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September 1991

UWFDM-863

Presented at the 14th IEEE/NPSS Symposium on Fusion Engineering, 30 September – 3 October 1991, San Diego CA; IEEE Cat. No. 91CH3035-1, Vol. 2, pp. 1110.

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Abstract

An efficient organic cooled low activation ferritic steel first wall and shield has been designed for the D-^{3}He power reactor ARIES-III. The design allows removal of the large surface heat load without exceeding temperature and stress design limits. The structure is expected to last for the whole reactor life. The major concerns regarding using the organic coolant in fusion reactors have been greatly alleviated.

Introduction

ARIES-III is a conceptual design for a D-^{3}He tokamak fusion power reactor. The 1000 MWe reactor operates in the second stability regime. The plasma major radius is 7.5 m and the aspect ratio is 3. The plasma current is 30 MA and the toroidal field on axis is 7.5 T. Only 4% of the fusion power is carried by neutrons with the rest being carried by charged particles that deposit energy as surface heat on the first wall (FW) and divertor. The average neutron wall loading is only 0.08 MW/m^2 with the peak value at midplane being 0.114 MW/m^2. Since no tritium breeding blanket is required in a D-^{3}He reactor, only a simple relatively thin shield is needed for magnet radiation protection. On the other hand, the peak surface heat flux in the FW is 1.86 MW/m^2. This has placed a premium on the design of the FW which should be capable of removing the high surface heat without exceeding temperature and stress limits. In addition, the FW should be capable of withstanding a plasma disruption. The detailed thermo-mechanical design and structural analysis of the FW is presented in a companion paper [1].

Organic coolants have been used in fission reactors [2] and useful experience of operating an organic cooled system was generated. Organic coolants can be used at a higher temperature than water (450°C vs. 350°C) with a much lower pressure (1 MPa vs. 20 MPa). The key reason that organic coolant was not considered for DT fusion reactors was the excessive radiolytic decomposition [3]. However, in a D-^{3}He reactor, the neutron power is only about 4% of the fusion power. Therefore, the concern regarding radiolysis is much alleviated. The high surface heat flux in ARIES-III requires a coolant with good heat removal capability. In addition, the high capital cost and recirculation power require good thermal conversion efficiency. Furthermore, the first wall synchrotron reflectivity is required to be 0.99. Be coating was identified as the only choice of material with sufficient electrical conductivity to provide such reflectivity. To limit the evaporation of Be, a maximum Be temperature of 750°C was selected. This puts severe limitations on the FW and coolant temperature. These requirements resulted in the selection of the organic coolant for the ARIES-III FW and shield. Since the organic coolant is limited to about 450°C, advanced structural materials are not required. The low activation ferritic steel (modified HT-9) was, therefore, selected as the structural material. The overall features of the ARIES-III FW and shield design are described in this paper.

Organic Coolant Issues

The unique design feature of the ARIES-III FW and shield is using organic coolant. The organic compounds of interest for fusion are the terphenyl isomers. These compounds have good irradiation stability, good thermal stability up to around 400°C, soluble decomposition products, and reasonable availability at relatively low cost. They are a by-product from the manufacture of benzene, a major industrial feedstock. Organic coolants are low pressure coolants with good heat removal capability which leads to simpler, more reliable mechanical designs. This allows operation at higher temperatures leading to higher thermal efficiency. They have low corrosion rates with a wide variety of structural alloys leading to low activity in the primary heat transport system. There have been some major concerns about organic coolants. However, the operating experience of the WR-1 reactor helps resolve most of these concerns. These specific issues are briefly summarized here.

At high temperatures and in radiation fields, organic coolants decompose leading to potential surface fouling or channel plugging. These were significant problems in early fission reactors, but were successfully resolved in the WR-1 reactor. Coking is the formation of carbonaceous deposits in low-flow regions due to precipitation and growth of decomposition products. Coking is controlled by reducing the total decomposition rate and by maintaining high coolant velocity. The coolant velocity in ARIES-III is maintained above 10 m/s to prevent coking. Fouling is the formation of films on high-temperature heat transfer surfaces, normally dependent on the nature and concentration of the coolant impurities. Fouling is prevented through coolant chemistry control, particularly minimizing chlorine and oxygen.

