ORNL/FEDC--84/8

DE85 010450

ORNL/FEDC-84/8

Dist. Category UC-20 c,d

Fusion Energy Division

IFCX PUMPED LIMITER AND VACUUM PUMPING
SYSTEM DESIGN AND ANALYSIS

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Date Published - April 1985

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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ABSTRACT

Impurity control system design and performance studies were performed in support of the Tokamak Fusion Core Experiment (TFCX) pre-conceptual design. Efforts concentrated on pumped limiter and vacuum pumping system design configuration, thermal/mechanical and erosion lifetime performance of the limiter protective surface, and helium ash removal performance. The reference limiter design forms a continuous toroidal belt at the bottom of the device and features a flat surface with a single leading edge. The vacuum pumping system features large vacuum ducts (diameter approximately 1 m) and high-speed, compound cryopumps. Analysis results indicate that the limiter/vacuum pumping system design provides adequate helium ash removal. Erosion, primarily by disruption-induced vaporization and/or melting, limits the protective surface lifetime to about one calendar year or only about 60 full-power hours of operation. In addition to evaluating impurity control system performance for nominal TFCX conditions, these studies attempt to focus on the key plasma physics and engineering design issues that should be addressed in future research and development programs.

1. INTRODUCTION

Since the Tokamak Fusion Core Experiment (TFCX) will operate with a relatively long burn duration (hundreds of seconds), impurity removal is required to exhaust the helium "ash" formed by the deuterium-tritium (D-T) fusion process. Various magnetic divertor and pumped limiter designs were considered in previous studies to perform this impurity control function.^{1,2} Because of the attractive economic and configurational aspects of the pumped limiter, TFCX impurity control system design efforts concentrated on this design. Although some aspects of the design and analysis vary for these two types of impurity control systems, a considerable amount of the effort is independent of the choice between magnetic divertors and pumped limiters. For example, both approaches require a protective surface that can withstand high fluxes of energetic particles, and both require a high-speed vacuum pumping system to exhaust the helium ash.

Impurity control systems were examined for each of the four TFCX design options, which are characterized as the nominal superconducting (S/C) toroidal field (TF) coil option, the high-performance S/C TF coil option, the nominal copper TF coil option, and the high-performance copper TF coil option. Major parameters of the four design options are listed in Table 1.

This document describes the design configuration, requirements, operating conditions, and performance evaluation for the TFCX pumped limiter and vacuum pumping system. Key design and performance issues for the impurity control system are also discussed.

2. PUMPED LIMITER

2.1 CONFIGURATION

Design options considered for the pumped limiter include its location in the plasma chamber, its surface topology, and the location of the pumping slot. A sketch of the reference pumped limiter configuration defined for TFCX is shown in Fig. 1. The limiter forms a continuous

Table 1. TFCX parameters

Parameter	Design option			
	Nominal S/C	High-performance S/C	Nominal copper	High-performance copper
Major radius, m	4.08	3.61	3.55	2.35
Minor radius, m	1.52	1.30	1.37	0.83
Plasma current, MA	11.2	10.4	11.0	8.9
Field on axis, T	3.73	4.23	3.88	5.83
Fusion power, MW	264	269	238	244
Wall load, MW·m ²	0.65	0.87	0.78	2.00
Pulse length, s	647	470	509	184
TF resistive power, MW			420	490
ICRH power, MW	6 (31)	10 (36)	6 (29)	14 (37)
LH power, MW	32	26	28	15

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Guideline: Leading Edge Located to Allow 10% of the
Particles Leaving the Plasma to Enter the Limiter Slot

Fig. 1. Pump limiter used for helium ash removal in TFCX.

toroidal belt at the bottom of the device and features a flat limiter surface with a single leading edge.

The continuous toroidal belt configuration provides a large surface area and an axisymmetric geometry, both of which lead to manageable heat and particle fluxes. The location at the bottom minimizes the space required in the outboard wall for limiter access and permits the limiter blade to be located in the region where the magnetic flux surfaces are most widely spread, thus resulting in a spreading of the particle and heat fluxes.

A flat limiter surface with a single leading edge was selected because it allows the fraction of particles pumped to be adjusted by moving the plasma inboard and outboard (i.e., changing the plasma major radius). Although the limiter surface could, in principle, be contoured to obtain a lower peak heat flux, the flat limiter has the advantage that it is less sensitive to the highly uncertain plasma edge conditions.³ The flat limiter is also easier to fabricate than a contoured limiter.

2.2 PERFORMANCE REQUIREMENTS AND OPERATING CONDITIONS

To ensure adequate helium ash removal, the limiter is designed to allow 10% of the total estimated particle flux leaving the plasma to pass behind the limiter's leading edge and into the vacuum pumping slot. The normal operating heat loads and particle loads to the limiter, taken from the TFCX Preconceptual Design Specification,⁴ are shown in Table 2. It is assumed that 64% of the total alpha power P_α reaches the limiter via charged particle impingement. The total ion current $\dot{N}_i$ to the limiter is estimated to be

$$\dot{N}_i = n_e \frac{V}{\tau_p} \quad (1)$$

where n_e is the electron density, V is the plasma volume, and τ_p is the particle confinement time, which is 0.1 s for TFCX. The distribution of the heat and particle fluxes along the limiter surface was determined using the Schmidt model,⁵ which predicts an exponential falloff of the

