NEUTRON-INDUCED MICROSTRUCTURAL EVOLUTION OF Fe-15Cr-16Ni ALLOYS AT ~ 400°C DURING NEUTRON IRRADIATION IN THE FFTF FAST REACTOR - T. Okita, T. Sato and N. Sekimura (University of Tokyo), F. A. Garner and L. R. Greenwood (Pacific Northwest National Laboratory)*, W. G. Wolfer (Lawrence Livermore National Laboratory), Y. Isobe (Nuclear Fuel Industries Ltd., Japan)

OBJECTIVE

The purpose of this effort is to determine the influence of dpa rate on void swelling of fcc alloys.

SUMMARY

An experiment conducted at ~400°C on simple model austenitic alloys (Fe-15Cr-16Ni and Fe-15Cr-16Ni-0.25Ti, both with and without 500 appm boron) irradiated in the FFTF fast reactor at seven different dpa rates clearly shows that lowering of the atomic displacement rate leads to a pronounced reduction in the transient regime of void swelling. While the steady state swelling rate (~1%/dpa) of these alloys is unaffected by changes in the dpa rate, the transient regime of swelling can vary from <1 to ~60 dpa when the dpa rate varies over more than two orders of magnitude. This range of dpa rates covers the full span of fusion, PWR and fast reactor rates.

The origin of the flux sensitivity of swelling arises first in the evolution of the Frank dislocation loop population, its unfaulting, and the subsequent evolution of the dislocation network. There also appears to be some flux sensitivity to the void nucleation process. Most interestingly, the addition of titanium suppresses the void nucleation process somewhat, but does not alter the duration of the transient regime of swelling or its sensitivity to dpa rate. Side-by-side irradiation of boron-modified model alloys in this same experiment shows that higher helium generation rates homogenize the swelling somewhat, but do not significantly change its magnitude or flux sensitivity.

The results of this study support the prediction that austenitic alloys irradiated at PWR-relevant displacement rates will most likely swell more than when irradiated at higher rates characteristic of fast reactors. Thus, the use of swelling data accumulated in fast reactors may possibly lead to an under-prediction of swelling in lower-flux PWRs and fusion devices.

INTRODUCTION

The void swelling phenomenon was the life-limiting aging phenomenon of austenitic stainless steels in fast reactors (1). Until very recently it was not thought that void swelling would occur in the austenitic internal components of light water reactors (LWRs). Similar predictions have been made for some fusion devices operating at lower dpa rates and lower temperatures. The two reactor concepts share many similarities, including high generation rates of helium and hydrogen.

It was predicted in 1994, however, that the 316 and especially 304 stainless steels used in the baffle-former-barrel assembly of pressurized water reactors (PWRs) were probably already swelling at relatively low levels and would continue to swell at accelerating rate as the nuclear plants continued to age (2,3). Due to the accelerating development of swelling

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rate at higher exposures it was suggested that void swelling might become an important issue in plant life extension of PWRs. Stainless steels used in boiling water reactors (BWRs) experience much lower neutron exposures and are not expected to develop significant amounts of swelling.

Even more importantly, it was predicted that not only would the higher rates of gamma heating and helium generation characteristic of LWRs tend to somewhat accelerate the onset of void swelling, but the lower neutron fluxes and atomic displacement rates of PWRs, compared to those of fast reactors, would strongly accelerate the onset of swelling. The acceleration was predicted both in lowering the threshold neutron dose and the threshold irradiation temperature, pushing the swelling temperature regime down toward the PWR inlet temperature (2).

Subsequent papers published by Garner and co-workers have examined void development in various Russian steels irradiated at very low neutron fluxes in either fast reactors or PWRs (4-9). These studies demonstrate the onset of swelling at very low temperatures and neutron exposures, down to ~300°C and at doses below 10 dpa (displacements per atom). Voids have also recently been found in cold-worked 316 and 347 bolts removed from various Western reactors at unexpectedly low temperatures and neutron exposures (10,11). Even charged particle irradiation experiments conducted at higher atomic displacement rates have shown that void swelling can occur in 300 series steel at temperatures as low as 300°C (12-14). Since the majority of the PWR baffle-former assembly that is exposed to high neutron exposures exists at temperatures above 300°C, this implies that the potential for swelling at some level exists throughout the assembly. It is only the magnitude of swelling that is uncertain under PWR conditions.

Garner proposed, however, that the most important environmental variables for swelling in PWRS would be the irradiation temperature and especially the rate of atomic displacement, the latter being roughly linear with the fast neutron flux (2). The dependence of swelling on atomic displacements per atom per second (dpa/sec) is somewhat more difficult to study, but one recent study indicated that the swelling of annealed 304 stainless steel at ~380°C appeared to accelerate as the dpa rate decreased through the PWR-relevant range (15).

A number of comprehensive experiments have been initiated to study the separate effects of dpa rate and helium generation. The first of these is a fast reactor study on annealed 304 stainless steel, which clearly shows an acceleration of void swelling with decreasing dpa rate (16). Unfortunately, this study on 304 stainless does not provide strong clues illuminating the microstructural origins of the sensitivity of swelling to dpa rate. The second flux-effect study is the current study, which not only confirms the flux-sensitivity of swelling, but also provides evidence of the microstructural origins of the flux dependency of void swelling during neutron irradiation. A companion study on the same alloy using charged particle irradiation at much higher dpa rates reaches similar conclusions while providing additional insight on the microstructural origins of the flux sensitivity of swelling (17).

Okita and coworkers earlier published the first small fraction of the results from the current neutron irradiation experiment (18). The large specimen matrix of this experiment is still being analyzed but the major results of the experiment are presented here.

Experimental Details

Simple model austenitic alloys, ternary Fe-15Cr-16Ni and quaternary Fe-15Cr-16Ni-0.25Ti (atomic %) and boron-doped (500 appm natural boron) variants of each were prepared by

arc melting from very pure Fe, Ni, Cr and Ti. Microscopy showed that no titanium or boron-containing precipitates were present, indicating that these elements were well dispersed.

The alloys were rolled to sheets of 0.2 mm thickness. Afterward, standard 3 mm microscopy disks were punched and then annealed for 30 minutes at 1050°C in a very high vacuum. Each specimen was marked with a unique identification code by laser engraving. The specimens were then loaded in a well-defined order into sealed, helium-filled tubes of 0.88 in length. The tubes were helium leak-checked to insure tube integrity. All alloys of interest in a given experiment were placed side-by-side into the same tube to insure that there were no differences in environmental history between the various alloys. Multiple tubes with identical contents and packing order were placed at all positions and irradiation conditions of interest.

Each tube was placed in one of canisters of the Materials Open Test Assembly (MOTA) at one of seven axial locations ranging from below the core of the Fast Flux Test Facility (FFTF) to far above the core. In the FFTF-MOTA experiment the temperature of each canister was measured by thermocouples and was actively controlled to ± 5°C of the target temperature throughout the irradiation. The target temperatures of the individual canisters varied over a limited range, 390 to 444°C.

The first irradiation sequence occurred in Cycle 11 of FFTF operation in MOTA-2A, and a subset of tube packets was then removed. Other identical tube packets continued in Cycle 12 with irradiation in MOTA-2B, and then the packets were removed. With one exception all tube packets remained at the same canister level during the transition to MOTA-2B. One set moved from Level 3 to level 2 with a slight increase in dose rate.

