Ion-induced swelling of ODS ferritic alloy MA957 tubing to 500 dpa

M. B. Toloczko^{1*}, F. A. Garner², V. N. Voyevodin³, V. V. Bryk³, O. V. Borodin³, V. V. Mel'nychenko³, and A. S. Kalchenko³

Abstract

In order to study the potential swelling behavior of the ODS ferritic alloy MA957 at very high dpa levels, specimens were prepared from pressurized tubes that were unirradiated archives of tubes previously irradiated in FFTF to doses as high as 110 dpa. These unirradiated specimens were irradiated with 1.8 MeV Cr⁺ ions to doses ranging from 100 to 500 dpa and examined by transmission electron microscopy. No coinjection of helium or hydrogen was employed. It was shown that compared to several ferritic/martensitic steels irradiated in the same facility, these tubes were rather resistant to void swelling, reaching a maximum value of only 4.5% at 500 dpa and 450°C. In this fine-grained material, the distribution of swelling was strongly influenced by the presence of void denuded zones along the grain boundaries.

1. Introduction

The ODS ferritic alloy MA957 is under investigation in anticipation that it will not only exhibit superior creep resistance at high temperatures in both thermal and irradiation environments, but also because it hoped that it will resist void swelling more effectively than conventional ferritic or ferritic-martensitic alloys due to a perception that the YTiO oxide particles will act as recombination sites for vacancies and interstitials.

Various heats of this alloy have been previously irradiated with neutrons in other studies. For example, Ribis did not observe cavities in MA957 irradiated in the PHENIX fast reactor to (412°C, 50 dpa) and (430°C, 75 dpa) [1]. Gelles reported that two experimental heats of MA957 supplied by International Nickel Company showed irregular swelling behavior at temperatures near 420°C when irradiated in the FFTF fast reactor [2]. While large regions of both heats showed no cavities, there were areas where swelling measured via microscopy in both heats reached ~3.6%. The bulk density changes measured for the two heats were 0.25 and 1.75%, reflecting not only the volume-averaged void swelling, but probably density change

contributions arising from phase instabilities. Yamashita and coworkers irradiated MA957 in the JOYO fast reactor to ~100 dpa at 500 to 700°C [3]. Small cavities were observed before and after irradiation, but these were deduced to be argon gas bubbles trapped during fabrication.

Currently, the maximum neutron-induced displacement levels reached in MA957 were pressurized creep tubes irradiated in FFTF ranging from 109 dpa at 412°C to 121 dpa at 750°C. Recent microscopy has revealed that void swelling has not yet occurred in those tubes [4, 5]. The measurement of irradiation creep of MA957 over a range of irradiation temperatures has been reported previously [6-8] and density changes indicative of low swelling appear to arise primarily from phase instabilities [8].

The question remains as to whether the observed swelling resistance will continue to higher doses, but there is no possibility that significantly higher neutron-induced doses can be attained on any time frame of less than 10-20 years in currently operating fast reactors. Therefore it was decided to explore swelling of this alloy to higher damage exposures using self-ion irradiations as a surrogate irradiation technique. One previous ion irradiation study by Asano and coworkers to 150 dpa at 450 and 550°C showed no cavities under single-beam irradiation but small amounts of cavities (<0.1% swelling) under simultaneous helium coinjection [9].

The objective of the current project was to irradiate specimens of alloy MA957 to high displacement exposures with 1.8 MeV chromium ions at 1×10^{-2} dpa/sec over a range of reactor-relevant temperatures, followed by transmission electron microscopy to measure swelling. The ion data were then compared to ion-induced swelling in two other ferritic-martensitic steels irradiated in the same facility at identical ion fluxes. The ion data will eventually be compared with microstructural development observed in identical material that was neutron irradiated in FFTF-MOTA to 109-121 dpa.

2. Experimental details

2.1 Preparation of specimens for irradiation

Specimens of alloy MA957 were cut using an electro-spark machining from unirradiated pressurized creep tubes that served as archives for identical tubes irradiated in FFTF-MOTA. These were the EV series of 0.230 inch (5.8mm) diameter pressurized tubes [7, 8]. The cut specimens used for this study were curved discs of 3 mm planar diameter, but other types of specimens were prepared for mechanical and FIB microstructural studies as shown in Fig. 1.