The flammability of organic coolants is a serious concern. However, experience with the OS-84 coolant in twenty years of operation of the WR-1 reactor has shown that this hazard is readily managed. The combustion temperature is estimated to be about 1000°C and the combustion process is slow. In addition, if the building atmosphere is maintained with $< 12\%$ oxygen, the organic coolant cannot be ignited.

The organic coolant decomposes due to both radiation and temperature. The decomposition rates can be predicted [4]. The decomposition product actually makes the organic coolant more stable. About 90% of the decomposition products can be recovered by the hydro-cracking process [5]. Decomposition will cause only a minor economic penalty.

Mechanical Design

There are 20 TF coils in the reactor. The inboard (IB) shield is divided into 40 equal modules and the outboard (OB) shield is divided into 80 equal modules. At the midplane, the width of an IB module is 76 cm, allowing for a one centimeter assembly gap between modules. Similarly the OB modules are 84.8 cm wide at the midplane with a 1 cm assembly gap. The IB shield is straight from top to bottom and thus the horizontal cross section of the modules remains constant throughout. The OB shield, however, curves following the contour of the plasma. It is widest at the midplane where the radius is 10.93 m and narrowest at the extremities where the radius is 8.0 m.

The first wall is the most important part of the shield. It is designed to be capable of absorbing the incident high surface heat in the coolant while maintaining the thermal stresses at acceptable levels. The FW is composed of segments divided in the toroidal direction with poloidal coolant flow. The FW skin is composed primarily of MHT-9, 1.0 mm thick and is coated on the surface facing the plasma with tungsten and Be. The

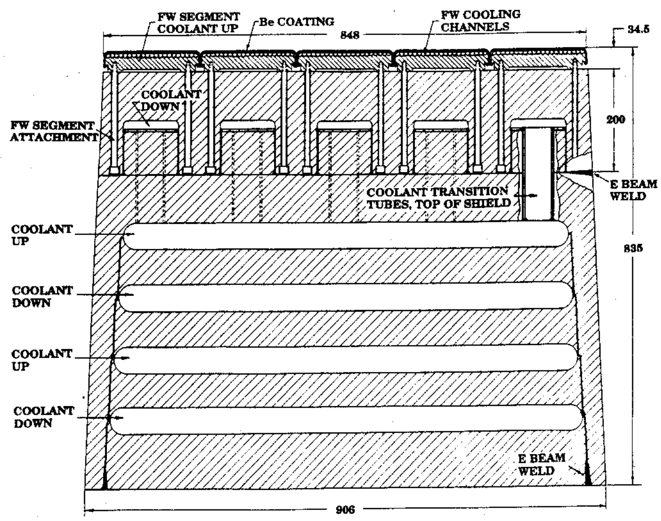

Fig. 1. Midplane cross section of outboard shield module.

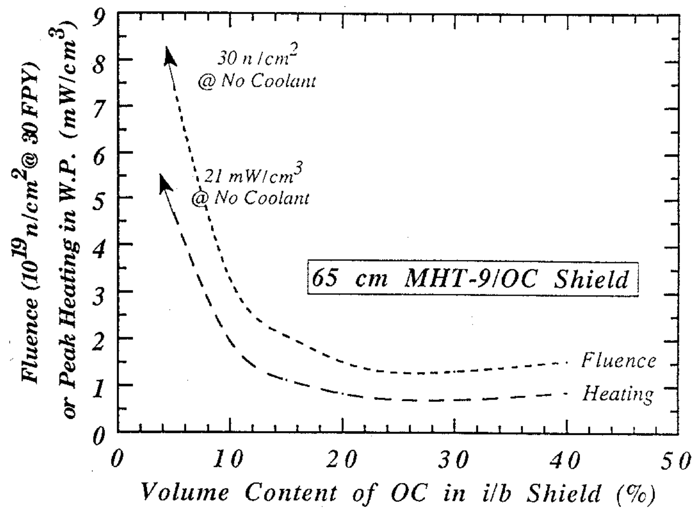

Fig. 2. Impact of organic coolant content on magnet damage.

