1. Introduction

As a method for irradiation with fusion neutrons at high doses is not available at present, the effects of irradiation on the properties of material at high doses must be derived from fission neutron irradiation experiments. Therefore an understanding of fission-fusion correlations is important. Many studies have been performed using 14 MeV neutrons with the Rotating Target Neutron Source II (RTNS-II) at LLNL in the USA. From observing the defect structures of metals irradiated with fission and fusion neutrons by transmission electron microscope (TEM), Kiritani et al. concluded that the reaction of freely migrating interstitials had a great influence on the damage structure, and those authors reported factors of fission-fusion correlation for the development of a variety of defect structures.1) Okada et al. compared the mechanical properties of Ni, Cu, Au and Fe, and austenitic stainless steel and ferritic stainless steel irradiated with fission and fusion neutrons.2-4) Yoshida et al. reported the microstructure-tensile property correlation of 316 SS irradiated at 363 K and 563 K in the RTNS-II and in the OWR (Omega West Reactor, at LANL in the USA).5)

Recently developed fusion reactor candidate materials were not examined in the irradiation experiments with the RTNS-II, which has already been shut down. Vanadium alloys and ferritic/martensitic steels are recognized as attractive candidate materials for neutron interactive structural components of fusion energy systems. Vanadium alloys have high temperature strength, high thermal stress factors and low activation properties. Reduced activation ferritic/martensitic steels have good dimensional stability under high irradiation doses and are suitable for commercial production without a large industrial investment.

In the present work, the irradiation effects of fission and fusion neutrons on fusion reactor candidate alloys V-4Cr-4Ti and F82H were studied using the Fusion Neutron Source (FNS)6) at JAERI (the deuterium–tritium (D–T) neutron source facility) and the Kyoto University Reactor (KUR). As the irradiation dose was low in the present study, the vacancies and interstitial type dislocation loops were analyzed and compared using positron annihilation lifetime spectroscopy, and relation between the point defect formation and subcascade formation was discussed.

2. Experimental

2.1 Specimens

High purity V-4Cr-4Ti alloy of NIFS-HEATs7) was used as a vanadium alloy. The specimens for positron annihilation lifetime spectroscopy were prepared from cold-rolled sheets by punching (3 mm in diameter) followed by annealing at 1373 K for 2 hours in a vacuum. F82H alloy prepared by JAERI8) was used after cutting and chemical polishing to remove the deformed area.

2.2 Neutron irradiation

Fusion neutron irradiation was performed using a rotating tritium target in target room II of the FNS facility,6) where values of fusion neutron reaction; tritium breeding ratio, nuclear heating, induced radioactivity, shielding and so on can be examined. Specimens are bundled and then inserted into hole of a copper block. As shown in Figs. 1(a) and (b), the blocks are set on a copper board into which an electric heater is inserted. The maximum number of the blocks which we can set is ten. The temperature at which the blocks are kept can range from room temperature to 673 K. In order to cool specimens rapidly after irradiation experiments, air-cooling fins are attached. Because of these fins, it is difficult to achieve more than 673 K. During irradiation, specimens are held with less than $10^{-4}$ Pa using a turbo-molecular pump. In 14 MeV neutron irradiation in the FNS, the neutron dose is varied within the same irradiation run by placing a...
number of samples at various distances from the position closest to the neutron source. In this study, the bundled specimens were inserted into the block closest to and the fifth block from the neutron source. The irradiation temperature, neutron fluence and dpa (displacement per atom) calculated with threshold energy for knock-on, 24 eV for V-4Cr-4Ti and 40 eV for F82H, are listed in Table 1.

Fission neutron irradiation was performed using the KUR, 5MW light water reactor. The irradiation experiment at room temperature was carried out in the Hydraulic Conveyor Facility (Hyd.) and that at 673 K was carried out in the Materials Controlled Irradiation Facility (SSS). For irradiation at room temperature, the reactor power was reduced to 300 kW to avoid an increase of specimen temperature due to nuclear heating. The neutron fluence and dpa are also listed in Table 1.