The irradiation exposure was determined by extensive dosimetry measurements involving radioactivation of a number of pure metals. The dpa rates specified in this paper were determined for the midpoint of the tube packet length and for the various packets ranged from 8.9×10^{-9} to 1.7×10^{-6} dpa/sec. The mid-point dpa levels varied from 0.23 to 43.8 dpa in MOTA-2A and 0.38 to 24.0 dpa in MOTA-2B. Wherever possible, two identical packets were placed in MOTA-2A and one of them moved to MOTA-2B at essentially identical dpa rates. In some out-of-core canisters, however, the position and associated dpa rate of individual packages changed somewhat when moved from MOTA-2A to MOTA-2B, and consideration of such changes is necessary in interpretation of the swelling data.

Even more importantly, the packets near or outside of the core boundary will have a gradient along their length. Although the ternary and quaternary alloys were usually side-by-side in the tube packet with little potential difference in dpa rate, this was not necessarily always the case for the comparable boron-doped alloys, with some consequences in the interpretation of the influence of boron addition. In general the boron-doped alloys were 0.5 to 0.7 cm away from the undoped alloys. Thus the swelling will be subject to the combined effects of both boron and dpa rate.

The exposures were calculated in displacements per atom (dpa) using the standard NRT model (19). The target irradiation temperatures, dpa levels and dpa rates experienced by each specimen group are listed in Table 1. Spectral-dependent calculations were performed to assess the production of helium in both the base alloys and B-doped alloys. The fractional burnup of ^{10}B per dpa was highly dependent on the location in the core, being larger at the out-of-core locations where the neutron spectra are softer. Table 1 also provides the helium levels reached in the alloys.

Table 1. Irradiation Conditions in MOTA-2A and 2B

MOTA		Dose, dpa			dpa/sec		Temperature		appm He	
2A	2B	2A	2B	Total	2A	2B	2A	2B	without B	with 500appm B
Yes	No	0.23	-----	0.23	8.90E-09	-----	436	-----	0.013	3.59
Yes	Yes	0.23	0.38	0.61	8.90E-09	2.20E-08	436	444	0.021	6.1
Yes	No	0.71	-----	0.71	2.74E-08	-----	434	-----	0.23	7.84
Yes	Yes	0.71	1.16	1.87	2.74E-08	6.60E-08	434	437	0.35	12.6
Yes	No	2.36	-----	2.36	9.11E-08	-----	430	-----	0.45	12.2
Yes	Yes	2.36	3.7	6.36	9.11E-08	2.10E-07	430	431	0.7	19
Yes	No	8.05	-----	8.05	3.11E-07	-----	411	-----	1.84	27.5
Yes	Yes	5.69	5.36	11.1	2.20E-07	3.00E-07	411	410	3.22	37.6
Yes	No	14	-----	14	5.41E-07	-----	430	-----	3.06	14.1
Yes	Yes	14	14.8	28.8	5.41E-07	8.40E-07	430	424	5.48	22.7
Yes	No	20	-----	20	7.80E-07	-----	390	-----	6.64	19.6
Yes	Yes	15.6	16.8	32.4	6.00E-07	9.50E-07	390	387	10.9	31.1
Yes	No	43.8	-----	43.8	1.70E-06	-----	427	-----	8.96	22.3
Yes	Yes	43.8	24	67.8	1.70E-06	1.40E-06	427	408	15.5	38.2

After removal of the TEM specimens from the tube packet, they were cleaned and then measured by one and sometimes two methods to determine the swelling. The first method involved the use of an immersion density technique known to be accurate to ~ 0.2%, but which is incapable of discriminating between void swelling and other contributions to density change. This technique is especially effective in determining the volume-averaged swelling at large levels. The second technique involved the use of electropolishing and transmission electron microscopy (TEM), which is very effective to determine low levels of void swelling, but cannot easily discriminate between swelling variations that are rather heterogeneously distributed. TEM is not particularly effective to measure swelling at large levels where significant intersection of voids with the electropolished surfaces occurs. In some cases both methods were used to determine the swelling. Usually, there is only one TEM determination from a single specimen, but often there are two, three or four separate disks measured for density.

Results

Microscopy examination reveals that voids, occasional bubbles, Frank interstitial loops and unfaulted perfect dislocation loops, and finally network dislocations are the only microstructural features observed. There were no pre-existing or radiation-induced precipitates observed in any sample.

Figure 1 shows typical void microstructures of quaternary Fe-15Cr-16Ni-0.25Ti, both without and with 500 appm boron, after irradiation to 28.8 dpa at 430/424°C in MOTA-2A and 2B. Figure 2 shows typical loop and dislocation microstructures of Fe-15Cr-16Ni-500appmB after irradiation to 0.61dpa at 436/444°C in MOTA-2A and 2B. Note that most of the loops are already unfaulted and/or heavily decomposed into network dislocations.

When more than one specimen was measured by density change, the swelling was remarkably consistent between specimens. Figures 3 and 4 show that the ternary and quaternary alloys exhibit remarkably similar behavior, with the transient regime of swelling progressively increasing in duration as the dpa rate increases, ranging from less than 1 dpa to greater than 50 dpa. Figure 4 expands the scale in order to better visualize the behavior of the two alloys at the lowest two displacement rates. It is very clear from Figures 3 and 4