function of the W which is 100 μm thick is as a diffusion barrier between the Be and the steel. A coating of Be, 1.5 mm thick, is deposited on the W. Its function is to provide a high electrical conductivity at the surface to reflect synchrotron radiation and also as a sacrificial coating to mitigate against energy deposited by a plasma disruption. The FW skin is attached by a continuous spot welding process to a machined MHT-9 steel plate, and the two together constitute the FW segments. Immediately behind the FW skin there is a continuous series of rectangular channels 6 mm wide and 8 mm deep. These channels run in the poloidal direction in a continuous fashion from the bottom to the top. At the interface between the FW segments and the front shield zone, the FW segments are relieved such that they only make contact on the ends where the bolts which attach the segments to the front shield are located. This is done to thermally isolate the FW segments from the shield behind it.

Figure 1 is a midplane cross section of an OB module. There are five FW segments in the OB module each 16.97 cm wide at the midplane. At the extremities, the two side segments are reduced in width, while the remaining three segments have the same width as at the midplane. The channels in the side segments are shunted to the side of the modules, as the segment width is reduced. Shunting the channels to the side while providing the needed flow area permits a smooth coolant transition with a minimal loss of pressure, and prevents the existence of undercooled areas which will develop into hot spots.

The front part of the shield on which the FW segments are attached is an MHT-9 steel forging 20 cm thick and has a 5% coolant fraction. In the OB shield this piece is curved to conform to the plasma contour and is tapered from the midplane to the extremities. This front shield has the primary function of supporting the FW segments by means of bolts inserted from the back side. A single coolant channel is machined behind each FW segment. This coolant channel cools the front shield segment and also ducts coolant to the FW segments.

The rear shield is made of MHT-9 steel plates separated by rather large coolant channels. The large amount of coolant (30%) is needed for neutronic purposes and not from thermal hydraulic requirements. Both IB and OB rear shields have four coolant passages extending the full length of the modules. On the OB side, the rear shield is 50 cm thick and each channel is 3.75 cm deep. The IB side is only 35 cm thick, and the channels are 2.6 cm deep. The channels are connected in series, such that all the coolant flows through them. Coolant enters the rear shield at the top through a tube which feeds into the last channel. It flows down the full length of the module then crosses over to the next to last channel at the bottom of the module and travels up. After making four traversals of the module vertical height, the coolant is ducted into the front shield zone through coolant transition tubes at the top of the modules. The coolant then travels down through the front shield zone, then crosses over to the FW segments and finally travels up through the FW coolant channels.

Magnet Shielding

The intent of the shielding analysis was to design an efficient low activation shield that protects the superconducting magnets against radiation. In order to insure the proper performance of the TF coils of ARIES-III, the radiation effects must be below certain limits. For instance, at the end of 30 full power years (FPY) of operation the fast neutron fluence ($E_n > 0.1$ MeV) should not exceed 10^{19} n/cm^2 to avoid degradation of the critical properties of the Nb_3Sn superconductor material. It is undesirable to subject the magnet to a nuclear heating above 50 kW to avoid excessive cryogenic load. A limit of 2 mW/cm^3 is imposed on the peak nuclear heating in the winding pack. The end of life dose to the polyimide insulator is limited to 10^{11} rads to ascertain the mechanical and electrical integrity. Our neutronics calculations indicate that the predominant magnet radiation limits are the end-of-life fast neutron fluence and the nuclear heat load to the magnets. Hence, the shield is optimized to primarily minimize these effects.

The neutronics analysis was performed using the one-dimensional code ONEDANT [6] with a P_3-S_8 approximation and cross section data derived from the ENDF/B-V evaluation. In the calculational model, the different components of the first wall and shield were modeled in toroidal cylindrical geometry around the machine axis, permitting representation of the IB and OB sides simultaneously. The neutron source has an energy distribution in which 36% of the neutrons are at 14.1 MeV and 64% at 2.45 MeV.