Table 2. Normal operating heat and particle loads to limiter

Radiation load	
Power	$0.20P_a^a$
Distribution	Uniformly to entire first wall
Conduction/convection to limiter	
Power $\dot{Q}_T$	$0.64P_a$
Distribution	
Model	Schmidt ^b
Heat flux e-fold distance $\lambda_Q(Z)$, mm	10 (at midplane)
Charge-exchange neutrals to limiter and first wall	
Power	$0.16P_a$
Distribution	
Region	Deposited over limiter and first wall region, $\pm 45^\circ$ toroidally and poloidally from point of limiter/plasma tangency
Peaking factor	2
Ions incident on limiter	
Current $\dot{N}_i$	$n_e V / \tau_p$
Distribution	
Model	Schmidt ^b
Particle flux e-fold distance $\lambda_p(Z)$, mm	30 (at midplane)
Alpha particle density in plasma	$0.05n_e$

^aIn designing the first wall, it is assumed that one-half of the total power ($0.5P_a$) is radiated.

^bJ. Schmidt, "Tokamak Impurity-Control Techniques," *Comments Plasma Phys. Controlled Fusion* 5, 225 (1980).

heat flux $\dot{q}$, the particle flux Γ , and the particle energy U in the scrapeoff layer. The distribution of the heat flux along the toroidally continuous limiter surface is determined by

$$\dot{q}(Z) = \frac{\dot{Q}_T}{4\pi R_L(Z)\lambda_Q(Z)} \exp[-x(Z)/\lambda_Q(Z)] \sin \theta(Z) ; \quad (2)$$

that of the ion flux, by

$$\Gamma_i(Z) = \frac{\dot{N}_i}{4\pi R_L(Z)\lambda_p(Z)} \exp[-x(Z)/\lambda_p(Z)] \sin \theta(Z) ; \quad (3)$$

that of the average energy of ions striking the limiter, by

$$U_i(Z) = \frac{\dot{q}(Z)}{2\Gamma_i(Z)(1 + \gamma)} (3/2 + \gamma) . \quad (4)$$

The following quantities are used in Eqs. (2)-(4):

- Z = distance along limiter surface
- $\dot{Q}_T$ = conduction/convection power to limiter
- $R_L(Z)$ = major radius distance to point Z on the limiter surface
- $\lambda_Q(Z)$ = heat flux e-fold distance
- $x(Z)$ = distance from the plasma edge
- $\theta(Z)$ = angle of incidence between the limiter and poloidal flux line
- $\lambda_p(Z)$ = particle flux e-fold distance
- γ = sheath heat transmission factor = 3.1 .

Using these equations and the local limiter/field line geometry, flux distributions were calculated for the four TFCX options. These distributions are plotted in Fig. 2 for the nominal S/C 1F coil option. Peak values are listed in Table 3 for all four options. The peak heat flux, including the contribution from both charged particles and charge-exchange neutrals, varies from about 2.6 MW/m² for the nominal S/C and nominal copper options to 5.5 MW/m² for the high-performance copper

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Fig. 2. Normal operating conditions for limiter.

Table 3. Limiter conditions during normal operation

Condition	Design option			
	Nominal copper	High-performance copper	Nominal S/C	High-performance S/C
Flat surface				
Peak heat flux, MW/m ²	2.6	5.5	2.6	3.3
Peak ion flux, m ⁻² ·s ⁻¹	1.0 x 10 ²²	0.9 x 10 ²²	1.0 x 10 ²²	1.0 x 10 ²²
Average energy of ions striking limiter at peak ion flux location, keV	0.6	1.2	0.5	0.6
Peak neutral flux, m ⁻² ·s ⁻¹	2.2 x 10 ²¹	2.6 x 10 ²¹	2.2 x 10 ²¹	2.2 x 10 ²¹
Energy of neutrals, keV	0.32	0.65	0.28	0.36
Leading edge				
Heat flux	0.25	0.45	0.25	0.30
Ion flux	1.0 x 10 ²²	0.9 x 10 ²²	1.1 x 10 ²²	1.1 x 10 ²²
Average energy of ions striking limiter, keV	0.09	0.19	0.08	0.10
Neutral flux, m ⁻² ·s ⁻¹	2.2 x 10 ²¹	2.6 x 10 ²¹	2.2 x 10 ²¹	2.2 x 10 ²¹
Energy of neutrals, keV	0.32	0.65	0.28	0.36

option. The leading edge is located to allow 10% of the particles leaving the plasma to pass underneath the limiter surface. The normal incidence of the field lines ($\theta = 90^\circ$) at the leading edge leads to a relative maximum in the fluxes at this point. The heat flux at the leading edge peaks at a value significantly lower than that on the flat surface and therefore should present no additional design problem. The particle flux at the leading edge is essentially the same as the peak value on the flat surface.

Parameters used to define the plasma disruption heating conditions⁴ for the limiter are listed in Table 4. Most (80%) of the plasma internal energy E_I is released during the thermal quench phase of the disruption. The duration of this phase is scaled as 0.1 ms per megampere of plasma current. The limiter receives 75% of this energy via conduction and convection with the deposition profile expected during normal operation. The remaining 25% of the energy released during the thermal quench is radiated uniformly to all first wall surfaces.