To guarantee uniform and efficient heat transfer between the heating stage and the beam-heated specimen over the entire specimen surface, it was necessary to develop a new preparation technique applicable to these curved specimens. First, the concave side of the specimen was mechanically polished to produce a flat plate surface. The convex side was then subjected to electrochemical jet polishing using 90% ethanol and 10% perchloric acid. This was performed to insure that ion irradiation would be incident on an electropolished surface and not on a mechanically prepared surface that would a microstructure not representative of the bulk material.

2.2 Irradiation procedure

The target complex shown in **Fig. 2** was modified to accommodate the new specimen configuration with the polished, convex side of the specimen facing the ion beam. Good thermal contact between specimen and target complex was maintained using a low-melting temperature (370°C) foil (0.2 mm thick) of an alloy called Babbit B-83.

Only one specimen at a time was irradiated in the center of the ~1 cm diameter ion beam. A holder plate was used to clamp the 3 mm specimen with only the central 2 mm diameter of the specimen exposed to the beam. The ion beam was stationary without rastering in order to avoid the "void throttling" phenomenon described in a much earlier study where void nuclei are thought to evaporate during the long beam-off periods associated with rastering, especially at higher temperatures characteristic of accelerated radiation via ion bombardment [10]. The beam current was stable within 4% of nominal over the entire irradiation and there were no beam interruptions.

The steady-beam, non-rastering approach employed in this study is also consistent with ASTM standard E521-83, "Standard Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation" [11] that states, "It is recommended that a rastered beam be avoided for the simulation of a constant neutron flux."

The target complex was mounted on the end of the accelerator beam tube and the temperature was maintained by a balance of electrical and beam heating without active cooling. Beam heating at the maximum beam current used produced ~320°C during irradiation. Monitoring of heater temperature was performed with a telemetric control system with a thermocouple fixed in the target support and used as the temperature-sensitive element. Since special attention was paid to maintain good thermal contact between specimen and target support the error of temperature measurement did not exceed $\pm 1^\circ\text{C}$. The ion beam current during irradiation was measured directly from the specimen. The error of beam current and, consequently of the damaging dose, did not exceed $\pm 1\%$.

Irradiations were performed using an accelerator called ESUVI. It is a van de Graf electrostatic accelerator of heavy ions with an external injector of 1.8 MeV Cr^{3+} ions. This facility has been used to irradiate other alloys [12-20]. Even though ESUVI has the ability to simultaneously and accurately implant both helium and hydrogen in the region to be examined [18], these gases were not employed in the current study. This choice was made for two reasons. First, this study was performed to simulate fast reactor irradiations where very little helium is produced in Ni-free ferritic alloys. More importantly, the primary objective was determine the base behavior of the alloy in response to displacive irradiation as a function of composition and microstructure. Once the base behavior is established, then subsequent studies can address the perturbations associated with helium and hydrogen if needed.

The dpa profile shown in **Fig. 3** was calculated using the SRIM-2006 computer code [21] employing the Kinchin-Pease option with a displacement energy of 40 eV. This option was chosen to be consistent with the model employed in the SPECTER code used to calculate dpa for

the neutron-irradiated specimens. The choice of the Kinchin-Pease option as the appropriate method is discussed by Stoller and coworkers [22] as well as by Bratchenko and coworkers [23].

In order to reach 500 dpa in the examined region, the peak dose approached is ~1000 dpa. In the region where the ions came to rest, the peak concentration of injected chromium reached ~20 at% as estimated by SRIM. However, SRIM does not include thermal or radiation-enhanced diffusion into the Cr-profile calculation, and the actual distribution after irradiation is likely to be much different. Pechenkin, Chernova and Garner have recently demonstrated the dynamic redistribution of Cr along the path of 1.8 MeV Cr⁺ ions in ferritic alloys [24].

In the region examined by microscopy, SRIM predicts that only ~0.6% chromium will be directly added in a 500 dpa irradiation, again without accounting for diffusion. Additionally, if significant swelling occurs along the ion path, the dose rate in the examined region will be minimally affected compared to that at deeper depths. The dose rate in the investigated area was 1×10^{-2} dpa/sec, producing ~5 dpa every 3 minutes.