Very critical to the overall size and cost of the machine is the inboard space between the plasma and the magnet. Hence, an extensive optimization study was performed to determine the optimal composition and thinnest IB shield that minimizes magnet damage. The major factors influencing the shield performance are the composition, materials arrangement and coolant content within the shield. The optimization of the shield has focused on these factors. Figure 2 illustrates how both the fluence and heating change with the organic coolant (OC) content in a 65 cm thick MHT-9 shield. The results indicate that the magnet damage is minimized at 30% OC. A concern for the OC is the radiolysis of the coolant particularly in the high radiation zone of the shield. A viable solution is to reduce the OC content in the front layer of the shield from 30 to 5%. The effect of the thickness of the 5% OC front layer on the magnet damage was investigated. The fluence slightly reduces at 20 cm thick front zone and there is no significant change in heating. Therefore, a 20 cm thick front zone with 5% OC is used in the reference ARIES-III design. Calculations performed for the reference shield design indicated that the end-of-life fast neutron fluence limit is satisfied and the total nuclear heating in the TF coils is 25 kW.

Radiation Damage

The damage rate profiles for the modified HT-9 structural material have been determined. The peak damage rate is 2.1 dpa/FPY and occurs at the front surface of the outboard FW at midplane. For 30 FPY reactor lifetime, the peak accumulated damage will be 63 dpa implying that FW and shield change-out is not required during the whole reactor lifetime. The peak helium production rate is 13.1 appm/FPY. The peak helium production rate in the beryllium coating is 441 appm/FPY yielding a burnup rate of only 0.023% per FPY. At reactor end-of-life the peak beryllium burnup is less than 0.7% and is not of concern. While DT neutrons represent only 36% of the source neutrons, they carry 75% of the neutron power. The DT source neutrons contribute 46%, and 100% of the first wall atomic displacements and helium production, respectively.

Nuclear Heating

Accurate determination of energy deposition in the different regions of the FW and shield is essential for performing the thermal-hydraulics analysis. While the thermal performance of the first wall is influenced primarily by the surface heat flux, nuclear heating deposited volumetrically is the main driver for the thermal performance of the shield. The neutron energy multiplication for the ARIES-III first wall and shield was calculated to be 2.2. This value was calculated using the mixed neutron source spectrum of ARIES-III with 75% of the neutron power being carried by 14.1 MeV neutrons and the rest carried by 2.45 MeV neutrons. Notice that the energy multiplication in ARIES-III is higher than that achieved in D-T reactors due to the large energy multiplication for the 2.45 MeV DD component of the neutron source spectrum calculated to be 4.37. The energy multiplication for the 14.1 MeV DT component of the spectrum is 1.47. Based on a total neutron power of 109.5 MW generated in the plasma, the amount of nuclear heating in the FW and shield is estimated to be 241 MW. 84.5% of the total nuclear heating is contributed by gamma heating. Nuclear heating represents only 8% of the total thermal power of ARIES-III. Most of the nuclear heating is deposited in the FW and front 20 cm of shield. The radial variation of nuclear heating in the outboard first wall and shield at the reactor midplane is shown in Fig. 3. The peak power densities in the FW are 2.37 and 2.18 W/cm^3 in the outboard and inboard regions, respectively. The peak power densities in the beryllium coating are 2.06 and 1.93 W/cm^3 for the outboard and inboard regions, respectively.

Thermal Hydraulics

The high capital cost and the high recirculation power requirement of a D-^{3}He reactor dominate the selection of the thermal design point of the ARIES-III reactor. The thermal efficiency of the power conversion system has to be maximized. Thus, both the maximum coolant temperature and the average coolant temperature have been pushed as high as possible. Based on organic cooled fission reactor experience, 425°C is selected as the coolant outlet temperature. To reduce the size of the steam generator, a coolant inlet temperature of 350°C is selected for the ARIES-III study. The pinch point ΔT will be 15°C. The steam temperature is 399°C, and the steam pressure is 17.3 MPa. The anticipated cycle efficiency is 44%.

The heat transfer coefficient of the organic coolant is less than that of water, primarily due to the much lower thermal conductivity. To improve heat transfer, fission reactor applications used high coolant velocity and small coolant channels. The size of the ARIES-III first wall coolant channel is selected to be 0.8×0.6 cm. This size is selected from the tradeoff between pressure drop and heat transfer. With the energy deposited along the coolant tube, and the selected coolant inlet and outlet temperatures, the coolant velocity is calculated to be 16 m/s.

