Initial Nuclear Assessment for a Low Aspect Ratio Power Plant

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INITIAL NUCLEAR ASSESSMENT FOR A LOW ASPECT RATIO POWER PLANT

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ABSTRACT

Recent interest in the low aspect ratio (LAR) concept has led the U.S. ARIES team to examine the credibility of this advanced concept as a future source of fusion energy. The compactness of the LAR machine imposes severe constraints on the Cu center post (CP) which thus plays an important role in the design. In view of the fact that the machine operates for 40 y with a relatively high neutron wall loading of 4 MW/m^2, the CP will be operating in a severe radiation environment for an extended period of time. The analysis indicated that the lifetime of the CP is limited by the Class C low level waste disposal requirements. Identification of potential radioactive waste problems for the Cu conductor has resulted in either limiting the lifetime of the unshielded CP to 0.12 FPY (corresponding to a fluence of 0.3 MWy/m^2) or shielding the CP with 20-30 cm of shield. Since it is not feasible to replace hundreds of tonnes of Cu every 2 months, the CP should be shielded to prolong the lifetime to 4 years or more, reduce the cumulative radwaste and replacement cost, increase the system availability, and alleviate most of the CP radiation damage problems. We have assessed the effects of neutron fluence on conductor resistivity, swelling, and atomic displacement. Even though the radiation-induced swelling and changes to Cu resistivity due to transmutations are small at 0.3 MWy/m^2, there is serious concern about the degradation of properties as all Cu alloys experience hardening and loss of ductility under neutron irradiation.

I. INTRODUCTION

A preliminary scoping study was performed to identify the critical physics and engineering issues of the LAR concept in the context of a power plant.[1,2] The engineering activities included the material, structural, nuclear, and economic performance of the device. The work reported here covers the neutronics, activation, and shielding aspects of the design. The CP dominates the nuclear assessment. Minimizing the radial build is well-known to be important for the overall success of the concept. As the CP presents important design problems to the designers, most of this work was devoted to the CP with little attention paid to the outboard and divertor regions. It was important to identify potential radiation-induced effects and failure mechanisms so that the CP lifetime could be reasonably predicted. Thus, a scoping analysis was performed for a preliminary configuration for the LAR machine in order to guide the design toward the final configuration shown in Fig. 1.

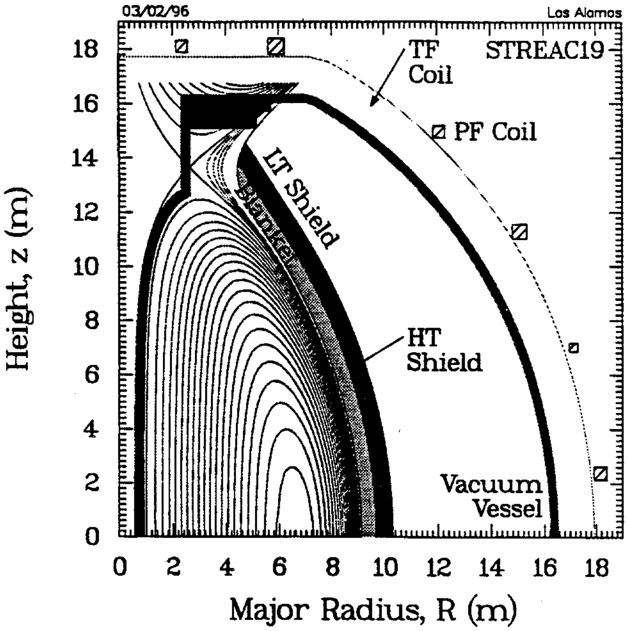

Fig. 1. Vertical cut through the LAR device (courtesy of C. Bathke [LANL]).

To illustrate how severe the radiation damage and activation levels are for the unshielded CP, the device was modeled for nuclear analysis with no intervening shield between the plasma and the CP. For the coil, there are concerns with mechanical degradation of Cu due to radiation damage, increase in Cu resistivity due to neutron-induced transmutations, and activation of Cu leading to an unacceptable level of radioactive waste. Unacceptable radiation damage or activation problems require redesign of the CP with inboard shield to ensure the operational integrity of the coil and, more importantly, to meet all the top level requirements developed by the ARIES team for U.S. fusion power plants. Generally, the U.S. designs emphasize the safety and environmental aspects of fusion and provides a strong incentive to generate low radwaste, not greater than Class C.

