Conf-910961--

OSTI

GA–A20734

ARIES–III DIVERTOR ENGINEERING DESIGN

by

C.P.C. WONG, K.R. SCHULTZ, E.T. CHENG, S. GROTZ, M.A. HASAN, F. NAJMABADI, S. SHARAFAT, J.N. BROOKS, D.A. EHST, D.K. SZE, J.S. HERRING, M. VALENTI, D. STEINER, and THE ARIES DESIGN TEAM

JANUARY 1992

GENERAL ATOMICS

DISCLAIMER

GA-A--20734

DE92 006913

ARIES-III DIVERTOR ENGINEERING DESIGN

by
C.P.C. WONG, K.R. SCHULTZ, E.T. CHENG,*
S. GROTZ,† M.A. HASAN,† F. NAJMABADI,†
S. SHARAFAT,† J.N. BROOKS,‡ D.A. EHST,‡
D.K. SZE,‡ J.S. HERRING,§ M. VALENTI,¶
D. STEINER,¶ and THE ARIES DESIGN TEAM

*TSI Research, Inc.
†University of California, Los Angeles
‡Argonne National Laboratory
§Idaho National Engineering Laboratory
¶Rensselaer Polytechnic Institute

This is a preprint of a paper to be presented at the 14th Symposium on Fusion Engineering, September 30–October 3, 1991, San Diego, California, and to be printed in the *Proceedings*.

Work supported by
Department of Energy
Contract DE-AC03-89ER52153

GENERAL ATOMICS PROJECT 3469
JANUARY 1992

GENERAL ATOMICS

ARIES–III DIVERTOR ENGINEERING DESIGN

C.P.C. Wong, K.R. Schultz
General Atomics
P.O. Box 85608
San Diego, California 92186-9784

E.T. Cheng
TSI Research
225 Stevens Ave., #110
Solana Beach, California 92075

S. Grotz, M.A. Hasan, F. Najmabadi, S. Sharafat
6288 Boelter Hall
Mechanical, Aerospace and Nuclear Engineering Department
University of California, Los Angeles
Los Angeles, California 90024-1597

J.N. Brooks, D.A. Ehst, D.K. Sze
Argonne National Laboratory
9700 S. Cass Avenue (Bldg. 205)
Argonne, Illinois 60439

J.S. Herring
Idaho National Engineering Laboratory
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415-3523

M. Valenti, and D. Steiner
Plasma Dynamics Laboratory
Rensselaer Polytechnic Institute
110 8th Street
Troy, New York 12181

and The ARIES Design Team

Abstract: This paper reports the engineering design of the ARIES–III double-null divertor. The divertor coolant tubes are made from W-3Re alloy and cooled by subcooled flow boiling of organic coolant. A coating of 4 mm thick tungsten is plasma sprayed onto the divertor surface. This W layer can withstand the thermal deposition of a few disruptions. At a maximum surface heat flux of 5.4 MW/m^2, a conventional divertor design can be used. The divertor surface is contoured to have a constant heat flux of 5.4 MW/m^2. The net erosion of the W-surface was found to be negligible at about 0.1 mm/year. After 3 years of operation, the W-3Re alloy ARIES–III divertor can be disposed of as Class A waste. In order to control the prompt dose release at site boundary to less than 200 Rem, isotopic tailoring of the W alloy will be needed.

Introduction

The Advanced Reactor Innovation Evaluation Study (ARIES) has completed the conceptual design of ARIES–III, a 1000 MW(e) tokamak reactor using the D-^{3}He advanced fuel cycle and operating in the second stability regime of physics [1]. The ARIES–III divertor engineering design is a critical part of the ARIES–III reactor study, representing an integrated design effort from different areas. The design goals are to use the same coolant and materials selected for the blanket and shield design; aim for design simplicity, and optimize the passive safety features of the design by making use of the relative low neutron wall loading of 0.07 MW/m^2 at the divertor. A summary of the outboard divertor design is reported in this paper. Areas covered in this paper are: divertor geometry and configurational design, divertor plasma characterization from Braams code modeling, surface coating and structural materials selection, net surface material erosion modeling, thermal-hydraulic and structural analyses, activation assessment, disruptions tolerance, and tritium issues.

