of 560 and 5600 μm^2 , respectively.

Leaks between the two vacuum chambers will not change the vacuum pumping performance of either. However, because the two chambers share a common boundary in some regions, operational events that involve opening one chamber to the surroundings while maintaining the vacuum conditions in the other (i.e., magnet chamber checkout, plasma chamber checkout, and maintenance in the plasma chamber) must be considered. Leaks between the chambers during these operations must be repaired if the maximum permissible leak rates (Table 3) are exceeded.

Contamination of the magnet chamber by leakage of tritium from the plasma chamber was investigated also. This concern can be handled by either of two approaches: (1) connecting the magnet vacuum system to the tritium processing equipment or (2) upon detecting a tritium leak from the plasma chamber to the magnet chamber, shutting down the device, repairing the leak, and removing the tritium from the magnet system. The factors that must be considered in choosing between these two approaches are the probability of leaks, the cost of additional tritium processing equipment, downtime required for tritium cleanup of the magnet system, the impact of device downtime, and the degree of difficulty in repairing the common vacuum vessel boundary.

In summary, detection and repair of leaks with total gas loads of less than 10^{-3} torr-L/s are required to ensure

acceptable performance of the DCT-8 fusion device. Interpretation of this requirement in terms of measurement sensitivity is discussed later. Depending on the torus location and degree of activation, it may be necessary to perform the leak detection and repair operations remotely.

LEAK DETECTION CONCEPT

The leak detection concept for the DCT-8 configuration was developed based on the types of joints and the overall concept of how the device is assembled and how it is expected to be maintained. Figure 5 is a trimetric view of the device with exploded views of some of the major components. There are three types of vacuum boundaries illustrated in the figure by different types of shading. The ring module can be seen in the center cutaway of the device. At the left of the cutaway is a window module in between two ring modules. At far left is a replaceable shield module that fits inside of the window module. When the shield module is in place, the vacuum boundary between the magnet chamber and the plasma chamber is formed by the combination of the ring modules and the window modules. The boundary between the plasma chamber and the outside (air) is the face of the replaceable shield module.

The dome surface and the cylindrical outer wall form the boundary between the magnet chamber and the outside surroundings.

DURING OPERATION

- PLASMA VACUUM TO AIR
- TF MAGNET SYSTEM
VACUUM TO AIR
- TF MAGNET SYSTEM
VACUUM TO PLASMA VACUUM

Types of Surface Conditions Conductive to Leaks and Design Options

Types of surface conditions are listed in Table 4 and correlated to the frequency of being "broken" and remade. Continuous surfaces are included because of the possibility of surface flaws. The design approach is as follows:

1. Make the basic vacuum vessels leak tight (i.e., those surface configurations consisting of continuous surfaces and structural weld joints) and
2. Select design features for sealed joints which, when leaks occur, isolate flaws and provide for remote detection.

Making the basic vacuum vessel leak tight requires a thorough quality assurance program for components and subassemblies. It requires, for instance, leak-checking at the manufacturer's location before shipping, acceptance testing at the erection site, and handling control procedures at both the manufacturer's site and the erection site. When field welds are made in the assembly sequence at the erection site, the welds must be leak-checked at appropriate points in the assembly schedule.

Seal Configurations

Figure 6 is a limited view of the major components for identifying details of the various seals. These are

Table 4. Types of surface conditions

Surface configuration	Frequency of installation/removal
Continuous surface	Zero for operating phases
Structural weld joints	Very low – only for unscheduled outages
Sealed joints	Medium to high
Mechanical seals	High
Welded seals	Medium

"Detail A," the outer wall in the vicinity of the window opening, including the window module seal, the replaceable shield module seal, and the replaceable impurity control module seal; "Detail B," the seal between the ring module and the window module; and "Detail C," the seal between the dome and the cylindrical outer wall.

Seals at "Detail A"

Shown in Fig. 7 is "Detail A" of Fig. 6. Portions of three major torus components are shown: the replaceable shield module, the window module, and the limiter vacuum door.

The gap (1) between the shield module and the window module contains the plasma chamber vacuum. It is sealed from the surroundings, which consist of atmospheric air, by primary seal elements (2) and (3) and by a secondary seal element (4). Seal element (2) is welded to the window module, while the shield module is absent. Seal element (3) is welded to the window module before insertion in the window. The sealing by welding of (2) and (3) is accomplished after the shield module is installed in the window module. The secondary seal (4), the holddown bracket, and the bracket support ring (5) are assembled as a unit. The holddown bracket contains a pressure tap connected to the leak-integrity instrumentation and is configured to sense the pressure between the primary and secondary seals. The pressure is 1.0 torr, and pressure changes may indicate a leak as well as which seal is leaking. A holddown stud clamps a mechanical seal ring to the shield module.

The gap (7) between the limiter door and the shield module also contains the plasma chamber vacuum. It is sealed by double mechanical seals (8). The seal flange of the limiter door is grooved to permit detection of leaks in either the primary or the secondary seal. The clamping studs are located outside of the vacuum seal.

The gap between the window framing and the window module contains the magnet chamber vacuum. This vacuum is sealed in this region with a primary seal consisting of a split bellows seal [parts (10) and (11)] and a secondary bellows seal (12). The top side of the primary seal is welded directly to the window frame. The top end of the secondary seal is, however, welded to a seal ring that contains a mechanical seal. The bottom end of the secondary bellows seal is welded to another seal ring with a mechanical seal. This seal ring contains a pressure tap that permits the cavity in between the primary and secondary seals to be pumped to 1.0 torr.