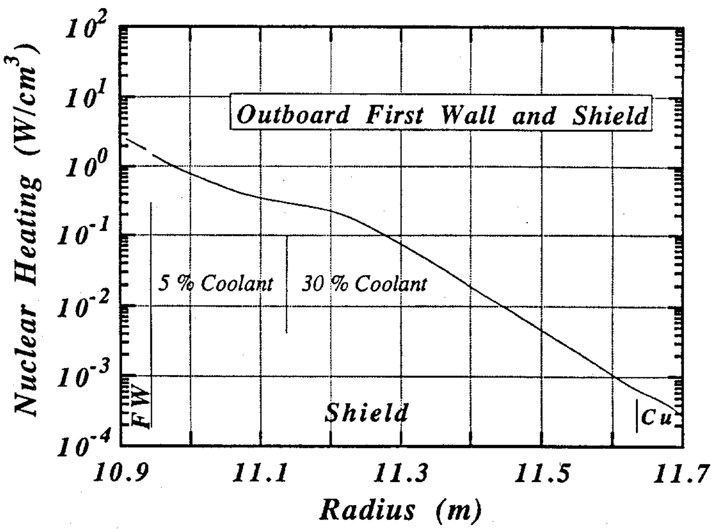

Fig. 3. Spatial variation of power density in the outboard FW and shield.

Table I. Thermal Hydraulics Parameters

First wall configuration	Poloidal flow, once through
Coolant path length	8 m
Max. first wall heat load	1.86 MW/m^2
Coolant tube dimensions	0.6×0.8 cm
Inlet temperature	350°C
Exit temperature	425°C
Max. Be temperature	571°C
Max. steel temperature in FW	531°C
Thermal energy per tube	126 kW
Coolant velocity	16 m/s
Re number	1.63×10^5
Max. heat transfer coefficient	2.19 W/cm^2-°C
Max. coolant film ΔT	128°C
Coolant pressure drop	1.6 MPa
Coolant pressure	2.6 MPa
Pumping power	9 MW

The ARIES-III reactor has a very high surface heat load. In addition, the second stability plasma pushes the plasma axis toward the outboard FW. Therefore, there is a very high peaked surface heat load at the middle point of the outboard FW. To reduce this peak heat load, the outboard scrape-off zone thickness at midplane is increased to 90 cm. This reduces the maximum heat flux from 2.8 MW/m^2 to 1.86 MW/m^2. This heat load can be handled by the organic coolant with the conditions described here. Two-dimensional finite element analysis of the FW and shield has been carried out using ANSYS [7] and utilizing the nuclear heating profiles. At the midplane where the surface heating peaks, the combined primary and secondary stresses are 353 MPa at a bulk steel temperature of 497°C. The peak Be coating temperature is 571°C and the interface between W and Be is at 531°C. These values satisfy the thermal stress and peak temperature requirements for these materials. The thermal-hydraulics parameters are summarized in Table I.

Coolant Decomposition

Organic coolants decompose due to both temperature and radiation. The pyrolytic decomposition is temperature dependent. Therefore, the reactor design has to minimize the coolant in the high temperature region. The ARIES-III coolant passes through the shield first to absorb the neutron power and then through the FW to absorb the surface heat. Thus, all the coolant in the shield is near the coolant inlet temperature. To minimize the coolant in the primary loop, the coolant temperature rise is maximized

Table II. Organic Coolant Decomposition Summary

Radiolysis yield	171 kg/hr
In reactor pyrolysis	43 kg/hr
Out of reactor pyrolysis	264 kg/hr
Total decomposition rate	478 kg/hr
Recoverable (90%)	430 kg/hr
HB waste	48 kg/hr

to reduce the coolant flow rate. The total coolant volume inside the reactor is 188 m^3 and the coolant volume in the primary loop outside the reactor is 167 m^3. The radiolytic decomposition rate depends on the absorbed dose rate. The total absorbed dose rate in the organic coolant was calculated to be 1.05×10^{26} eV/s. The decomposition rate of the organic coolant is summarized in Table II. The total decomposition rate is 478 kg/hr. A hydro-cracking process was developed for processing the decomposition waste [5]. It has been demonstrated that 90% of the waste can be recovered. Therefore, only 48 kg/hr of the organic coolant decomposed waste has to be disposed of by incineration.

