IEEE Pub. No. 81CH1715-2 NPS

9th Symposium on Engineering Problems of Fusion Research

Palmer House
Chicago, Illinois
October 26-29, 1981

PROCEEDINGS

Volume I

Editor
Chan K. Choi
University of Illinois at Urbana-Champaign

Meeting Cosponsors

University of Illinois, Fusion Studies Laboratory
Institute of Electrical and Electronics Engineers
  Nuclear and Plasma Sciences Society
Department of Energy, Office of Fusion Energy
American Nuclear Society
Argonne National Laboratory
Electric Power Research Institute

Available from:
IEEE Service Center
Single Publication Sales Dept.
445 Hoes Lane
Piscataway, N.J. 08854

---

345 East 47th Street, New York, N.Y. 10017

Printed in USA

U.S. INTOR DIVERTOR DESIGN

R. F. Mattas, M. A. Abdou, J. Brooks, Y. Gohar, B. Misra, and D. L. Smith

Fusion Power Program
Argonne National Laboratory
Argonne, Illinois 60439

and

G. D. Morgan, D. Bowers, M. Delaney, and C. D. Grewing

McDonnell Douglas Astronautics Company
St. Louis, Missouri 63166

Abstract

The impurity control system in INTOR is a single null poloidal divertor. The total power to the divertor is 80 MW, primarily in the form of ionized particles that have escaped from the plasma. The ionized particles strike the divertor collector plates, resulting in high surface heating and sputtering that limits the lifetime to ~2 yr. This short lifetime means that the plates must be replaced several times during the reactor life, and, therefore, the divertor module has been designed to be replaced independently of the other reactor components. The divertor collector plates have been analyzed in detail, and the results of thermal and stress calculations are presented.

Design Summary

The impurity control system chosen for INTOR is a single null poloidal divertor located at the bottom of the plasma chamber, as shown in Fig. 1. (1) The purpose of the divertor is to divert and collect ionized particles that have escaped from the plasma as well as sputtered particles from the first wall. The advantages of a single null divertor are that the overall space required for the vacuum chamber is reduced and the maintenance time is reduced compared to a double null divertor. The disadvantages are that the power loading to a single divertor chamber is increased and the scrape-off width is increased at the inboard section of the plasma. The fraction of the diverted plasma which is pumped is limited to that required to exhaust the helium ash (~5%). The tritium burnup this mode of operation is estimated to be ~4%. Tl exhausted gas is pumped by cryopumps via vacuum du located at the outside channel of the divertor chamber. The remaining neutrals refuel the plasma the divertor throat.

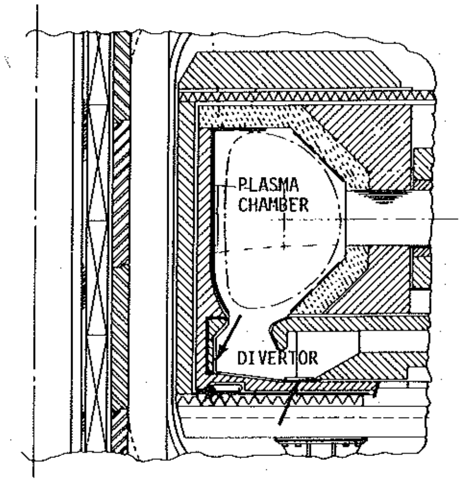

Fig. 1. Cross section of INTOR reactor showing divertor at bottom of plasma chamber. Arrows indicate locations of collector plates.

The total power to the divertor is 80 MW, whi equally divided between the inner and outer channe A total of 70 MW of that power impinges directly o divertor collector plates. A summary of the opera conditions is given in Table 1. The high power lo results in high surface heat and particle fluxes t collector plates. The inner plate is placed at an angle of 30° and the outer plate is placed at an a of 14.5° with respect to the magnetic field lines. angular placement reduces the peak surface heat fl $2\ MW/m^2$ and the peak particle flux to $1.5 \times 10^{22}/m$

Table 1. Divertor Operating Conditions

Design concept	Single null poloidal di
Total power to divertor	80 MW
Ion power to divertor plates	35 MW
Electron power to divertor plates	35 MW
Charge-exchange power to throat and walls	5 MW
Radiation power to throat and walls	5 MW
Power to channels - Outboard	40 MW
- Inboard	40 MW
Peak power flux to channels at null (normal to separatrix) - Outboard	$8\ MW/m^2$
- Inboard	$4\ MW/m^2$
Total ion flux to divertor	$5.5 \times 10^{22}/s$
Average energy of ions	400 eV
Peak ion flux to channels at null (normal to separatrix) - Outboard	$6 \times 10^{22}/m^2s$
- Inboard	$3 \times 10^{22}/m^2s$