II. DESIGN PARAMETERS

The preliminary configuration calls for a meter diameter CP composed of 70% dispersion-strengthened copper alloy with 0.25 wt% Al (DS GlidCop Al25) and cooled with 30% water at an average temperature of 66°C. The maximum temperature of Cu is kept below 100°C. The CP is a single turn conductor, connects at the top/bottom to the outer legs of the 16 TF coils, and is the conduit for the return electric current for all coils. The peak inboard wall loading occurs at the midplane at a value of 3.6 MW/m^2. The poloidal average neutron wall loading over the CP is 2.5 MW/m^2. The total height of the CP for this preliminary case is 16 m. The CP is protected by a 1.4 cm thick heat removal surface. The machine has an aspect ratio of 1.25 and generates a net electric power of 1 GW.

The neutronics model employed the 1-D transport code ONEDANT[3] with the P_3 legendre expansion for the scattering cross section and the S_8 angular quadrature set. The associated 46 neutron and 21 gamma group cross section library was derived from the ENDF/B-V evaluation. The problem was modeled in toroidal cylindrical geometry around the machine axis and calculations were carried out to investigate the various responses of interest.

III. WASTE DISPOSAL RATING

The activation calculations were conducted using the DKR-ICF computer code[4] with activation cross sections taken from the USACT93[5] library and radial neutron flux distribution generated by ONEDANT. The neutron transmutation data used is in a 46-group structure format. The center post activation results were utilized in the radwaste classification. The radwaste of all alloys were evaluated according to both NRC 10CFR61[6] and Fetter's[7] waste disposal concentration limits. The Class C waste disposal ratings (WDR) for the center post as a function of operation time are given in Table I.

TABLE I

Class C Waste Disposal Rating for the
DS GlidCop Al25 Center Post
(2.5 MW/m^2 and 1 y Cooling Off Period)

Time of Operation	Fetter's Limits	NRC Limits
6 months	2.64 2.56 (^{108m}Ag), 0.081 (^{26}Al)	4.11 ^{63}Ni
1 year	4.94 4.76 (^{108m}Ag), 0.16 (^{26}Al)	8.53 ^{63}Ni
3 years	12.2 11.6 (^{108m}Ag), 0.48 (^{26}Al)	29.1 ^{63}Ni

The philosophy adopted by the ARIES team is that all U.S. fusion power plants should meet both NRC and Fetter's limits for Class C low level waste (LLW) until the U.S. Nuclear Regulatory Commission (NRC) develops official guidelines for fusion. Class C waste should have a WDR below one. As shown in Table I, the center post will not qualify for disposal as LLW regardless of the time of operation or the limits used. Note that ^{63}Ni ($T_{1/2}$ = 100 y) is dominating the WDR according to NRC. Longer cooling off periods of 10 y or more will not change the WDR for such long lived radionuclides. ^{63}Ni is produced directly from Cu while Ag is an impurity and Al is an additive to the GlidCop alloy. Since ^{63}Ni is generated by Cu, using different Cu alloys would not make a difference in the WDR. Reducing the silver content in the Cu alloy (currently at 20 wppm) by an order of magnitude would allow for the disposal of the CP after 1 FPY as LLW according to Fetter's limits only.

Table I indicates that the NRC limits are more stringent and will thus be used to determine the CP lifetime and shielding requirements. In order to dispose of the CP as Class C LLW, the CP should be subjected to a lower fluence of 0.3 MWy/m^2. Since the economics mandate operating at high neutron wall loading, it is therefore necessary to either limit the CP lifetime to 0.12 full power year (FPY), or shield the CP for longer life. It was estimated that in order

TABLE II

Transmutation Products Produced
in the Unshielded Center Post
(in appm at 0.12 FPY)

Nuclide	Peak	Average
Ni	2108	360
Co	23.6	2.6
Zn	1258	259

to replace the CP every 3 FPY (same as blanket) or more, the WDR should drop by a factor of > 30. This could be achieved by placing 20–30 cm of shield between the plasma and CP. The shielded CP will thus have an end-of-life fluence of 0.3 MWy/m^2 or less.

IV. RADIATION-INDUCED CHANGES TO Cu RESISTIVITY

Neutron irradiation will increase the Cu resistivity due to the production of neutron-induced transmutations, defects, and dislocations. The resistivity effect due to radiation damage is small compared to those due to transmutations[8] due to the fact that a large fraction of the defect-induced resistivity is expected to anneal out at the operating temperature of the CP (∼ 100°C). Moreover, the defect-induced resistivity saturates at low fluence while the transmutation-induced resistivity scales somewhat linearly with fluence. Increasing resistivity with time means increasing power dissipation in the coil, leading to higher recirculation power, lower net efficiency, and a larger machine.

