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J.F. Bates
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Abstract

Studies involving high fluence irradiations of compositionally modified AISI 316 stainless steel have demonstrated that the irradiation-induced creep and swelling of this alloy can be modified through a selective choice of alloying elements. Irradiation-induced swelling of specimens irradiated to fluences of 7 to 12 x 10^{22} n/cm^2 (E >0.1 MeV) is strongly influenced by the concentration of alpha-stabilizing elements such as Si and Mo. Relative minima and maxima in swelling vs. composition diagrams are shown to exist. Irradiation-induced creep strain of AISI 316 is, in general, reduced by the same elements which reduce irradiation-induced swelling. It was found that the compositional dependence of swelling and creep in this alloy system can both be described through a description of the screening of dislocation strain fields. Compositional modifications which increase the mobility of the screening agents or allow the formation of more effective screening agents will decrease the swelling and irradiation creep. This screening results in a decrease in the interstitial-dislocation bias, which results in lower swelling and in-reactor creep.

INTRODUCTION

The effects of compositional variations on swelling in AISI 316 stainless steel have received considerable attention in the literature and in various ongoing worldwide programs.[1-6] These compositional effects were reviewed in a recent paper.[7] In general, it was found that the ferritic stabilizing minor alloying elements (silicon, molybdenum, etc.) were effective in reducing swelling in AISI 316. It was also suggested that there was a complex relationship between these alpha stabilizers and other elements which tended to remove them from the lattice through precipitation, and that phase instabilities would be encountered once the amounts of these alpha stabilizers were increased beyond a certain critical limit, with both the major and the minor element compositional variations having an effect. Figure 1, reproduced from reference 7, summarizes these findings for 20% cold worked AISI 316. In the present investigation, minor elements compositional effects on swelling were examined at significantly higher fluences than previously studied. Many of the trends observed at lower fluences have continued to higher fluences, and phase instabilities at high concentrations of alpha stabilizers are apparent.

EXPERIMENTAL PROCEDURES

The swelling data in this report are from reirradiation of specimens which were initially irradiated to fluences of 2 to 4 x 10^{22} n/cm^2 (E >0.1 MeV).[8] The specimens were reirradiated in Row 2 of EBR-II in NaK-filled subcapsules as part of the X-216 (MV-II) experiment to cumulative fluences ranging from 7 to 12 x 10^{22} n/cm^2 (E >0.1 MeV). There were three reirradiation temperatures in the MV-II experiment, 400, 510 and 620°C, and some specimens underwent a somewhat complex thermal history. The majority of specimens were solution annealed or 20% cold worked with some aged and cold worked plus aged specimens also included. The compositions and thermomechanical treatments are listed in Tables 1 and 2, respectively. The specimens were 0.6 cm in diameter right cylinder with a maximum length of 1.3 cm. Fabrication details of the various heats are discussed elsewhere.[8]

The creep specimens investigated [9] were fabricated from 0.64 cm diameter rod stock which was in the 20% cold worked condition. The specimens were manufactured by initially grinding the rods to a 0.58 cm diameter. Then, after cutting the rods into 3.8 cm lengths, a 2.5 cm deep hole with a 0.51 cm diameter was drilled into one end. A cap was welded onto the open end and each tube was pressurized to generate a hoop stress of 172 MPa during irradiation at 450°C. The specimens consisted of a pressurized portion for determining irradiation creep and a solid portion for determining stress free swelling. The diameter of each specimen was measured to an accuracy of 7.5×10^{-5} cm with an LVDT probe system before irradiation. After irradiation, the diameters were measured with a laser interferometer system [10] to 2.5×10^{-5} cm.

RESULTS

All swelling values are based on pre- and postirradiation immersion density measurements. In general, comparisons are made only among specimens which were irradiated in the same subcapsule. This ensures that the temperatures of irradiation were identical. This nature of comparison is vital since temperature variations have been shown to affect swelling [11,12] and comparison from subcapsule to subcapsule would be misleading. The results of the density measurements are shown in Table 3.

Silicon

The effect of silicon variations on swelling in AISI 316 stainless steel is depicted in Figure 2 and 3 for both the solution annealed and 20% cold worked conditions.

Increasing the silicon content reduces the swelling observed at 400°C, as indicated on Figure 2. A very marked reduction in swelling occurs in the solution annealed material as the silicon is increased from zero up to approximately 1.5 weight percent. Swelling in the cold worked material is also reduced as silicon is increased, although the effect is not as pronounced as in the solution annealed case. These results are consistent with observations of low fluence behavior.[8]

At 510 and 620°C, Figure 3, there is a distinct difference between the trends suggested by the low fluence results [8] and these new higher fluence data. While the reduction in swelling on going from zero silicon up to approximately 0.5 weight percent silicon is still quite evident, also evident in the high fluence data is a subsequent rise in swelling on going from 0.5 up to approximately 1.5% silicon. The cold worked material also shows evidence of a minimum in swelling with respect to silicon content.

The RDT specification for silicon in Fast Flux Test Facility cladding and duct alloys is 0.5 to 0.75 weight percent. The minimum in swelling with respect to silicon content, as it appears in Figure 3, occurs at around 0.5 weight percent. This minimum is approximately the same for both the solution annealed and the 20% cold worked material.

In Figure 4 the swelling versus temperature data are plotted for various levels of silicon. The fluences are 9.1×10^{22} n/cm^2 (E >0.1 MeV) for the two lower temperatures and 12.0×10^{22} n/cm^2 (E >0.1 MeV) for the highest temperature. In constructing Figure 4, the high fluence, high temperature data were normalized to 9.1×10^{22} n/cm^2 and the assumption made that the peak swelling temperature in these alloys is around 580°C.

The swelling data at 0.48% silicon suggests a more complex relationship, but it cannot be definitely established that there is a temperature shift in the peak swelling temperature due to variations in silicon content.

The swelling versus fluence behavior for various levels of silicon in the solution annealed material are plotted in Figure 5. The data indicate that variations in silicon content affect the swelling rate of the material.

A variation in the incubation parameter, τ (the zero swelling intercept of the extrapolated linear portion of the swelling curve), may be offered as another interpretation. However, the intermediate data point at over 8×10^{22} n/cm^2(E >0.1 MeV) for the specimens with 2% silicon tends to dissuade one from interpretations based on the incubation parameter variations.

Molybdenum

Variation of swelling with molybdenum content is shown in Figure 6 for specimens irradiated at 400°C to a fluence of approximately 8.8×10^{22} n/cm^2 (E >0.1 MeV). Both the solution annealed and cold worked specimens exhibit reductions in swelling as the molybdenum content is increased. These results are consistent with lower fluence results for the same alloys.(8) However, the data points from the solution annealed specimens indicate that there is a shallow minimum in the swelling versus composition diagram extending from approximately 1.0 to approximately 5.0% Mo. The increase as Mo approaches 5.0% is presumably due to phase instabilities.

Carbon-Nitrogen Variations

Modified heats of AISI 316 containing both high and low carbon levels and high and low nitrogen levels were fabricated to study both singular and synergistic effects on swelling which may occur as a result of these variations. The various heat treatments of these materials are outlined in Table 3.

Nitrogen has very little effect on the irradiation induced swelling in the solution annealed alloy condition, as shown in Figure 7(a). However, increasing the carbon concentration in the solution annealed alloy results in increased swelling as shown in Figure 7(b). This increased swelling due to increased carbon is found in both the high and low nitrogen levels at a temperature of 620°C to fluences of 12.2 x 10^{22} n/cm^2 (E >0.1 MeV).

When AISI 316 is solution annealed and aged before irradiation, the effect of carbon is essentially eliminated, as shown in Figure 8. During aging the carbon concentration is probably reduced in the matrix by carbide precipitation.

In 20% cold worked AISI 316 at low nitorgen concentrations, carbon is again effective in increasing the swelling. This increase is depicted in Figure 9. However, as nitrogen is increased, the effect of the carbon becomes less prominent. This behavior indicates synergistic effects between the carbon and nitrogen.