Configuration

ARIES–III is a D-^{3}He advanced fuel tokamak reactor design [1]. It has a double-null divertor configuration. Its major radius, aspect ratio, and plasma elongation are 7.5 m, 3, and 1.84, respectively. There are twenty TF coils and the vacuum pumps are located at the bottom of the machine [2]. A schematic of the ARIES–III divertor is illustrated in Fig. 1. The detailed configuration of the divertor geometry was selected by the design iteration between the plasma boundary physics study which specifies the distribution of the divertor surface heat load; and thermal-hydraulic and structural designs which specify material temperature and structural loading details. The reference divertor design has its plasma facing surface contoured to allow a constant heat flux of 5.44 MW/m^2, as shown in Fig. 2. This design approach leads to a minimum outboard divertor length of 97 cm.

Plasma Boundary Physics Results

The Braams code [3], a two-dimensional, multifluid code was used to study the particle and energy transport in the plasma edge of the ARIES–III design. The results obtained are the divertor surface heat flux distribution and edge plasma conditions. These are inputs for the calculation of the structural material temperature distribution and the net erosion rate of the selected divertor surface material. Details of the Braams code calculation and results are reported in Ref. [4]. In summary, based on the configuration that the divertor surface is inclined 10° to the

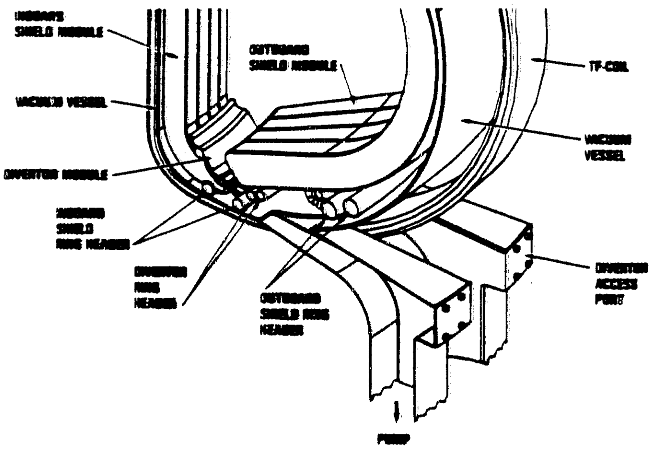

Fig. 1. ARIES–III bottom divertor.

poloidal flux line at the divertor, the Braams code results show that at a recycling coefficient of 0.993, and a core radiation fraction of 25%, the divertor maximum heat flux can be controlled to 5.44 MW/m^2 and the electron temperature at the divertor to 28.2 eV. The heat flux distribution is illustrated in Fig. 3. This high recycling divertor also leads to high neutral density at the divertor which eases the design of the vacuum pumps [4]. Based on this result of modest surface heat flux, a conventional divertor design cooled by subcooled flow boiling of organic coolant was selected as the reference design.

Materials Selection

Materials were selected for the ARIES–III divertor design, these are the plasma surface and the coolant tube structural materials. The design goal is to cool the divertor plate with organic coolant and with similar inlet and outlet conditions as the first wall and shield design.

The choice of the divertor surface material is driven by the requirements of low total sputtering yield and its ability to withstand disruptions. High Z materials such as W or Ta were considered. Relatively, tantalum is susceptible to hydrogen embrittlement, and tungsten has a high melting temperature of about 3400°C and a boiling point of about 5550°C. It was also found that as long as the plasma temperature at the sheath edge can be maintained in the range of 20 eV to 40 eV the rate of sputtering of W is very small. These properties make W to be one of the most disruption-resistant target materials, and was selected for the ARIES–III design. The W coating at close to 95% theoretical density can be applied to the W-3Re cooling tubes by plasma spray [5].