During the subsequent current quench phase of the disruption, the remaining plasma internal energy E_I (20%) and 50% of the plasma magnetic energy E_M (assumed to be converted to plasma internal energy) is deposited. The duration of this phase is specified to be 1 ms per megampere of plasma current, an order of magnitude longer than the thermal quench. The energy is split between uniform radiation (75%) to the entire first wall and conduction/convection (25%). Uncertainty exists as to how and where the conduction/convection energy released during the current quench is split between the limiter and inboard first wall. A "worst-case" approach is used in designing both components to withstand the full load. A peak-to-average ratio of two in the energy flux distribution is assumed.

The resulting plasma disruption energy densities and durations for the four TFCX design options are listed in Table 5. The disruption heating conditions are essentially the same for all four options. Thus, for all four options, limiter design performance calculations were performed assuming a thermal quench duration of 1 ms, with an

Table 4. Plasma disruption heating parameters

	Thermal quench	Current quench
Duration, ms per megampere of current I_p	0.1	1
Plasma energy deposition	$0.8E_I$	$0.2E_I + 0.5E_M$
Via conduction/convection to limiter	75% ^a	25% ^b
Via radiation uniformly to entire first wall	25%	75%

^a Assuming normal operating deposition profile.

^b Peaking factor of 2.

Table 5. Plasma disruption heating conditions

	Design option				Parameters used for analysis
	Nominal copper	High-performance copper	Nominal S/C	High-performance S/C	
Thermal quench					
Duration, ms	1.1	0.9	1.1	1.0	1.0
Energy density, MJ/m ²	4.9	5.0	5.0	5.2	5.0
Current quench					
Duration, ms	1.1	8.9	11	10	10
Energy density, MJ/m ²	2.1	2.2	1.9	2.0	2.0

energy density of 5 MJ/m^2 , and a current quench duration of 10 ms, with an energy density of 2 MJ/m^2 .

As indicated in Table 6, major disruptions are expected to occur at a frequency of 1 per 10 burn cycles during the first year of operation and 3 per 100 burn cycles during the remaining 9 years of operation. Since each year of operation contains 1.1×10^4 burn cycles, a total of 4070 disruptions is expected during the lifetime of TFCX.

2.3 PROTECTIVE SURFACE DESIGN AND ANALYSIS

As shown in Fig. 3, the limiter blade is constructed of protective surface tiles attached to an actively cooled copper substrate. The tile and substrate assembly forms a replaceable sleeve that is mechanically attached to a reusable stainless steel core structure. The tiles are directly exposed to the plasma environment and undergo erosion by sputtering and disruption-induced melting and vaporization. The copper substrate provides structural integrity and a heat removal path for the tile. Since tile erosion is expected to limit the lifetime of the protective surface, tile thickness is maximized, consistent with handling the projected "steady-state" heat loads.

Beryllium and graphite are the leading protective surface tile material candidates. Both materials have a low atomic number and are therefore more compatible with the plasma than higher-Z candidates such as tungsten, molybdenum, or tantalum. In addition to compatibility with the plasma, key issues in selecting a reference tile material are (1) resistance to thermal shock fracture, (2) sputtering, (3) disruption erosion response, and (4) tritium permeation and retention characteristics.

2.3.1 Thermal/Mechanical Analysis

Thermal shock resistance was examined analytically for TFCX-type disruption conditions.⁶ A nondimensional thermal shock parameter P' that depends on material properties and specific heating conditions was found. This parameter is simply the ratio of the compressive strength

Table 6. TFCX operating schedule and
expected disruption frequency

Number of burns per year	
Hydrogen	10^4
D-T	10^3
Average burn duration, s	20
TFCX lifetime, years	10
Total burn time, s	
Hydrogen	2×10^6
D-T	2×10^5
Major disruption frequency, burn ⁻¹	
First year	0.10
After first year	0.03

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Fig. 3. Limiter design featuring expendable protective surface and reusable core.

of the material relative to thermal stress at the heated surface, given by

$$P' = \frac{\sigma_c (1 - \mu)}{E \alpha \dot{q}} \frac{\rho c k}{\tau_f},$$

where

- σ_c = compressive strength
- μ = Poisson's ratio
- E = Young's modulus
- α = coefficient of thermal expansion
- $\dot{q}$ = heat flux
- ρ = density
- c = specific heat
- k = thermal conductivity
- τ_f = heating duration .

If P' is less than unity, thermal shock damage is expected. A comparison with test results demonstrated that this parameter predicts reasonably well the conditions at which thermal shock damage occurs.⁶

A comparison of several candidate tile materials is shown in Fig. 4. The line formed by $P' = 1$ for these materials is indicated. Thermal shock damage is expected if conditions fall above the line. As shown in Fig. 4, the nominal disruption parameters exceed the threshold value ($P' = 1$) for all candidates. Therefore, thermal shock damage of the limiter is expected. The consequences of this damage are unknown; however, the damage may be highly localized (e.g., spalling). Tests are required to examine the characteristics of the thermal shock damage for candidate materials with disruption-type heating conditions.

Thermal/mechanical studies were performed to determine the maximum allowable tile thickness. Temperature and thermal stress distributions were calculated as a function of tile thickness. The duplex limiter protective surface configuration assumed for this study is shown in Fig. 5. The substrate was assumed to be a double-walled copper panel

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Fig. 4. Possibility of shock damage to TFCX limiter and inboard first wall.