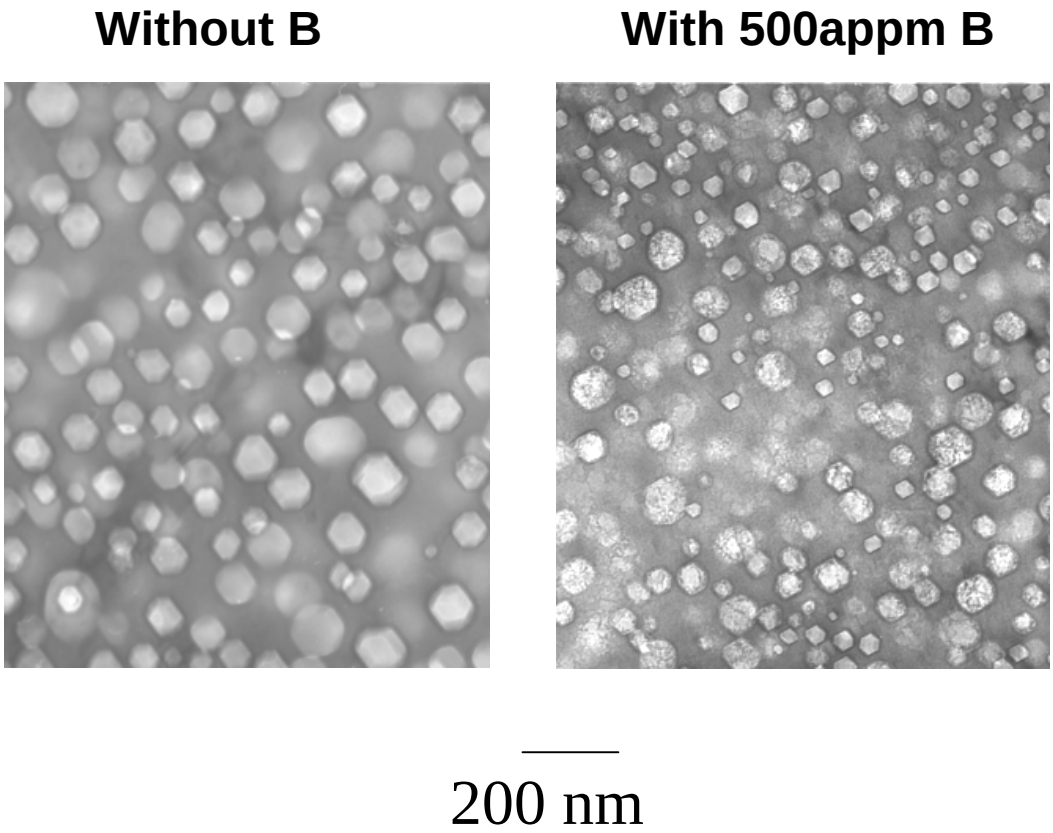

Figure 1. Void microstructures observed in Fe-15Cr-16Ni-0.25Ti after irradiation to 28.8 dpa at 430/424°C in MOTA-2A and 2B. Note that addition of 500 appm boron caused a slight increase in void density as a result of increasing the helium content from 5.5 to 22.7 appm.

that the steady-state swelling rate over the entire range of dpa rates is ~1%/dpa, in agreement with earlier results on ternary model alloys irradiated in the EBR-II reactor (20-21) and all austenitic stainless steels irradiated in a variety of reactors (1, 22).

Figure 5 presents a comparison for the ternary and quaternary alloys at several irradiation conditions to emphasize that titanium addition made very little difference in the macroscopic swelling behavior at this irradiation temperature. On the microscopic level, however, there were distinct differences in behavior with titanium appearing to suppress somewhat the nucleation of voids as shown in Figure 6, with compensating increases in void sizes, as shown in Figure 7.

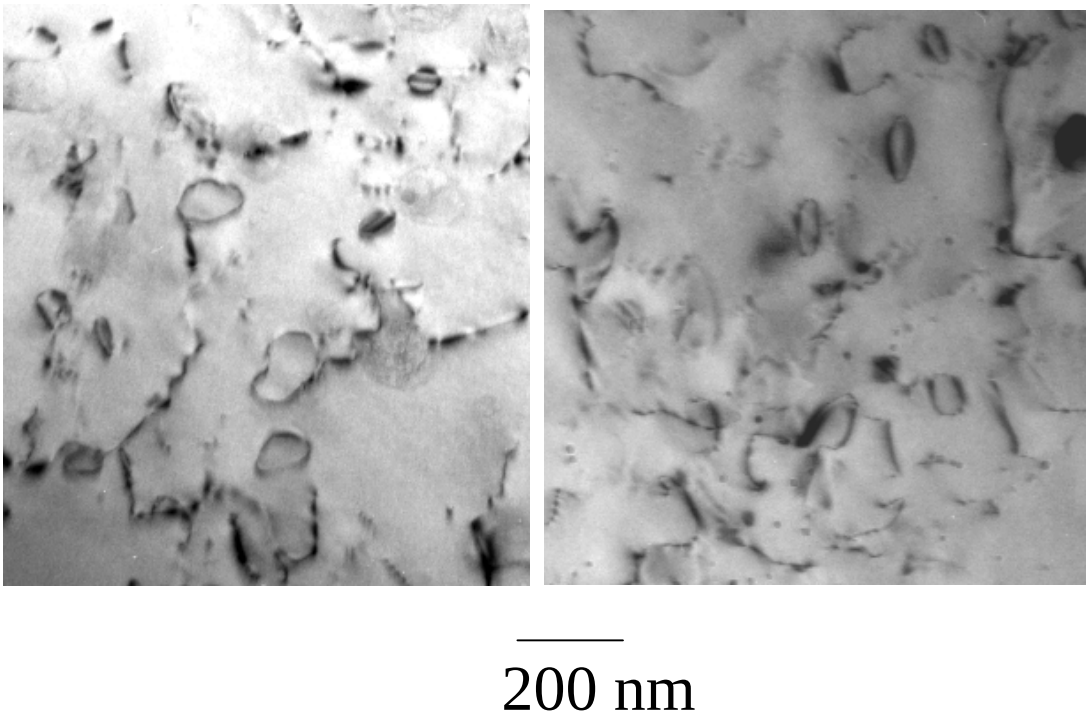

Figure 2. Dislocation loop microstructure of Fe-15Cr-16Ni-500appmB at 0.61dpa and 436/444°C after irradiation in MOTA-2A and 2B. Note that, even at this low dose, most of the loops are unfaulted and dislocation network evolution is well in progress.

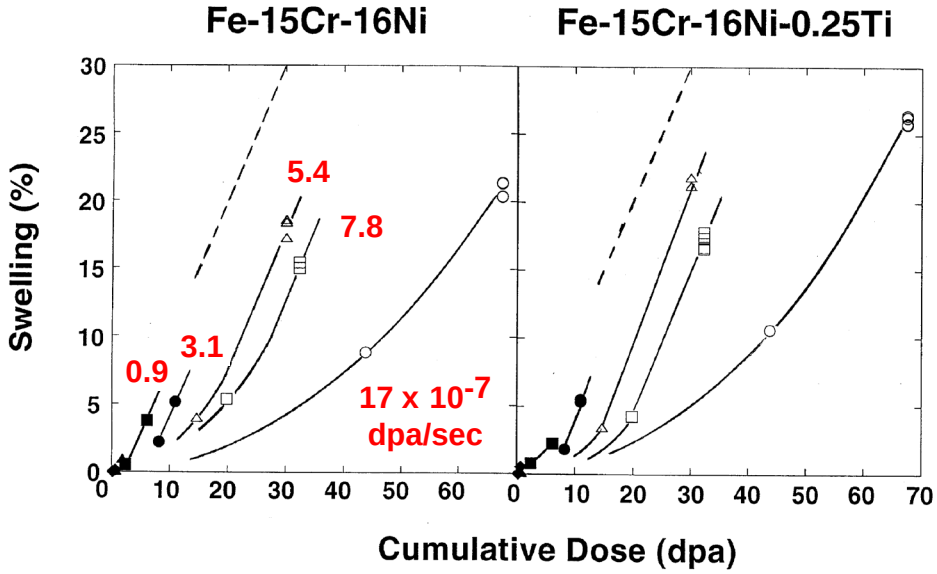

Figure 3. Swelling observed at ~400°C in the ternary and quaternary alloys as a function of dpa rate. In these comparisons the ternary and quaternary alloys are side-by-side with no significant gradient in dpa rate.

