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COMPARISON OF SWELLING FOR STRUCTURAL MATERIALS ON NEUTRON AND ION IRRADIATION*

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The swelling of V-base alloys, Type 316 stainless steel, Fe-25Ni-15Cr alloy, ferritic steels, Cu, Ni, Nb-1% Zr, and Mo on neutron irradiation is compared with the swelling for these materials on ion irradiation. The results of this comparison show that utilization of the ion-irradiation technique provides for a discriminative assessment of the potential for swelling of candidate materials for fusion reactors.

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1. Introduction

Irradiation-induced microstructural evolution will determine the dimensional stability (swelling) and the response to applied stress of structural materials for a magnetic fusion reactor (MFR). In the absence of a MFR, it is necessary to utilize simulation facilities to evaluate the impact on microstructural evolution in materials of parameters that pertain to the expected MFR environment, viz., irradiation damage rate and helium generation to damage level ratio. At the present time fission neutron and charged particle irradiation facilities are used for these evaluations. In this paper the swelling values reported in the literature for several structural materials on neutron irradiation are compared with the swelling of these materials on ion irradiation. It remains to be demonstrated that the swelling induced in materials by the use of either of these simulation facilities is equivalent to the swelling of materials in a MFR.

2. Experimental Results

The experimental results on the swelling of V-base alloys, Type 316 stainless steel, Fe-25Ni-15Cr alloy, ferritic steels, Cu, Ni, Nb-1Zr, and Mo that have been reported by several investigators are presented in the following figures. The composition of the alloys are expressed in weight percent. The experimental details that pertain to the irradiations can be

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obtained from the appropriate references.

Vanadium and vanadium-base alloys

The swelling of V and several V-base alloys on neutron irradiation is compared with the swelling for these materials on single- and dual-ion irradiation in Fig. 1. On the basis of limited irradiation data, the alloying of V with 1-20 w/o Ti reduces the swelling rate of V from ~0.05%/dpa (displacement per atom) to < 0.002%/dpa for neutron- and ion-irradiations in the range of 400 to 800°C. The addition of 10-15 w/o Cr to V causes the swelling rate of V to increase to ~0.2%/dpa for neutron- and ion-irradiations in the range of 650 to 800°C. However, the presence of chromium in a V-15Cr-5Ti alloy does not result in significant swelling for radiation damage levels up to ~250 dpa. On the basis of the present data, the steady-state swelling rate for the V-15Cr-5Ti alloy is < 0.001%/dpa. Ion-irradiation results for the V-15Cr-5Ti alloy have also shown that the simultaneous production of radiation damage and implantation of helium does not significantly alter the swelling of this alloy [16].

Fe-25Ni-15Cr and Type 316 stainless steel

The swelling of the Fe-25Ni-15Cr alloy on neutron irradiation in the EBR-II reactor is compared with the swelling of this material on ion irradiation in Fig. 2. Also in Fig. 2, the swelling of solution-annealed Type 316 stainless steel on irradiation in the EBR-II or HFIR reactors is compared with the swelling of this material on single- or dual-ion irradiation. The obvious difference between the neutron- and ion-irradiation data for these materials is the damage level required before the attainment of a "steady-state" swelling rate, viz., 10-30 dpa for neutron irradiation and 60-90 dpa for ion irradiation. The neutron irradiation data for the Fe-25Ni-15Cr alloy are interpreted to show a "steady-state" swelling rate of 0.8-1.0%/dpa, whereas the ion-irradiation data suggest a lower rate of 0.2-0.5%/dpa. The neutron irradiation data for the solution-annealed Type 316 stainless steel are interpreted to show a "steady-state" swelling rate of 0.5-0.8%/dpa, and the ion irradiation data suggest a rate of 0.3-0.5%/dpa. On the basis of limited data (especially for the HFIR irradiation), there is evidence for the saturation of swelling at high damage levels in solution-annealed Type 316 stainless steel containing helium.

Ferritic steels

The swelling of several ferritic steels on neutron irradiation is compared with the swelling of these materials on ion irradiation in Fig. 3. The neutron- and ion-irradiation data for the ternary ferritic alloys are interpreted to show a "steady-state" swelling rate of 0.01-0.02%/dpa. A lower Cr content in the ternary alloy appears to result in a lower swelling rate, i.e., 0.01%/dpa for EM-12 versus 0.02%/dpa for HT-9. On the basis of the neutron data, the Fe-9,12Cr ferritic alloys may have swelling rates of ~0.06%/dpa. The limited data for the ferritic steels suggest that the swelling values obtained on neutron irradiation or ion irradiation are essentially in agreement.