Figure 10 shows the effect of carbon and nitrogen variations for the same series of alloys in the 20% cold worked plus aged condition. Increasing the carbon increases the swelling but the magnitude of the increase appears to be dependent on the nitrogen concentrations, the same behavior as indicated by the cold worked specimens. The effects of carbon are summarized in Table 4.

The effect of carbon on increasing swelling is completely opposite to results obtained by Levy et al.[13] who, on conducting irradiation simulation experients, concluded that carbon inhibited swelling while in solution at high concentrations. These investigators did not report nitrogen content of their alloys, and it is possible that variations in nitrogen were also affecting the swelling. However, this is not the first time a discrepancey between neutron and simulation irradiation results has been observed. The effect of carbon content on swelling in ternary Fe-Ni-Cr alloys appeared to be opposite for neutron irradiations than for nickel ion bombardment.[7] However, upon further investigation it was concluded that the difference could be attributed to differences in the composition of the major elements such as nickel.

Increased carbon doesn't necessarily mean increased carbon in solution. An increase in carbon may induce more carbide precipitation. Increased precipitation can lead to removal of swelling inhibitors or provide additional sites for heterogeneous void nucleation. Slight variations in other minor alloying elements, such as titanium or molybdenum can also interact synergistically with carbon to alter the swelling.

Irradiation-Induced Creep

The effect of composition on in-reactor creep is summarized in Table 5, reproduced from reference 9. The first column is the main feature of the compositional variation. The second column represents three times the fractional diameter increase of the unstressed solid end. The percentage diametral increase for cold worked AISI 316 stainless steel was assumed to be approximately one-third of the percentage change in immersion density. The irradiation creep strain is presented in column three and represents the increase in the diameter of the pressurized portion of the specimen less that of the unstressed portion, thus providing a correction for swelling.

The irradiation creep strain is plotted versus composition in weight percent in Figure 12(a). The irradiation creep strain drops sharply as the solute content is increased for all except the cobalt modification, which appears to have little effect on irradiation creep.

The results suggest that a stainless steel alloy containing approximately the nominal amounts of Mo, Si, P and C found in AISI 316 is a reasonable compromise for irradiation creep limitation. However, the irradiation creep could be reduced by the addition of approximately 0.1 weight % N.

DISCUSSION

It is evident from the data that initial alloy composition is a major factor in neutron irradiation induced swelling and creep behavior. Minor element additions such as silicon [14] or major elemental variations such as nickel and chromium [7] can result in a many-fold variation in swelling. There are (at least) two major effects of compositional variations on irradiation-induced creep and swelling. The first of these occurs during the initial additions of a minor alloying element when, for alpha stabilizers, the swelling is reduced. As incremental additions of the alloying element are added, the swelling generally goes through a minimum and then increases again as the second consequence of compositional variations, phase instabilities, is attained. The nature of swelling reductions due to compositional variations of a stable (with respect to secondary phase precipitation) alloy are addressed in this report.

We believe that carbon is one of the key elements which determine the compositional dependence of swelling and irradiation creep. The effect is not necessarily directly through the carbon concentration but is related to the behavior of carbon in the matrix as a result of the addition of other elements. The areas of possible synergism include changes in carbon solubility or carbon mobility with variations in the concentration of other elements.

Two elements which dramatically reduce swelling produce a decrease in carbon solubility and a subsequent reduction in the matrix carbon concentration. Figure 12 illustrates the variation of carbon solubility with nickel content. It is clear that the solubility of carbon in austenite is greatly decreased as the nickel content is increased. Also illustrated in this figure is the observed variation in swelling with nickel content. It is also known from Darken's [15] experiment that Si alters the activity of carbon in iron and leads to a decrease in carbon solubility.

An even greater correspondence exists between elements which increase carbon mobility and those elements which decrease swelling. Additions of nickel and silicon to austenite results in an increase in the diffusivity of carbon and a decrease in swelling (until instabilities are encountered in the case of silicon). Chromium additions reduce carbon mobility [16] and lead to an increase in swelling. It is also well known that carbon diffuses faster in bcc iron than in fcc iron and generally ferritics swell less than austenitics.

The possibility exists that carbon mobility is merely an indicator of other lattice effects which are actually controlling swelling. An element which increases the mobility of carbon by reducing its activation energy for motion will also decrease the activation energy for motion of self-interstitials and vacancies. This is because a relaxation in the saddle point configuration between one lattice site and another (i.e., a lower energy barrier for atomic jumps) will benefit the diffusion of all atoms, not just carbon. In addition, for a given crystal structure, diffusion and elastic properties are interrelated through the importance of interatomic potentials in both the saddle point configuration for diffusion and the elastic constants. Thus any of these effects could be operating and probably all are affecting the swelling and creep to a certain extent. More detailed reasoning discussed below supports the hypothesis that carbon mobility is controlling.

Various mechanisms could be invoked to explain the importance of carbon mobility on swelling resistance. One mechanism receiving widespread attention has been termed "fast-diffusing species."[17] Another which has previously been proposed is related to the formation of micro-complexes and a resulting effect through their action as recombination centers.[18] The one proposed here deals with the interaction of carbon with dislocations.

The fast diffusing species argument has been used to explain the effect of silicon in reducing swelling in a number of alloys. In essence, the addition of a relatively fast diffusing element to an alloy will result in an increase in the effective diffusivity of vacancies with an accompanying decrease in the steady-state irradiation-induced vacancy concentration. In a certain temperature range (depending on the magnitude of the vacancy diffusivity increase), this decrease in vacancy concentration will lead to decreased void nucleation and decreased void growth. However, at lower temperatures the increased vacancy mobility (relative to the base alloy) will lead to a reversal of this effect with the overall result being that the peak swelling temperature is reduced.[19] The technological importance of this mechanism will depend on whether the vacancy mobility can be increased sufficiently to reduce the peak swelling temperature to below reactor operation temperature.

It is tempting to apply the fast diffusing species argument to the case of carbon mobility, but the mechanism is not viable in this case. Carbon diffuses interstitially so that (neglecting binding between a carbon atom and a vacancy) the presence of highly mobile carbon does not result in a lower effective vacancy diffusivity. Another argument must be invoked to explain the correlation between carbon mobility and swelling resistance.

A more feasible effect is that due to micro-complexes. A few metal atoms combined with carbon may produce a strain field sufficiently great to allow the complexes to act as recombination centers and reduce the point defect concentrations. The increase in carbon mobility would allow such complexes to form more quickly and at lower temperatures, but the diffusion of the other components of the cluster is likely to be controlling.

A mechanism which can explain the increased swelling resistance with carbon mobility is that involving interaction between anisotropic strain centers and dislocations. A solute atom (or micro-complex) which produces an anisotropic distortion of the lattice will interact with both the hydrostatic and shear stress fields of a dislocation. This interaction with the shear stress field of the dislocation is due to the anisotropy of the distortion and results in the partial screening of the dislocation stress field.[20] Since the interstitial-dislocation bias is determined by the interaction of the self-interstitial and dislocation stress fields, a reduction in the dislocation stress field results in a decrease in the interstitial-dislocation bias. It is well known [21-23] that a reduction in this bias will decrease the void nucleation and growth rates and since the relative attraction between dislocations and interstitials is reduced, irradiation creep must also be reduced.

To establish whether this mechanism can operate in the present case, the case of carbon in a matrix of a fcc iron-nickel alloy was considered. If the elastic constants are isotropic, then the strain field associated with the interstitial carbon would also be isotropic and no screening of the dislocation stress field would result. However, few metals have isotropic elastic constants and, in fact, nickel is more anisotropic than most fcc metals,[24] resulting in an anisotropic strain field associated with interstitial carbon. Thus carbon would not only be attracted to both edge and screw dislocations but it would also reduce the dislocation bias by partially screening the dislocation stress field. If the carbon mobility is high enough (and there is no upper bound for this effect) for a concentration of carbon to keep up with a moving dislocation, then the swelling and creep will be reduced. Elements which increase the mobility of carbon, such as silicon and nickel, would therefore decrease swelling and irradiation creep by allowing the carbon atmosphere to screen a climbing dislocation. Similarly, elements which reduce carbon diffusivity, such as chromium,[18] would increase swelling and irradiation creep.