### 3. Results

#### 3.1 Room temperature irradiation

The results of positron lifetime measurement of specimens irradiated at room temperature are shown in Figs. 2(a) and (b) for V-4Cr-4Ti, and in Figs. 3(a) and (b) for F82H. Figs. 4(a) and (b) show the variation in the positron mean lifetime with irradiation dose for V-4Cr-4Ti and F82H, respectively. After neutron irradiation, the mean lifetime is longer than that before irradiation. The effect of neutron irradiation on positron annihilation lifetime was detected even at a low irradiation dose of $10^{14}$ dpa. For both alloys, the effects of the fission and fusion neutron irradiation on positron lifetime were almost the same, if they were compared at the same dpa. The long lifetime was less than the positron lifetime for single vacancies, and the defects produced by the neutron irradiation were vacancies and dislocation loops.

#### 3.2 673 K irradiation

The results of positron lifetime measurement for specimens irradiated at 673 K are shown in Fig. 5 for V-4Cr-4Ti, and in Fig. 6 for F82H. Defects were detected only in fusion-neutron-irradiated F82H, and the mean lifetime increased slightly. Since the irradiation temperature was high and the irradiation dose was small, the defects produced by the neutron irradiation were expected to migrate to sinks and disappear. Judging from the long lifetime of fusion-neutron-irradiated F82H, the defects formed in the specimen were interstitial type dislocation loops. Vacancy clusters are more unstable than the interstitial clusters at 673 K, and are dissociated and disappear at sinks. The defects remained only in fusion-neutron-irradiated F82H due to the effect of cascade size.

### 4. Discussion

#### 4.1 Subcascade energy of V

The origin of the formation of subcascades and factors which determine the subcascade parameters, such as subcascade energy and subcascade zone size, were discussed by Satoh et al. The mean distance between collisions ($D$ in

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Table 1 Irradiation temperature, neutron fluence and dpa of fusion neutron irradiation in the FNS and fission neutron irradiation in the Hyd. and the SSS.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Irradiation temperature</th>
<th>Neutron fluence, $\text{cm}^{-2}$</th>
<th>Total dose (dpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>V-4Cr-4Ti</td>
<td>F82H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{14}$</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>FNS RT</td>
<td></td>
<td>$2.63 \times 10^{16}$</td>
<td>$1.19 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5.13 \times 10^{15}$</td>
<td>$2.32 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2.41 \times 10^{15}$</td>
<td>$1.09 \times 10^{-5}$</td>
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<tr>
<td></td>
<td></td>
<td>$5.90 \times 10^{14}$</td>
<td>$2.52 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>400 K</td>
<td>$2.24 \times 10^{16}$</td>
<td>$1.01 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4.73 \times 10^{15}$</td>
<td>$2.13 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$3.49 \times 10^{14}$</td>
<td>$1.58 \times 10^{-6}$</td>
</tr>
<tr>
<td>Hyd. RT</td>
<td></td>
<td>$8.05 \times 10^{15}$</td>
<td>$2.26 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.41 \times 10^{14}$</td>
<td>$3.20 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2.06 \times 10^{14}$</td>
<td>$5.77 \times 10^{-6}$</td>
</tr>
<tr>
<td>SSS 400 K</td>
<td></td>
<td>$6.38 \times 10^{17}$</td>
<td>$3.24 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Fig. 7) that transfer a large amount of kinetic energy to a target atom, and the size of the vacancy-rich region (R in Fig. 7) produced by the target atom can be compared as a function of the transferred energy to a target atom. The relationship between these two parameters appeared to be a criterion for subcascade formation. When the collision distance \( D \) is larger than the range \( R \), two damage zones formed from an incident atom do not overlap with each other and become separate subcascades (Fig. 7(a)). On the other hand, when the collision distance \( D \) is smaller than the range \( R \), two damage zones overlap and become one subcascade (Fig. 7(b)).

Using these criteria we estimated the subcascade energy of V. The size of the damage zone, in which a dense population of vacancies is produced (called here the range of vacancies) by cascade collisions of a target atom, was calculated using MARLOWE code (13) and is shown in Fig. 8 with bold lines. When the incident energy is 10 keV in Fig. 8, the mean distance \( D \) does not overlap with the range \( R \), so the subcascade energy is smaller than 10 keV in V. The distance \( D \) decreases with a decrease of the incident energy, and \( D \) begins to cross \( R \) at an incident energy around 5 keV. Here, the energy divided into a subcascade is about 5 keV in V. The average values for the distance \( D \) and the range \( R \) are adopted.
in the above criterion for simplicity. It is obvious that the distributions of $D$ and $R$ result in the distribution of subcascade energies.

