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ORGANIC COOLANT FOR ARIES-III*

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ABSTRACT

ARIES-III is a D-He₃ reactor design study. It is found that the organic coolant is well suited for the D-He₃ reactor. This paper discusses the unique features of the D-He₃ reactor, and the reason that the organic coolant is compatible with those features. The problems associated with the organic coolant are also discussed.

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I. INTRODUCTION

Organic coolant has been considered as the coolant for fission reactors. The key advantage of organic coolant over water is its capability to operate at a higher temperature ($\sim 400^{\circ}\text{C}$) at much lower pressure ($\sim 1\text{MPa}$). The only electric generating organic cooled fission reactor was PIQUA.[1] It operated between 1963 and 1966. However, problems associated with the polymerization in stagnant region of the moderator forced its shutdown in 1966.

It was recognized that velocity control was a key factor on fouling control. Therefore, the WR-1 reactor, which was built in the Whiteshell Nuclear Research Establishment, used the organic coolant only as the coolant, while selected the heavy water as the moderator.[2] The WR-1, a 60 MW(t) reactor, operated successfully for over 20 years until its shutdown in 1985. During this period of operation, useful experience of operating an organic coolant system had been generated. This experience included coolant chemistry control, coolant decomposition characteristics, fouling control etc. This experience is used for the application of the organic coolant to a fusion reactor system.

The organic coolant has been considered in the D-T fusion reactor design study. However, the radiation decomposition rate was judged to be too high.[3,4] For a D-He₃ reactor, such as the recently completed ARIES-III design study, the neutron production rate is a factor 50 lower than that of a D-T reactor. Therefore, organic coolant becomes possible. Some unique requirements of a D-He₃ reactor first wall and shield also lead to the use of organic coolants. The first is that the plasma requires a highly conductive first wall. The coating materials

selected to provide this conductivity is Be. The Be coating limits the first wall temperature, and it also limits the coolant temperature. The second requirement is due to the large recirculation power of the plasma. Thus, D-He₃ reactor requires an efficient power conversion system. This requirement of efficient power conversion with a limited temperature makes organic coolant a logical choice for D-He₃.

II. UNIQUE FEATURE OF D-He₃ REACTOR

There are three unique features of D-He₃ reactor which have major impact on the first wall and shield design.

A. First Wall Heating Load

For a D-T reactor, 80% of the fusion energy is in the neutrons. Thus, only 20% of the fusion energy will be deposited on the first wall and the divertor surface. For a D-He₃ reactor, over 90% of the fusion power will be deposited on the surface. To keep the reactor in reasonable size, the heat flux to the first wall and divertor will be large. Therefore, a coolant with good heat transfer capability is required.

B. First Wall Reflectivity

A highly conducting first wall is required for synchrotron radiation reflection. High synchrotron reflection is needed for plasma power balance. For the ARIES-III design, the first wall synchrotron reflectivity required is 0.99. To achieve this reflectivity, Be was selected. (W could also be used, but only at a temperature of a few hundred degree C.) To limit the evaporation of the Be, a maximum Be temperature of 750°C was selected. This maximum allowable Be

temperature put severe limitations on the temperature of the first wall and coolant.

C. Plasma Recirculation Power

The ARIES-III reactor operates in the second stability plasma region. A large power is required for plasma current profile control. This large power requirement results in engineering Q at only 4.1. Therefore, an efficient power conversion system is required.

Organic coolant is thus selected for the ARIES-III design due to its high heat transfer capability and its potential to achieve high thermal converting efficiency at a modest coolant temperature.

III. ORGANIC COOLANT CONCERNS

There have been some major concerns about organic coolant. However, those concerns have been resolved from the operating experience of the WR-1 reactor.

A. Decomposition

The organic coolant decomposes due to both radiation and temperature. The decomposition rates can be predicted.[5] The decomposition product actually makes the organic coolant more stable as can be seen in Table 4. The decomposition product can be recovered by the hydro-cracking process.[6] For a typical organic cooled fission reactor, the decomposition rate is about 500 kg/hr, out of which about 90% can be recovered. Decomposition will cause only a minor economic penalty.