Copper

The swelling of Cu on neutron irradiation is compared with the swelling of Cu on ion irradiation in Fig. 4. The extremely limited data on the neutron-induced swelling of copper (100-200 appm oxygen) suggest a swelling rate of ~0.4%/dpa. The ion irradiation data show that the swelling rate is strongly dependent on the oxygen and helium concentration. The swelling rate for copper can be reduced to < 0.001%/dpa by reduction of the oxygen concentration to less than 1 appm for radiation damage levels of < 40 dpa.

Ni, Nb-1%Zr, and Mo

The swelling of Ni, Nb-1%Zr, and Mo on neutron and ion irradiation is shown in Figs. 5, 6, and 7 respectively. These materials may not be used as structural materials in a MFR because of high induced radioactivity [51], but the swelling data are included for the purpose of additional comparison.

3. Discussion

The post-transient (steady-state) swelling rates that were obtained from the experimental data for the structural materials are listed in Table 1. An apparent difference between the "steady-state" swelling rates for the different materials on neutron irradiation and ion irradiation seems to exist only for the austenitic stainless steels. An additional apparent difference for the stainless steels is a longer incubation period on ion irradiation for the initiation of a "steady-state" swelling rate. On the basis of the data presented for stainless steel, the simultaneous production of radiation damage and implantation of helium has an impact on the swelling in these irradiated materials. The effect of helium implantation on the microstructural evolution in the V-base alloys and the ferritic steels is less apparent because of their intrinsically low swelling.

It may be considered that structural materials in a MFR can be relatively tolerant of swelling. However, it is possible that high swelling may have an impact on the physical and mechanical properties of a material, e.g., thermal conductivity, elastic moduli, and radiation-induced creep. The results of this comparison of experimental swelling data for neutron- and ion-irradiated structural materials are taken to show that the ion-irradiation technique can be utilized for a discriminative assessment of the potential for swelling of these materials.

4. Conclusions

1. Ion-irradiation of candidate MFR structural materials can provide a discriminative assessment of the potential for swelling.

2. Ion-irradiation can provide an assessment of the effect of high irradiation damage fluence (100-300 dpa) on the evolution of alloy microstructure.

3. Ion-irradiation can make an assessment of the impact of varying the helium concentration/dpa ratio on swelling of materials.

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Table 1. Swelling rate for MFR alloys

Material	Swelling rate (%/dpa) Neutron Irradiation	Ion Irradiation
V-15Cr	~ 0.2	~ 0.2
V-1,5,10,20Ti	< 0.002	< 0.002
V-15Cr-5Ti	< 0.001	< 0.001
Fe-25Ni-15Cr	0.8-1.0	0.2-0.5
S.A. 316 SS	0.5-0.8	0.3-0.5
EM-12 (Fe-10Cr-2Mo)	~ 0.01	~ 0.01
HT-9 (Fe-12Cr-1Mo)	~ 0.02	~ 0.02
Copper (48 appm Oxygen)	—	0.1
Copper (< 1 appm Oxygen)	--	< 0.001
Copper (100-200 appm Oxygen)	~ 0.4	~ 0.3
Ni	0.1	0.1
Nb-1%Zr	0.1-0.2	0.1-0.2
Mo	0.1-0.3	0.1-0.3

Fig. 1. Comparison of swelling for V and V-base alloys on neutron and ion irradiation. References for symbols are: ◇ -[1], [2], [3], [4], [5], [6]; □ -[3], [7], [8]; ○ -[3], [8],; Δ -[3]; ◆ -[9], [10], [11], [12]; ■ -[11]; ○ -[13]; ▲ -[14], [15], [16], [17].

Fig. 2. Comparison of swelling for the Fe-25Ni-15Cr alloy and solution-annealed 316 stainless steel on neutron and ion irradiation. References for symbols are: ○ -[18]; Δ -[19]; □ -[20]; ● -[21], [22]; ▲ -[23]; ■ -[24].