Data on doses and irradiation temperatures chosen for this study are presented in the Table 1. Irradiations were carried out in the temperature range of 400-500°C over a dose range of 100-500 dpa. Irradiations at 100 dpa and at 500 dpa were used to determine the temperature regime of swelling. The dose dependence of swelling was examined at the temperature where swelling at 100 dpa was the largest, 450°C for this study.

2.3 Examination of irradiated specimens

To select the depth of studied layer, there were two major competing factors. First, the investigated layer had to be of sufficient depth from the ion-incident surface to minimize its influence as a defect sink. Second, implanted chromium ions, acting both as injected interstitials and as a chemical species, had to be minimized. The injected interstitial effect is very strong to suppress swelling via depressing void nucleation, especially in ferritic alloys [25-29]. The optimum balance of these effects resulted in the choice to remove a layer of 100 nm from the incident surface after irradiation. This was accomplished using an electro-chemical pulse method [30]. This technique has been calibrated by measurement of the thickness of removed material after pulse trains of 10-20 pulses, using MII-4 interferometer and a Russian Model 201 profilograph-roughness indicator. The accuracy of measurement was ± 30 nm for the interferometer and ± 10 nm for the profilograph.

The final thinning of the specimen to the thickness suitable for microscopy was carried out on the unirradiated back-surface of the specimen, using a TENUPO-5 with the same electrolyte as used for the preliminary polishing.

The structure of both starting and irradiated specimens was studied with JEM-100CX and JEM-2100 transmission electron microscopes. The value of swelling was determined from the resulting images by the formula:

$$S(\%) = 100 \times \frac{\frac{\rho}{6 \times A \times h} \sum_{i=1}^N d_i^3}{1 - \frac{\rho}{6 \times A \times h} \sum_{i=1}^N d_i^3}, \quad (1)$$

where d_i is the diameter of the i -th void, N is the number of all voids, A is the image area, h is the foil thickness of the specimen area under examination. The calculation error is estimated not to exceed $\pm 20\%$.

3. Experimental results

3.1 Initial structure

Ferritic ODS alloy MA957 in the unirradiated state had a banded structure of highly elongated grains oriented in the z-axis of the tubing. The elongated grain shape is due to the oxide particles acting as a strong barrier to high temperature recrystallization during tube extrusion and drawing processes. The grain width varies in the range 300-600 nm while the length is roughly an order of magnitude greater (**Fig. 4**). A high dislocation density is apparent in the bright-field images in **Fig. 5** with the variation in dislocation structure likely due to differences in diffracting contrast within a grain as well as from grain-to-grain. Defects that were likely larger oxide particles were observed in bright-field imaging, but their presence has not yet been confirmed or quantified by more advanced imaging methods such as EFTEM or HAADF.

3.2 Structure after heavy ion irradiation

3.2.1 Microstructures at 100 dpa

Analysis of microstructure of the irradiated specimens showed the presence of dislocation loops, dislocation networks, precipitates and voids. For this first phase study of these specimens, the main attention was paid to the analysis of swelling. Voids were observed at 100 dpa in MA957 over the range of 400-450°C, but not at 500°C (see **Figs. 6-9**). Increasing temperature caused an increase of mean void size from 2 to 10 nm and a decrease of their concentration from 2×10^{17} to $3 \times 10^{15} \text{ cm}^{-2}$ (**Fig. 10**). Maximum swelling at 100 dpa appears to lie between 420–450°C.

3.2.2 Microstructures at 500 dpa

As shown in **Figs. 11-14**, void swelling was observed at 500 dpa for all temperatures investigated, including 500°C, although at a relatively low level at this temperature. Increasing temperature from 400 to 500°C at 500 dpa causes an increase of mean void size from 3 to 32.5 nm and a decrease of their concentration from 2×10^{17} to $8 \times 10^{13} \text{ cm}^{-2}$ (**Fig. 16**). The maximum of swelling at 500 dpa was observed at 450°C, reaching $\sim 4.5\%$ (**Fig. 15**).