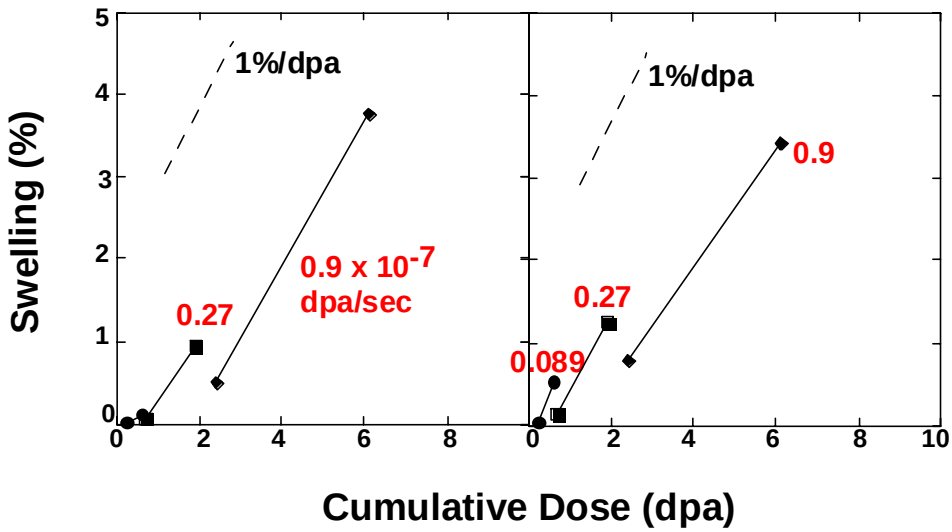

Figure 4. Expand version of Figure 3 to more clearly show swelling at the lowest three dpa rates.

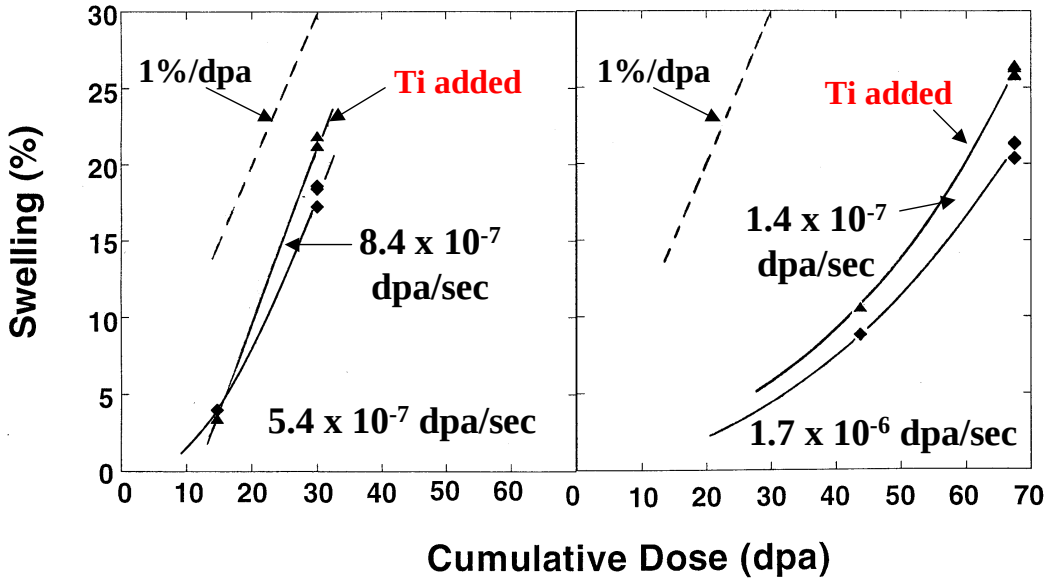

Figure 5. Small influence of titanium on void swelling at ~400°C for two conditions where the dpa rates changed somewhat.

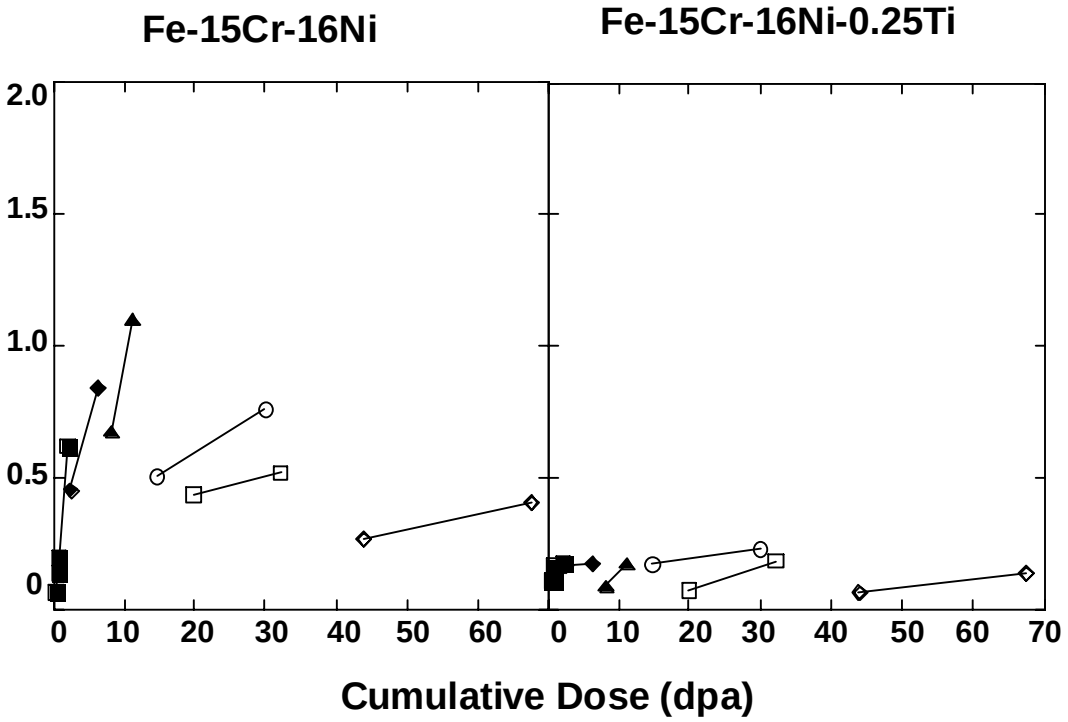

Figure 6. Dose dependence of cavity density in the two alloys.

