Neutron Radiation Damage Estimation in the Core Structure Base Metal of RSG GAS

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Abstract. Radiation damage in core structure of the Indonesian RGS GAS multi purpose reactor resulting from the reaction of fast and thermal neutrons with core material structure was investigated for the first time after almost 30 years in operation. The aim is to analyze the degradation level of the critical components of the RSG GAS reactor so that the remaining life of its component can be estimated. Evaluation results of critical components remaining life will be used as data completeness for submission of reactor operating permit extension. Material damage analysis due to neutron radiation is performed for the core structure components made of AlMg3 material and bolts reinforcement of core structure made of SUS304. Material damage evaluation was done on Al and Fe as base metal of AlMg3 and SUS304, respectively. Neutron fluences are evaluated based on the assumption that neutron flux calculations of U3Si8-Al equilibrium core which is operated on power rated of 15 MW. Calculation result using SRAC2006 code of CITATION module shows the maximum total neutron flux and flux >0.1 MeV are 2.537E+14 n/cm2/s and 3.376E+13 n/cm2/s, respectively. It was located at CIP core center close to the fuel element. After operating up to the end of #89 core formation, the total neutron fluence and fluence >0.1 MeV were achieved 9.063E+22 and 1.269E+22 n/cm2, respectively. Those are related to material damage of Al and Fe as much as 17.91 and 10.06 dpa, respectively. Referring to the life time of Al-1100 material irradiated in the neutron field with thermal flux/total flux=1.7 which capable of accepting material damage up to 250 dpa, it was concluded that RSG GAS reactor core structure underwent 7.16% of its operating life span. It means that core structure of RSG GAS reactor is still capable to receive the total neutron fluence of 9.637E+22 n/cm2 or fluence >0.1 MeV of 5.672E+22 n/cm2.

Keywords: RSG GAS, critical component, irradiation embrittlement, material damage, ageing component.

1. Introduction
G.A. Siwabessy multipurpose reactor (RSG GAS reactor; previous name MPR-30) is the 3rd owned and operated research reactor by National Nuclear Energy Agency of Indonesia (BATAN) after two research reactor namely TRIGA Mark II type of 2 MW power in Bandung and Kartini Research Reactor of 250 kW in Yogyakarta. RSG GAS reactor was built from 1983 and reached its first criticality on July 29th 1987, then formally inaugurated by the President of the Republic of Indonesia on August 20th, 1987. The power ascension test to achieve nominal power of 30 MWth was reached
after completion of 5th core transitions commissioning operation. This full core power configuration was achieved in March 1992. After that achievement from 7th to 30th core configuration the reactor is operated at varying rated power of 10–25 MW according to the needs. Furthermore for efficiency reasons, until now the reactor is operated at half nominal power of 15 MWth [1-4].

In the RSG GAS reactor, various irradiation tests have been carried out to develop the fuels, materials and also to produce radioisotopes for medical and industrial purposes and other experiments. Therefore a continued and scheduled reactor operation, neutron fluence and spectrum are key parameters in availability aspect and the post irradiation test analysis [5-7]. The readiness to operate RSG GAS reactor with specified accuracy’s for neutron fluence in and around core are set of each type of irradiation test as specified according its requirement. In order to meet the needs of continuity and availability of reactor operation, in RSG GAS reactor has implemented the obligations of ageing management program [8-10]. In this ageing management program document, it was mentioned that RSG GAS reactor has selected several critical components to support safety systems among others are core structures and reactor tanks. Research on material damage of reactor critical component due to neutron irradiation stressor has never been done in RSG GAS reactor. The core structure and reactor tank are made of AlMg3 material [11,12].