3.2.3 Microstructures at 450°C with increasing dose

After determining the temperature dependence at both 100 and 500 dpa, it was decided to more closely examine the dependence of swelling at the peak swelling temperature of 450°C. **Figs. 8, 13 and 16-18** provide examples of the void microstructures at doses of 100, 200, 300, 400 and 500 dpa.

Increasing dose at 450°C caused an increase of mean void size from 10 to 13.5 nm and an increase of their concentration from 3×10^{15} to $1.6 \times 10^{16} \text{ cm}^{-2}$ (**Fig. 19**). At all doses, a relatively low rate of increase of mean void size was observed, and the concentration of voids increased continuously with increasing dose. Therefore, it can be concluded that even to a dose of 500 dpa, the swelling is still in the transient regime and has not yet reached the steady-state regime of swelling, not exceeding 0.015 %/dpa by 500 dpa. However, it should not be overlooked that the swelling rate is continuously but slowly increasing with increasing exposure.

3.2.4 Void Size Distributions

Void size distributions for all irradiation conditions where voids were observed are shown in **Fig. 20**. The void size generally has a log normal distribution that is typically observed for voids in irradiated materials. The width of the distribution appears to scale roughly with the peak in the void size.

4. Discussion

The results show very clearly the high resistance of MA957 to the onset of steady-state swelling to doses up to 500 dpa in the range 400-500°C. Instead of reaching the ~0.2%/dpa observed in other alloys **[31, 32]**, the swelling rate at 500 dpa had not yet exceeded 0.015 %/dpa, although the swelling rate was clearly increasing with accumulating dpa. Averaged over the slightly heterogeneously swelling microstructure, only 4.5% swelling was reached at 500 dpa.

Part of the swelling resistance appears to arise from the strong influence of closely spaced, near-parallel grain boundaries in these highly elongated grains. The resultant void-denuded zone volume in thin grains reduces the overall swelling, with a number of excellent examples shown in some grains in **Fig. 13**, where for some grains only a single line of voids exists between two denuded zones. It has been suggested that high swelling resistance in ODS ferritic alloys may be enabled by the high density of oxide particles acting as recombination sites, similar to that of the grain boundaries, but this could not be confirmed or refuted based solely on these microstructure observations due to the lack of ability to simultaneously image the void and the oxide particles.

However, comparison of oxide particle surface area to grain boundary surface area provides some insight into the possible contribution of the oxide particles to swelling resistance.

Assuming a columnar grain shape with square cross section of 500 nm x 500 nm, the volumetric grain boundary surface area is found to be $4 \times 10^4 \text{ cm}^{-1}$. Oxide particle observations performed by atom probe tomography on unirradiated material revealed an average oxide particle diameter of 2 nm and a number density of $2 \times 10^{17} \text{ cm}^{-3}$ **[5]**, resulting in a volumetric surface area of $2.5 \times 10^4 \text{ cm}^{-1}$ that is in the same order of magnitude as the volumetric grain boundary surface area. If the

point defect recombination strength of the oxide particles and grain boundaries are similar, they may contribute approximately equally to the swelling resistance. It is worth noting that the high grain boundary surface area is due to the oxide particles preventing recrystallization during inter-pass anneals, and so the swelling resistance can potentially be attributed to the oxide particles by a combination of direct and indirect methods.

The swelling resistance of MA957 to these high doses can be compared to that of two other ion irradiation studies conducted using the ESUV1 facility at KIPT. These involved the swelling of Russian alloy EP-450 to a dose of 300 dpa and of steel HT-9 to a dose of 600 dpa at the temperatures of maximum swelling, 480 and 450°C, respectively [31, 32].

As shown in **Fig. 21**, both of these alloys exhibited a lengthy transient stage of swelling before rapidly accelerating to a rate of ~0.2%/dpa. EP-450 is a duplex steel with a 50-50 mix of ferrite and tempered martensite grains. The transient in the ferrite grains lasts up to ~150 dpa, and while the post-transient swelling rate is significantly lower than that of austenitic steels, 27% swelling was still reached by 300 dpa. The tempered martensite grains, however, resisted the onset of steady-state swelling to ~300 dpa [31]. Fully tempered HT-9 has almost no delta ferrite grains and therefore exhibited an overall higher resistance to the onset of swelling with the transient stage lasting until ~450 dpa. It should be noted that the post-transient swelling rate of ~0.2%/dpa was predicted earlier based on swelling of Fe-Cr binary alloys neutron irradiated in both the EBR-II and FFTF fast reactors [33].