The effects of compositional variations on carbon mobility are summarized in the following chart.

Alloying Element	Effect of Increased Concentration on Carbon Mobility	Effect of Increased Concentration on: Swelling in AISI 316	Effect of Increased Concentration on: In-Reactor Creep in AISI 316[+]
Ni	Increase (+)	Decrease (-)	
Cr	Decrease (-)	Increase (+)	
Si	Increase (+)	Decrease (-)	(-)
Co*	Increase (+)	Decrease (-)	(0)
Mo	Temperature Dependent	Decrease (-)	(-)
Mn*	No Change (0)	No Change (0)	

* Reference (8).
[+] Reference (9).

In general, there is excellent agreement between variations in carbon mobility and the resultant swelling and irradiation-induced creep in AISI 316.

If the arrival rate of carbon atoms at a dislocation is comparable to the arrival rate of interstitials at the same dislocation, then changes in the mobility of the carbon atoms can affect the climb rate of the dislocation.

The maximum benefit of the carbon screening effect can be obtained by increasing the carbon content to, but not over, the saturation limit (thus avoiding phase instabilities) together with alloying additions which increase the carbon mobility.

The effect of carbon in screening the dislocation stress field can also be applied to the ferritic alloys. In bcc iron, interstitial carbon produces a tetragonal strain field even if elastic isotropy is assumed.[20] In addition, carbon diffuses much faster in bcc iron than in austenite.[15] Thus the dislocation screening effect can explain the lower swelling associated with ferritic alloys.

Dislocation screening can also be applied to more complex alloys without considering carbon as the screening agent. In γ'/γ'' alloys, the γ'' precipitates are tetragonal and produce an anisotropic strain field in the γ matrix. Thus, redistribution of γ'' during irradiation to regions near dislocations will effectively reduce the system bias, resulting in low swelling and low irradiation creep.

CONCLUSIONS

Irradiation creep and swelling of AISI 316 are strongly influenced by compositional variations and thermomechanical treatments. In general, alpha stabilizers reduce swelling when added to AISI 316. There is a limit to the amount of alpha stabilizing elements which can be added without inducing phase instabilities. If phase instabilities occur, swelling again increases. Synergistic effects of elements are apparent and carbon appears to have a governing role in the swelling of this alloy.

Irradiation creep and swelling are related. Those elements which reduce swelling also reduce the amount of irradiation-induced creep.

It is proposed that the compositional dependence of swelling and creep is due to the effect of various elements on the efficiency of anisotropic strain centers in screening the dislocation strain fields. Screening the strain fields of dislocations results in a lower system bias and therefore less swelling and irradiation creep. The screening agents can be mobile carbon, microcomplexes or small precipitates; the only requirement being the formation of an anisotropic strain field (due to any reason, including elastic anisotropy in the matrix). Compositional modifications which increase the mobility of the screening agents or allow the formation of more effective screening agents (such as γ'') will decrease the swelling and irradiation creep.

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TABLE 1

ALLOY COMPOSITIONS

ALLOY NO		ELEMENT (WEIGHT %)											
CARBON-NITROGEN VARIATIONS		C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Co	B	N
1	7.98131	0.003	0.92	0.40	0.009	0.008	16.95	12.01	2.35	0.10	0.11	0.0011	0.007
3	7.96941	0.047	0.94	0.39	0.010	0.007	16.99	12.05	2.33	0.10	0.12	0.0008	0.050
4	7.963	0.127	0.96	0.38	0.012	0.008	17.06	12.08	2.32	0.10	0.11	0.0010	0.006
5	7.95223	0.128	0.97	0.43	0.011	0.008	17.00	12.10	2.34	0.10	0.11	0.0008	0.111
45	7.9684	0.012	1.12	0.41	0.010	0.007	16.98	12.12	2.31	0.10	0.11	0.0012	0.13
PHOSPHORUS-SULFUR-BORON VARIATIONS													
6	7.96666	0.048	0.92	0.35	0.001	0.004	16.89	11.99	2.36	0.12	0.12	0.0005	0.054
12	7.96583	0.046	0.93	0.36	0.039	0.004	17.01	12.12	2.33	0.11	0.11	0.0005	0.057
SILICON VARIATIONS													
25	7.99698	0.046	0.95	0.01	0.010	0.008	16.88	11.98	2.31	0.10	0.11	0.0011	0.052
26	7.96249	0.045	0.94	0.48	0.009	0.008	17.00	12.12	2.34	0.11	0.11	0.0010	0.054
27	7.92499	0.045	0.94	0.95	0.011	0.007	17.06	12.19	2.35	0.10	0.11	0.0007	0.049
28	7.88573	0.044	0.93	1.47	0.010	0.008	17.07	12.30	2.38	0.10	0.11	0.0007	0.054
29	7.85047	0.045	0.94	1.96	0.010	0.007	17.13	12.39	2.41	0.11	0.11	0.0010	0.050
MOLYBDENUM VARIATIONS													
30	7.9363	0.044	0.99	0.40	0.010	0.007	16.89	12.31	0.01	0.10	0.11	0.0011	0.049
31	7.93893	0.041	0.98	0.38	0.010	0.007	16.86	12.04	0.11	0.10	0.11	0.0011	0.048
32	7.94894	0.045	0.99	0.40	0.010	0.008	16.90	11.99	1.00	0.10	0.11	0.0012	0.049
33	7.97632	0.047	0.92	0.38	0.011	0.008	16.96	12.09	3.03	0.10	0.11	0.0012	0.049
34	7.9536	0.045	0.87	0.40	0.011	0.008	17.09	12.24	4.93	0.10	0.11	0.0010	0.051
COBALT VARIATION													
39	8.00137	0.042	0.90	0.38	0.011	0.008	17.00	12.04	2.30	0.10	4.45	0.0013	0.049

TABLE 2

HEAT TREATMENTS OF CARBON/NITROGEN MODIFIED 316 STAINLESS STEEL

A = Solution Anneal at 1050°C/10 min/Water Quench
B = A + 20% Cold Work
C = A + 815°C/100 hour/Water Quench
D = B + 650°C/100 hour/Water Quench

TABLE 3

IRRADIATION SWELLING DATA

PART 1: CARBON AND NITROGEN MODIFIED ALLOYS

Pin/Level	Alloy	Previous Capsule	Previous Temp. (°C)	Previous Fluence*	Current Fluence*	Accumulated Fluence*	Current Temp. (°C)	$-\Delta\rho/\rho_0$ (%)
123/2	1B	44-5-1B	488-538	2.59	7.17	9.76	510	3.05
123/2	4B	47-5-4B	489-538	2.63	7.17	9.80	510	2.53
123/3	1A	44-8-1A	572-692	3.86	8.44	12.3	620	6.43
123/3	1B	44-8-1B	572-692	3.86	8.44	12.3	620	2.05
123/3	1D	44-8-1D	572-692	3.86	8.44	12.3	620	2.97
123/3	3C	46-8-3C	698-797	3.77	8.44	12.2	620	11.60
123/3	3D	46-8-3D	698-797	3.77	8.44	12.2	620	4.22
123/3	4A	47-8-4A	569-691	3.77	8.44	12.2	620	14.68
123/3	4B	47-8-4B	569-691	3.77	8.44	12.2	620	11.49
123/3	4C	47-8-4C	569-691	3.77	8.44	12.2	620	18.30
123/3	4D	47-8-4D	569-691	3.77	8.44	12.2	620	8.67
123/3	5A	48-8-5A	569-691	3.84	8.44	12.3	620	16.90
123/3	5B	48-8-5B	569-691	3.84	8.44	12.3	620	3.00
123/3	5C	48-8-5C	569-691	3.84	8.44	12.3	620	8.82
123/3	5D	48-8-5D	569-691	3.84	8.44	12.3	620	3.95
123/3	45A	45-8-45A	568-689	3.84	8.44	12.3	620	7.71
123/3	45B	45-8-45B	568-689	3.84	8.44	12.3	620	1.79
123/3	45C	45-8-45C	568-689	3.84	8.44	12.3	620	9.63
123/3	450	45-8-45D	568-689	3.84	8.44	12.3	620	2.37
123/4	1A	46-16-1A	382-414	2.63	7.17	9.80	400	7.39
123/4	45A	45-16-45A	288-421	2.67	7.17	9.84	400	5.66