At any instant of time, the two stable isotopes of copper (69.2% Cu^{63} and 30.8% Cu^{65}) interact with neutrons and give rise to transmutation products. The reactions of interest are Cu (n, H) Ni, Cu (n, α) Co, Cu (n, γ), and Cu $(n, 2n)$. The last two reactions produce unstable Cu isotopes that emit β leading to Zn and Ni stable isotopes. The time-dependent inventory of both stable and unstable Ni, Co, and Zn isotopes is computed using the activation code DKR-ICF. The transmutation products will continue to build up. Depending on the lifetime of the CP, the effect could be very significant. After 0.12 FPY (the maximum lifetime allowed for the unshielded center post to meet Class C waste disposal limits), the peak and average nuclide productions are listed in Table II. The peak values represent the maximum values obtained at the center post plasma facing surface having a peak wall loading of 3.6 MW/m^2. The average values are calculated for an average wall loading of 2.5 MW/m^2 and averaged radially over the center post ($R = 51$ cm).

TABLE III

Percentage Increase in Cu Resistivity of
Unshielded CP at 0.12 FPY

Nuclide	Peak	Average
Ni	13.8	2.36
Co	0.88	0.1
Zn	2.21	0.45

TABLE IV

Radiation Damage to Unshielded Center Post

	Peak	Average*
Neutron wall loading (MW/m^2)	3.6	2.5
Atomic displacement (dpa/FPY)	48	8
Helium production (appm/FPY)	540	130
Hydrogen production (appm/FPY)	2,840	330
Nuclear heating	100 W/cm^3	160 MW

*For Cu/H$_2$O homogeneous mixture

It should be mentioned that the inventory of transmutations that is used to calculate the change in the CP Cu resistivity should be based on the average value, not on the peak. The average value is quite lower (factor of ∼ 6) than the peak which occurs at the midplane outermost layer of the CP. The difference is due to the exponential attenuation of the neutron flux with radial distance through the coil and the vertical drop of the neutron wall loading over the height of the CP. The outermost layer of the CP exhibits a large inventory of ^{62}Ni, ^{64}Ni and Co produced by $(n, 2n)$ and (n,α) reactions which have threshold energies of 9 and 5 MeV, respectively. These reactions decrease rapidly within the coil. The resulting resistivity change in the Cu conductor can then be computed from the transmutations using a linear combination of the induced resistivity from the different elements as given by the relation:

$$\rho = \rho_{\mathrm{Cu}} + \sum_i \rho_i \, A_i$$

where ρ_i and A_i are the specific resistivity (in Ωm) per atom percent and the atom percentage of the transmutation product i, respectively. The room temperature resistivity of Cu and the specific resistivities of Ni, Co, and Zn are 1.71×10^{-8}, 1.12×10^{-8}, 6.4×10^{-8}, and 3×10^{-9} Ωm, respectively.[9]

The percentage increases in Cu resistivity due to Ni, Co and Zn transmutations are listed in Table III. Ni has the highest impact on Cu resistivity followed by Zn and then Co. The average change in Cu resistivity amounts to $\sim$ 3% at 0.12 FPY implying that the power dissipation in the unshielded CP due to transmutation-induced resistivity is small compared to the intrinsic ohmic losses in the CP. The same conclusion holds true for the case of shielded CP which is subjected to ~ 0.3 MWy/m^2 fluence at a much softer neutron spectrum. The softer spectrum will result in a significant reduction in the high energy neutron-induced transmutations generated by the $(n, 2n)$ and (n, α) reactions. Thus, the shielded CP will experience an even lower change ($< 3\%$) in resistivity due to transmutations. It is pertinent to mention that for longer times of operation the transmutations will continue to build up leading to a large change in Cu resistivity and a significant increase in ohmic losses. For example, 0.3 at.% Ni and 0.2 at.% Zn would exist in the unshielded CP after one FPY of operation, contributing 25% additional ohmic losses.

V. ATOMIC DISPLACEMENT AND EMBRITTLEMENT OF Cu ALLOYS

There is serious concern about ductility degradation of the Cu conductor under irradiation. The DS GlidCop Al25 alloy proposed for the CP undergoes rapid radiation hardening and loss of ductility at irradiation temperatures below 200°C. Recent irradiation data showed rapid embrittlement of all Cu alloys and complete loss of work hardening by 0.1 dpa[10]. The 0.1 dpa is reached for the unshielded CP after one day of operation. For longer times of operation, the Cu will be extremely brittle. Thus, the Cu will have no structural integrity and design rules for brittle material should be used in designing the CP. The effects of microcracking on resistivity need to be assessed.