Reduced activation ferritic steel (RAFS) and tungsten-rhenium (W-Re) alloy were considered for the coolant tube structural material. Due to high temperature creep deformation, the RAFS is limited to a maximum operating temperature of 520°C. Calculations showed that this temperature limit will be exceeded at the coolant exit. Therefore, the W-Re alloy, which has a maximum temperature allowable of 1500°C, was selected. Comparatively, W-Re alloy is favored over pure W metal because the former has higher strength and toughness and lower ductile-to-brittle transition temperature (DBTT). The strength of W-Re alloys increases somewhat with increasing rhenium content. However, from an activation point of view, the content of rhenium is minimized to 3%.

When organic coolant is used as the coolant and W alloy is used as the structural material, WC can be formed. It may not only embrittle the material but can also lead to crack initiation sites on the W-Re tubes. A suitable carbon-pickup barrier coating would have to be identified and applied inside the W-Re tubes if WC formation is shown to occur at an unacceptable level.

Erosion and Redeposition

A sputtering erosion analysis of the ARIES–III divertor was performed using the REDEP code [6,7] with plasma scrape-off layer parameters supplied from Braams code runs [4]. The maximum plasma electron temperature at the plate is about 28 eV. To account for the actual poloidal field line geometry of the divertor design, the ion flux was multiplied by a factor of $\sin 10° = 0.174$ for input to the REDEP code. A net field angle (poloidal and toroidal) of 3° was also incorporated into the code calculations. The ion species hitting the divertor plate consists of hydrogen and helium isotopes, a trace oxygen content, and a self-consistently determined plate impurity content.

Two plate materials, tungsten and beryllium, were examined. For the reference case of W coating, the gross erosion rate peaks at about 1 cm/burn·yr while the net erosion rate is everywhere much lower (<0.1 mm/burn·yr). The high redeposition rate is due to the short mean free paths (<1 mm) of sputtered tungsten atoms for ionization and subsequent redeposition. In terms of sputtering coefficient, when compared to the D-T fuel cycle, the lack of tritium in ARIES–III (except for trace amounts) tends to reduce the sputtering rate compared to a D-T reactor, while the high helium content tends to increase the sputtering rate, and these effects roughly balance each other in the plasma regime studied.

For beryllium, the eroded area is much wider and so active sweep control [7] would be required. For example, an erosion reduction factor of ~4X is obtainable with a sweep distance of ±10 cm. Sweeping would still not appear to permit an adequate lifetime for a beryllium coated divertor plate. In contrast, tungsten appears to yield an acceptable sputtering erosion lifetime with the overall lifetime being limited by disruption erosion.

Thermal-Hydraulic and Structural Designs and Analyses

The guidelines of the thermal-hydraulic design of the divertor plates of ARIES–III are to use organic coolant, HB-40, as the coolant with the same inlet/exit temperatures, 340°C/ 425°C, as in the first-wall/shield circuit, and to achieve a safety

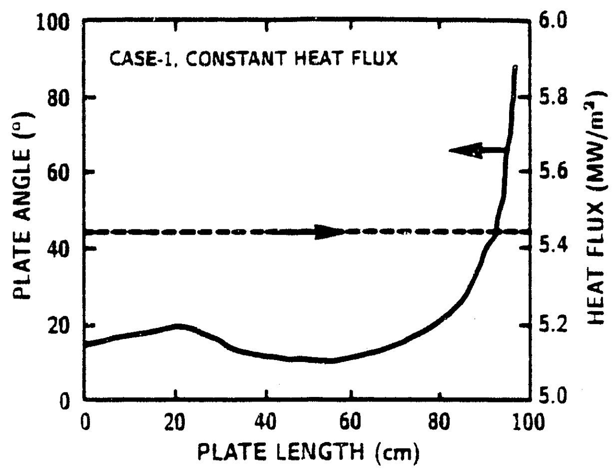

Fig. 2. Divertor plate angle variation for a constant heat flux design of 5.44 MW/m^2.