PART 2: SILICON AND MOLYBDENUM MODIFIED ALLOYS

Pin/Level	Alloy	Previous Capsule	Previous Temp. (°C)	Previous ϕt	MV-II ϕt	Accumulated ϕt	Current Temp. (°C)	$-\Delta\rho/\rho_0$ (%)
123/2	3A	46-5-3A	487-535	2.63	7.17	9.80	510	2.92
123/3	3A	46-8-3A	698-797	3.77	8.44	12.2	620	13.69
123/3	3B	46-8-3B	698-797	3.77	8.44	12.2	620	4.84
123/4	3A	46-16-3A	382-414	2.63	7.17	9.80	400	3.22
124/2	25A	48-3-25A	462-476	1.97	7.17	9.14	510	17.24
124/2	26A	48-3-26A	462-476	1.97	7.17	9.14	510	0.93
124/2	27A	48-3-27A	462-476	1.97	7.17	9.14	510	5.82
124/2	28A	48-3-28A	462-476	1.97	7.17	9.14	510	9.47
124/2	29A	4-3-29A	462-476	1.97	7.17	9.14	510	8.51

TABLE 3 (Cont'd)

PART 2: SILICON AND MOLYBDENUM MODIFIED ALLOYS (Cont'd)

Pin/Level	Alloy	Previous Capsule	Previous Temp. (°C)	Previous ϕt	Current ϕt	Accumulated ϕt	Current Temp. (°C)	$-\Delta\rho/\rho_0$ (%)
124/2	25B	49-3-25B	477-491	1.85	7.17	9.02	510	4.41
124/2	26B	49-3-26B	477-491	1.85	7.17	9.02	510	1.49
124/2	27B	47-3-27B	477-491	1.85	7.17	9.02	510	2.10
124/2	28B	49-3-28B	477-491	1.85	7.17	9.02	510	4.59
124/2	29B	49-3-29B	477-491	1.85	7.17	9.02	510	6.78
124/3	25A	44-7-25A	578-684	3.53	8.44	12.0	620	13.27
124/3	25A	49-14-25A	542-609	3.53	8.44	12.0	620	13.75
124/3	26A	49-14-25A	542-609	3.53	8.44	12.0	620	4.02
124/3	27A	49-14-25A	542-609	3.53	8.44	12.0	620	8.78
124/3	28A	49-14-25A	542-609	3.53	8.44	12.0	620	15.45
124/3	29A	49-14-25A	542-609	3.53	8.44	12.0	620	10.48
124/3	30A	49-15-30A	422-472	3.07	8.44	11.5	620	4.76
124/3	34A	49-15-34A	422-472	3.07	8.44	11.5	620	13.52
124/3	30A	45-7-30A	573-678	3.54	8.44	12.0	620	3.13
125/3	3A	Previously Unirradiated			8.44	8.44	620	6.52
125/3	3B	Previously Unirradiated			8.44	8.44	620	3.45
125/3	25A	Previously Unirradiated			8.44	8.44	620	7.37
125/3	29A	Previously Unirradiated			8.44	8.44	620	7.37
125/3	25B	Previously Unirradiated			8.44	8.44	620	3.59
125/3	29B	Previously Unirradiated			8.44	8.44	620	3.42
125/3	30A	Previously Unirradiated			8.44	8.44	620	
125/3	34A	Previously Unirradiated			8.44	8.44	620	
125/3	30B	Previously Unirradiated			8.44	8.44	620	2.71
125/3	34B	Previously Unirradiated			8.44	8.44	620	2.71
125/4	25A	48-18-25A	396-405	1.97	7.17	9.14	400	3.84
125/4	26A	48-18-26A	396-405	1.97	7.17	9.14	400	2.24
125/4	27A	48-18-27A	396-405	1.97	7.17	9.14	400	1.47
125/4	28A	48-18-28A	396-405	1.97	7.17	9.14	400	0.37
125/4	29A	48-18-29A	396-405	1.97	7.17	9.14	400	
125/4	25B	49-18-25B	428-437	1.85	7.17	9.02	400	0.42
125/4	26B	49-18-26B	428-437	1.85	7.17	9.02	400	0.44
125/4	27B	49-18-27B	428-437	1.85	7.17	9.02	400	0.01
125/4	28B	49-18-28B	428-437	1.85	7.17	9.02	400	0.17
125/4	29B	49-18-29B	428-437	1.85	7.17	9.02	400	0.25
125/4	30A	44-19-30A	393-397	1.53	7.17	8.70	400	4.56
125/4	31A	44-19-31A	393-397	1.53	7.17	8.70	400	4.49
125/4	32A	44-19-32A	393-397	1.53	7.17	8.70	400	2.07
125/4	33A	44-19-33A	393-397	1.53	7.17	8.70	400	1.84
125/4	34A	44-19-34A	393-397	1.53	7.17	8.70	400	2.65

TABLE 3 (Cont'd)

PART 2: SILICON AND MOLYBDENUM MODIFIED ALLOYS (Cont'd)

Pin/Level	Alloy	Previous Capsule	Previous Temp. (°C)	Previous ϕt	Current ϕt	Accumulated ϕt	Current Temp. (°C)	$-\Delta\rho/\rho_0$ (%)
125/4	30B	45-19-30B	389-394	1.66	7.17	8.83	400	1.53
125/4	31B	45-19-31B	389-394	1.66	7.17	8.83	400	2.15
125/4	32B	45-19-32B	389-394	1.66	7.17	8.83	400	
125/4	33B	45-19-33B	393-397	1.66	7.17	8.83	400	0.18
125/4	34B	45-19-34B	393-397	1.66	7.17	8.83	400	

* All fluences are 10^{22} n/cm^2 (E >0.1 MeV).

TABLE 4

EFFECTS OF CARBON ON SWELLING

Alloy Condition Prior to Irradiation	Effects of Carbon
Solution Annealed	Increase (+)
Solution Annealed + Aged	No effect (0)
20% Cold Worked	Low N - Increase (+) High N - No effect (0)
20% Cold Worked + Aged	Increase (+)

TABLE 5

EFFECT OF SELECTIVE ELEMENTS ON IRRADIATION CREEP OF 20% COLD WORKED 316 STAINLESS STEEL AT 172 MPa, 450°C AND 4.6×10^{22} n/cm^2 (E >0.1 MeV)

Composition	Swelling* $\Delta V/V_0$ (%)	Irradiation Creep** $\Delta D/D_0$ (%)	Total*** $\Delta D/D_0$ (%)
Nominal	0.02	0.78	0.79
Low Si	0.86	1.86	2.15
High Si	-0.03	0.46	0.45
Low P	0.68	3.28	3.51
High P	0.005	0.39	0.39
Low Mo	0.20	2.24	2.31
High Co	-0.26	0.76	0.68
Low N, High C	-0.056	1.41	1.40
High N, Low C	-0.014	0.38	0.38

* $3 \times \Delta D/D_0$ on unstressed solid cylinder.