Fig. 21 shows that of the three alloys, the MA957 tubing is the most swelling-resistant alloy, extending the transient regime of swelling to 500 dpa or greater under the current irradiation conditions. While these ion-induced swelling levels may not allow a direct prediction of neutron-induced swelling, the relative swelling behavior provides a good indication that this ODS ferritic alloy has better swelling resistance than these two tempered ferritic/martensitic alloys.

Conclusions

These results show that ion irradiated MA957 tubing has exceptional swelling resistance in comparison to two other ferritic-martensitic steels that have been ion irradiated under similar conditions. Swelling of the 100 dpa specimens at 400 and 500°C is less than 0.1%, reasonably consistent with the lack of swelling observed in this same material when neutron irradiated to 110 dpa at the same temperatures.

It has been proposed by others that oxide particles in ODS ferritic alloys may contribute to swelling resistance by acting as point defect recombination sites. Based on TEM observations of MA957, the swelling resistance appears to be additionally influenced by the high grain boundary areal density introducing a high volume fraction of denuded zones. High resolution TEM and APT observations are underway to study this effect and also to observe the effect of irradiation on the oxide particle stability.

In conclusion, these results provide a conclusive demonstration that ODS ferritic alloys can resist the onset of steady-state swelling and provides confidence that improved ODS alloys may serve

to very high doses, especially if care is taken to produce a homogeneous and stable dispersion of oxide particles.

Acknowledgements

This research was funded by the Fuel Cycle R&D Program Core Materials research area sponsored by the U.S. Department of Energy, Office of Nuclear Energy. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830. Collaborate with KIPT in the Ukraine was made possible by the CRDF Organization.

References

1. J. Ribis, "Structural and chemical matrix evolution following neutron irradiation in a MA957 oxide dispersion strengthened material", J. Nucl. Mater. 434 (2013) 178-188.
2. D. S. Gelles, "Microstructural examination of commercial ferritic alloys at 200 dpa", J. Nucl. Mater. 233-237 (1996) 293-298
3. S. Yamashita, N. Akasaka, S. Ukai, S. Ohnuki, "Microstructural development of a heavily neutron-irradiated ODS ferritic steel (MA957) at elevated temperature", J. Nucl. Mater. 367-370 (2007) 202-207.
4. D. S. Gelles and M. B. Toloczko, "Preliminary observations of oxide particle and dislocation interactions in neutron irradiated MA957 pressurized tubes", PNNL-20974, 2011.
5. M. B. Toloczko, A. Certain, D. S. Gelles, F. A. Garner, manuscript in preparation.
6. M. B. Toloczko, F. A. Garner, C. R. Eiholzer, "Irradiation creep of various ferritic alloys irradiated at ~400°C in the PFR and FFTF reactors", J. Nucl. Mater. 258-263 (1998) 1163-1166.
7. M. B. Toloczko, D. S. Gelles, F. A. Garner, R. J. Kurtz and K. Abe, "Irradiation Creep and Swelling from 400 to 600°C of the Oxide Dispersion Strengthened Ferritic Alloy MA957", J. Nucl. Mater. 329-333 (2004) 352-355.
8. M. B. Toloczko, F. A. Garner and S. A. Maloy, "Irradiation Creep and Density Changes Observed in MA957 Pressurized Tubes Irradiated to Doses of 40-110 dpa at 400-750°C in FFTF", J. Nucl. Mater. 428 (2012) 170-175.
9. K. Asano, Y. Kohno, A. Kohyama, T. Suzuki, H. Kusanagi, "Microstructural evolution of an oxide dispersion strengthened steel under charged particle irradiation", J. Nucl. Mater. 155-157 (1988) 928.
10. J. A. Sprague and F. A. Smidt, Jr., NRL Memorandum Report 2629, Naval Research Laboratory, 1975.
11. Standard Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation (Designation E 521-96). Annual Book of ASTM Standards Vol. 12.02. Philadelphia, PA, USA, 2004, pp. 141-160, American Society for Testing and Materials.
12. V. N. Voyevodin, V. F. Zelenskiy, I. M. Neklvudov, O. V. Borodin, "Peculiarities of Microstructural Changes in Austenitic and Ferritic Stainless Steels during Irradiation", Fizika Metallov i Metallovedenie 81 (3) 1996, pp. 90-96.