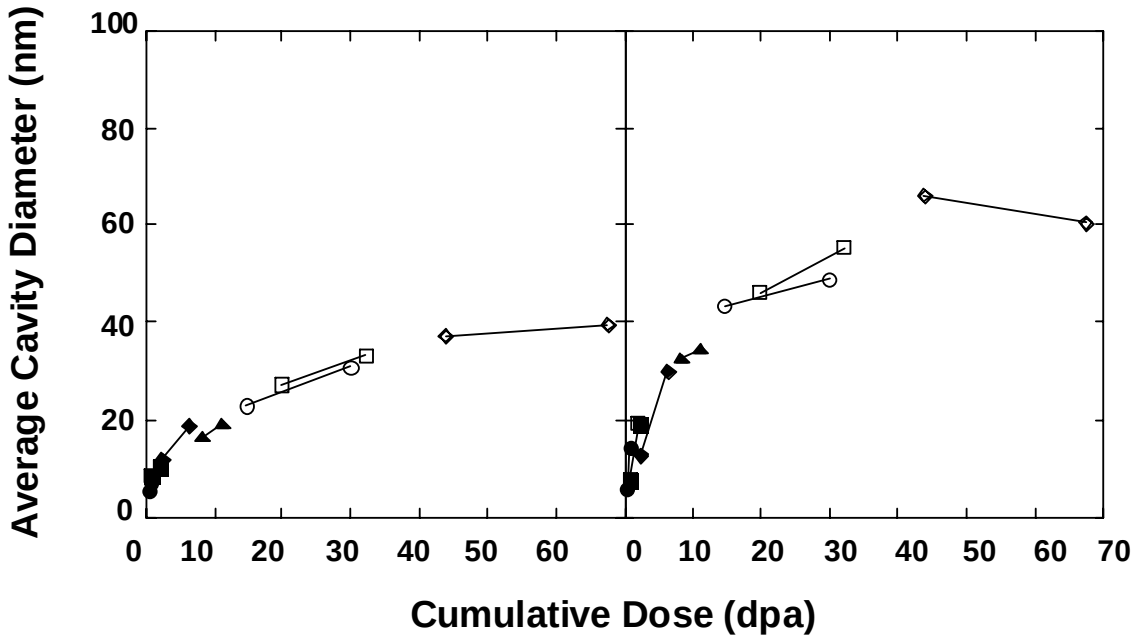

Figure 7. Dose dependence of average cavity diameter in the two alloys.

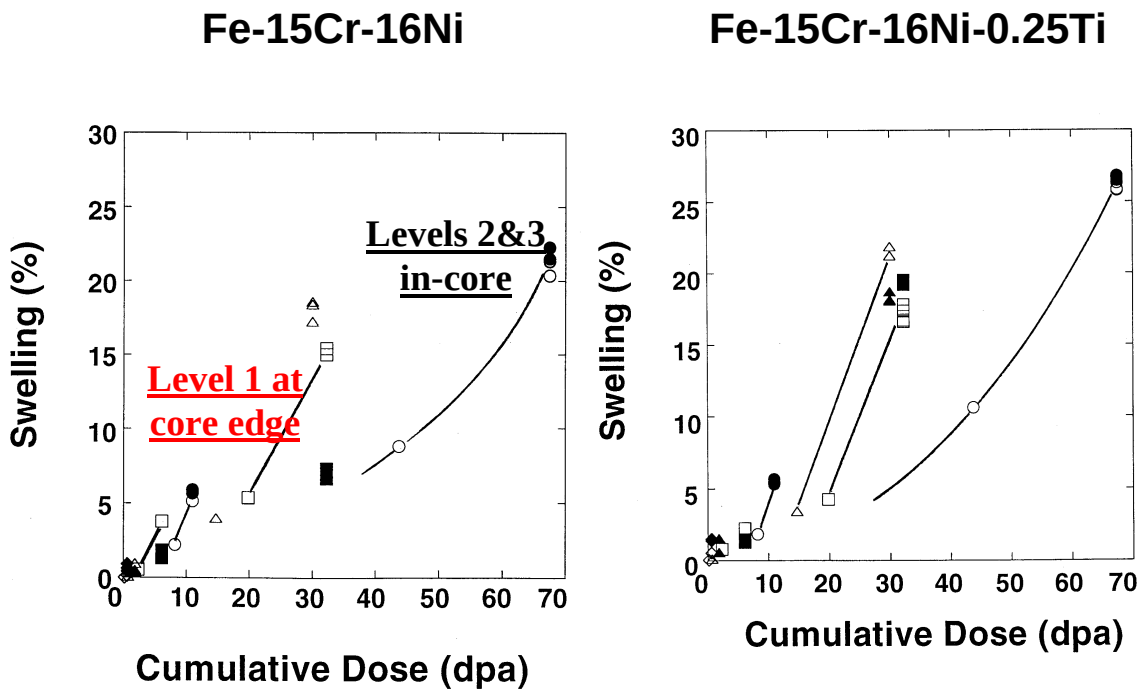

Figure 8. Influence of 500 appm boron addition (solid symbols) on total swelling of the ternary and quaternary alloys. The sometimes large apparent depression of swelling with boron addition (e.g. Level 1) results from the spatial separation of the B-doped and undoped alloys along a gradient in dpa rate, with the depression actually arising from a slightly higher dpa rate. When the gradient is very small such as in levels 2 and 3, there is very little effect of boron on swelling. The ternary alloy seems to be more sensitive to such spatial variations compared to the quaternary.

Figure 8 shows that, with a few striking exceptions, the macroscopic swelling of both alloys is not appreciably affected by boron addition that produces both He and Li via the ^{10}B (n,α) ^{6}Li reaction. However, it appears that in those several cases where the boron appeared to strongly depress swelling, there was a small but significant difference in dpa rate of the boron-doped and undoped alloys due to their 0.5 to 0.7 cm separation in the packing order. Once again the dpa rate effect overshadowed the action of composition and transmutation.

Remember that the helium levels are dependent on both the dpa level and on the position in the reactor, thereby exerting different influence at different dpa rates. In Figure 1 an increase from 5.5 to 22.7 appm/dpa caused a slight increase in the void density with concurrent reduction in void size, and the swelling was reduced by several percent.

It is important to note that ^{11}B is 89% of natural boron and is not transmuted, so any variations in swelling behavior as a result of boron addition cannot be attributed to He alone, but to the combined effect of He, Li and retained B. It has shown that both He and Li tend to increase void nucleation in boron-doped austenitic steels (23, 24).

Figure 9 at first glance appears to imply that the loop density of the ternary alloy at the four lowest dpa rates is insensitive to dpa rate, tending toward saturation with increasing dpa.

This conclusion is misleading, however. Note that loops are absent at the highest three dpa rates, indicating that loop unfaulting and network formation now completely dominates the dislocation microstructure. As shown in Figure 10 it is obvious that loop unfaulting and network formation was occurring even more strongly at the lowest dpa rates. One strong consequence of the flux-sensitivity of loop unfaulting is a progressive delay of network dislocation evolution with increasing dpa rate. As shown in Figure 11 titanium addition appears to slightly depress the nucleation of Frank loops, but the mean loop size is slightly larger, leading to no large change in the total loop line length or the evolution of the dislocation network. Thus titanium's influence on both voids and dislocation evolution appears to be similar, with a reduction in number density that is almost exactly offset by an increase in size.

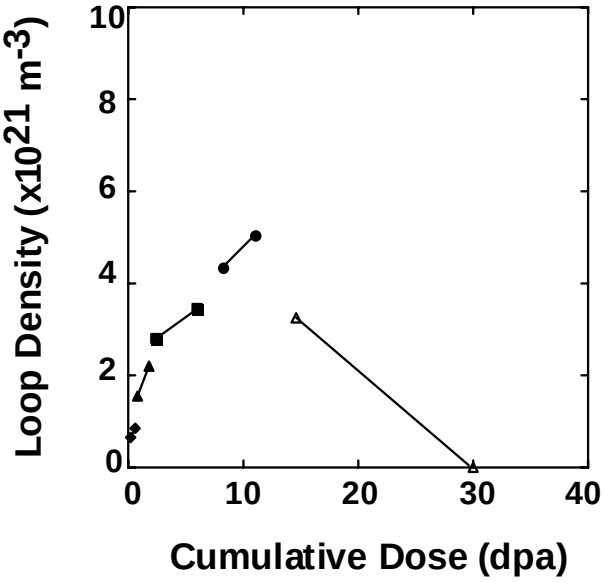

Figure 9. Dose dependence of loop density in the ternary alloy.