Fig. 3. Comparison of swelling for ferritic steels on neutron and ion irradiation. References for symbols are: ◇ -[25], [26]; ⬡ -27; Δ -[28]; ◒ -[29], [30]; ◑ -[29], [30]; ◩ -[30]; ◪ -[30]; ◆ -[31]; ● -[31]; ▲ , ⬢ -[32].

Fig. 4. Comparison of swelling for copper on neutron and ion irradiation. The references for the symbols are: ▲ -[33]; ● , ■ , ◆ , ▼ -[34]; Δ -[35]; □ -[36]; ○ -[37].

Fig. 5. Comparison of swelling for Ni on neutron and ion irradiation. References for symbols are: Δ -[39]; ◇ -[40]; ○ -[4], [41]; □ - [42]; ∇ -[1]; ● -[43]; ■ -[44]; ▲ -[45].

Fig. 6. Comparison of swelling for the Nb-1%Zr alloy on neutron and ion irradiation. References for symbols are: ○ , Δ , □ -[46]; ● , ▲ , ■ -[47].

Fig. 7. Comparison of swelling for Mo on neutron and ion irradiation. References for symbols are: □ , ⫿ -[48]; Δ -[49]; ● , ▲ , ■ -[50].

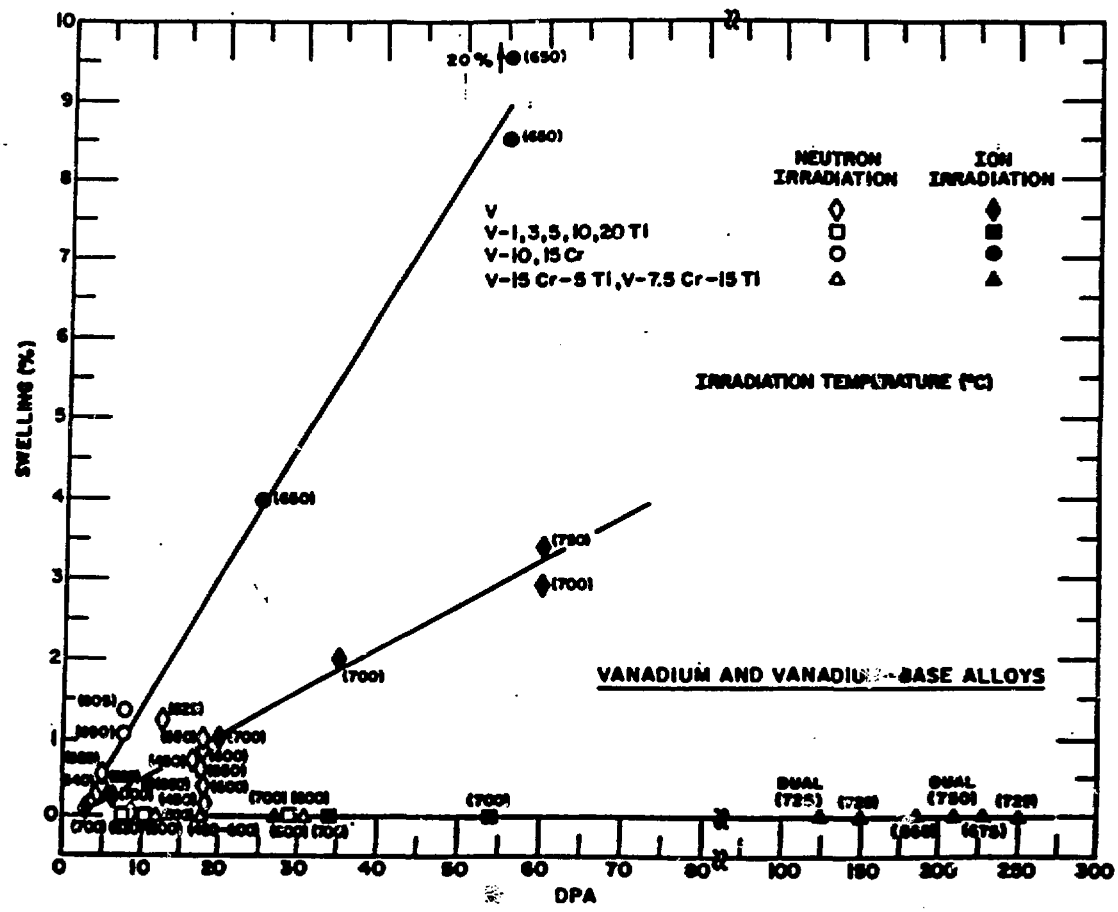

Fig. 1. Comparison of swelling for V and V-base alloys on neutron and ion irradiation. References for symbols are: ◇ -[1], [2], [3], [4], [5], [6]; □ -[3], [7], [8]; ○ -[3], [8],; Δ -[3]; ◆ -[9], [10], [11], [12]; ■ -[11]; ○ -[13]; ▲ -[14], [15], [16], [17].

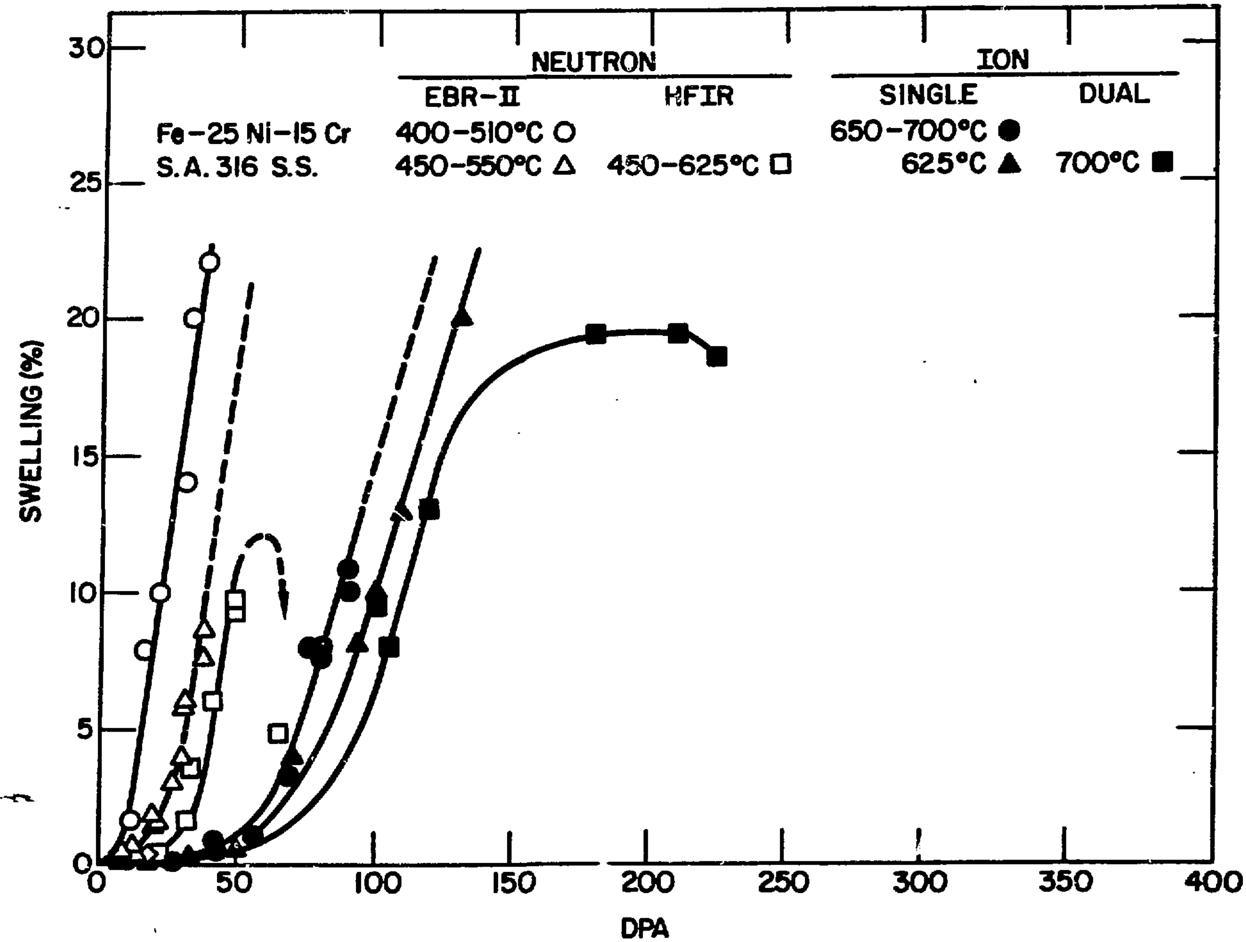

Fig. 2. Comparison of swelling for the Fe-25Ni-15Cr alloy and solution-annealed 316 stainless steel on neutron and ion irradiation. References for symbols are: ○ -[18]; Δ -[19]; □ -[20]; ● -[21], [22]; ▲ -[23]; ■ -[24].