13. V. N. Voyevodin, I. M. Neklyudov, V. V. Bryk, O. V. Borodin, *Journal of Nuclear Materials* 271-272 (1999) , pp. 290-295.
14. O. V. Borodin, V. V. Bryk, R. L. Vasilenko, V. N. Voyevodin, I. A. Petelguzov, N. D. Rybalchenko, "Influence of oxygen content on evolution of the structure of alloy Zr1%Nb under ion irradiation ", *Problems of Atomic Science and Technology*(2) 2008 , pp. 53-61.
15. O. V. Borodin, V. V. Bryk, A. S. Kalchenko, I. M. Neklyudov, A. A. Parkhomenko, V. N. Voyevodin, *J. Nucl. Mater.* 329-333 (2004) 630–633.
16. O. V. Borodin, V. V. Bryk, A. S. Kalchenko, A. A. Parkhomenko, B. A. Shilyaev, G. D. Tolstolutskaia, V. N. Voyevodin, *J. Nucl. Mater.* 385 (2009) 325–328.
17. A. S. Kalchenko, V. V. Bryk, N. P. Lazarev, I. M. Neklyudov, V. N. Voyevodin, F. A. Garner, *J. Nucl. Mater.* 399 (2010) 114–121.
18. O. V. Borodin, V. V. Bryk, A. S. Kalchenko, V. V. Melnichenko, V. N. Voyevodin, F. A. Garner, "Synergistic effects of helium and hydrogen on self-ion-induced swelling of austenitic 18Cr10NiTi stainless steel", *J. Nucl. Mater.* 442 (2013) S817–S820.
19. O. V. Borodin, V. V. Bryk, V. N. Voyevodin, A. S. Kalchenko, Y. E. Kupriyanova, V. V. Melnichenko, I. M. Neklyudov, A. V. Permyakov, "Radiation swelling of ferritic-martensitic steels EP-450 and HT-9 under irradiation by metallic ions to super-higher doses" *Problems of Atomic Science and Technology* (2) 2011 , pp. 10-15.
20. O. V. Borodin, V. V. Bryk, A. S. Kalchenko, V. V. Melnichenko, "Influence of 5 % cold-worked deformation on behaviour of 18Cr-10Ni-Ti steel under ion irradiation", *Problems of Atomic Science and Technology*(4) 2011 , pp. 9-13
21. J. F. Ziegler and J. P. Biersack, "SRIM2006: The Stopping and Range of Ions in Matter: Version 2006", available at <http://www.srim.org>.
22. R. E. Stoller, M. B. Toloczko, G. S. Was, A. G. Certain, S. Dwaraknath, F. A. Garner, "On the use of SRIM for computing radiation damage exposure", *Nuclear Instruments and Methods in Physics Research B*, 310 (2013) 75–80.
23. M. I. Bratchenko, V. V. Bryk, S. V. Dyul'dya, A. S. Kalchenko, N. P. Lazarev, V. N. Voyevodin, "Comments on DPA calculation methods for ion beam driven simulation irradiations", VANT report series 2013, No. 2, (84) Kharkov, Ukraine, ISSN 1562-6016
24. V. A. Pechenkin, A. D. Chernova, F. A. Garner, "Modeling of local changes in alloy composition along the projected range under high dose ion irradiation", *Proceedings of AccApp-2013*, in press.
25. F. A. Garner, "Impact of the Injected Interstitial on the Correlation of Charged Particle and Neutron-Induced Radiation Damage," *J. Nucl. Mater.* 117 (1983) 177-197.
26. E. H. Lee, L. K. Mansur, M. H. Yoo, *J. Nucl. Mat.* 85&86, 577 (1979).
27. L. K. Mansur and M. H. Yoo, 85 and 86 (1979) 523-532.
28. D. L. Plumton and W. G. Wolfer, *J. Nucl. Mater.* 120 (1984) 245-253.
29. L. Shao , C.-C. Wei, J. Gigax , A. Aitkaliyeva, D. Chen, B. H. Sencer, F. A Garner, Effect of defect imbalance on void swelling distributions produced in pure iron irradiated with 3.5 MeV self-ions", submitted to *J. Nucl. Mater.*
30. V. F. Zelenskyi, I. M. Nekyludov, B. V. Matvyenko et.al., "A few issues of the techniques to study radiation swelling of metals", *Proceedings of Conference on Reactor Material Science*. Alushta, 1978, Vol.2, pp. 3-19. (in Russian).
31. V. V. Bryk, O. V. Borodin, A. S. Kalchenko, V. N. Voyevodin, F. A. Garner, "Self-Ion Induced Swelling of Alloy HT-9 to 200-600 dpa", manuscript in preparation.