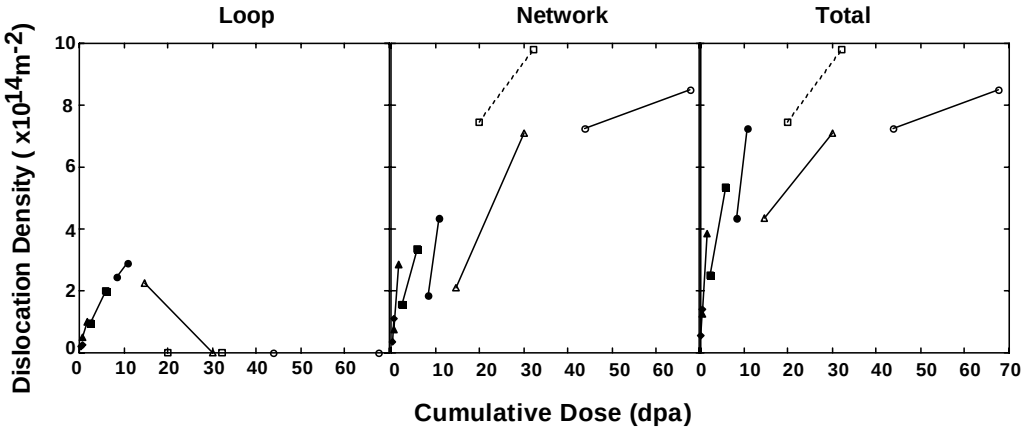

Figure 10. Evolution of the components of the dislocation line length in the ternary alloy.

Discussion

One interesting aspect of these results is the influence of titanium at ~400°C was its effect to reduce somewhat both the loop density and the void density, but having no effect on the aggregate dislocation or swelling behavior. Similar behavior was observed in several similar experiments also conducted in the JOYO or FFTF fast reactors at ~400°C (25-27). In these constant dpa rate irradiations both Fe-13Cr-14Ni (0.12Ti) and Fe-15Cr-16Ni (0.25Ti), the addition of titanium had no influence on total swelling at 400°C, but caused an increasing suppression of swelling at higher temperatures (500, 600°C).

Such a solute-induced dependence of void nucleation on temperature in simple model Fe-Cr-Ni alloys is consistent with the addition of a fast diffusing solute (28, 29). Indeed titanium is a fast diffusing species, diffusing in γ-iron at a rate 4.2 times faster than that of iron (30).

Yoshiie and co-workers note, however, that 0.25% titanium addition to Fe-15Cr-16Ni slowed down Frank loop growth, and that was a consequence of a titanium-induced decrease in vacancy diffusivity (31), and that this view was supported by electrical resistivity measurements by Dimitrov and co-workers showing that mobility is decreased with titanium addition (34). Is it possible that addition of a fast-diffusing element can suppress the overall vacancy diffusivity of the alloy?

Such a proposal has merit and will require further study. While it is frequently assumed that addition of a faster or slower-diffusing solute will speed up or slow down overall vacancy diffusion of the alloy, this is not always a safe assumption. For example, addition of more fast-diffusing Cr actually depresses overall vacancy diffusion in Fe-Cr-Ni alloys, while addition of additional slower-diffusing Ni actually elevates vacancy diffusion of the alloy matrix (33). Perhaps Cr and Ti are very similar in this respect.

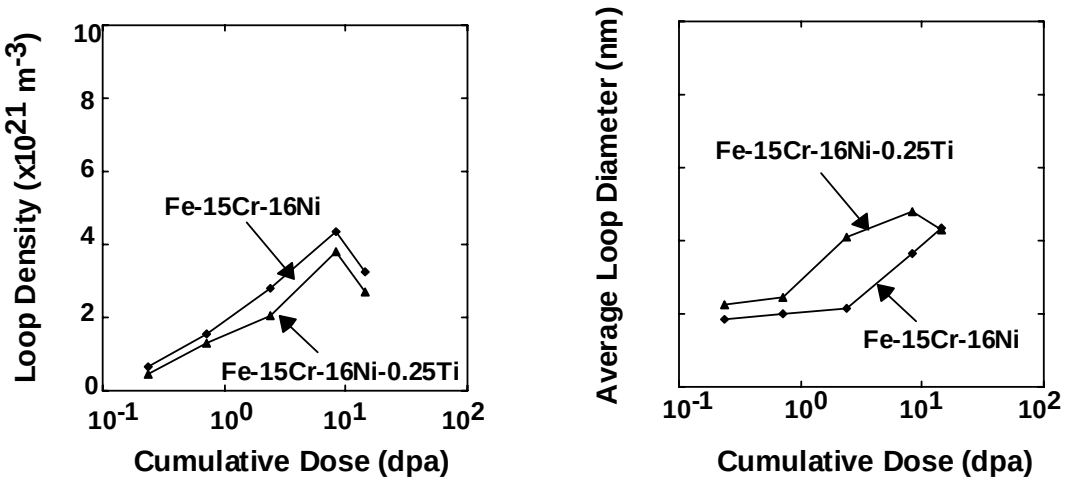

Figure 11. Influence of titanium addition on loop evolution, as observed in MOTA-2A specimens.

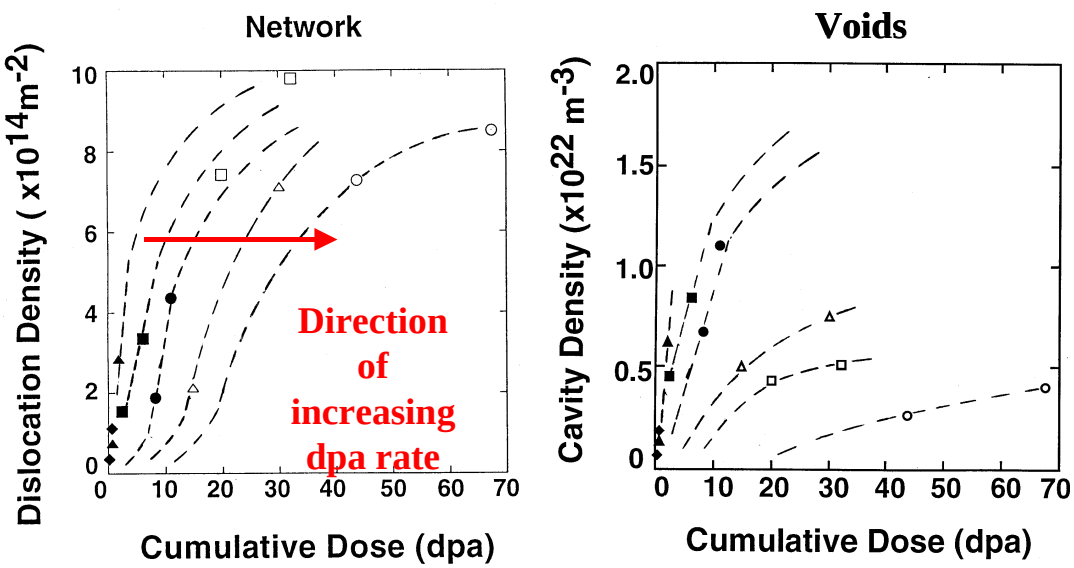

Figure 12. Interpretation of the trends exhibited by the microstructural data.