The severe operating conditions mean that the divertor collector plates will be the most severely damaged torus components, and they are predicted to have a relatively short lifetime. The collector pl potentially will be subjected to large temperature stress gradients, large physical sputtering rates, radiation damage in the form of swelling, embrittle ment, and creep of the plate materials. Because of short lifetime of the collector plates, the diverto module is designed to be removed independently of tl rest of the blanket and shield. In order to ease th design and maintenance requirements, the module is designed to be non-breeding. For the reference breeding material, Li_2SiO_3, the breeding ratio is estimated to be ~0.6 without a breeding divertor module.

The concept chosen for the collector plate desi was to separate the problems of sputtering from thos of cooling and structural support. The plate design shown in Fig. 2, consists of a low-sputtering protection plate that is mechanically attached to a heat sink composed of a standard structural alloy. The protection plate will be eroded during particle bombardment and eventually will require replacement. The mechanical attachments result in poor thermal conductance between the plate and heat sink, but they allow the plate to freely expand and rotate as the temperature changes during the burn cycle, thus minimizing the thermal stresses. During the burn cycle, the plate temperatures increase to 2000-2400°C, at which point 40-50% of the incident heat is radiated back to the divertor chamber and plasma chamber, reducing the thermal gradient in the protection plate and the heat flux incident upon the heat sink. Because of the severe operating environment, a major effort was devoted to the design and evaluation of the collector plates. The remainder of this paper will report the results of that effort.

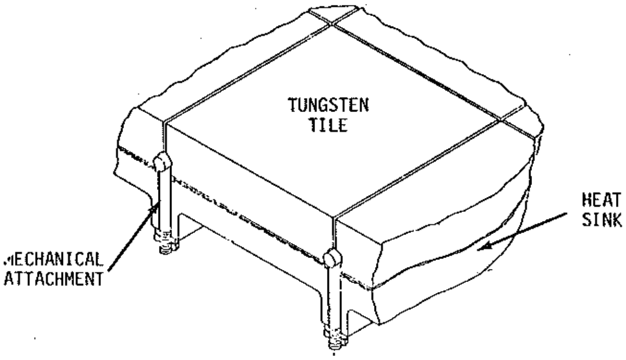

Fig. 2. Divertor collector plate design.

Materials

The principle requirements for the protection plate material are a low sputtering coefficient and adequate strength at the high operating temperatures. In addition, the material should have a high thermal conductivity, a low coefficient of thermal expansion, and a low elastic modulus in order to minimize the thermal stresses. The material which most closely meets all of these requirements is tungsten, and, therefore, it has been selected as the reference protection plate material.

The lifetime of the protection plate is likely to be limited by physical sputtering. The calculated physical sputtering coefficients for the different particle species with an assumed energy of 400 eV are shown in Table 2. At the maximum ion flux of 1.5 x 10^{22}/m^2-s, the tungsten loss rate is calculated to be 5.1 x 10^{-10} m/s or 8 mm/yr at a 50% duty factor. For the present design, this sputtering ratio results in a ~2 yr lifetime before the protection plates must be replaced. It should be noted that there are considerable uncertainties in the predicted sputtering coefficients. The coefficients determined by model calculations and by extrapolation of existing data are believed to be accurate only to within a factor of two. The small amount of oxygen impurity in the incoming particles may lead to significant chemical sputtering of tungsten at temperatures greater than 1000°C. Finally, there also may be considerable redeposition of the sputtered particles, leading to a reduced sputtering loss.

Several advantages and disadvantages of using tungsten are related to the high operating temperatures. Radiation damage will readily anneal out at elevated temperatures (~0.65 T_m) so that no radiation swelling, creep, or embrittlement are expected. However, recrystalized tungsten which is found at elevated temperatures is brittle at temperatures < 300°C (2), and, therefore, special precautions are required during initial startup and shutdown to prevent cracking. Fatigue at elevated temperatures is a major concern, but there are no fatigue data available from which to evaluate the problem. Another concern is the surface emissivity value for tungsten. Since the protection plate is assumed to be primarily radiation cooled, the surface emissivity will have a significant effect on the operating temperatures. The total hemispherical emittance for polished tungsten at 2000-2400°C varies from 0.28 to 0.34 (3). A roughened surface increased the emissivity to 0.4-0.65, which is adequate for the present design. A major concern is the effect of sputtering on surface roughness. If sputtering results in a smooth surface and a low value of emissivity, then the operating temperatures would be excessive (~2800°C). Unfortunately, there are no appropriate experimental data available to evaluate sputtering effects on emissivity.