32. V. N. Voyevodin, V. V. Bryk, O. V. Borodin, A. S. Kalchenko, F. A. Garner, "Use of ion irradiation to study swelling of ferritic-martensitic alloy EP-450 to 200 dpa and higher", manuscript in preparation.
33. F. A. Garner, M. B. Toloczko and B. H. Sencer, "Comparison of Swelling and Irradiation Creep Behavior of fcc-Austenitic and bcc-Ferritic/Martensitic Alloys at High Neutron Exposure", J. Nucl. Mater. 276 (2000) 123-142.

TABLES

Table 1. Matrix of irradiation doses and temperatures.

400 °C 100 dpa				400 °C 500 dpa
420 °C 100 dpa				420 °C 500 dpa
450 °C 100 dpa	450 °C 200 dpa	450 °C 300 dpa	450 °C 400 dpa	450 °C 500 dpa
500 °C 100 dpa				500 °C 500 dpa

FIGURES

Fig. 1. Typical cutting of MA957 pressurized tubes to produce various types of specimens.

Fig. 2. Design of ion irradiation target complex.

Fig. 3. Profiles of dpa and injected ion distribution of 1.8 MeV Cr^{3+} ions computed using the SRIM-2006 code. The shaded area at $\sim 500 \text{ dpa}$ shows the depth of the layer chosen for study by electron microscopy. Note that the deposited chromium in this layer was only 0.6% after 500 dpa.

Fig. 4. Optical and SEM images of highly elongated grain structure.

Fig. 5. Initial microstructure of MA957 tube as imaged using transmission electron microscopy.

Fig. 6. Microstructure of MA957 tube after irradiation at 400°C to 100 dpa.

Fig. 7. Microstructure of the MA957 tube after irradiation at 420°C to 100 dpa.

Fig. 8. Microstructure of MA957 tube after irradiation at 450°C to 100 dpa.

Fig. 9. Microstructure of MA957 tube after irradiation at 500°C to 100 dpa. No voids were observed.

Fig. 10. Temperature dependencies of mean void size, void concentration, and void swelling of MA957 tube after irradiation to 100 dpa.

Fig. 11. Microstructure of MA957 tube after irradiation at 400°C to 500 dpa.

Fig. 12. Microstructure of MA957 tube after irradiation at 420°C to 500 dpa.

Fig. 13. Microstructure of MA957 tube after irradiation at 450°C to 500 dpa.

Fig. 14. Microstructure of the MA957 tube after irradiation at 500°C to 500 dpa.

Fig. 15. Temperature dependencies of void size, void concentration, and void swelling of MA957 tube after irradiation to 100 dpa (solid line) and 500 dpa (dotted line).

Fig. 16. Microstructure of MA957 tube after irradiation at 450°C to 200 dpa.

Fig. 17. Microstructure of MA957 tube after irradiation at 450°C to 300 dpa.

Fig. 18. Microstructure of MA957 tube after irradiation at 450°C to 400 dpa.

Fig. 19. Dose dependencies of void size, void concentration, and void swelling as a function of dose in MA957 tube after irradiation at 450°C.

Fig. 20. Void size distribution plots for all irradiation conditions where voids were observed.

Fig. 21. Dose dependence of swelling of MA957 and two ferritic-martensitic alloys.