B. Fouling

Fouling of the heat transfer surface was a real concern for the fission reactors. However, chemistry control and flow condition control

standard have been established from the WR-1 experience. Those conditions were maintained in the WR-1 reactor routinely.

Table 1 shows the impurity levels which have to be kept in the organic coolant.[5] Of particular importance is the level of the Cl. It was shown that significant fouling could occur at a Cl concentration of 100 to 1000 μ -g/g. Therefore, an upper limit of 50 μ -g/g was established.

Water is continuously added and removed from the coolant. The water would pick up the Cl from the organic coolant so that it was used as the Cl control. As will be discussed later, this water stream could also be used for a tritium control system, if is necessary.

Table 2 shows the flow condition required to control fouling. As can be seen later, this flow condition can easily be maintained.

C. Flammability

Organic coolant burns in air. The combustion temperature is estimated to be about 1000°C. However, the combustion process is slow, and the combustion temperature is modest. In addition, if the building atmosphere is maintained with < 12% oxygen, the organic coolant can not be ignited.

IV. THERMAL HYDRAULICS

Table 3 compares the heat transfer capability of organic coolant to that of water. The velocity used for the organic coolant is 20 m/sec, based on the WR-1 experience. The velocity used for water is 10 m/sec, based on light water reactor experience. The coolant material properties are taken from ref. [4].

As can be seen from this table, the organic coolant has a larger hDT compared to water, but smaller h . For the first wall, the heat transfer boundary condition is constant heat flux. The key parameter governing heat transfer is hDT . Since water is used very near the critical temperature, it has a small film DT , typically $20^{\circ}C$. On the other hand, the organic coolant can have a much larger film DT . Therefore, the organic coolant has a larger heat transfer capability under constant heat flux condition than water, even though the heat transfer coefficient is much smaller. In the steam generator design, the boundary condition is constant temperature difference. There, the heat transfer coefficient is the key parameter. Water has a much better heat transfer capability than the organic coolant under this condition.

The higher coolant velocity of the organic coolant requires a much higher pressure drop than that required by the water. However, the pumping power required are small in both cases.

V. DECOMPOSITION

Organic coolant decomposes due to both temperature and radiation. The decomposition rates have been established and are summarized on Table 4.[5]

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 200 MW neutron power, and then to the first wall to absorb the first wall power, as shown on Fig. 1. Thus, all the coolant in the shield is near the coolant entrance temperature. To minimize the coolant in the

primary loop, the coolant temperature rise is maximized to reduce the coolant flow rate.

The radiolysis decomposition rate depends on the rate of energy deposition (dose rate). In a fusion reactor, energy is deposited in the coolant as a result of neutron and gamma photon interactions with the constituent elements of the organic coolant. These elements are hydrogen and carbon for the organic coolant. Neutrons come directly from the fusion reactions in the plasma while the gamma photons result from neutron reactions with the reactor material. The energy deposition rate per unit volume of the coolant varies spatially in the first wall, blanket and shield of a fusion reactor. It is highest in the high neutron flux first wall and decreases as one moves deeper in the blanket and shield away from the plasma due to the reduction and softening (reduced energy) of the neutron flux. Hence, in order to reduce the total absorbed dose rate and consequently the radiolytic decomposition rate, it is essential to reduce the organic coolant content in the high flux zones without jeopardizing heat removal. In the D-He₃ fusion reactor ARIES-III, the organic coolant is used to remove the heat from the ferritic steel first wall and shield. Although the shielding optimization indicated that the optimum coolant content is 30%, only 5% coolant is used in the front 20 cm of the shield to reduce the total absorbed dose rate as shown in Fig. 1. Because of the high surface heat flux in D-He₃ reactors, a relatively large coolant volume fraction of 80% is used in the first wall. Although the coolant in the first wall represents only 4% of the total coolant volume, 60% of the total absorbed dose is contributed by the first wall. The front 20 cm thick

zone of the shield contributes 25% of the total dose. The total absorbed dose rate in the organic coolant is 1.13×10^{26} eV/s. Only 15% of this dose results from gamma photon interactions with the coolant and the rest is due to neutron interactions. Based on this dose rate, the radiolytic decomposition rate for the organic coolant of ARIES-III is estimated to be 170 kg/hr.