** Total $\Delta D/D_0 - \Delta V/3V_0$.

*** Measured on stressed tube.

FIGURE CAPTIONS

1. Swelling vs. Composition for 20% Cold Worked AISI 316.
2. Swelling vs. Weight Percent Silicon at 400°C.
3. Swelling vs. Weight Percent Silicon at 510 and 620°C.
4. Swelling vs. Temperature For Silicon-Modified 316 Stainless Steel. (a) Data not normalized; (b) data normalized to 9.1×10^{22} n/cm^2 (E >0.1 MeV).
5. Swelling vs. Fluence For Silicon-Modified 316 Stainless Steel.
6. Swelling vs. Molybdenum Content at 400°C.
7. Swelling in Carbon and Nitrogen Modified Alloys in the Solution Annealed Condition.
8. Swelling in Carbon and Nitrogen Modified AISI 316 in the Solution Annealed and Aged Condition. (a) Vs. weight percent nitrogen; (b) vs. weight percent carbon.
9. Swelling in Carbon and Nitrogen Modified Alloys in the 20% Cold Worked Condition. (a) Vs. weight percent nitrogen; (b) vs. weight percent carbon.
10. Swelling in Carbon and Nitrogen Modified Alloys in the Cold Worked and Aged Conditions. (a) Vs. weight percent carbon; (b) vs. weight percent nitrogen.
11. Effect of Solute Content on Irradiation Creep.
12. Swelling and Carbon Solubility vs. Weight Percent Nickel.

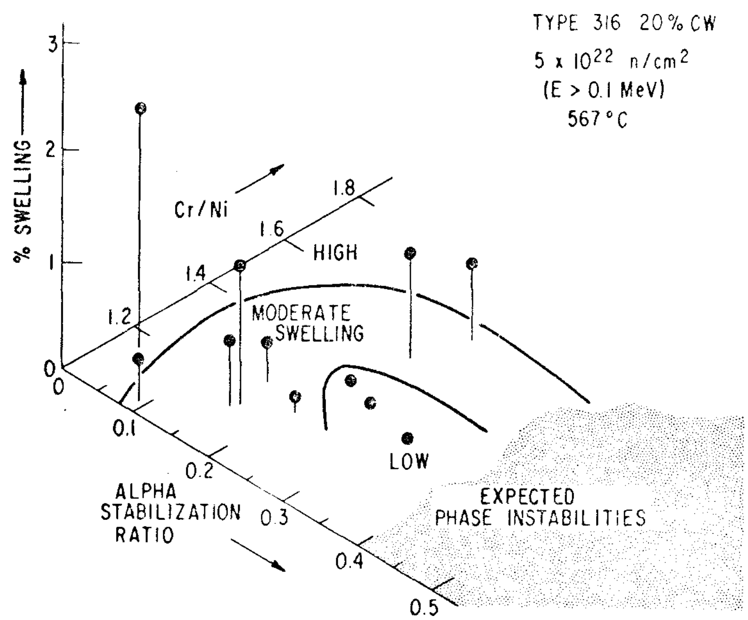
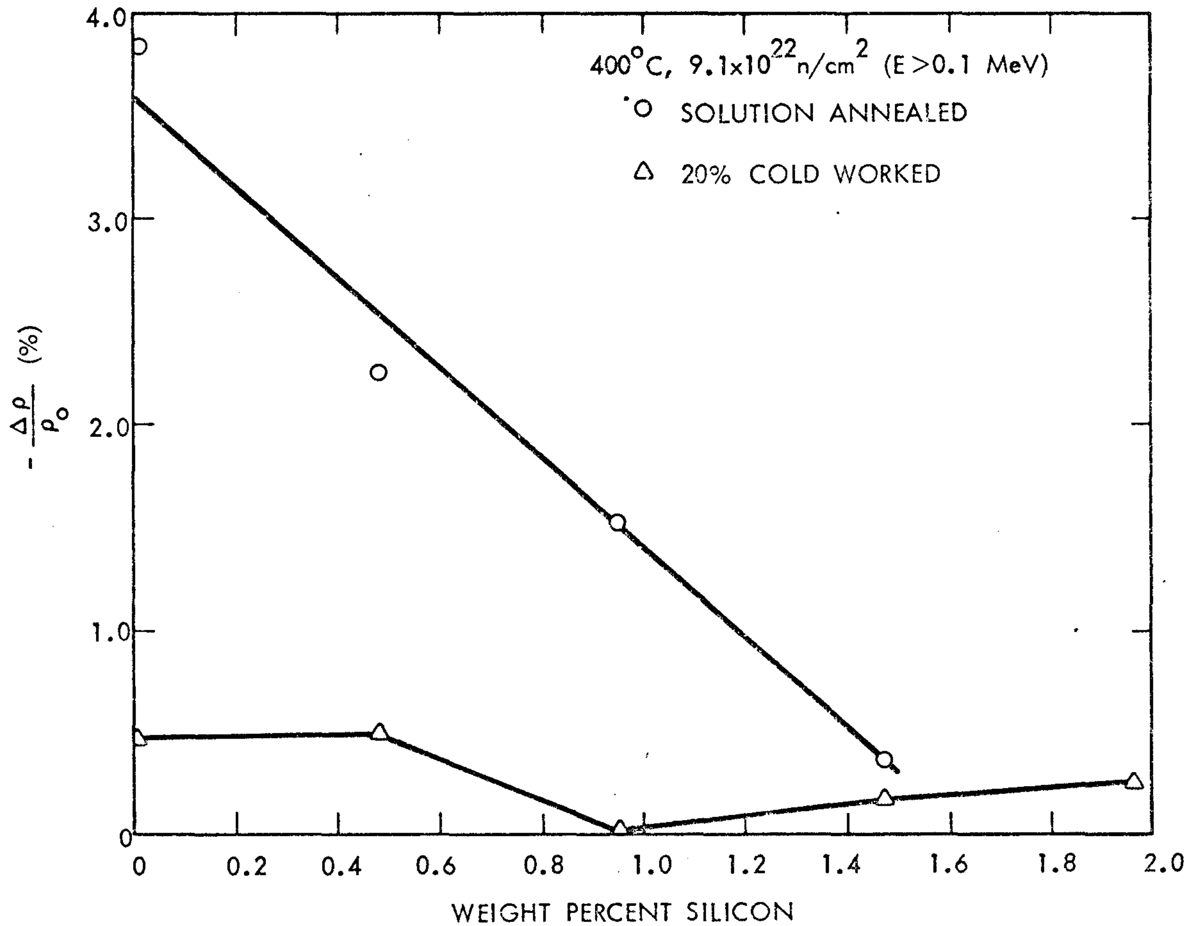


Fig. 1 - Swellings, measured by density changes, in various heats of neutron-irradiated, cold-worked Type 316. The space defined by the two compositional parameters, the Cr/Ni ratio and the "Alpha stabilization factor", is divided into regions of low, moderate and high swelling to conform with the swelling data.