Aluminum alloys are a common material to be used for core structures and reactors tanks in research reactors due to its high tolerance to radiation damage, short activated total half-life, and relatively low cost. Aluminum is also a good conductor of thermal energy, making it an attractive candidate for reactor core use [13]. Researches of such material damage by highly neutron irradiated under low temperature are of paramount importance due to nuclear research reactor safety concerns [14]. Research on the AlMg3 materials damage due to neutron irradiation is still very rare and is still very little found in scientific publication reports [15]. However, research on the effects of neutron irradiation on core structural materials and pressure vessels on nuclear power reactors has been widely conducted. It has been many experimental data collected related to changes in the mechanical properties of the material at various neutron fluence and temperatures [16,17].

The need for research on the effect of neutron irradiation on various advanced materials continue to grow and become a major concern for the material research society. An accurate experimental techniques for determining displacement per atom (dpa) materials irradiated in the ex-vessel of belt line area have been widely developed in either experimental reactor [18] or power reactors [19]. A simple method to calculate the dpa of SiC an advanced material used in HTGR has also been developed by collapsed material cross section into 47 energy group structures and published in a table form as a proposed methodology that can be developed easily for other materials [20]. The correlation of microstructure change and hardening process of Fe and Fe-Cr materials for Gen IV fissions reactor material was investigated by neutrons irradiated as much as 0.01, 01 and 1 dpa at temperatures of 300° C [21]. The effect of neutron irradiation on single crystalline pure tungsten was investigated by irradiating it in HIFAR and JMTR reactor. The results show that the hardness and microstructure change a clear dependence on the neutron energy spectrum. The hardness appeared to increase with increasing thermal neutron when fast fluence exceeds 1 E+21 n/cm² (E>0.1 MeV) [22]. Other studies have reported the results of Ti2AIc, combined attractive properties of both ceramics and metals for Gen. IV reactor material due to its resistance to irradiation reason [23].

IAEA through CRP activities seek to establish a database material property for irradiated core structure components for the purpose of continued safe operation and lifetime extension of ageing research reactor [24]. These 4-year term activities have been approved since 2012, and it is participated by 13 member states and is still ongoing until now. There has been quite a lot of important data from each member states has been collected. An intensive literature review has been conducted in [15] to collect research results of various irradiation damage mechanisms of 5xxx and 6xxx series aluminum alloy by neutron irradiation. The displacement damage, transmutation damage, evolution of microstructure and mechanical properties of materials are discussed in detail. An irradiated and unirradiated AlMg3 specimen of BER II research reactor operated in Berlin Germany, in order to assess the allowable operation time of a conic neutron beam tube [25]. Using AlMg3 of archived
material and from a highly irradiated decommissioned component of the same material, the tensile specimens have been manufactured and then tested. The experiment result shows that below the designed end of life fluence of 1.0 E+22 n/cm² for E>0.1 MeV a uniform elongation of at least 5% was confirmed which is the minimum to ensure sufficient ductility during operation.

The purpose of this paper is to estimate radiation damage of core structure of RSG GAS reactor after it has been irradiated with neutron from the beginning first core to the end of 89th core configuration for almost 30 years RSG GAS reactor operation. Core structure is arranged by core frame support made by AlMg₃ materials and some part of reinforcement bolts made by SS304 material. The Al and Fe as metal base of core structure components were considered as main and critical component to support fuels element. The core structure components will experience the highest influence due to neutron irradiation along reactor operation. The displacement per atoms of these base core structure materials are analyzed and estimated as a measure of the remaining operating life of core component by comparing dpa value from equivalent materials. Result estimation will be used as one of the complementary supporting data to get the extension of RSG GAS reactor operating licence.

2. Methodology

2.1. Damage Calculation

Material damage calculation models have been widely developed by some researchers and research institutes [14, 26-27], even some have been standardized by ASME or others standard institution [28]. The radiation damage estimation in core structure under neutron irradiation required the knowledge of: (i) the neutron flux spectrum as a function of neutron energy E and irradiation time t, \( \phi(E,t) \), (ii) the atomic displacement cross section for particular material \( \sigma_d \) which is also a function of the neutron energy E, \( \sigma_d(E) \), and (iii) the neutron irradiation time \( t_i \) [14]. The total amount of displacement per atom is obtained by integrating over the exposure time, \( t_i \), as follows:

\[
dpa = \int_0^{t_i} dt \int_0^\infty \phi(E,t)\sigma(E) dE
\]  