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Fig. 5. Configuration used for thermal/mechanical analysis.

with water coolant. The wall thickness on each side of the coolant passage is 2 mm, and the coolant passage depth is 3 mm.

Analysis conditions are summarized in Table 7. A bulk coolant temperature of 60°C, which corresponds to the temperature at the outlet of an intermediate heat exchanger, was assumed. The convection heat transfer coefficient was set at 75 kW/m²·K. This relatively large heat transfer coefficient corresponds to a flow velocity of 16 m/s and a pressure drop of 0.5 MPa (75 psi) for a 0.5-m flow length through the 3-mm-deep limiter coolant passages. The tiles are assumed to make "perfect" thermal contact with the copper substrate. This can be achieved if the tiles are bonded to the substrate using a process such as brazing. Radiation heat transfer from the graphite tile to the cooler first wall surfaces (300°C) was included in the analysis.

Material properties are listed in Table 8. Fatigue failure data and design curves for the copper substrate are shown in Fig. 6. Because of a lack of data, room-temperature data were used to define stress limits. The design curve applies safety factors of 2 on the stress or 10 on the cycles to failure, whichever is more limiting. For two years of TFCX operation (2.2×10^4 cycles), the elastically calculated fatigue stress range limit is 210 MPa.

The effects of the constraint of the tile on the substrate stresses are included in this analysis. The width of the tile is assumed to be large compared with its thickness. The entire blade is free to expand but is constrained from bending. As demonstrated in ref. 2, for small enough tiles (less than 10 mm x 10 mm), the tiles provide essentially no constraint. If tiles of this size were feasible, stresses in the substrate would be lower than those computed in this study. For beryllium tiles, the allowable thickness could be significantly increased. Since graphite tile thicknesses are limited by peak surface temperature, reducing tile size would have no impact on the allowable graphite tile thicknesses determined in this study.

The transient temperature response for a 10-mm-thick graphite tile was determined using a one-dimensional, finite-difference model. The temperature rise at several tile and substrate locations is plotted in

Table 7. Analysis conditions

Bulk coolant temperature, °C	60
Convection heat transfer coefficient between coolant and wall, kW/m ² ·K	75
Thermal contact resistance between tile and substrate for bonded attachment (e.g., brazed)	0
Radiation heat transfer from tile surface to surroundings	
Temperature of surroundings, °C	300
Emittance of graphite	0.8
View factor	1.0

Table 8. Material properties for protective surface
tile candidates and copper substrate

	Graphite GraphNOL-N3M	Beryllium	Copper (OFHC)
Density, Mg/m^3	1.89	1.85	8.94
Thermal conductivity, $^a \text{ W/m}\cdot\text{K}$	$185.5 - 0.138 T$ $+ (3.13 \times 10^{-5} T)$	$233 - 0.15 T$	370
Coefficient of thermal expansion, $10^{-6}/^\circ\text{C}$	5.0	16	17
Young's modulus, GPa	8.3	250	103
Poisson's ratio	0.15	0.03	0.34

a Temperature T in kelvins.

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Fig. 6. Fatigue design curve for pure copper at room temperature.

Fig. 7. Steady-state temperatures are reached in well under 10 s. Since TFCX burns will last longer than 10 s, a steady-state thermal analysis can be used to determine maximum temperatures during the burn cycle.

Peak tile temperatures and substrate thermal stresses are presented in Figs. 8 and 9. Limits based on maximum temperature, material strength, and fatigue are indicated in these plots. Resulting tile thickness limits are presented in Table 9 for all four options.

As shown in Fig. 8, two upper temperature limits were considered for graphite. If it is necessary to maintain the graphite temperature below the threshold for chemical sputtering erosion (approximately 400°C), the maximum tile thickness ranges from 5 mm to 14 mm, depending on the TFCX design option. Based on a review of chemical erosion data,⁷ it is likely that chemical erosion at the particle fluxes experienced by the limiter will be negligible compared to physical sputtering erosion. Since radiation-enhanced sublimation at surface temperatures above about 1000°C remains a concern, we established this as an upper temperature limit. At the 1000°C limit, the maximum allowable tile thickness ranges from 14 mm to 36 mm, depending on the TFCX design option. Thermal stress limits in the graphite tiles and copper substrate were found to be less restrictive than either graphite temperature limit.

Results presented in Fig. 9 demonstrate that the copper substrate thermal stresses exceed the fatigue limit corresponding to two years of TFCX operation (2.2×10^4 cycles) with a beryllium tile thickness ranging from 2 mm to 7 mm, depending on the TFCX design option. Thickness limits based on sublimation of beryllium are less restrictive.

2.3.2 Erosion/Lifetime Analysis

Erosion of the limiter protective surface by both sputtering and disruption-induced vaporization and melting was evaluated. Erosion rates were estimated using the nominal set of operating and disruption parameters discussed in Sect. 2.2.

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Fig. 7. Steady-state temperatures reached in less than 10 s.

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Fig. 8. Graphite tile thickness limits.

Fig. 9. Beryllium tile thickness limits.

Table 9. Thickness limits for protective surface tiles

Device option	Maximum tile thickness (mm)		
	Graphite		Beryllium ^a
	400°C	1000°C	
Nominal copper	14	36	7
High-performance copper	5	14	2
Nominal S/C	14	36	7
High-performance S/C	10	26	5

^aBeryllium limit based on 2-year fatigue lifetime for copper substrate.