Table 2. Predicted Sputtering Coefficients for Tungsten Bombarded by 400 eV Particles

Ion	Composition	Sputtering Coefficient
D	47%	4 x 10^{-4}
T	47%	2 x 10^{-3}
He	5%	7 x 10^{-3}
C	0.5%	1 x 10^{-2}
O	0.5%	2 x 10^{-2}
Self		0.5
Effective		2.2 x 10^{-3}

The purpose of the heat sink material is to provide structural support for the tungsten plates and to contain the pressurized coolant. The material must maintain its mechanical integrity and dimensional stability under the severe radiation, thermal, chemical, and stress conditions of the divertor environment. For the INTOR operating conditions, Type 316 stainless steel was selected as the best sink material. It has sufficient mechanical strength and radiation damage resistance to last the lifetime of the reactor. Its primary limitation is related to its poor thermophysical properties that can result in high thermal stresses. However, since 50% of the incident power on the collector plate is radiated back toward the plasma chamber, the peak heat load to the heat sink is a relatively modest 1.1 MW/m^2. For this surface heat flux, the thermal stresses in Type 316 stainless steel are low enough to meet all stress and fatigue requirements for the lifetime of the reactor.

Additional materials information can be found in Ref. 4.

Temperature Analysis

A set of two dimensional calculations was carried out to establish the temperature distribution under the pulsed mode for the reference conditions. The reference burn cycle for INTOR is:

Startup	10 s
Burn	200 s
Shutdown	15 s
Dwell	20 s

For these calculations, the startup and shutdown steps were assumed to be linear, and the reactor power was assumed to be constant during the burn. The parameters used for the calculations are given in Table 3. The only conductive heat transfer is assumed to occur at the corner attachments of the tiles. This assumption is considered a worst case since additional heat conduction between the tile and heat sink could occur with the present design and minor design changes would insure additional heat conduction. The reflection viewing factor for the tile top surface has been conservatively estimated from the reactor design geometry to be 0.25.

Table 3. Reference Parameters for Two-Dimensional Transient Analysis

Surface heat flux	2 MW/m^2
Neutron heating rate	18 MW/m^3
Tungsten plate thickness	25 mm
Plate width	100 mm
Heat sink material	Austenitic stainless steel
Heat sink thickness	15 mm
Heat sink top skin thickness	0.75 mm
Coolant temperature (in/out)	50/100°C
Tile/heat sink conductance	0 W/m^2-K
Tile/attachment conductance	568 W/m^2-K
Tungsten emissivity	0.6
Stainless steel emissivity	0.8
Viewing factor	0.25
Maximum surface temperature	2376°C
Maximum ΔT	320°C

The temperature variation for the top surface, middle, and back surface of the tungsten plate during the initial burn cycle is presented in Table 4. An evaluation of the transient calculations show that the largest temperature gradients occur during the first burn cycle. The temperature distribution approaches quasi-steady state after five cycles.

Table 4. Transient Temperature Calculations for Initial Burn Cycle

Time (s)	Temperature (°C)		
	Top Surface	Middle	Back Surface
10	452	298	260
20	847	640	570
40	1493	1285	1192
110	2296	2150	1990
210	2376	2240	2070
245	1661	1672	1601

Stress Analysis

The results of the thermal calculations have been used to calculate the thermal stresses in the tungsten plate. A two-dimensional model was constructed to investigate the thermal stresses near the mechanical attachments of the tungsten protection plate for the operating conditions given in Table 3. Figure 3 shows the resultant temperature and stress distribution in the plate for t = 210 s. Temperature gradients near the corners are increased by the additional heat flowing through the attachments, resulting in higher predicted stresses near the corners. The predicted stresses in the plate are all below the yield stren of recrystalized tungsten at the relevant temperatures. The low stresses are the result of t plate being able to expand freely and rotate as the temperature changes.