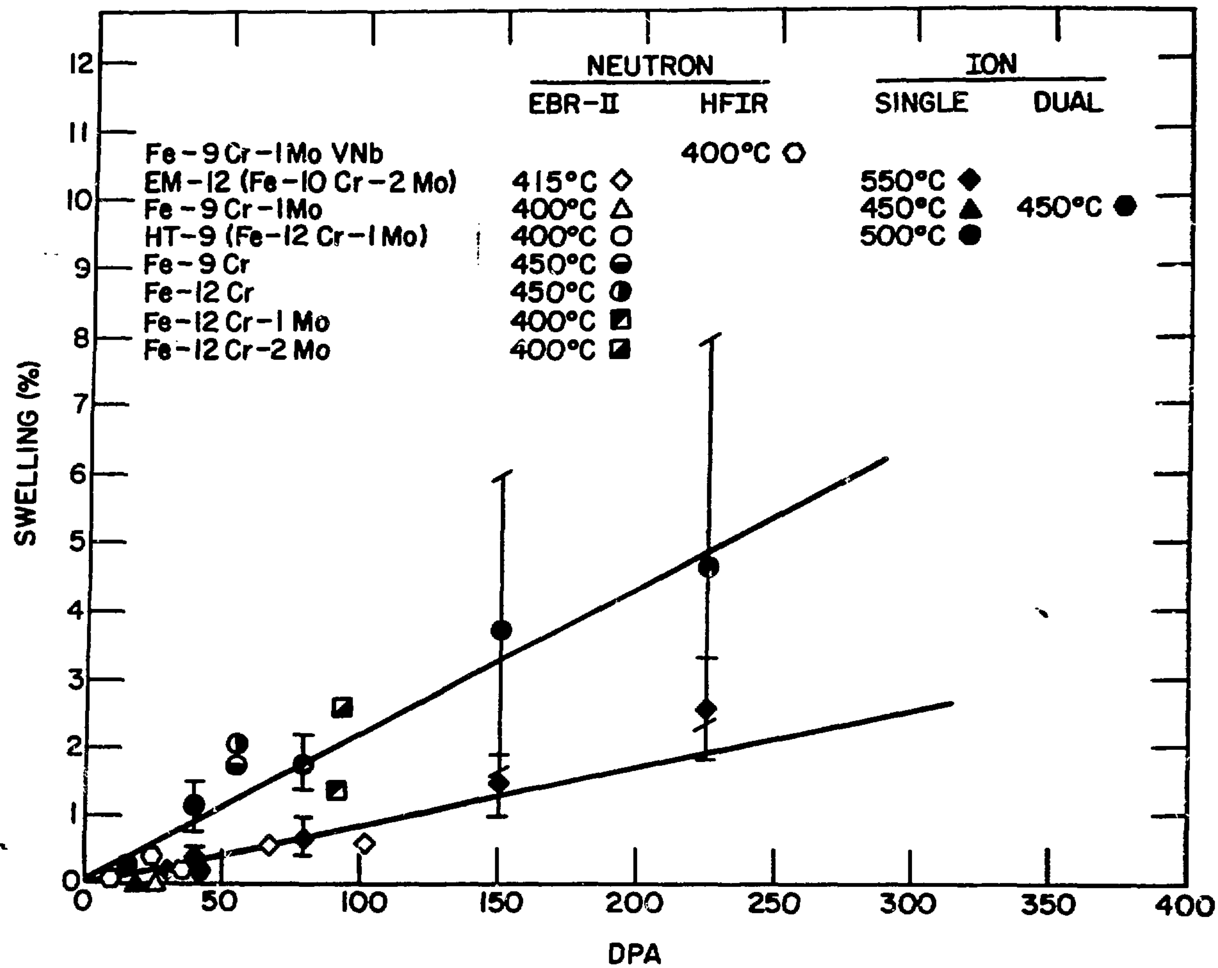

Fig. 3. Comparison of swelling for ferritic steels on neutron and ion irradiation. References for symbols are: ◇ -[25], [26]; ○ -27; Δ -[28]; ⊖ -[29], [30]; ◐ -[29], [30]; ◪ -[30]; ◩ -[30]; ◆ -[31]; ● -[31]; ▲ , ⬢ -[32].