Sputtering erosion of the tiles was examined for all four TFCX options. Peak ion and neutral particle fluxes and particle energies at the locations where these peak fluxes occur are listed in Table 3. Curves of the physical sputtering yield Y_p for graphite and beryllium are shown in Figs. 10 and 11. Sputtering yield enhancement by a factor of 1.4 due to incidence at an angle of $\theta = 45^\circ$ was assumed. Physical sputtering erosion rates are shown in Table 10 for all four TFCX design options. Redeposition of sputtered material and self-sputtering are not included in this analysis. In determining the net erosion rate for graphite, sputtering erosion was increased by a factor of 2 above the physical sputtering erosion to account for some chemical sputtering. It is likely that this is an overestimate of the actual chemical sputtering at the TFCX ion and neutral fluxes. Although the physical sputtering erosion rates shown in Table 10 are significant when specified in terms of full-power hours of operation, the erosion rate in calendar time is quite low due to the low availability of TFCX.

Disruption erosion was calculated using the model described in ref. 1. The model includes heat transfer by conduction into the bulk tile material and reradiation from the heated surface. The phase change energy for both melting and vaporization and the effect of the moving melt front and vaporization front are accounted for in the model. Interaction of the vaporized material with the plasma is not included. This effect would tend to decrease the heat flux to the most critical regions and thus would lead to erosion rates lower than those predicted.

Disruption erosion rates calculated using the analysis parameters of Table 5 are presented in Table 11. Graphite is expected to lose 36 μm per disruption by sublimation. Beryllium loses 44 μm per disruption by vaporization; in addition, a 160- μm -thick melt layer is formed. The stability of this melt layer is a key issue in the comparison and selection of a reference tile material. The total disruption-induced erosion, over the entire ten-year TFCX lifetime, is 150 mm for graphite and ranges from 180 mm to 650 mm for beryllium, depending on the portion of melt layer that is lost.

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Fig. 10. Energy-dependent physical sputtering yields for beryllium.

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Fig. 11. Energy-dependent physical sputtering yields for graphite.

Table 10. Physical sputtering erosion of limiter surface

Parameter	Nominal copper		High-performance copper		Nominal S/C		High-performance S/C	
	Be	C	Be	C	Be	C	Be	C
Sputtering erosion rate, μm per full-power hour								
D-T	19	22	18	18	19	20	19	22
H	8	6	8	4	8	6	8	6
Amount sputtered per calendar year, mm ^a	0.55	0.46	0.54	0.32	0.55	0.44	0.55	0.46
Total physical sputtering during TFCX lifetime, mm	5.5	4.6	5.4	3.2	5.5	4.4	5.5	4.6

^a2 x 10⁴ s of D-T operation and 2 x 10⁵ s of hydrogen operation per calendar year.

Table 11. Disruption erosion rates for nominal disruption conditions

Parameter	Beryllium		Graphite
	Vaporized	Melted	
Erosion per disruption event, μm	44	160	36
Disruption erosion per equivalent full-power hours, mm^a	0.24	0.85	0.19
Erosion over entire TFCX lifetime, mm	180	650	150

^aAssumes disruption frequency of 0.03 burn^{-1} , average burn duration of 20 s.

The disruption erosion rates listed in Table 11 are much larger than the sputtering erosion rates listed in Table 10. This is in direct contrast to the results obtained in the Fusion Engineering Device (FED) and the International Tokamak Reactor (INTOR) studies, as shown in Table 12. This can be explained by examining the disruption frequency, which is the number of disruptions divided by the total full-power operating period. TFCX has significantly more disruptions and a much shorter operating period, thus leading to more disruption erosion and much less physical sputtering erosion.

The erosion lifetimes for the protective surfaces, calculated by combining the tile thickness sizing and erosion rates, are shown in Fig. 12. Depending upon the TFCX design option, lifetimes with graphite tiles allowed to operate at 1000°C vary from 70 full-power hours (1.2 calendar years) to 170 full-power hours (2.8 calendar years). If the graphite tiles are limited to temperatures below 400°C, lifetimes are reduced by approximately a factor of 2.5. Lifetimes for a limiter with beryllium tiles range from 10 full-power hours (0.15 calendar years) to 30 full-power hours (0.5 calendar years) if the melt layer remains intact. Lifetimes are reduced by a factor of 3 if the entire melt layer is lost.

3. VACUUM PUMPING SYSTEM

3.1 REQUIREMENTS

The TFCX vacuum pumping system is designed to pump down the vacuum chamber initially and between burns and to exhaust the helium ash during the burn period. Guidelines established for vacuum pumping system performance are listed in Table 13. During the burn cycle, the neutral gas pressure in the limiter slot is estimated⁴ to be 2.0×10^{-2} Pa (1.5×10^{-4} torr). The vacuum pumping system should be adequately sized to remove helium as it is produced by fusion with only a 5% helium concentration. Since the fusion power differs for each of the four TFCX options, the pump speed required for helium ash removal varies. The required speeds for each option are listed in Table 14.