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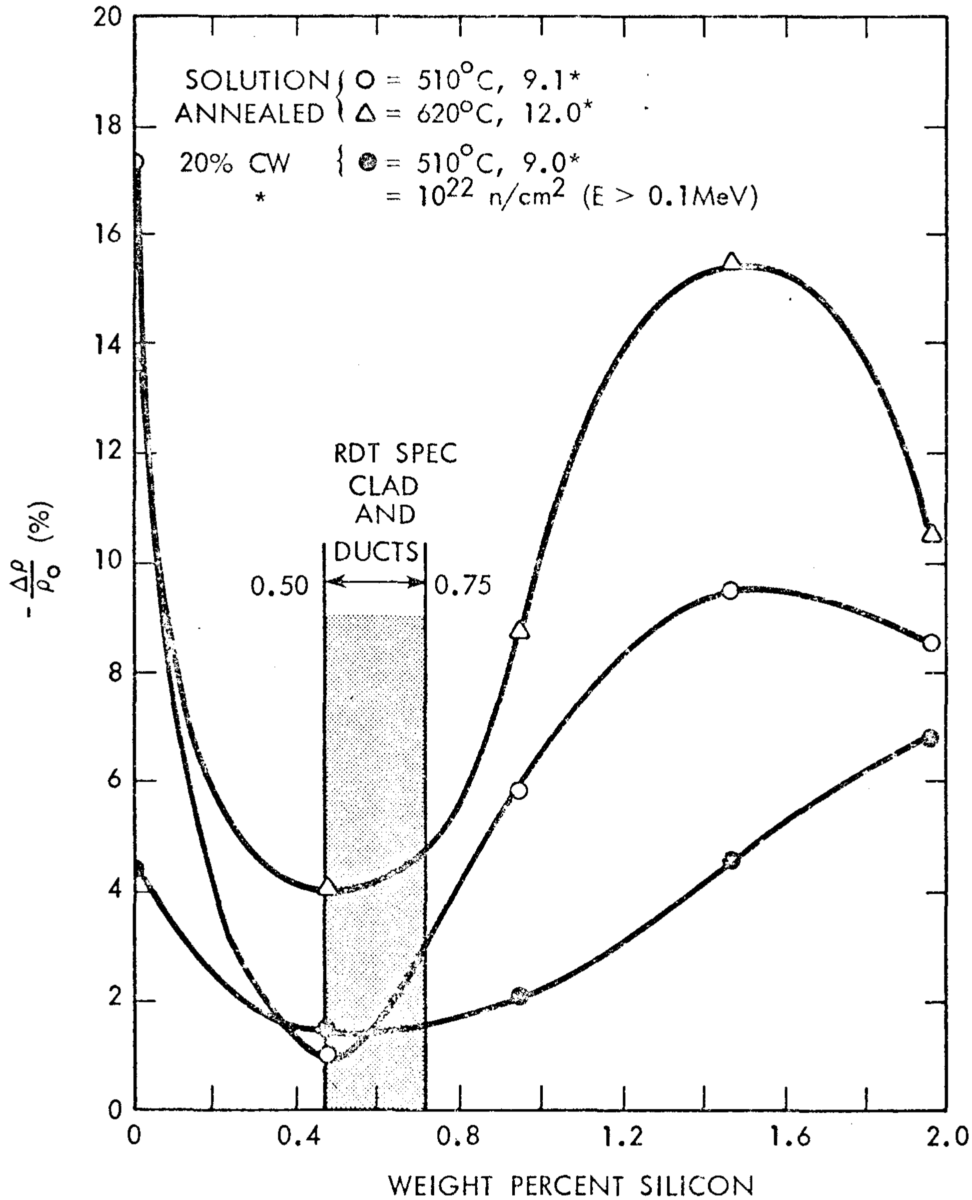

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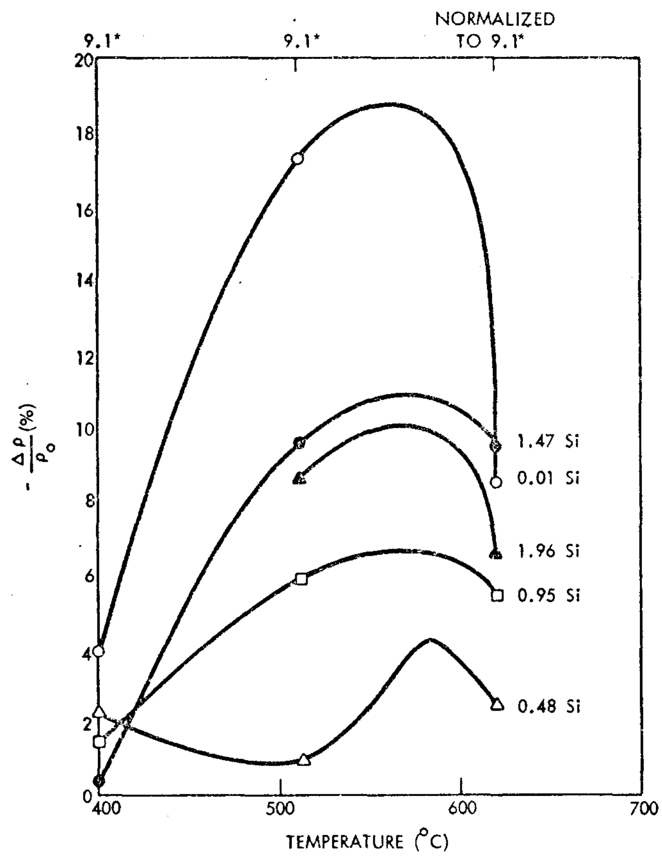

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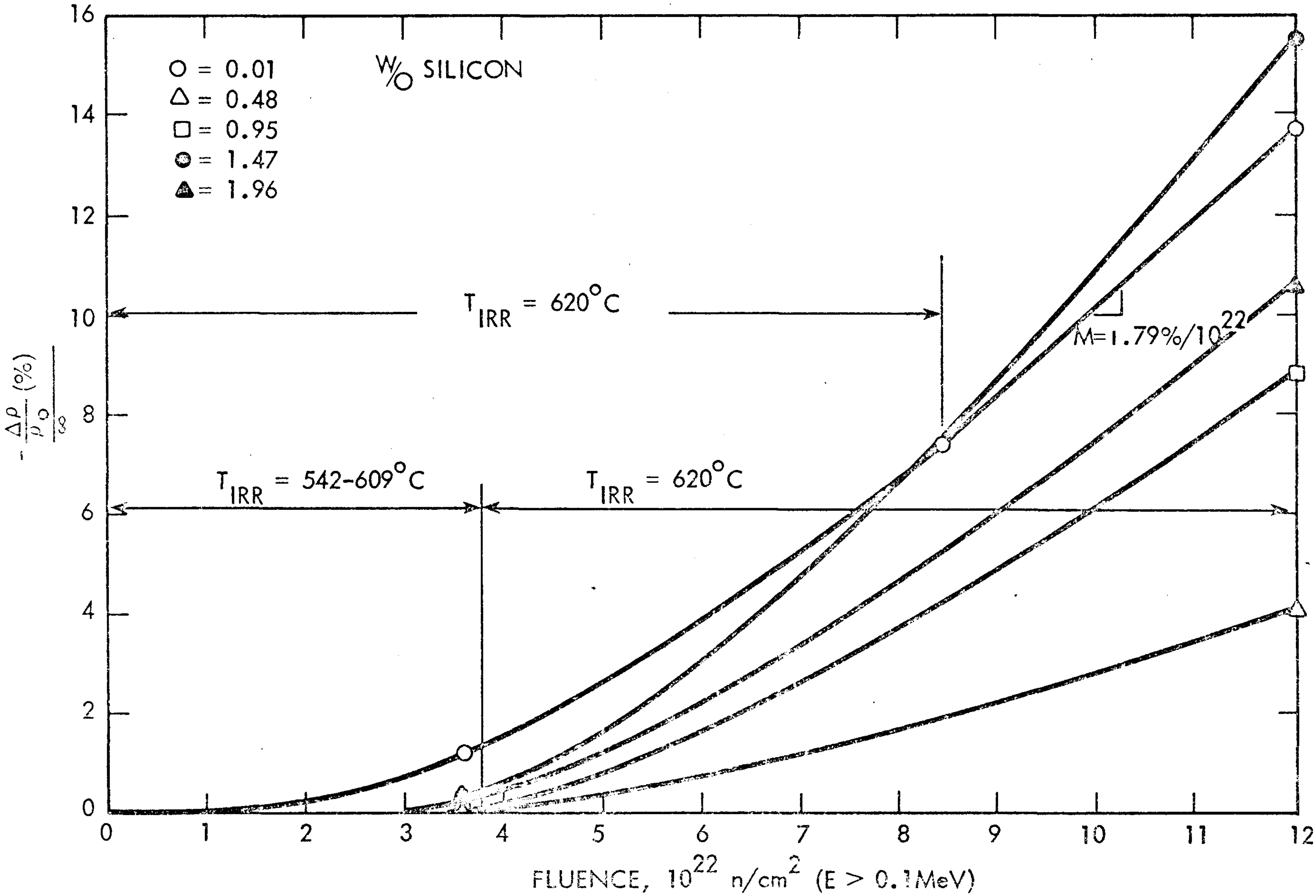