The decomposition rate of the organic coolant is summarized in Table 5. The total decomposition rate is 478 kg/hr, which is comparable to the decomposition rate for a fission reactor with similar power output. A hydro-cracking process was developed for processing the decomposition waste.[6] It has been demonstrated that 90% of the waste is recoverable and reused. The 10% waste product will be disposed by incineration.

VI. TRITIUM PRODUCTION

In a nuclear environment, 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. In ARIES-III, 7 kg of deuterium exist initially in the organic coolant based on the natural abundance of deuterium in hydrogen. Additional deuterium is produced during reactor operation at the rate of 0.12 kg per full power year (FPY) due to the $H(n, \gamma)D$ reaction. Deuterium builds up on the

coolant to 10.6 kg at end-of-life of the ARIES-III reactor (30 FPY) if no coolant reprocessing is employed. The maximum tritium production rate in the coolant at reactor end-of-life is determined to be 8×10^{-5} g/FPY which corresponds to 2.2 mCi/d. This is a very small amount compared to tritium production rates in the beryllium coating and steel structure which are 73 and 8 Ci/d, respectively. Hence using the organic coolant in fusion reactors results in negligible tritium production.

The tritium produced will be distributed between the organic coolant, the decomposition waste, and the water stream added for Cl control. Calculations indicated that the tritium produced can be released as part of the waste. If the tritium release needs to be reduced, a water distillation system can be used to recover the tritium from the water. The cost of such a system is only about 10 M\$, based on the ITER cost scaling.[7]

VII. COOLANT ACTIVATION

Induced radioactivity can be produced in the organic coolant in a nuclear environment. The level of activity as well as the contributing radionuclides depend on the constituent elements and impurity levels in the coolant. The constituent elements of the organic coolant (hydrogen and carbon) do not lead to the production of radionuclides of concern. The impurity levels in the organic coolant are very low. The major impurities are iron and silicon which were detected at levels up to 100 ppb and 600 ppb, respectively. Much lower levels were detected for other elements. The induced radioactivity associated with organic

coolant impurities was found to be very low in the nuclear environment of ARIES-III. For example, ^{60}Co is produced at the rate of only 19 mCi/yr. An additional source of activity in the coolant can result from activating the nitrogen and argon present in the coolant after being in contact with air. In order to quantify this, we considered the worst case with the 400°C coolant assumed to be saturated with nitrogen and argon from air at atmospheric pressure. This results in N and Ar concentrations of 80 $\mu\text{g}/\text{cm}^3$ and 1.3 $\mu\text{g}/\text{cm}^3$, respectively. Activation calculations for this worst case in ARIES-III resulted in a coolant activity of 500 Ci at shutdown following a continuous reactor operation of 30 FPY without coolant reprocessing. This is much lower than the total first wall and shield activity of 1600 MCi at shutdown. The long term ^{14}C activity resulting from the (n,p) reaction with nitrogen is produced at the rate of 1.2 Ci/yr and will reach an equilibrium level of only 0.9 Ci in less than a year as a result of continuous removal of decomposed coolant. This corresponds to a very low ^{14}C specific activity of 2.5 mCi/m 3 .

VIII. POWER CONVERSION

Due to the large recirculation power required by the D-He $_3$ plasma, an efficient power conversion system is desirable. However, the coolant temperature is severely limited by the first wall conducting requirement. It is a major challenge to achieve an efficient power conversion with a limited temperature. Lewis [8] proposed that if organic coolant could be heated up to 425°C, a power conversion system can be designed with a gross efficiency of 44%. The flow diagram of

this system is shown in Fig. 2. It uses two reheat and 10 feed water heaters. It was judged that this power conversion is possible, but may be expensive due to the large number of heat exchangers required. Due to the high capital cost of the fusion power, and the high recirculation power of the D-He₃ plasma, it is decided that the high efficiency can off-set the cost of the power cycle.