An alternate interpretation of the effect of titanium to reduce the void density would focus on the potential of this element to act as a getter for gases, especially any residual oxygen, and thereby reducing void nucleation somewhat.

The most significant observation of this study is the very clear and progressive reduction in the transient regime of swelling in both the ternary and quaternary alloys, approaching zero dpa at the lowest dose rates. Secondly, the results of this study reconfirm the universally observed steady-state swelling rate of ~1%/dpa that is characteristic of all austenitic steels over a very wide range of dpa rates, temperatures and other environmental or material variables. It is significant that the approach to this rate can be very languid at dpa rates much higher than relevant to PWR operation.

It appears, that in this irradiation series, the effect of dpa rate overwhelms the influence of boron, lithium, helium and titanium, even though each has significant but different impacts on modifying the void density. In general, it has been shown that the steady-state swelling rate is expected to be relatively independent of cavity density, providing cavity densities are reached in excess of ~10^{14} cm^{-3} (34).

The strong onset of unfaulting and dislocation evolution at very low dpa rates erases any meaningful evidence of the dependence of Frank loop nucleation on dpa rate in this experiment, but the charged particle companion experiment (17) mentioned earlier clearly shows that Frank loop nucleation is strongly sensitive to dpa rate. This conclusion is in agreement with a more comprehensive series of experiments by Muroga and co-workers (35) where the saturation density of Frank interstitial loops increased with $(\text{dpa rate})^{1/2}$ over more than three orders of magnitude in dpa rate. In general, higher densities of loops develop concurrently with smaller loop sizes and therefore different probabilities of intersection, interaction and unfaulting.

It appears that the primary flux-sensitivity of the microstructural evolution resides in the development of the Frank interstitial loop population, followed by a flux-dependent delay in the unfaulting and network formation processes. Following the formation of the dislocation network it is expected that void nucleation will also exhibit sensitivity to dpa rate (36). The flux-sensitive delay in the onset of void swelling appears to first involve a delay in the formation of the dislocation network. Figure 12 presents our interpretation of the network and void nucleation of Fe-15Cr-16Ni when viewed in this context. Theoretical modeling of these results is in progress and will be presented in a later paper.

Conventional wisdom holds that there is a “temperature shift” in the temperature regime inhabited by void swelling (37). This shift envisions that void swelling would respond similarly to decreases in temperature and increases in dpa rate. One anticipated consequence of the temperature shift concept would be that decreasing dpa rates ought to bring decreases in void nucleation, since the irradiation would proceed at a higher effective temperature. As can be seen from Figure 12, however, exactly the opposite behavior is observed in void nucleation as a function of dpa rate.

In previous papers Garner and co-workers showed that the dependence of the transient regime of swelling on displacement rate has been observed in both 304 and 316 stainless steels, and also in model Fe-Cr ferritic steels (16, 38, 39). Ongoing studies on pure nickel and V-Cr alloys also indicate a strong flux sensitivity of the transient regime, leading to the conclusion that the flux effect might be a universal aspect of the swelling phenomenon, independent of crystal system or composition.

The results of these other studies and the current study support the prediction that austenitic alloys irradiated at PWR-relevant displacement rates will most likely swell more than when irradiated at higher rates characteristic of fast reactors. A similar concern exists for some regions of various fusion concepts. Thus, the use of swelling data accumulated in fast reactors will most likely lead to an under-prediction of swelling in PWRs and lower-flux fusion devices.

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REFERENCES

[1] F. A. Garner, Chapter 6: “Irradiation Performance of Cladding and Structural Steels in Liquid Metal Reactors”, Vol. 10A of Materials Science and Technology: A Comprehensive Treatment, VCH Publishers, 1994, pp. 419-543.

[2] F. A. Garner, L. R. Greenwood and D. L. Harrod, “Potential High Fluence Response of Pressure Vessel Internals Constructed from Austenitic Stainless Steels”, Proc. Sixth

Intern. Symp. on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, San Diego, CA. August 1-5, 1993, pp. 783-790.

[3] F. A. Garner, "Materials Issues Involving Austenitic Pressure Vessel Internals Arising From Void Swelling and Irradiation Creep", Trans. Am. Nucl. Soc., 71 (1994) 190.

[4] F. A. Garner and M. B. Toloczko, "Irradiation Creep and Void Swelling of Austenitic Stainless Steels at Low Displacement Rates in Light Water Energy Systems", J. of Nucl. Mater. 251 (1997) pp. 252-261.

[5] S. I. Porollo, A. N. Vorobjev, Yu. V. Konobeev, A. M. Dvoriashin, and F. A. Garner, "The Influence of PWR-Relevant Atomic Displacement Rates and Temperatures on Void Swelling in the Russian Equivalent of AISI 304 Stainless Steel", International Symposium on "Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, 14-18 Sept. 1998, Fontevraud, France, pp. 271-280.

[6] V. S. Neustroev, V. K. Shamardin, Z. E. Ostrovsky, A. M. Pecherin, and F. A. Garner, "Temperature-Shift of Void Swelling Observed at PWR-Relevant Temperatures in Annealed Fe-18Cr-10Ni-Ti Stainless Steel Irradiated at High and Low Dpa Rates in BOR-60", International Symposium on Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, 14-18 Sept. 1998, Fontevraud, France, pp. 261-269.

[7] F. A. Garner, S. I. Porollo, A. N. Vorobjev, Yu. V. Konobeev and A. M. Dvoriashin, "Void Swelling at Low Displacement Rates in Annealed X18H10T Stainless Steel at 30-56 dpa and 280-332°C", 9th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, 1999,pp. 1051-1059.

[8] S. I. Porollo, Yu. V. Konobeev, A. M. Dvoriashin, V. M. Krigan, and F. A. Garner, "Determination of the Lower Temperature Limit of Void Swelling of Stainless Steels at PWR-relevant Displacement Rates", Proc. of Tenth Inter. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 5-9, 2001, in press.

[9] V. S. Neustroev V. N. Golovanov, Z. Ye. Ostrovsky, A. M. Pecherin, and V. K. Shamardin, "Radiation Effects in 18Cr-10Ni-Ti Steel Irradiated in Different Reactors under Conditions Close to VKU VVER Reactors Operating Conditions", Proceedings of the Fourth International Ural Seminar on Radiation Damage Physics of Metals and Alloys, Feb. 25 – Mar. 3, 2001. Snezhinsk, Russia, in press.

[10] D. J. Edwards, F. A. Garner, B. A Oliver and S. M. Bruemmer, "Microstructural Evaluation of a Cold-Worked 316SS Baffle Bolt Irradiated in a Commercial PWR", Proc. of Tenth Inter. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 5-9, 2001, in press.

[11] J. M. Conermann, R. P. Shogan, D. R. Forsyth, Ian L. W. Wilson and H. T. Tang, "Characterization of Baffle-Former Bolts Removed from Service in U.S. PWRs – 50", Proc. of Tenth Inter. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 5-9, 2001, in press.