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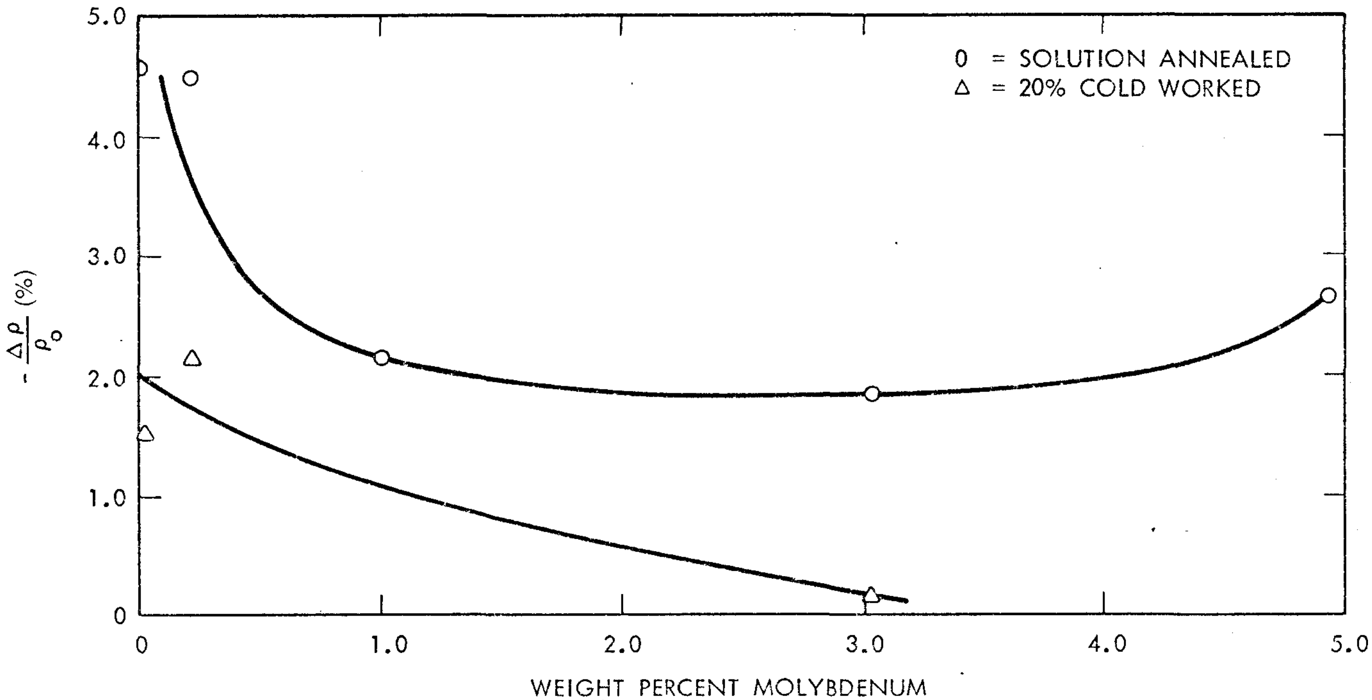

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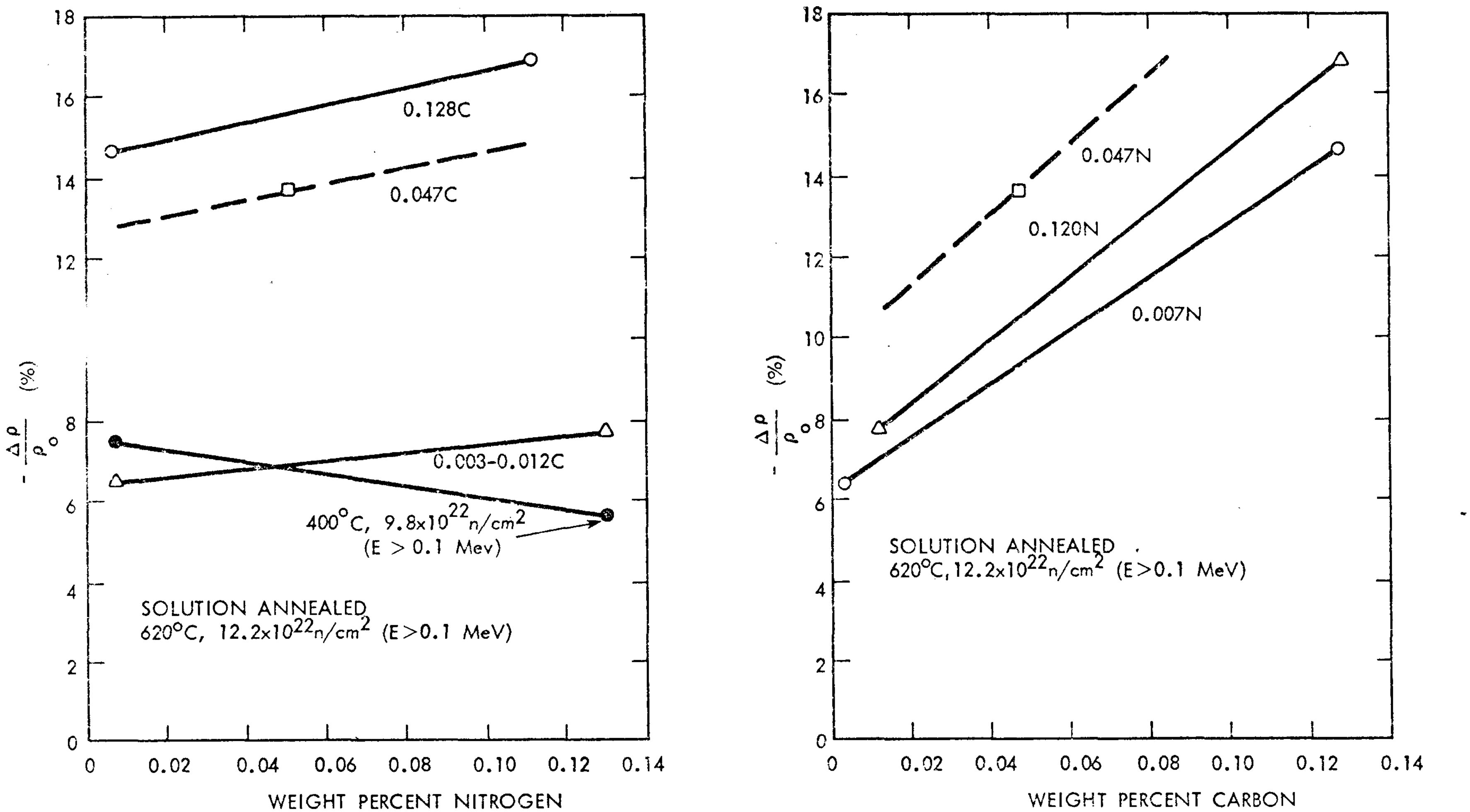