The power balance of the ARIES-III reactor is shown in Table 6, together with the power balance of a water cooled version of the same reactor. Even with 44% gross efficiency, the net efficiency of the ARIES-III reactor is only 33%. If water is used as the coolant, the net efficiency would be only about 25%, which is clearly not acceptable.

IX. CONCLUSIONS

Due to the low radiation yield, the organic coolant appears to be ideal for a D-He₃ reactor. The organic coolant has good heat transfer capability. It can operate at a reasonably high temperature with a moderate pressure. The activation is low. the engineering problems associated with the use of the organic coolant in the D-He₃ reactor have been evaluated. It has been concluded that the major concerns regarding the organic coolant can be resolved.

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Table 1. Impurity Level Limits.

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1. Cl < 50 $\mu\text{g/kg}$
 2. O < 200 $\mu\text{g/g}$
 3. 200 $\mu\text{g/g}$ < H₂O < 600 $\mu\text{g/g}$
 4. Fe < 500 $\mu\text{g/kg}$
 5. Particulates < 1000 $\mu\text{g/kg}$
-

**Table 2. Flow Conditions Required
for Organic Coolant.**

Channel velocity	> 4.1 m/s
Channel NRe	> 2.2×10^4
Channel h	> 8500 W/m ² · °K

Table 3. Comparison of Heat Transfer Capabilities
of Organic Coolant and Water.

	Organic Coolant	H ₂ O
Density (kg/m ³)	850	800
Viscosity ($\times 10^{-4}$ kg $\cdot$ m ⁻¹ $\cdot$ s ⁻¹)	6	0.8
Thermal conductivity (W $\cdot$ m ⁻¹ $\cdot$ K ⁻¹)	0.11	0.6
Specific heat (J $\cdot$ kg ⁻¹ $\cdot$ K ⁻¹)	2500	6000
Velocity (m $\cdot$ s ⁻¹)	20	10
Diameter (m)	0.01	0.01
Re	2.8×10^5	1×10^6
Pr	13.6	0.8
Nu	2136	1347
Heat transfer coefficient, h (W $\cdot$ m ⁻² $\cdot$ K ⁻¹)	2.35×10^4	8.1×10^4
Typical heat transfer ΔT , (K)	100	20
$h\Delta T$	2.35×10^6	1.62×10^6

Table 4. Coolant Decomposition Rate.

Total rate: $D = D_r + D_p$

Radiolysis rate:

$$D_r = C_r (100 - \text{HB})^2 \times (\text{Absorbed dose rate})$$

$$\text{where } C_r (100 - \text{HB})^2 = 0.0096 \text{ kg} \cdot \text{h}^{-1} \cdot \text{kW}^{-1}$$

for 40 wt.% HB and the WR-1 neutron spectrum.

Pyrolysis rate:

$$D_p = \Sigma (\text{Coolant mass at temperature } T) \times K_p (T) \times (100 - \text{HB})$$

$$\text{where } K_p = 2.14 \times 10^9 e^{-21767/T} \text{ kg/h per kilogram of coolant}$$

Table 5. Organic 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

Table 6. Comparison with Water Cooled Reactor.

	OC	Water
Net Electrical Power	1000 MWe	1000 MWe
Recirculating Power	341 MWe	341 MWe*
Gross Electrical Power	1341 MWe	1341 MWe
Gross Thermal Efficiency	44%	35%
Reactor Thermal Power	3087 MW	3831 MWe
Net Thermal Efficiency	33%	26%

*The recirculating power for water cooled system will be larger due to the high fusion power. If the recirculating power is proportional to fusion power, the net efficiency will be ~24%.

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Figure 1. Midplane Cross Section of Outboard Shield Module.

Figure 2. ARIES-III Steam Cycle.

**MIDPLANE CROSS SECTION OF OUTBOARD
SHIELD MODULE**