Equation (1), then can be simplified when consider the flux spectrum to be constant over time exposure as follows:

\[
dpa = t_i \phi_{tot} \int_0^\infty \sigma_d(E) \Psi(E,t) dt
\]  

Equation (2), then can be simplified when consider the flux spectrum to be constant over time exposure as follows:

\[
dpa = t_i \phi_{tot} \int_0^\infty \sigma_d(E) \Psi(E) dE
\]  

From equation (3), for given the main features of the operating nuclear reactor and the composition of core structure materials, \( t_i \) is known and the decomposed neutron spectrum can be calculated using appropriate neutron physics codes, or can be measure using reactor dosimetry experiment.

In general, the atomic displacement cross section is determines by weighting the result of different processes: (1) nuclear reaction the incident neutron and atomic nucleus of given material and energy transfer from neutron E to target nucleus (T); (2) energy loss acquired by nucleus by interaction of the electrons of the material system (T to T_d); (3) actual displacements per atom production based on equation (1), assuming by given \( E_d \) then \( T_d \) is known. Material damage cross section for the nuclear reaction obtain from nuclear data libraries which are conveniently available and directly useable from codes calculation such as NJOY, SAND II, etc.[29-33].
2.2. Evaluation Method

The research methodology used to estimate the radiation damage of the base metal of RSG GAS reactor core structure is shown in Figure 1.

![Flowchart research procedure of material damage estimation.](image)

2.3. Assumption

2.3.1. Critical Component Materials

In research reactor, the main concern in ageing management programs due to neutron irradiation stressor typically are pressure tank and connecting pipes, reflector systems, core support structure components, guide tubes, beam related devices highly irradiated portion and shielding structures. Those components are generally fixed and difficult to replace and is classified as a critical component [10,24].

For reasons of RSG GAS reactor remaining life analysis, its convinient by selecting components that was most suffering neutron irradiation such as core structure and reactor tank. Core support structure components are arranged by core support grid and other structural and internal support structure. Core frame, core support grid as well as reactor tank of RSG GAS reactor are made by AlMg3. Core frame and core support grid are constructed to form a core basket with reinforcement bolts made of SS 304 material [11-12]. The effect of neutron irradiation to reactor tank is not be considered since 2950 mm away length distant from core center, therefore the neutron flux intensity is significantly reduced.

In this study it is assumed that the material damage under consideration is limited only due to the neutron irradiation in the base material, therefore displacement per atom of AlMg3 and SS 304 material are reviewed by material damage of Al and Fe element, respectively. Life time of Al1100 material of HIFAR reactor tank will be used as reference of life time AlMg3 of RSG GAS reactor core structure [34-35]. Table 1 shows the elemental composition of Al1100, AlMg3 and SUS304, respectively. The content of Al base metal on Al1100 and AlMg3 is so similar that it expected its physical parameters did not deviate too much.

| Material | Element | Cu | Mn | Zn | Mg | Fe | Si | Ti | Cr | Ni | Mn, Cr | Other | Base Metal |
|----------|---------|----|----|----|----|----|----|----|----|----|--------|--------|------------|
| Al1100   | min     | 0.05 | 0.05 | 0.01 | 0.95 | 0.95 | - | - | - | - | 0.05 | 99.00 |
|          | max     | 0.20 | 0.05 | 0.01 | 2.60 | 3.60 | 0.4 | 0.40 | 0.1 | 0.30 | 0.60 | 93.80 |
| AlMg3    | min     | - | - | - | 2.60 | 3.60 | 0.4 | 0.40 | 0.1 | 0.30 | 0.60 | 66.00 |
|          | max     | 0.10 | 0.50 | 0.20 | 3.60 | 20.0 | 11.0 | - | - | - | - | - | - | - | - | - |