4.2 The number of subcascades

One of the features of high energy particle irradiation is the formation of subcascades. A recoil atom with large energy makes several well separated damaged areas. In each subcascade, a vacancy-rich area is surrounded by an interstitial-rich area. The concentration of point defects in the area is high and nucleation of defect clusters is expected to occur in this area. Therefore, the number of subcascades formed by a primary knock-on atom (PKA) is an important factor in determining the damage structure. Not all of the PKA energy is transferred to lattice atoms in elastic collisions. An appreciable part of the PKA energy is lost by inelastic scattering processes along the path of a high energy recoil atom, such as the excitation of electrons. The damage energy $T(E_{PKA})$ that is the part of the primary recoil energy $E_{PKA}$ lost in elastic collisions with lattice atoms is obtained according to the theory of Lindhard et al.\cite{14} A larger fraction of PKA energy is lost inelastically at higher PKA energy. For example, 46.5% is lost at PKA energy of 200 keV and 68.4% for 1 MeV in the case of V.

The partitioning of the damage energy $T$ to subcascades is considered by assuming a threshold energy for subcascade formation, in a procedure analogous to the Kinchin-Pease model for Frenkel Pair production. An area with energy above the threshold energy $E_{SC}$ is assumed to evolve into a subcascade. The number of subcascades $N_{SC}$ produced from a primary recoil atom with the energy of $E_{PKA}$ is

$$N_{SC}(E_{PKA}) = \begin{cases} 0 & T(E_{PKA}) < E_{SC} \\ \frac{1}{2T(E_{PKA})} & E_{SC} \leq T(E_{PKA}) \leq 2E_{SC} \\ \frac{T(E_{PKA})}{2E_{SC}} & 2E_{SC} < T(E_{PKA}) \end{cases} \quad (1)$$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Comparison of the positron mean lifetime of (a) V-4Cr-4Ti and (b) F82H specimens irradiated in the FNS versus the Hyd.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{Variation in the positron long, mean and short lifetimes and their intensities in V-4Cr-4Ti irradiated at 673 K in the FNS and the SSS. “—” denotes bulk lifetime (109 ps).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{Variation in the positron mean lifetime of (a) V-4Cr-4Ti and (b) F82H specimens irradiated at 673 K in the FNS versus the Hyd.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7}
\caption{Schematic illustration of the criterion of subcascade formation.}
\end{figure}
where $T(E_{PKA})$ is the damage energy for the PKA energy of $E_{PKA}$. We can obtain the subcascade production rate $C_{SC}$ from

$$\frac{dC_{SC}}{dt} = \varphi \int_{0}^{t_{MAX}} N_{SC}(E_{PKA}) \frac{d\sigma}{dE_{PKA}} dE_{PKA},$$

where $\varphi$ and $\sigma$ are the neutron flux and PKA displacement cross section, respectively.

### 4.3 The number of subcascades and dpa

As mentioned above, a large cascade is divided into subcascades. The subcascade energy of Fe and V was calculated to be $10\text{keV}$\(^{15}\) and $5\text{keV}$ in this study, respectively. The number of subcascades calculated with eq. (1) for V and Fe is shown in Table 2. The number of subcascades per dpa was almost the same in the three facilities. If the subcascade energy is below 20 keV, the number of subcascades is roughly proportional to the displacement damage measured by dpa in the case of Ni and Fe, which have medium atomic weight.\(^{16}\) If the same number of freely migrating defects is generated from each subcascade and the same number of defects remains in each subcascade in fission- and fusion-neutron-irradiated V-4Cr-4Ti and F82H, no effect of cascade size occurs. At room temperature, irradiation defects are formed in the subcascade and the defect structure evolution can be estimated according to the dpa. At high temperature, such as 673 K, interactions between subcascades occur and the damage structural evolution does not depend on the number of subcascades and consequently also not on dpa.

#### 5. Conclusion

Vacancies and dislocation loops formed in two fusion reactor candidate alloys were compared between fusion neutron irradiation and fission neutron irradiation. Even though the irradiation doses were low, irradiation defects at room temperature were detected by positron annihilation lifetime spectroscopy, but the defects in the alloys irradiated at 673 K were detected only for the fusion-neutron-irradiated F82H. As the subcascade energies of V and Fe were as low as 5 keV and 10 keV, respectively, we were able to compare the defects of V-4Cr-4Ti and F82H produced by irradiation of fission neutrons and fusion neutrons at room temperature as a function of dpa. Higher irradiation doses and different irradiation temperatures will be required to detect the effects of irradiation with neutrons more precisely.

### Acknowledgements

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### REFERENCES