The radiation damage to the unshielded CP is listed in Table IV for an arbitrary operation time of 1 FPY. The peak values are evaluated at the midplane for a peak inboard wall loading of 3.6 MW/m^2. The average values are 4-8 times lower than the peak. This reduction is due to the radial attenuation of the neutron flux over the 50 cm thick CP and the vertical drop in wall loading over the inboard side. At 0.12 FPY, the peak value is 6 dpa for the unshielded CP. Using a 20–30 cm shield to protect the CP will result in a slightly lower peak value than 6 dpa.

Present knowledge of the annealing process indicates that a significant fraction of the radiation damage in the Cu alloys could be removed by periodic annealing at 200–300°C for a few hours. However, this might not be feasible for power plants. Periodic annealing for a few hours after each day of operation (upon reaching 0.1 dpa) will certainly lower the availability of the system. Continuous annealing is also unacceptable due to the increase in Cu resistivity, neutron-induced swelling, and coolant corrosion at high operation temperature (200–300°C).

TABLE V

Neutron-Induced Swelling in DS GlidCop for Unshielded Center Post

Operating Temperature	Swelling Rate	Peak Swelling	Average Swelling
$<$ 180°C	$<$ 0.019 %/dpa	1%	0.16%
220°C	0.3%/dpa	14%	2.5%
250°C	0.5%/dpa	24%	4.2%

VI. SWELLING OF Cu

Experimental data showed a rapid increase in the GlidCop swelling rate in the 100-250°C temperature range of interest. Higher temperature swelling behavior is not relevant to this LAR design. Table V lists the swelling rates at various temperatures and the peak/average swelling for an arbitrary operation time of 1 FPY. The peak swelling occurs at the midplane where the wall loading peaks at 3.6 MW/m^2. The average value is a factor of 6 lower than the peak. At 0.12 FPY, the peak swelling is $< 2\%$. The shielded CP should have a lower swelling rate. It is recommended keeping the maximum temperature below 180°C to limit the swelling of Cu.

VII. SUMMARY AND CONCLUSIONS

Radiation-induced effects have a major impact on the design of the center post of LAR machines. Four radiation effects are likely to degrade the performance and thus limit the life of the CP, namely the embrittlement of Cu alloy, changes in Cu resistivity due to transmutations, neutron-induced swelling, and activation of Cu leading to high level waste. At present, the lifetime of the CP appears to be limited by the Class C waste disposal requirements.

Identification of potential radioactive waste problems for the Cu conductor has resulted in either limiting the lifetime of the unshielded CP to 0.12 FPY (for a fluence of 0.3 MWy/m^2) or shielding the CP with 20–30 cm of shield. Since it is not feasible to replace 100 tonnes of Cu every 2 months, the CP should be shielded to prolong the lifetime to 4 years or more, reduce the cumulative radwaste and replacement cost, increase the system availability, and alleviate most of the CP radiation damage problems. Interestingly, the economic analysis has indicated that the inboard shield is not a cost driver.[11] In fact, the unshielded case is more expensive than the shielded case. The smaller size of the unshielded CP machine is offset by the lower availability, higher CP replacement cost, and larger radioactive waste.

The effects of neutron fluence on conductor resistivity, swelling, and atomic displacement were assessed. Nickel and zinc productions are unavoidable in any Cu alloy. These transmutations will continue to build up and the effect on Cu resistivity could be very significant. For example, after one FPY of operation without inboard shield, 0.3 at.% Ni and 0.2 at.% Zn would contribute 25% additional ohmic losses. Even though the radiation-induced swelling and changes to Cu resistivity due to transmutations are small at 0.3 MWy/m^2, there is a serious concern on the ductility degradation and the consequences of the high atomic displacement on the conductor strength. All Cu alloys experience hardening and loss of ductility under a low level of neutron irradiation. The Cu will embrittle quite rapidly at 0.1 dpa which is reached after one day of operation for the unshielded CP and after 1–2 months for the shielded CP. Designing a CP with extremely brittle Cu alloy will be a challenging engineering task. A mechanical design which is licensable must be developed for the LAR concept. Code rules for brittle structures are unavailable, but it is likely that some additional measures will be needed to provide mechanical stability for the CP and prevent failure.

The shielded CP is the reference design for the LAR machine. The inboard shield helps improve the design in many aspects. For instance, the shield can be used to add mechanical support for the CP. The nuclear heating ($\sim$ 150 MW) can be removed as useful heat from the inboard shield, instead of being dumped at low temperature, and turned into electricity, reducing the CP thermal hydraulic problems. The shield alleviates most of the CP radiation damage problems and helps tremendously to reduce the radwaste stream, replacement cost, and changeout frequency, and increase the availability of the machine. Overall, the CP shield improves the LAR design significantly.

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