Note: 1. Al1100 APA Product Data Sheet UNS A91100
2. AlMg3 DIN EN 573-3 Germany Standard
3. Stainless Steel - Grade 304 (UNS S30400)
2.3.2. Neutron Flux Spectrum Calculation
Neutron flux of equilibrium of RSG GAS reactor with U$_3$Si$_2$-Al of 2.96 g U/cc density is calculated using Citation module of SRAC2006 code. This program is used to calculate neutron flux at any given points inside and around the reactor core, based on neutron diffusion theory [36]. RSG GAS reactor core is modeled in three dimensional geometry (X,Y,Z) and divided into 69 mesh, 94 mesh and 72 plane of each X, Y and Z axes direction, respectively [37]. The highest neutron flux intensity is located at core center (CIP) near to the fuel element. Calculated neutron flux intensity in this point is used a bases to calculate the material damage as a function of damage cross section and neutron fluence. This assumption means that the fluence parameters such as neutron flux as a function of energy, irradiation time, as well as applied energy groups structure of neutron fluence are used as a base case from which materials damage are estimated.

2.3.3. Normalized Irradiation Time
Since RSG GAS reactor reaching the first criticality in 1st core configuration to test power ascention to 30 MWh nominal power till in 6th core configuration, the reactor is operated in variety rated power from a 10.7–30 MWh. After that, from 7th to 30th core configuration, the reactor is operated varying from 10–25 MW rated power. For efficiency reason, then RSG GAS reactor is operating at half of nominal power 30 MW [1,3,6]. Furthermore, the core configuration 31st-89th is operated at a constant rated power of 15 MW. The neutron flux intensity calculations by SRAC2006 code of CITATION module were conducted only at 15 MWh of rated power [37], therefore it is necessary to normalize all core configuration to the rated power of 15 MWh. Total irradiation time is determined as a summation of each number core configuration radiation time after normalizing to 15 MWh rated power.

2.3.4. Material Damage Cross Section
Material damage cross section data was provided from Public Library Document [29-33]. In this research used material damage cross section from IRDF2002. Generally the energy group structure used extends from 0–20 MeV. In order to calculate the magnitude of displacement per atom (dpa) of material damage it is necessary to use the same energy group structure as used in the neutron flux calculation on the equilibrium core of RSG GAS reactor fueled U$_3$Si$_2$-Al. With these assumptions the damage cross section needs to be collapsed in an energy group structure corresponding to the energy group structure to calculate the neutron flux spectrum.

3. Result and Discussion

3.1. Flux Calculation
In core neutron flux calculation were conducted using Citation module of SRAC2006 code applying the energy group structure of the Public Libraries consist of 107 energy groups structure; 74 groups for fast and 48 groups for thermal neutron groups energy, with 12 overlapping groups, covered from 1.00 MeV to 1.0 E-05 MeV. These 107 energy groups structure were then condensed from 74 groups of fast and 48 groups of thermal energy neutron into 5 and 3 energy groups structure, respectively [37]. The RSG GAS reactor core area with a 1.79E+02 cm width; 1.79E+02 cm depth; and 1.79E+02 height is modeled 3D dimensional slab geometry (X,Y,Z). The equilibrium core consist of 40 fuels element (FE), 8 control elements (CE), 4 irradiation position (IP), 4 central irradiation positions (CIP), 4 irradiation positions (IP), 1 pneumatic rabbit system (PNRS), 4 hydraulic rabbit system (HYDR), beryllium reflector (BE), beryllium reflector with stopper (BS), and power ramp test facility PRFT-J7 (1) and power ramp test facility PRFT-K7 (2), as seen in Figure 2. The standard fuel element consists of 21 plates of U$_3$Si$_2$/Al fuel with U-235 enrichment of 19.75 wt% and density of uranium of 2.96 g U/cc. The nominal uranium weight of each fuel is about 250 g. The control fuel elements CE are basically the same shape with a fuel elements (FE), but 3 outer plates replace by
placing absorber blade, so the element has 15 fuel plates. Control elements are made of absorber material that is composed of Ag-In-Cd with composition of 80%, 15%, 5%, respectively [3].