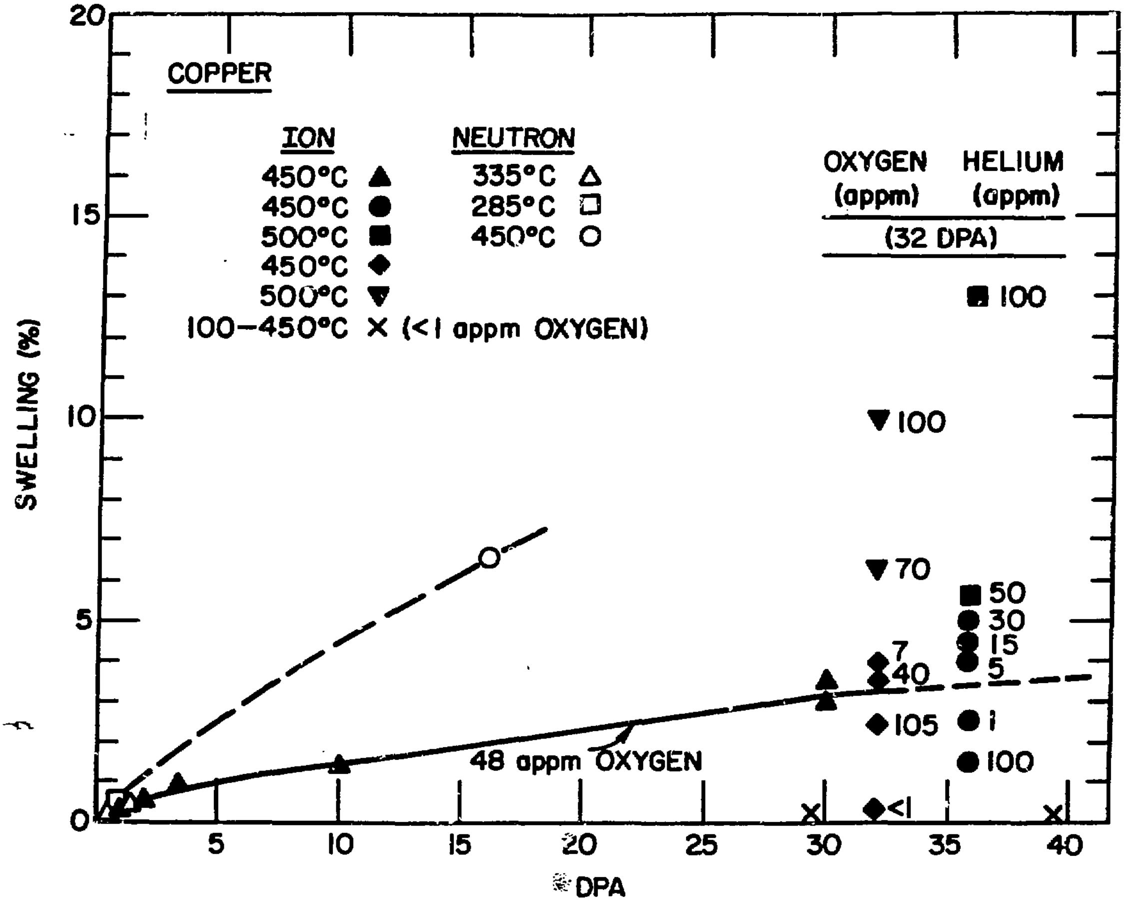

Fig. 4. Comparison of swelling for copper on neutron and ion irradiation. The references for the symbols are: ▲ –[33]; ● , ■ , ◆ , ▼ –[34]; △ –[35]; □ –[36]; ○ –[37].