Table 12. Comparison of disruption frequency in TFCX, FED, and INTOR

Device	Number of disruptions	Total device operating time (s)	Frequency (disruption/s)	Frequency normalized to FED
TFCX	4070	2.2×10^6	1.9×10^{-3}	30.0
FED	1670	2.6×10^7	6.4×10^{-5}	1.0
INTOR	1100	1.3×10^8	8.5×10^{-6}	0.13

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Fig. 12. Limiter erosion rate and lifetime.

Table 13. Vacuum pumping system design guidelines

Base pressure in plasma chamber, Pa (torr)	1.3×10^{-6} (10^{-8})
Postshot pressure, Pa (torr)	0.2 (1.5×10^{-3})
Preshot pressure, Pa (torr)	1.3×10^{-3} (10^{-5})
Pumpdown time between burns, s	30
Pressure in limiter slot during burn, Pa (torr)	2.0×10^{-2} (1.5×10^{-4})
Helium in limiter slot, %	5

Table 14. Helium ash removal guidelines

Device	Helium gas load [Pa·m ³ /s (torr·L/s)]	Desired pump speed ^a (m ³ /s)
Nominal copper	0.30 (2.3)	310
High-performance copper	0.32 (2.4)	320
Nominal S/C	0.34 (2.6)	350
High-performance S/C	0.36 (2.7)	360

^aAssuming 5% helium in plasma.

The base pressure required before device operation is specified to be 1.3×10^{-6} Pa (10^{-8} torr). The postshot pressure was estimated to be 2×10^{-1} Pa (1.5×10^{-3} torr). The chamber must be pumped down from this pressure to a prefill or preshot pressure of 1.3×10^{-3} Pa (10^{-5} torr) in 30 s.

3.2 REFERENCE DESIGN

The reference design for the vacuum pumping system is shown in Fig. 13. During the burn cycle, plasma particles enter the toroidally continuous entry slot underneath the limiter blade. The entry slot is connected to 16 passages called limiter slots, one in each torus sector. The limiter slots are connected to ducts that lead to 0.8-m-diam valves and compound cryopumps. The duct area varies as it passes through the region between the TF coils. The 0.8-m-diam valves are required to be all metal for tritium compatibility.

Each of the 16 compound cryopumps has cryocondensation panels for pumping hydrogen and cryosorption panels for pumping helium. The pump speed for helium is $50 \text{ m}^3/\text{s}$, and the hydrogen pumping speed must be approximately the same.

Scroll pumps were selected for regenerating the cryopumps and for rough pumping of the plasma chamber. These are sealed pumps that have no bearing lubricant in contact with the tritium stream. Two single-stage scroll pumps service all 16 compound cryopumps. A single scroll pump would be adequate; however, two scroll pumps are included for redundancy. Also, using two pumps serves to reduce the regeneration and pumpdown times.

The cryopumps are regenerated by closing the valve leading to the limiter slot and allowing the cryopanel to warm up. The scroll pumps are then activated to pump the hydrogen and helium evolved at a pressure of about 2.66×10^3 Pa (20 torr). The gas is compressed by the scroll pumps to about 1×10^5 Pa (1 atm) and returned to the D-T process stream.

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Fig. 13. Vacuum system configuration.

3.3 DESIGN PERFORMANCE

The major design parameters for the vacuum pumping system are listed in Table 15. Vacuum pump characteristics are shown in Table 16. The net helium pumping speed from the limiter slot to the vacuum pumps ranges from 170 m³/s for the high-performance copper option to 280 m³/s for the nominal S/C option. As shown in Table 17, these pump speeds are slightly lower than those required to remove the helium ash at a 5% helium concentration. The helium concentration of the plasma will therefore increase slightly, and the fusion power will decrease slightly. The self-consistent helium content and fusion power are shown in Table 17 for all four options. These relatively slight changes to the nominal TFCX parameters are judged to be acceptable.

Using the vacuum pumping system optimized for helium ash removal, the performance during chamber pumpdown was evaluated. Results are presented in Table 18. It is assumed that outgassing limits the ultimate base pressure achievable with this vacuum pumping system. For analysis purposes, the outgassing source was assumed to be stainless steel with a surface area equal to ten times the first wall area. Using an outgassing rate of 1.0×10^{-8} Pa·m/s, which is a typical value for a baked stainless steel surface, the base pressure was estimated to range from about 1.3×10^{-7} Pa for the high-performance copper device to 2.3×10^{-7} Pa for the nominal S/C device. These base pressures satisfy the guideline of 1.3×10^{-6} Pa (10^{-8} torr).

The time t required to pump down the plasma chamber between burns was estimated from

$$t = \frac{V}{S} \ln \frac{P_1}{P_2} ,$$

where

S = vacuum pumping system speed from the plasma chamber to the pumps

V = plasma chamber volume

P_1 = postshot pressure (0.2 Pa)

P_2 = preshot pressure (1.3×10^{-3} Pa) .

Table 15. Vacuum pumping system design parameters

Component	Conductance/speed for helium removal ^a (m ³ /s)			
	Nominal copper	High-performance copper	Nominal S/C	High-performance S/C
Entry slot C ₀	300	200	340	300
Duct C ₁	380	245	590	510
Valve C ₂	1600	1600	1600	1600
Cryopump speed S _p	800	800	800	800
Net pumping speed for helium ash removal $(1/C_1 + 1/C_2 + 1/S_p)^{-1}$	220	170	280	260
Net pumping speed for chamber pumpdown $(1/C_0 + 1/C_1 + 1/C_2 + 1/S_p)^{-1}$	130	90	150	140

^aIncludes 16 pump/duct assemblies (one per torus sector).