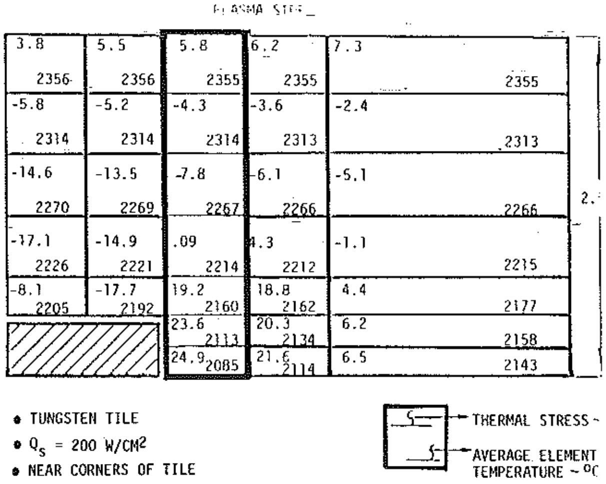

Fig. 3. Calculated stresses and temperatures in tungsten tile at 210 s of burn cycle.

Figure 4 presents the thermal and final strain distributions of the row of elements outlined in Fi after 10 s of heating when the heat flux reaches th full power, and three similar distributions at subsequent time points over an equilibrium burn cycle. The final strains are linear and represent conditions where the edges are allowed to rotate ar expand freely. The difference between the thermal strain and the final strain is the mechanical strai which actually produces stresses in the tile. The mechanical strains on the elements actually change over the burn cycle. Plastic straining does occur various times during the cycle. The hottest condit at 210 s, is not necessarily the worst; the thermal stresses are greater as temperature distributions become more nonlinear. The cooler region in the co of the alumina insulator causes greater nonlinearit and, thus, the highest stresses throughout the cycl were found in that region. A refinement of the analysis permitted the history of plastic strains or each element to be accounted for in determining the overall section response. The effect of accumulate plastic strains is clearly visible in the 245 s plot Fig. 4.

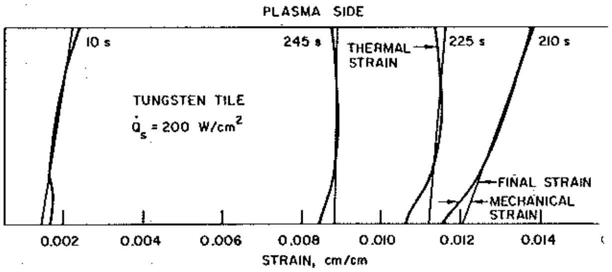

Fig. 4. Strain distribution in tungsten tile for various times during burn cycle.

The calculated stresses and strains are all qu low and appear to be acceptable for the high temperature design.

Conclusions

The use of a single null poloidal divertor in INTOR leads to several reactor design constraints due to the high surface loading of the divertor collector plates. At present, it is believed that the divertor lifetime will be determined by the loss of material from physical sputtering of the divertor collector plates. For the U.S. INTOR design, the sputtering lifetime is estimated to be ~2 yr at a 50% duty factor. Since the rest of the first wall/blanket system is estimated to last the lifetime of the reactor, provision has been made to replace the divertor chamber independently of the other components. The divertor module has been designed to be nonbreeding in order to reduce the design complexity and the maintenance time required for replacement. The net breeding ratio for this design is only ~0.6, necessitating the use of outside sources for tritium.

A major part of the divertor design effort was devoted to the divertor collector plate. The U.S. design consists of a 2.5 cm thick tungsten protection plate that is mechanically attached to a stainless steel heat sink. The use of the mechanical attachment results in high temperature and low stress conditions in the tungsten. At present, it appears that these operating conditions do not significantly impact the collector plate lifetime. There are, however, large uncertainties in the analysis because of the lack of relevant tungsten data. Areas where additional information is required include chemical sputtering, high temperature fatigue, and the emissivity of sputtered surfaces.

References

(1) W. M. Stacey, et al., "U.S. INTOR Conceptual Design," USA INTOR 81/-1 (1981).

(2) T. C. Teitz and J. W. Wilson, Behavior and Properties of the Refractory Metals, Stanford University Press, California (1965).

(3) Y. S. Touloukian and D. P. DeWitt, eds., Thermophysical Properties of Matter, Vol. 7, IFI/Phenum, New York (1970).

(4) R. F. Mattas, et al., "Materials Selection for the U.S. INTOR Divertor Collector Plate," Second Topical Meeting on Fusion Reactor Materials, Seattle, Washington, August 9-12, 1981 (to be published).