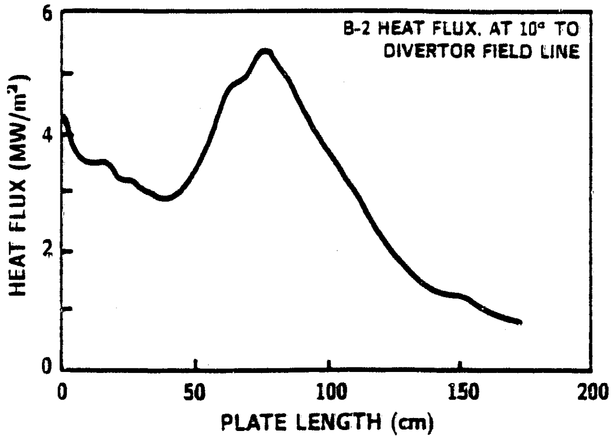

Fig. 3. Divertor heat flux distribution at 10° incline to the poloidal field line.

factor of ≥2 with respect to the critical heat flux (CHF). Details of the ARIES–III thermal-hydraulic design and structural design analyses are presented in Ref. [8].

The ARIES–III design has two poloidal divertors which remove a total thermal power of 629 MW. The total power is shared equally by the top and bottom divertors, and in each of the divertors, the outboard plate was assumed to receive twice as much power as the inboard plate. W-3Re alloy is the structural material. The heat receiving surface of the ARIES–III divertor consists of 3 mm inside diameter W-3Re alloy tube bank with 0.2 mm thick walls. In order to withstand the thermal power deposition of a few disruptions, the plasma facing surface of the tube bank is coated with a 4 mm thick isotopically tailored tungsten. The coolant tubes are laid normal to the toroidal direction with the inlet manifold under the X-point and the outlet manifolds at the end of the plate, as shown in Fig. 1.

To enhance the cooling capability of organic coolant, subcooled flow boiling heat transfer has to be used. The film temperature drop in nonboiling heat transfer is obtained from convective heat transfer equation for organic coolant. The calculated heat transfer coefficient is reduced by 37% to account for the effect of nonuniform surface heat flux [9]. It is assumed that subcooled flow boiling (SFB) takes place when the coolant/wall interface temperature exceeds the saturation temperature by 35°C or more, which is lower than the observed wall superheat limit for the onset of nucleate boiling at 55°C. By controlling the coolant pressure at the exit end of the coolant tube, a safety factor of 2 with respect to CHF was obtained [8].

Pressure and thermal stress analyses in the coolant tube were performed by the finite element code ANSYS [10]. The coolant tube is analyzed using an axisymmetric model. Conservatively, symmetry between adjacent tubes was assumed. Results show that the maximum stress occurs at the inlet section where the coolant pressure is the highest. Maximum equivalent stresses at the coolant inlet section is 347 MPa. These equivalent stress are significantly smaller than the design limits of 400 MPa for tungsten alloy [8].

Selected results of the thermal-hydraulic and structural designs are summarized in Table 1.

It should be emphasized that the heat transfer correlations for organic coolants are based on very limited experimental data which are mostly unpublished, only a few of them are published as institution reports. Further work is required to understand the phenomena of convective heat transfer and subcooled flow boiling of organic coolants.

Activation Assessment

Neutron activation analysis was performed for the ARIES–III divertor design using a one-dimensional model. The goal is to determine the induced radioactivities and afterheat contributions of the reference design. Details of this activation assessment can be found in reference [4]. The one-dimensional model consists of a 0.3 m plasma scrape-off region, a 2 mm homogenized zone of tungsten, a 2 mm structural tubing wall made of ferritic steel, and a 34 mm cooling zone composed of 25% organic coolant, 25% ferritic steel, and 50% void, all by volume percentages. A 0.55 m ferritic steel shield zone was also included in the neutronic calculation to determine the neutron flux and spectrum in the divertor components.

Neutron fluxes and spectra were calculated with the monte-carlo transport code, MCNP, and the continuous energy nuclear data library based on ENDF/B-V evaluations [11]. Activation calculations were performed using the REAC-2 code and libraries [12]. The total neutron wall loading employed in the activation calculations is 0.07 MW/m^2, with contributions from both DD (2.45 MeV) and DT (14.1 MeV) neutrons. A ratio of 3 was assumed for DD and DT neutron wall loadings based on the physics performance.