Tritium Production

Neutronics calculations have been performed to determine the tritium production rates in the different components of the FW and shield. Tritium is produced in the 1.5 mm thick beryllium coating at the rate of 67.5 Ci/d. Tritium is produced also as a result of (n,t) reactions with the constituent elements of the modified HT-9 structure. The total tritium production rate in the steel structure is 7.4 Ci/d. Deuterium and helium-3 particles from charge exchange of the edge plasma will impinge on the FW. It was estimated that the FW structure will saturate with inventories of about 20 grams of deuterium and 0.14 grams of helium-3. Neutron interactions with deuterium and helium-3 will produce tritium at the rates of 80 μCi/d and 3.6 Ci/d, respectively. Tritium is produced in the organic coolant as a result of neutron interactions with the constituent elements of the coolant. This is mainly due to (n,γ) reactions with the naturally existing deuterium in the organic coolant. In addition, tritium can be produced as a result of neutron double capture in the hydrogen by converting it first to deuterium via the (n,γ) reaction followed by (n,γ) reactions with the produced deuterium. The maximum tritium production rate in the coolant at reactor end-of-life is 1.6 mCi/d. This is a very small amount compared to tritium production rates in the beryllium coating and steel structure. Hence using the organic coolant in ARIES-III results in negligible tritium production.

Tritium will be released to the atmosphere as a result of incinerating the decomposed organic coolant waste. The tritium release rate to the environment will depend on tritium permeation into the coolant. A conservative estimate was made by assuming that all tritium produced in the FW and shield will diffuse to the coolant except for the beryllium coating where two-thirds of the tritium produced is assumed to go back to the plasma. Hence, the total tritium release rate is estimated to be 33.5 Ci/d. This results in an acceptable off-site effluent dose rate < 1.3 mrem/yr at 1 km from the reactor.

Activation Analysis

Detailed activation analysis has been performed for the MHT-9 and organic coolant in ARIES-III using the DKR-ICF code [8]. The total structure activity at shutdown is 1548 MCi and drops to 863 and 254 MCi in one day and one year following shutdown, respectively. The total decay heat at shutdown is 4.91 MW and drops to 1.43 MW in one day and 0.21 MW in one year. The MHT-9 shield qualifies as Class A low level waste after a waiting period of 15 years required for the specific activity of short-lived nuclides ($T_{1/2} \leq 5$ years) to drop below 7000 Ci/m^3. The Class A waste disposal rating (WDR) is 0.74. The Class C WDR value is only 0.053, one year after shutdown. The activity produced in the coolant was determined for the worst case with the coolant saturated with nitrogen and oxygen from the air. The constituent elements of the coolant (H and C) and the impurities do not produce significant radioactivity. ^{14}C is produced from N at the rate of 1.1 Ci/year and reaches an equilibrium level of 0.83 Ci in less than a year as a result of the continuous removal of decomposed coolant. This corresponds to a ^{14}C equilibrium concentration of less than 2.5 mCi/m^3 in the coolant.

Summary

The reduced neutron yield for a D-^{3}He fuel cycle reduces radiolytic decomposition and allows organic coolants to be used. In addition, organic coolants are capable of achieving high thermal efficiencies and have good heat removal capabilities required due to the high surface heat flux. Organic coolant at a pressure of 2.6 MPa and inlet and outlet temperatures of 350 and 425°C is used in ARIES-III. The low activation modified HT-9 alloy is used as structural and shielding material allowing the radwaste to qualify as Class A waste. The total inboard first wall and shield thickness required for protecting the TF coils is 65 cm. The first wall is coated by a 1.5 mm layer of beryllium which is separated from the steel wall by a 100 μm layer of tungsten. The first wall is subjected to a high surface heat flux with a peak of 1.86 MW/m^2. The steel front layer of the first wall is 1 mm thick resulting in a maximum temperature of 531°C and acceptable thermal stresses. The end-of-life peak damage is only 63 dpa implying that no change-out is required. The decomposed waste resulting from pyrolysis and radiolysis is produced at a rate of only 48 kg/hr. Tritium released to the environment yields < 1.3 mrem/yr offsite effluent dose rate. Coolant activity is negligible and the radwaste qualifies as Class A low level waste.

Acknowledgements

This work has been supported by the U.S. Department of Energy.

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