[12] T. Aoki, T. Fukuda, Y. Isobe, A. Hasegawa, M. Sato, K. Abe, K. Matsueda and Y. Nishida, "Comparison of Radiation Induced Degradation in Several Austenitic Stainless Steels Used for Core Internals in LWR", 9th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, 1999, pp. 1045-1050.

[13] T. Fukuda, M. Sagisaka, Y. Isobe, A. Hasegawa, M. Sato, K. Abe, Y. Nishida, T. Kamada and Y. Kaneshima, "Microstructural Changes of Austenitic Steels Caused by Proton Irradiation Under Various Conditions", J. of Nucl. Mater. 283-287 (2000) 263-267.

[14] M. Sagisaka, T. Fukuda, Y. Isobe, G. S. Was, F. A. Garner, B. H. Sencer, T. Kamada and G. M. Bond, "Evaluation of Potential Void Swelling Behavior in PWR Core Internals Using Light Ion Bombardment – 83", Proc. of Tenth Inter. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 5-9, 2001, in press.

[15] G. M. Bond, B. H. Sencer, F. A. Garner, M. L. Hamilton, T. R. Allen and D. L. Porter, "Void Swelling of Annealed 304 Stainless Steel at ~370-385°C and PWR-Relevant Displacement Rates", 9th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, 1999, pp. 1045-1050.

[16] F. A. Garner, M. L. Hamilton, D. L. Porter, T. R. Allen, T. Tsutsui, M. Nakajima, T. Kido, T. Ishii, G. M. Bond and B. H. Sencer, in preparation for submission to J. of Nucl. Mater.

[17] T. Okita, N. Sekimura, T. Iwai and F. A. Garner, "Investigation of the Synergistic Influence of Irradiation Temperature and Atomic Displacement Rate on the Microstructural Evolution of Ion-Irradiated Model Austenitic Alloy Fe-15Cr-16Ni", Proc. of Tenth Inter. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 5-9, 2001, in press.

[18] T. Okita, T. Kamada and N. Sekimura, "Effects of Dose Rate on Microstructural Evolution and Swelling in Austenitic Steels Under Irradiation", J. of Nucl. Mater. 283-287 (2000) 220-223.

[19] M. J. Norgett, M. T. Robinson and I. M. Torrens, Nuclear Engineering Design, 33 (1975) 50.

[20] F. A. Garner and H. R. Brager, "Swelling of Austenitic Fe-Cr-Ni Ternary Alloys During Fast Neutron Irradiation", Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870, F. A. Garner and J. S. Perrin, Eds., ASTM, Philadelphia, PA, 1985, pp. 187-201.

[21] F. A. Garner and A. S. Kumar, "The Influence of Both Major and Minor Element Composition on Void Swelling on Simple Austenitic Steels", Effects of Radiation on Materials: Thirteenth International Symposium (Part 1) Radiation-Induced Changes in Microstructure, ASTM STP 955, F. A. Garner, N. H. Packan and A. S. Kumar, Eds., ASTM, Philadelphia, PA, 1987, pp. 289-314.

[22] F. A. Garner, "Recent Insights on the Swelling and Creep of Irradiated Austenitic Alloys", Invited Paper, J. of Nucl. Mater. 122 and 123, (1984), pp. 459-471.

[23] D. S. Gelles and F. A. Garner, “An Experimental Method to Determine the Role of Helium in Neutron-Induced Microstructural Evolution”, J. of Nucl. Mater. 85 and 86 (1979) pp. 689-693.

[24] W. J. S. Yang, F. A. Garner and A. Kumar, “The Lithium Shell Effect and its Impact on Microscopy Determinations of Swelling Behavior”, J. of Nucl. Mater. 122 and 123, (1984), pp. 242-245.

[25] T. Muroga, K. Araki, Y. Miyamoto and N. Yoshida, “Void Swelling in High Purity Fe-Cr-Ni and Fe-Cr-Ni-Ti Alloys irradiated in JOYO”, J. of Nucl. Mater. 155-157 (1998) pp. 1118-1122.

[26] N. Sekimura and S. Ishino, “The Effect of Titanium Addition on Microstructural Evolution in Stainless Steel Irradiated with Fast Neutrons in FFTF”, J. of Nucl. Mater. 179-181, (1991)pp. 542-545.

[27] N. Sekimura, K. Hamada and S. Ishino, “The Observation and Interpretation of Microstructural Evolution and Swelling in Austenitic Steels Under Irradiation”, Effects of Radiation on Materials; 16th International Symposium, ASTM STP 1175, 1994, pp. 992-1000.

[28] F. A. Garner and W. G. Wolfer, “The Effect of Solute Additions on Void Nucleation”, J. of Nucl. Mater. 102, (1981), pp. 143-150.

[29] B. Esmailzadeh, A. S. Kumar and F. A. Garner, “The Influence of Silicon on Void Nucleation in Irradiated Alloys”, J. of Nucl. Mater. 133 & 134, (1985), pp. 590-593.

[30] H. Oikawa, “Review on Lattice Diffusion of Substitutional Impurities in Iron; A Summary Report”, Technology Reports, Tohoku University, 47, No. 2. (1982), pp. 215-224.

[31] T. Yoshiie, S. Kojima, Y. Sato, N. Yoshida and M. Kiritani, “A Study of Point Defect Processes in Candidate and Model Alloys for Fusion Reactor First Wall by HVEM”, J. of Nucl. Mater. 133-134 (1985) pp. 390-394.

[32] C. Dimitrov and O. Dimitrov, J. Physics F 14 (1984) p. 793.

[33] S. J. Rothman, L. J. Nowicki and G. E. Murch, “Self-diffusion in Austenitic Fe-Cr-Ni Alloys”, J. Physics F: Metal Physics 10 (1980) pp. 383-398.

[34] F. A. Garner and W. G. Wolfer, “Factors Which Determine the Swelling Behavior of Austenitic Stainless Steels”, J. of Nucl. Mater. 122 and 123, (1984), pp. 201-206.

[35] T. Muroga, H. Watanabe and N. Yoshida, “Correlation of Fast Neutron and Electron Irradiations Based on the Dislocation Loop Density”, J. of Nucl. Mater. 174 (1990) pp. 282-288.

[36] W. A. Coghlan and F. A. Garner, “Effect of Nickel Content on the Minimum Critical Void Radius in Ternary Austenitic Alloys”, Effects of Radiation on Materials: Thirteenth International Symposium (Part 1) Radiation-Induced Changes in Microstructure, ASTM

STP 955, F. A. Garner, N. H. Packan and A. S. Kumar, Eds., ASTM, Philadelphia, PA, 1987, pp. 315-327.

[37] L. K. Mansur, "Correlation of Neutron and Heavy Ion Damage, II. The Predicted Shift of Swelling with Changes in Radiation Dose Rate", J. of Nucl. Mater. 78 (1978) pp. 156-160.

[38] D. L. Porter and F. A. Garner, "Swelling of AISI Type 304L Stainless Steel in Response to Simultaneous Variations in Stress and Displacement Rate", Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870, F. A. Garner and J. S. Perrin, Eds., ASTM, Philadelphia, PA, 1985, pp. 212-220.

[39] 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. of Nucl. Mater. 276 (2000) pp. 123-142.