Table 16. Vacuum pump characteristics

High-vacuum pumps

Pump type	Compound cryopump
Pump speed for hydrogen per pump (cryosorption), m^3/s	50
Number of pump/duct assemblies	16 (one per torus sector)

Backing/roughing pumps

Pump type	Scroll
Number of stages	1
Number of pumps	2
Speed per pump, m^3/s	0.17

Table 17. Helium ash removal performance

Device option	Helium pumping speed (m^3/s)		Helium content in plasma (%)		Fusion power (MW)	
	Desired ^a	Actual	Desired	Actual	Desired	Actual
Nominal copper	310	220	5	6.7	238	226
High-performance	320	170	5	8.5	244	220
Nominal S/C	350	280	5	6.0	264	256
High-performance S/C	360	260	5	6.6	269	256

^aPump speed required to achieve 5% helium content in the plasma at the desired fusion power.

Resulting pumpdown times are presented in Table 18 for all four TFCX options. The vacuum pumping system for all options can pump down the chamber in less than the 30 s allotted between consecutive burns.

3.4 DESIGN OPTIONS

The principal selection made in the design of the pumping system was the selection of the plasma chamber high-vacuum pumps. These choices are constrained by the presence of tritium in the vacuum system and the requirement for a relatively high pump speed. Turbomolecular pumps and compound cryopumps were the main alternatives considered for the high-vacuum stage. A mercury diffusion pump was not considered seriously because of concern with mercury contamination of the plasma chamber.

Compound cryopumps, which remove most gases by cryocondensation and contain a sorption stage to remove helium, can easily be made with a high enough pump speed for the TFCX. Three pumps of this type are being tested in the Tritium Systems Test Assembly (TSTA). A significant drawback of the cryopumps is the tritium inventory that accumulates within them between regenerations. This characteristic raises safety concerns. To limit the tritium inventory present, frequent cycling of vacuum valves, which increases valve wear, is required.

Turbomolecular pumps are currently limited to lower pump speeds than cryopumps. The largest commercially available pump has a speed of $5 \text{ m}^3/\text{s}$ for air and $6.2 \text{ m}^3/\text{s}$ for hydrogen and helium. Manufacturers of turbomolecular pumps see no difficulty in producing pumps with higher speeds. For example, it is estimated that a turbomolecular pump with a pump speed of $20 \text{ m}^3/\text{s}$ could be developed and would cost about a factor of only 3.5 more (including development costs) than the $5\text{-m}^3/\text{s}$ pumps. However, it is currently perceived that a pumping speed of several hundred cubic meters per second is required for helium ash removal. This would lead to a prohibitively large number of turbomolecular pumps; therefore, compound cryopumps were selected over turbomolecular pumps for the reference design.

Table 18. Vacuum chamber pumpdown performance

Design option	Ultimate base pressure (Pa)	Pumpdown time required between burns (s)
Nominal copper	2.1×10^{-7}	9
High-performance copper	1.3×10^{-7}	4
Nominal S/C	2.3×10^{-7}	11
High-performance S/C	1.9×10^{-7}	8
Guideline	$<1.3 \times 10^{-6}$	<30

A design concept to reduce the required pumping speed is shown in Fig. 14. Getter panels of Zr-Al are placed in the limiter slot region. These getter pumps would remove hydrogen isotopes at a relatively high pump speed. Therefore, the neutral gas in the limiter slot would be predominantly helium, whereas the helium concentration in the plasma could be much lower, say 5%. This leads to a reduced helium pumping speed requirement. For example, if we assume that the neutral gas pressure remains at 2×10^{-2} Pa (1.5×10^{-4} torr) and is 100% helium, the net helium pumping speed required to remove the helium ash is reduced from about 300 m³/s without the getter pumps to about 15 m³/s with the getter pumps.

This relatively low pump speed requirement could be obtained with conventional turbomolecular pumps and smaller ducts. If an accident exposed the getter panels to the surroundings, the tritium, which is chemically bound in the getter panels, would not be released if the panels were not actively heated. Therefore, in addition to access advantages, this system would have a much lower vulnerable tritium inventory than the reference design.

The period between regenerations of the getter pumps could be on the order of one calendar year of TFCX operation. Since this is a relatively infrequent operation, it might be possible to remove the getter pumps from the device and transport them to the hot cell for the regeneration process.

A more detailed evaluation of the getter pumping concept is necessary before it is adopted in the reference design concept. Issues requiring further study are regeneration scenarios (in either the device or the hot cell), compatibility of the getter panels with a high-neutron-flux environment, and getter panel design details.

4. KEY ISSUES

Several key issues remain to be resolved before selecting a specific design and constructing the impurity control system. Experimental verification of pumped limiter performance before TFCX is built should

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- Getter Pumps Remove Hydrogen
- Neutral Gas In Limiter Slot Nearly 100 % He
- Lower He Pump Speed Required (15,000 l/s)
- Smaller Ducts With Turbomolecular Pumps
 - Lower Vulnerable Tritium Inventory
 - Improved Access

Fig. 14. Alternative approach for lower helium speed requirement.

be a high priority. Without this verification, the flexibility to include a poloidal divertor must be factored into the design and built into the device, thus negating much of the cost advantage of using pumped limiters.

