# DISCUSSION

*A. Boltax*[1]—Standring et al (Ref *13*), in their paper on creep-rupture properties of Type 316 stainless steel tubes, showed higher diametral rupture strains in the irradiated cold-worked tubes (total dose $\sim 3 \times 10^{22}$ n/cm$^2$, temperature >525 C) (977 F) than in the unirradiated cold-worked tubes (see Figs. 11 and 12, copied from Ref *13*). The authors hint that the results may be due to in-reactor recovery at temperatures above 600 C (1112 F). They also note that irradiation experiments with improved temperature control are at hand.

A comparison of the results of Standring et al and the present work shows several interesting points. A comparison of the CW316 creep strains at the beginning of tertiary creep (see Fig. 12) and the reported rupture strains indicated in Ref *13* reveals good agreement. Also, the improvement in the creep-rupture ductility at 700 C (1292 F) after irradation shown by the authors may relate to similar effect, just mentioned, in the work of Standring et al.

Would the authors please comment on the comparison of the two sets of results and in particular on the greater ductility observed after irradiation? Also, would they care to comment on the results of Dourenay Fast Reactor (DFR) irradiation experiments with improved temperature control? Finally, would they care to comment on the probable effects of higher fluence levels ($\sim 10^{23}$ n/cm$^2$) on the creep-rupture properties of cold-worked Type 316 cladding?

*E. E. Bloom and J. O. Stiegler*—The ductility of 20 percent cold-worked Type 316 stainless steel as measured either by the creep strain at the beginning of tertiary creep or the total elongation was reduced by irradiation when compared with the as-cold-worked condition for samples irradiated and tested at or below 650 C (1202 F). For these temperatures, all ductility values for the irradiated samples were below or at the very lower edge of the scatterband for the as-cold-worked material (Fig. 5). In these samples extensive recovery and/or recrystallization (as compared with samples irradiated above 650 C) were not observed. As noted, the increased ductility above 650 C was associated with recovery and recrystallization.

Standring et al reported their irradiation temperature as >525 C (977 F) and suggested that it could have been as high as 700 C (1292 F). Although they did not examine their specimens for signs of recovery, they found appreciable

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amounts of sigma phase. They pointed out that the lowest reported temperature for sigma-phase precipitation was 595 C (1103 F) and suggested that their specimens were irradiated at a significantly higher temperature or that irradiation enhanced the kinetics of sigma-phase precipitation. The latter explanation is unlikely, for no sigma phase was found in the present work for irradiation for comparable times at 580 C (1076 F). It appears likely to us that the higher creep rates and diametral rupture strains found by Standring et al are due to recovery and recrystallization occurring during irradiation at temperatures greater than 600 C (1112 F). This is consistent with the findings reported in the present paper.

Probable effects at higher fluences are difficult to predict. If the irradiation temperature is below about 650 C (1202 F), three factors must be considered: (*a*) If the cold-worked structure is stable, the matrix strengthening will remain; (*b*) if recovery of the cold-worked structure does occur, void and dislocation formation may commence and thus contribute to matrix strength; and (*c*) the helium concentration will increase with fluence. Results for annealed Type 304 stainless steel (Ref *10*) indicate that as the matrix strength and helium concentration increase the ductility will decrease. The exact value of the ductility will be quite sensitive to irradiation and test temperature.

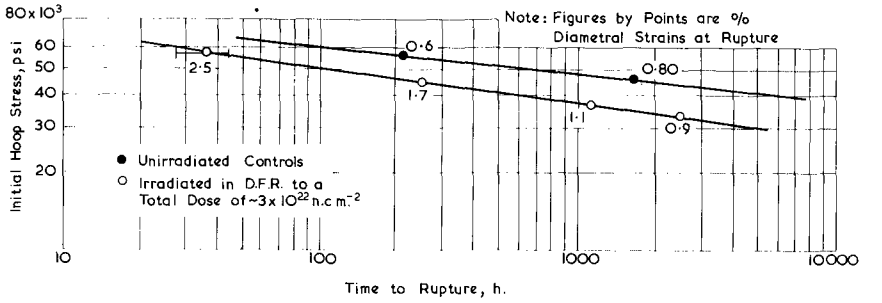


FIG. 11–*550 C (1022 F) rupture strength of cold-worked Type 316 tubing.*

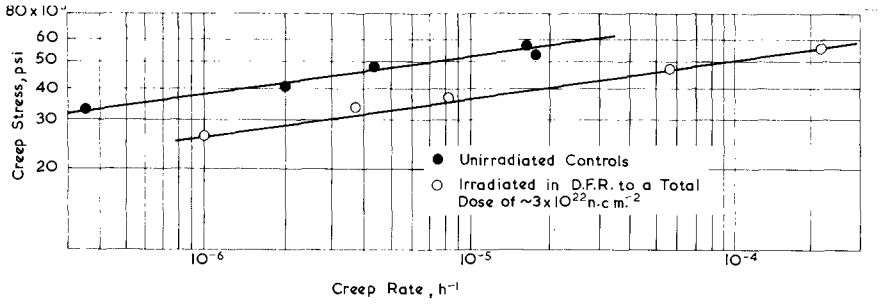


FIG. 12–*550 C (1022 F) creep rate of cold-worked Type 316 tubing.*