It was found that the induced radioactivities and afterheat heating rates in the tungsten layer are initially dominated by W-187, until about one day after shutdown. They are then dominated by W-185, at levels about two orders of magnitude smaller, until about one year after shutdown. The long-term activities are Hf-178m2 (half-life 31 year) and Re-186m (half-life 2.0×10^5 year). The heating rate in the tungsten layer is 0.71 W/cc at 1 h after shutdown. It reduces, by only a factor of 2, to 0.38 W/cc at one day after shutdown. At 10 days after shutdown, the heating rate decreases by about one order of magnitude and is 0.025 W/cc.

The waste disposal issues in the tungsten layer and the entire divertor component were evaluated. Hf-178m2, Re-186m, and Hf-182 (half-life 9 × 106 year), are identified as major long-lived radionuclides important for Class C and Class A waste disposal considerations. The concentration limits evaluated by

Table 1
Main Results of ARIES–III Divertor Design

Parameter	Value
Total thermal power (MW)	629
Outboard plate thermal power (MW)	209
Outboard plate length (m)	0.97
Constant heat flux (MW/m^2)	5.44
Coolant tube material	W-Re
Tube inside diameter (mm)	3.0
Tube wall thickness (mm)	0.2
Tungsten coating thickness (mm)	4.0
Organic coolant	HB-40
Coolant inlet/exit temperatures (°C)	340/425
Coolant flow velocity (m/s)	15.6
Coolant inlet/exit pressure (MPa)	5.34/1.0
Safety factor w.r.t. CHF	≥2
Total coolant flow rate (m^3/s)	3.35
Pumping power [MW(e)]	18
Maximum material temperature (°C)	821
Maximum equivalent stress (MPa)	347

Fetter [13] were employed for the Class C waste disposal criteria. For all Class A wastes, a factor of 10 lower than the concentrations suggested by Fetter, were assumed. When considering only the tungsten layer, the total waste disposal rating for Class A, which is dominated by the Hf-178m2 activity, is 0.19 after one year of operation. This implies that the tungsten layer alone will be allowed for at least 5 years of operation before the waste disposal rating reaches the limit for Class A disposal. For the W-3Re alloy, with the additional contribution from 3% Re, the divertor will be allowed for at least 3 years of operation before the waste disposal rating reaches the limit for Class A disposal.

Among the induced radioactive isotopes, W-180 and W-182 are the main isotopes to generate appreciate amounts of the waste disposal related long-lived radionuclide, Hf-178m2. Relatively, W-183 shows the least induced radioactivities affecting both the afterheat and waste disposal ratings. It is the best isotope chosen for ARIES–III reactor to reduce the prompt accidental dose. This will be needed in order to meet the accidental site boundary release limit of 200 rem [4].

Disruption Effect

For the ARIES–III design, it was estimated that during disruption, 6.2 GJ of thermal energy and a portion of the magnetic energy could be released on a small fraction of the divertor area (total $= 177\ m^2$). Typically, in 0.1 to 1.0 ms an energy density ranging from 35 to 70 MJ/m^2 could be experienced. Calculations show that about 0.3 to 0.6 mm of W would be removed per disruption due to thermal evaporation of divertor plate surface. (Assuming no vapor shielding or redeposition.) With a W coating thickness of 4 mm, ARIES–III will be able to withstand a few disruptions.

Divertor Tritium Issues

For the plasma driven tritium diffusion in the divertor regime, there is no fundamental difference between tritium permeation in a D-T and in a D-He^3 reactor. The key difference is on the flux level impinging the divertor. The flux of tritium particles for a D-^3He reactor is more than a factor of a hundred lower than that of a D-T reactor. Therefore, it is expected that the tritium permeation rate is also more than a factor of 100 lower. Relatively, this is a much less severe problem when compared to a D-T reactor design [14].