Large uncertainties in plasma edge and helium ash removal conditions lead to conservative design approaches and highly uncertain engineering performance characteristics. The effect of plasma edge uncertainties was reflected in the FED limiter studies,¹ which demonstrated that the uncertainty range in the limiter lifetime was from two months to four years. If the limiter slot pressure were assumed to be 10^{-2} torr (as it was in FED studies) instead of the 1.5×10^{-4} torr specified for TFCX studies, then the vacuum pumping speed requirement would be reduced by about two orders of magnitude, thus leading to dramatic changes in the vacuum pumping system design. Small ducts with small turbomolecular pumps would replace the large ducts and compound cryopumps in the current reference design. Efforts to understand and control the environmental conditions experienced by the limiter and vacuum pumping system are essential to focus limited research and development (R&D) funds and to optimize the design configuration.

Materials and fabrication R&D programs are required to address tile material selection and tile-to-substrate attachment issues. A data base for sputtering erosion of graphite at relevant particle fluxes, particle energies, and surface temperatures is required to establish chemical erosion characteristics. The stability of the beryllium melt layer formed during disruption-type heating must be resolved. The data base for tritium permeation and retention for these materials is poor. Techniques for reliably achieving the good tile-to-substrate thermal contact required to keep the tiles below upper temperature limits must be developed.

Development of large-diameter (approximately 0.8-m-diam), all-metal, high-conductance (in the open position) vacuum valves is required. Since valves of this type now exist in sizes up to only about 0.3 m in diameter, this represents the key feasibility issue in the design of the vacuum pumping system.

5. SUMMARY

Design and analyses of pumped limiters and vacuum pumping systems for several configuration options were performed as part of the TFCX effort. Options for the pumped limiter design include its location in the device, its configuration, the location of the pumping slot, and protective surface material and fabrication. A flat-surfaced, toroidal belt limiter located at the bottom of the device with a single leading edge was selected because of its relative ease of fabrication, flexibility in adjusting leading edge conditions, and decreased sensitivity to uncertainties in plasma edge conditions.

Since several critical design issues remain to be investigated in R&D studies, selection of a protective surface material and a technique for attaching the tile to the substrate is judged to be premature. Beryllium and graphite are the leading candidates. Both materials have a low atomic number and are therefore more compatible with the plasma than other candidates.

Tile thickness limits based on maximum temperature (to prevent excessive erosion by sublimation or chemical processes), material strength, and fatigue fracture were determined for limiter configurations with either graphite or beryllium tiles brazed to a copper substrate. Results indicate that the graphite tile thickness is limited to 14 mm at a surface temperature of 400°C and 36 mm at a surface temperature of 1000°C. The lower temperature limit is necessary to keep the graphite surface temperature below the threshold for chemical sputtering erosion. Based on a review of chemical erosion data, it is likely that chemical erosion at the fluxes experienced by the limiter will be negligible compared to physical sputtering erosion. Since radiation-enhanced sublimation at surface temperatures above 1000°C remains a concern, this temperature limit was also examined. Beryllium was limited to much thinner tiles, only 7 mm, by thermal stress fatigue of the rigidly attached copper substrate. Beryllium tile thickness limits based on sublimation were less restrictive.

Erosion of the limiter surface by both sputtering and disruption-induced melting and vaporization was evaluated. Disruption erosion is the dominant erosion mechanism for TFCX. This result is in direct contrast to results from the FED and INTOR studies.

Using the calculated tile thicknesses and erosion rates, erosion lifetimes for the nominal S/C TF coil version of TFCX are 2.8 years of operation for graphite with a temperature limit of 1000°C and 0.5 years of operation for beryllium, assuming that the entire melt layer formed during disruptions remains intact. Although these lifetimes appear to be acceptable from a maintenance scheduling viewpoint, it should be noted that they are relatively short in terms of actual burn time (one year of operation with the proposed TFCX schedule corresponds to only 61 full-power hours).

The TFCX vacuum pumping system is designed to pump down the vacuum chamber initially and between burns and to exhaust the helium ash during the burn period. Helium ash removal was found to set the size of the system. During the burn, some (about 10%) of the particles leaving the plasma enter the limiter slot and are neutralized underneath the limiter. The neutralized particles, both helium and hydrogen isotopes, are able to enter the 16 passages and ducts (one per torus sector) and proceed to the high-speed vacuum pumps. To satisfy the ash removal requirements, a high net vacuum pumping speed, approximately 300 m³/s, is required. This requirement led to the use of large vacuum ducts and to the selection of compound cryopumps.

Results of the impurity control and vacuum pumping system design effort are strongly dependent on the highly uncertain plasma edge and disruption heating conditions. These studies attempted to define the design and performance parameters of the impurity control system for a set of nominal conditions. The protective surface studies served to identify and quantify the key design issues that must be addressed in high-heat-flux materials R&D activities. Results of vacuum pumping system studies had a significant impact on the device configuration by requiring large duct space and creating safety concerns because of the relatively large tritium inventory in the cryopumps. Dramatic gains in system design and performance are possible if a better understanding of

the plasma edge and disruption heating conditions is developed. Efforts to understand and control these conditions are essential to focus the R&D program and to optimize the design.

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