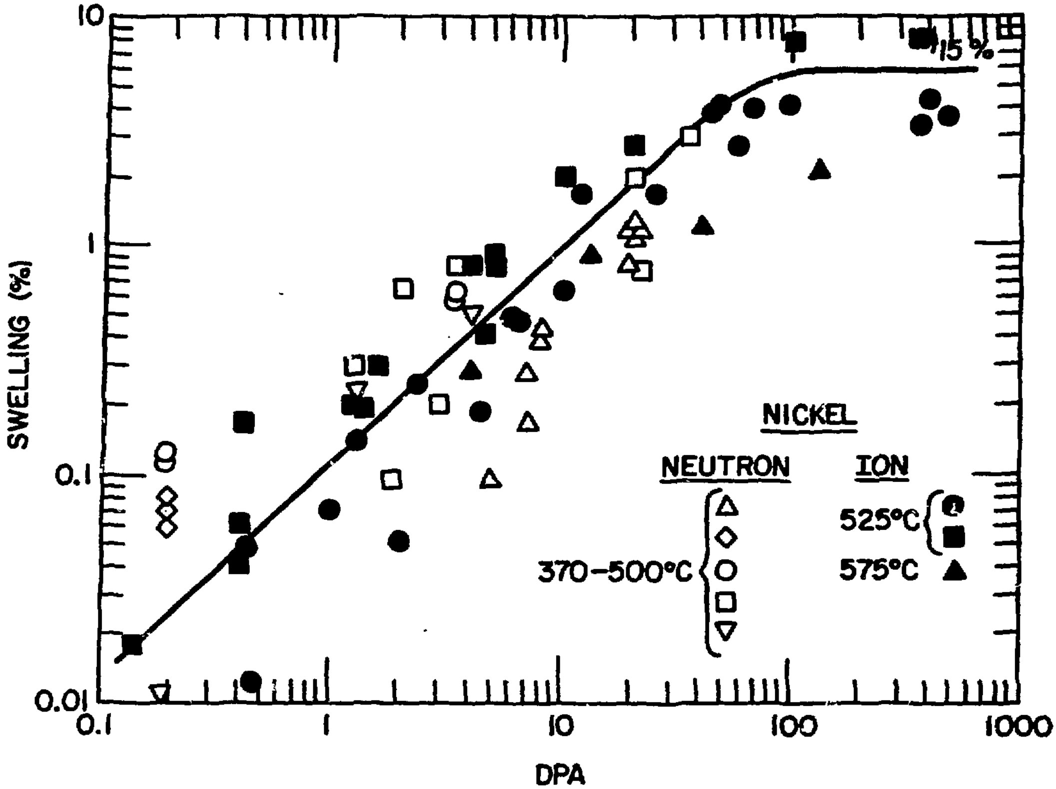

Fig. 5. Comparison of swelling for Ni on neutron and ion irradiation. References for symbols are: Δ –[39]; ◇ –[40]; ○ –[4], [41]; □ – [42]; ∇ –[1]; ● –[43]; ■ –[44]; ▲ –[45].