Figure 2. RSG GAS Equilibrium Core with U₃Si₂-Al Fuel [37]

For the purpose of reviewing the critical components ageing, it is preferred to take the maximum value of ageing stressors. The maximum flux neutron spectrum as the most influence material damage effect was taken in the center of core position closest to the fuel, since highest fast neutron flux is located in closer position to the fuel element position. The calculation results show that the maximum thermal neutron flux is located at mid core level at the slab position Z=36 plane, while the maximum fast neutron flux is obtained at the point close to fuel element with the coordinates X=25 mesh and Y=26 mesh, respectively. The calculated neutron flux of each energy group is shown in Table 2. The highest neutron flux is in the thermal neutron energy area at the order of $10^{14}$ $n/cm^2/s$ and decreases gradually in the epithermal neutron and the fast neutron areas.

Table 2. Calculated Neutron Flux of Each Energy Group at Core Center

| Group # | Energy Range (eV) | Neutron Flux (n/cm²/s) | Energy Group | Catagory |
|---------|------------------|------------------------|--------------|----------|
| 1       | 2.00E+07 ~ 3.68E+06 | 4.535E+12             |              | Fast Neutron |
| 2       | 3.68E+06 ~ 8.21E+05 | 1.652E+13             |              |          |
| 3       | 8.21E+05 ~ 6.74E+04 | 1.255E+13             |              |          |
| 4       | 6.74E+04 ~ 1.01E+02 | 1.255E+13             |              | Epithermal Neutron |
| 5       | 1.01E+02 ~ 6.83E-01 | 1.279E+13             |              |          |
| 6       | 6.83E-01 ~ 1.52E-01 | 9.432E+12             |              |          |
| 7       | 1.52E-01 ~ 1.85E-02 | 1.578E+14             |              | Thermal Neutron |
| 8       | 1.85E-02 ~ 1.00E-05 | 2.753E+13             |              |          |
3.2. Irradiation Time
At the beginning of operation, RGS GAS reactor uses U3O8-Al fuel with a low uranium enrichment 235U of 19.75% and a meat density of uranium of 2.96 g/cm³, running from 1st to 34th core configuration of reactor operation. With the advancement of RERTP (Reduced Enriched Uranium for Research and Test Reactor) program, RGS GAS reactor fuel then since 1999, is converted gradually from U3O2-Al uranium oxide to U3Si2-Al uranium silicide fuel with a meat uranium density of 2.96g/cm³. Full core conversion can be completed on 45th core configuration. The purpose of this transformation is to extend the reactor cycle operation efficiently with a higher level of burnup. Core conversion to full silicide fuel core was completed in August 2002. Subsequently, on the basis of efficiency reason, the reactor is operated using this silicide fuels.

Since RSG GAS reactor reaching the first criticality in 1st core configuration to test power ascention to 30 MWth nominal power till in 6th core configuration, the reactor is operated in variety rated power from a 10.7–30 MWth. After that, from 7th to 30th core configuration, the reactor is operated varying from 10–25 MW rated power. Furthermore, the core configuration 31st–89th is operated at a constant rated power of 15 MW. The neutron flux intensity calculations by SRAC2006 code of CITATION module were conducted only at 15 MWth of rated power, therefore it is necessary to normalize all core configuration to the rated power of 15 MWth. Total irradiation time is determined as a summation of each number core configuration radiation time after normalizing to 15 MWth rated power. Based on operating data from RSG GAS reactor Operating Report 1st to 89th core configuration [38], the rated power of reactor can be seen in Figure 3. After normalized to the 15 MWth rated power show that cumulative irradiation time was obtained as much as 3.76030 E+08 seconds.