Hence, we have a pumped double-seal system on all openings (Fig. 7), so that a leak can be detected in instrumentation and can be located in the primary seal (falling pressure) or in the secondary seal (rising pressure).

Seal at "Detail B"

The seal between the window module and the ring module typical of the region along the inboard wall is shown in Fig. 8. The configuration features a structural weld joint and a diaphragm seal. The seal is on the inside of the plasma chamber. The

structural joint is not expected to be disassembled in the life-time of the device. The cavity between the structural weld and the seal is ported to either a tracer gas feed line or to a pressurization line. In the latter case, the pressure may be monitored sector by sector. Changes in pressure, indicative of a leak, may be recorded and monitored by the system instrumentation and control (I&C) system.

The structural weld is a full-penetration weld made using automated welding techniques. A titanium inert gas (TIG) weld is made first to fill the gap at the apex of the weld surface. This technique fills the gap without back-spatter. Then, the rest of the weld is accomplished with the metal inert gas (MIG) process.

The leak-detection procedure would be based on the assumptions that the key leak environment occurs when the plasma chamber is at atmosphere and the magnet chamber is at high vacuum. Critical leak location is in the seal diaphragm. The procedure is then as follows:

1. Confirmation of the existence of a leak and its magnitude, as well as the location of the sector seal,
2. Removal of the shield module to provide access to the window module/ring module joint if the leak is sufficiently large,
3. Attachment of the tracer gas line to the appropriate nipple,
4. Injection of tracer gas,
5. Sniffing of the seal joint and pinpointing leak detection, and
6. Rewelding the leak area.

Seals at "Detail C"

The seal between the outer vacuum vessel dome and the cylindrical section of the vacuum vessel is illustrated in Fig. 9. The primary leak path is between the dome and the cylindrical wall. The dome contains a lip for coarse centering and locating pins for precise centering. The seal consists of two pieces of a single convolution bellows seal and an O-ring band. The lip of the dome-closing frame supports the bellows seal against the atmospheric pressure loads. The use of the O-ring band permits removal of the dome without tedious weld cutting and rewelding. The angled bracket secures the dome to the vertical wall.

An enlarged view of the O-ring band is shown in the inset of Fig. 9. The region between the two O-rings may be pumped if needed at a later date. The pumping ports are located between the clamping screws.

The maximum tolerable leak rate for this region is quite high (see Table 3). This region is very accessible for leak-checking. Hence, a secondary seal is not considered necessary.

Plasma Chamber Leak Sensing

The concept described herein for leak detection includes a means of sampling the plasma vacuum discharge. This is accomplished by inserting residual gas analyzer sensors in each of the 16 vacuum ducts. An earlier study [2] indicates that comparing readings should enable location of serious leaks within 90° of the toroidal span. In the event that the leak is through

the primary seal for a configuration that provides for secondary seal, detection by the gas analyzer would indicate that the offending region must also have a secondary seal leak.

LEAK ALLOCATION AND MEASUREMENT SENSITIVITY

A leak-allocation procedure is proposed for use on the DCT-8 device. This procedure aids equipment design in that it provides a basis for specifying the leak-detection sensitivity requirements during operation and also for setting maintenance schedules based on tracking multiple small leak levels with automated equipment.

The maximum tolerable leak levels are shown in Table 4 for the combined vacuum boundary configuration. The procedure is to divide the device into toroidal sectors, the number of which is equal to the number of TF coils. In the case of the DCT-8, this number is 16. This procedure means that, in the case of equilibrium burn conditions, we should be able to detect a leak rate for any one sector of $1.9 \times 10^{-3} \times 1/16 = 1.19 \times 10^{-4}$ torr-L/s. This would correspond to a situation in which all the sectors are identical. This, however, is not the case. Some sectors have ion cyclotron resonance heating (ICRH) penetrations, some have lower hybrid resonant heating (LHRH) penetrations, some have fueling penetrations, and all have pumped limiter penetrations.

In the leak-allocation process, therefore, all leak allocations to each sector are adjusted proportionately to the total length of seal surface for that particular penetration. Then, because it is rare that a single leak is the culprit, we assume

that the total leak rate per sector is the result of at least 100 smaller leaks. If we assume (1) that the distribution of penetrations results in a factor of two in the detection sensitivity requirement for an entire sector and (2) that the distribution of leaks within a given sector increases the sensitivity requirements by two orders of magnitude, then the net leak-detection sensitivity is $1.19 \times 10^{-4} (2 \times 100) = 5.95 \times 10^{-7}$ torr-L/s.

The above "requirement" is well within the range of current leak-detection technology (10^{-10} torr-L/s).

CONCLUSIONS

1. The DCT-8 tokamak fusion device employs double vacuum seals on all major joints where disassembly and replacement activities are frequent. The double seal permits a continuing assessment of leak conditions during operations. This assessment may be included as part of an automated monitoring and data acquisition system.
2. A common wall between the magnet chamber and the plasma chamber results in a minimum impact of leaks in this region during operation.
3. Leak-detection sensitivity requirements appear to be well within current technology.

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FIGURES

- Fig. 1. Vacuum boundary location concepts.
- Fig. 2. Fusion Engineering Device - Resistive Magnet device, elevation view.
- Fig. 3. Fusion Engineering Device - reference configuration, elevation view.
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