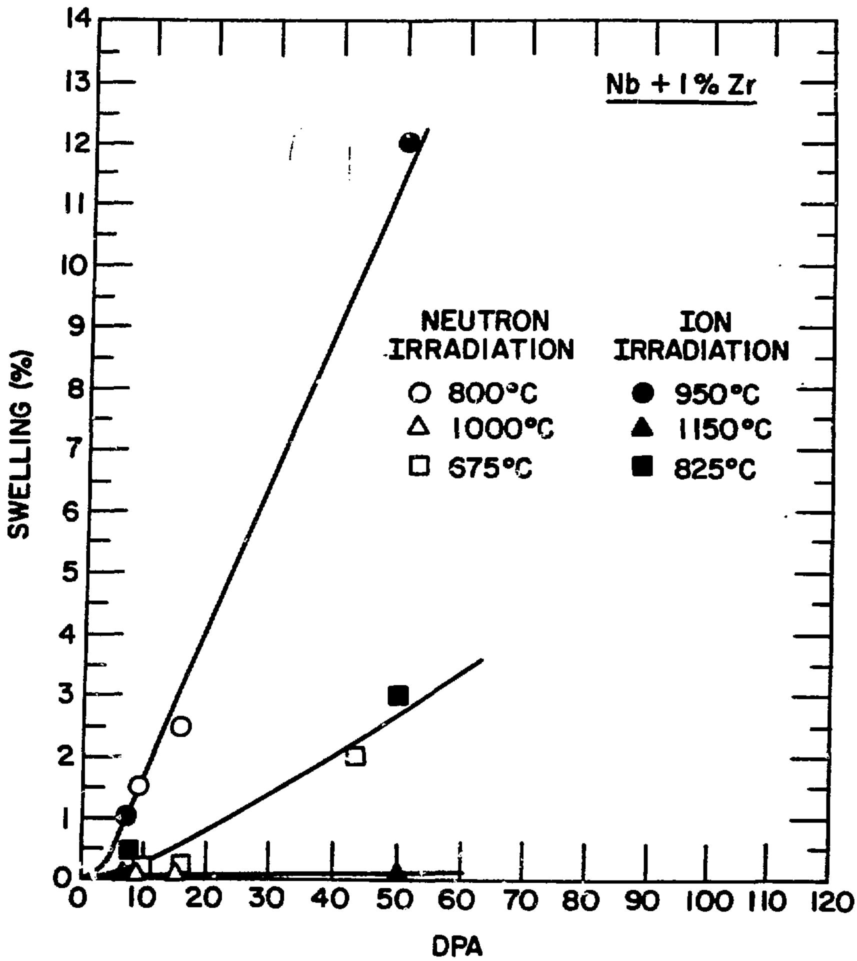

Fig. 6. Comparison of swelling for the Nb-1%Zr alloy on neutron and ion irradiation. References for symbols are: ○ , △ , □ -[46]; ● , ▲ , ■ -[47].

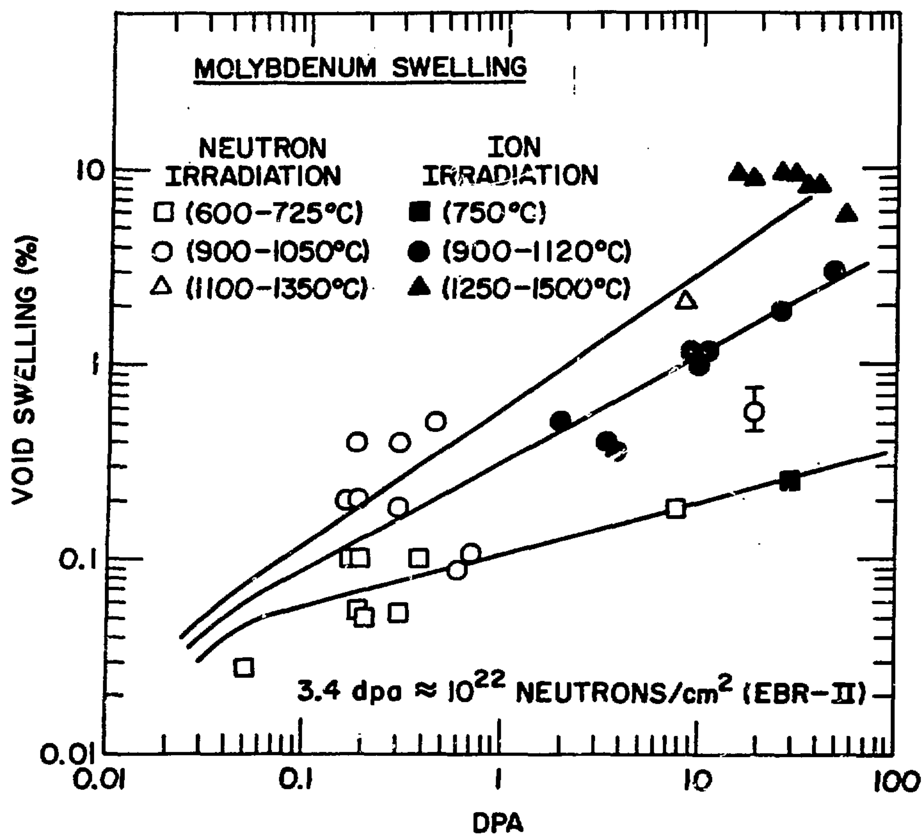

Fig. 7. Comparison of swelling for Mo on neutron and ion irradiation. References for symbols are: □ , ○ –[48]; △ –[49]; ● , ▲ , ■ –[50].