Conclusions

The ARIES–III divertor engineering design represents an integrated effort from different areas. The selected structural material and coolant are W-3Re alloy and organic coolant, respectively. The coolant inlet and outlet temperatures of 340° and 425°C were selected to match the blanket coolant conditions, in order to simplify the balance of plant design. At a recycling coefficient of 0.993, and a core radiation fraction of 25%, the maximum surface loading is at 5.44 MW/m^2. Based on conventional divertor design, the plasma facing surface was contoured to allow a constant heat flux of 5.44 MW/m^2, while maintaining the surface temperature of 821°C, which is less than the design limit of 1500°C. This was possible when subcooled flow boiling was used to improve the convective heat transfer property of the organic coolant. The maximum equivalent stress is 347 MPa, which is lower than the design limit of 400 MPa for W-alloy. To accommodate possible fluctuation in the peak heat flux and stay away from film boiling, a safety factor >2 has been maintained along the entire length of the coolant tubes. A 4 mm thick coating of W was applied to withstand at least a few disruptions without catastrophic damage to the divertor. The net surface material erosion was found to be negligible at about 0.1 mm/year. Neutronics results show that the generation of afterheat is very small. After 3 years of operation, the ARIES–III divertor can satisfy the rating of Class A waste. With isotopic tailoring of W, even under the worst accidental condition, the divertor total reactor release at site boundary will be less than 200 rem. This allows ARIES–III to be rated as a Level of Safety Assurance (LSA) Level-2 design. The key uncertainty of this design is the compatibility of the organic coolant with the W-3Re alloy. A surface coating to prevent the formation of WC will be needed. Subcooled flow boiling heat transfer of organic coolant will also need to be further studied.

Acknowledgment

This work was sponsored by the U.S. Department of Energy under Contract No. DE-AC03-89ER52153.

References

[1] F. Najmabadi, "The ARIES–III Design," to be published in these proceedings.

[2] S. Sharafat, *et al.*, "Design Layout and Maintenance of the ARIES–III Tokamak Reactor," to be published in these proceedings.

[3] B. J. Braams, "A Multi-fluid Code for Simulation of the Edge Plasma in Tokamaks," NET Report NR. 68, 1987.

[4] F. Najmabadi, *et al.*, "The ARIES–III Final Report," to be published by UCLA.

[5] M. F. Smith, Private communication, Sandia National Laboratories, March 1991.

[6] J. N. Brooks, "Modeling and Analysis of Erosion and Redeposition for Limiter and Divertor Impurity Control Systems," *Nucl. Fusion*, vol. 4, p. 33 (1983).

[7] J. N. Brooks, "The International Thermonuclear Experimental Reactor Divertor," *Fusion Technol.*, vol. 18, p. 239 (1990).

[8] H. Z. Hasan, "Thermal-Hydraulic Design of ARIES–III Divertor with Organic Coolant in Subcooled Flow Boiling," to be published in these proceedings.

[9] M. Z. Hasan and T. Kunugi, "Entry-Length Effect on the Thermal-Hydraulic Design of Plasma-Facing Components of Fusion Reactors, Part-II: MHD Flow," to be published in *Fusion Technology*.

[10] G. J. DeSalvo and J. A. Swanson, "ANSYS User's Manual," Swanson Analysis Systems, Inc. (1979).

[11] "MCNP — A General Monte Carlo Code for Neutron and Photon Transport, Version 3A," J. F. Briesmeister (ed.), Los Alamos National Laboratory, LA-7396-M, Rev. 2, September 1986.

[12] F. M. Mann, "REAC-2: Users Manual and Code Description," Westinghouse Hanford Company, WHC-EP-0282, December 1989.

[13] S. Fetter, E. T. Cheng, F. M. Mann, "Long-Term Radioactive Waste from Fusion Reactors: Part II," *Fusion Eng. Design*, vol. 13, p. 239 (1990).

[14] F. Najmabadi, *et al.*, "The ARIES–I Final Report," to be published by UCLA.

END

DATE
FILMED
3/12/92