![Figure 3. Cumulative Irradiation Time Normalized to the 15 MWth Rated Power](image)

3.3. Material Damage Cross Section
Material damage cross section of base material Al and Fe was taken from IRDF-2002 and were collapsed into 756 energy groups structure as shown in Figure 4. The processed cross section of Al-NRT and Fe-NRT damage cross section data are only available for 0–10 MeV. The damage material cross section pattern between Al and Fe is very similar. Cross section of these two elements decreases to a certain value in the 1.0 E+02 eV energy area and increases continue in the epithermal energy area, then rises sharply and fluctuates in fast neutron energy region reaching to high cross section
values. These cross-section data needs to be collapsed in accordance with 8 energy group structures of calculated neutron flux and the results are shown in Table 3 and also illustrated in Figure 4.

![756 POINT WISE TO 8 ENERGY GROUPS STRUCTURE](image)

**Figure 4.** Material Damage Cross Section of Al and Fe in 756 Energy Group Structure and after Collapsing into 8 Neutron Energy Group Structure

| Group # | Energy Range (eV) | Damage Cross Section (barn) | Al | Fe |
|---------|-------------------|-----------------------------|----|----|
|         | Upper             | Lower                       |    |    |
| 1       | 2.00 E+07 ~ 3.68 E+06 | 1942.900                   | 1646.300 |
| 2       | 3.68 E+06 ~ 8.21 E+05 | 1580.800                   | 876.170  |
| 3       | 8.21 E+05 ~ 6.74 E+04 | 980.030                    | 379.916  |
| 4       | 6.74 E+04 ~ 1.01 E+02 | 28.624                     | 22.148   |
| 5       | 1.01 E+02 ~ 6.83 E-01 | 0.155                      | 0.696    |
| 6       | 6.83 E-01 ~ 1.52 E-01 | 0.630                      | 2.841    |
| 7       | 1.52 E-01 ~ 1.85 E-02 | 1.590                      | 7.197    |
| 8       | 1.85 E-02 ~ 1.00 E-05 | 3.610                      | 16.275   |

**Table 3.** Damage Cross Section of Al and Fe in 8 Energy Group Structures

3.4. **Radiation Damage Estimation**

Radiation damage in aluminum core structure is mainly caused by the interaction and capture process. The effect depends on the composition of aluminum, manufacturing circumstances, irradiation temperature and fluence of thermal and fast neutron [13]. In the fast energy range displacement of atom occurs and nuclear reaction of the type Al-27(n, α)Na-23 and Al-27(n, p)Mg-26 takes place. In the thermal neutron field, aluminum atoms are transmuted to silicon according to Al-27(n, β)Si-28. The material damage of core structure consists of dislocations, cavities, and Si precipitated that grow with increasing fluence. The reference material for specific study of AlMg₃ materials end of life due to
neutron irradiation stressor at low temperatures are very rare and not obtainable. Therefore, as a comparison in this study, the reference material will be taken of similar investigation carried out in the reactor HIFAR as shown in Figure 5 [35]. The Al element content in AlMg3 of RSG GAS core structure and Al1100 of HIFAR reactor tank is very similar. The Al1100 specimens used in HIFAR reactor tank irradiated with 1.96 E+14 n/cm³/s of neutron thermal with a considerable fast component of 1.45 E+13 for E>0.1 MeV and 6.42 E+12 for E>1 MeV has been investigated under consideration of the total power history and operating time of 2.82 E+06 MWh [34]. Si-28 is produced in concentration as much as 2.32 Wt% in the form of precipitated particle and clusters which cause an increase tensile strength and decrease ductility. As shown in Figure 6, the critical value for the elongation representing the end of life value is reach at total fluence of 1.5 E+27 n/m³ or E>0.1 MeV neutron fluence of 4.8 E+26 n/m² corresponding to Si content of 5 Wt% and dpa of 250 cm.

![Figure 5](image_url)

*Figure 5. Fluence dependence of tensile properties of Aluminum [35]*

The calculation of radiation damage in AlMg3 core structure was performed by determining which position in reactor core that obtain the highest neutron flux at an equilibrium core configuration of U₃Si₂-Al fuel. The results are shown at Table 4. The calculations of displacement per atom of Al and Fe base material core structure using equation (3) are shown also in Table 4.

Total neutron flux at core center near the fuel is calculated as much as 1.870 E+23 n/cm². In order to obtain the neutron fluence of E>0.1 MeV, log-log interpolation in (8.21E+05~6.74E+04) MeV energy range was carried out. The result of neutron flux calculation of (8.21E+05~1.00E+05) MeV energy range was 3.760E+08 n/cm²/s, therefore the neutron fluence of E>0.1 MeV as much as 6.941 E+22 n/cm². The total dpa damage material for Al and Fe due to total neutron flux were 22.81 and 12.50 cm, respectively. Meanwhile the dpa damage material due to fluence of neutron energy E>0.1 MeV for Al and Fe was calculated at 17.91 and 10.06 cm, respectively.

Based on the research results conducted in HIFAR reactor on Al1100 material, it can be estimated that RSG GAS reactor core has undergone a material operating end of life of 7.16%, or has the equivalent of receiving neutron fluence of 1.269 E+22 n/cm². This means that the Al base metal core structure component is still safe to be used and operated in the long run or could be continued for additional E>0.1 MeV neutron fluence of 5.672 E+22 n/cm². For more accurate analysis it is necessary to include also the parameter of the amount of material damage in the 10~20 MeV energy range which in this study has not been considered.
Table 4. Calculated dpa of Al and Fe in 8 Energy Groups Structure of RSG GAS

| Energy Range (eV) | Damage Cross Section (Barn) | Neutron Fluence (n/cm²) | dpa Al (cm) | dpa Fe (cm) |
|------------------|-----------------------------|------------------------|------------|------------|
| 2.00E+07 ~ 3.68E+06 | 1942.900 1646.300 | 1.705E+21 3.313E+00 | 2.807E+00 |
| 3.68E+06 ~ 8.21E+05 | 1580.800 876.170 | 6.212E+21 9.820E+00 | 5.443E+00 |
| 8.21E+05 ~ 1.00E+05 | 1000.510 379.916 | 4.776E+21 4.778E+00 | 1.814E+00 |
| 8.21E+05 ~ 6.74E+04 | 980.030 379.916 | 4.719E+21 4.625E+00 | 1.726E+00 |
| 6.74E+04 ~ 1.01E+02 | 28.624 22.148 | 4.719E+21 4.625E+00 | 1.726E+00 |
| 1.01E+02 ~ 6.83E-01 | 0.155 0.696 | 4.809E+21 1.351E+01 | 1.045E-01 |
| 6.83E-01 ~ 1.52E-01 | 0.630 2.841 | 3.547E+21 7.455E+04 | 3.347E-03 |
| 1.52E-01 ~ 1.85E-02 | 1.590 7.197 | 5.934E+22 2.234E-03 | 1.008E-02 |
| 1.85E-02 ~ 1.00E-05 | 3.610 16.275 | 1.035E+22 9.435E-02 | 4.271E-01 |

4. Conclusions
Based on the CITATION module of SRAC2006 code modeling of equilibrium core of Al₃Si-Al fuels to roughly estimate the neutron spectrum at core center near the fuel, the material damage of Al and Fe were estimated. The results show that the calculation model can be used to estimate Al and Fe damage material of base metal of core structure. Until the end of 89th core configuration, the core structure has undergone maximum of neutron irradiation as much as 1.870 E+23 n/cm² for fast neutron energy E>0.1 MeV, respectively. These means that the AlMg₉ core structure components and the SS304 of bonding strengthen core structure have undergone 22.81 and 12.50 dpa, respectively. Referring to the assumption of All100 material end of life, it was found that core structure underwent 7.16% of its life span, or still safe to be used for additional E>0.1 MeV neutron fluence as much as 5.672 E+22 n/cm². For more accurate analysis it is necessary to collapse neutron energy into more detailed energy group structure and include variable material damage in the 10~20 MeV energy range which in this study has not been considered, although neutron flux in this area is very low.

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