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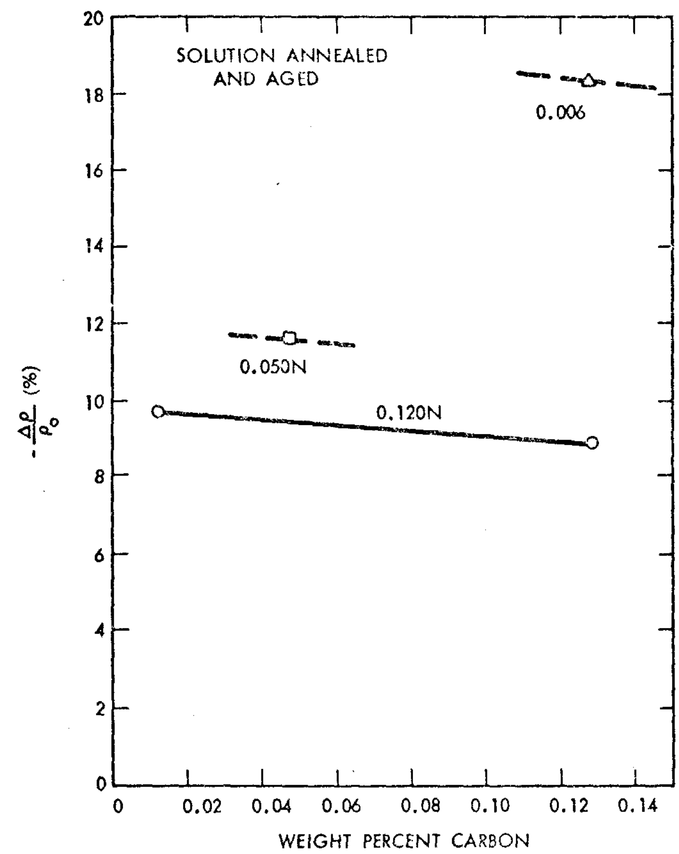

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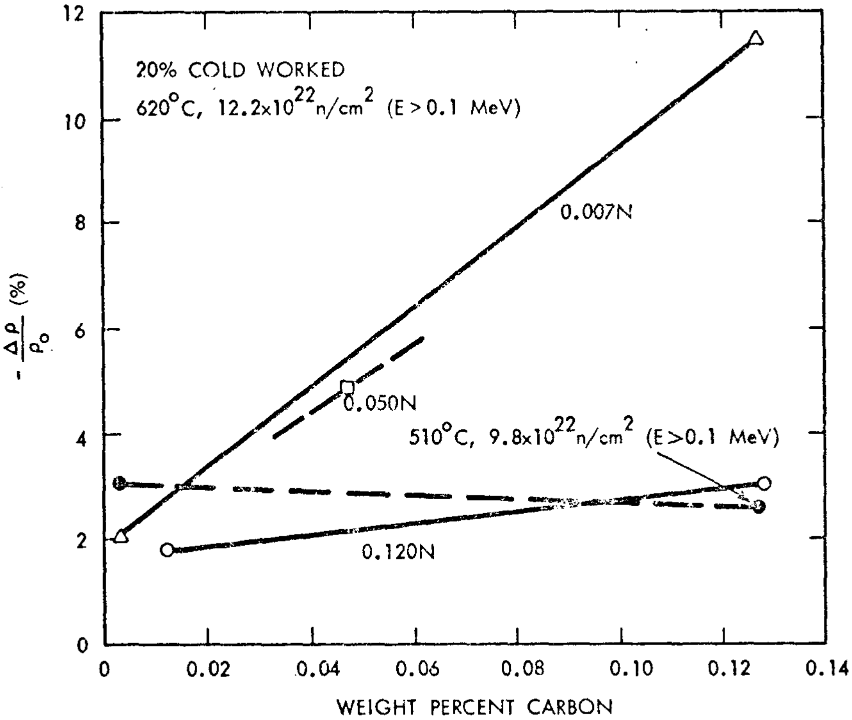

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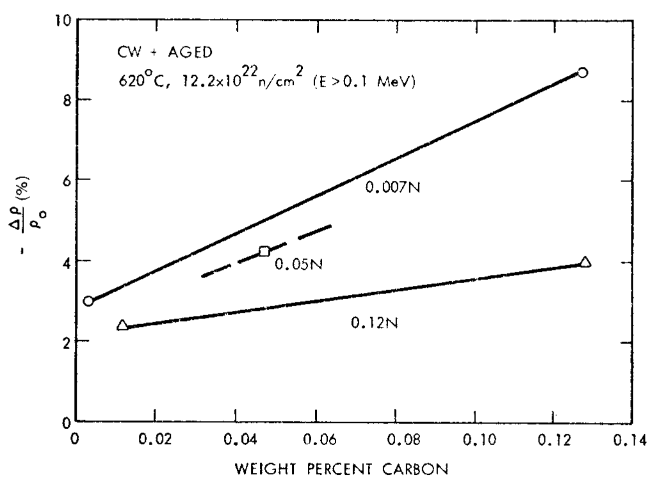
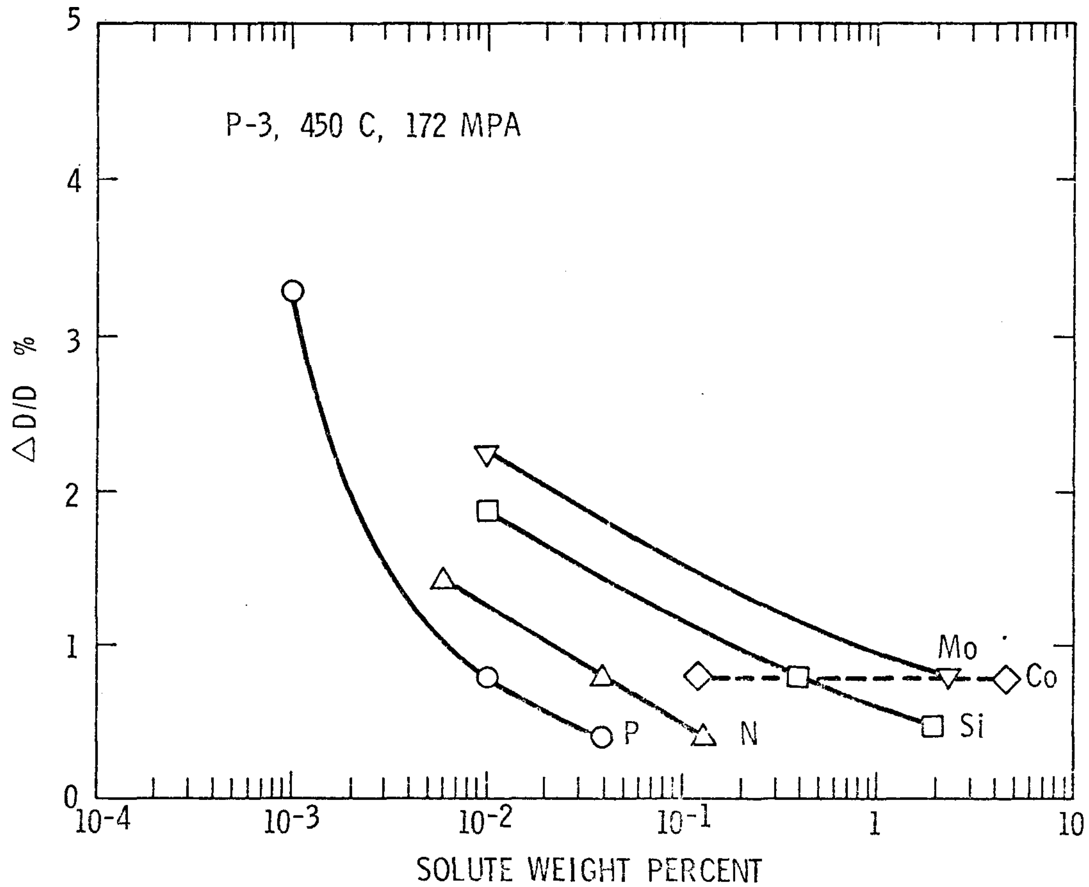

CW + AGED
620°C, 12.2x10^22 n/cm^2 (E > 0.1 MeV)
0.007N
0.05N
0.12N
- Δρ/ρ₀ (%)
0
2
4
6
8
10
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
WEIGHT PERCENT CARBON



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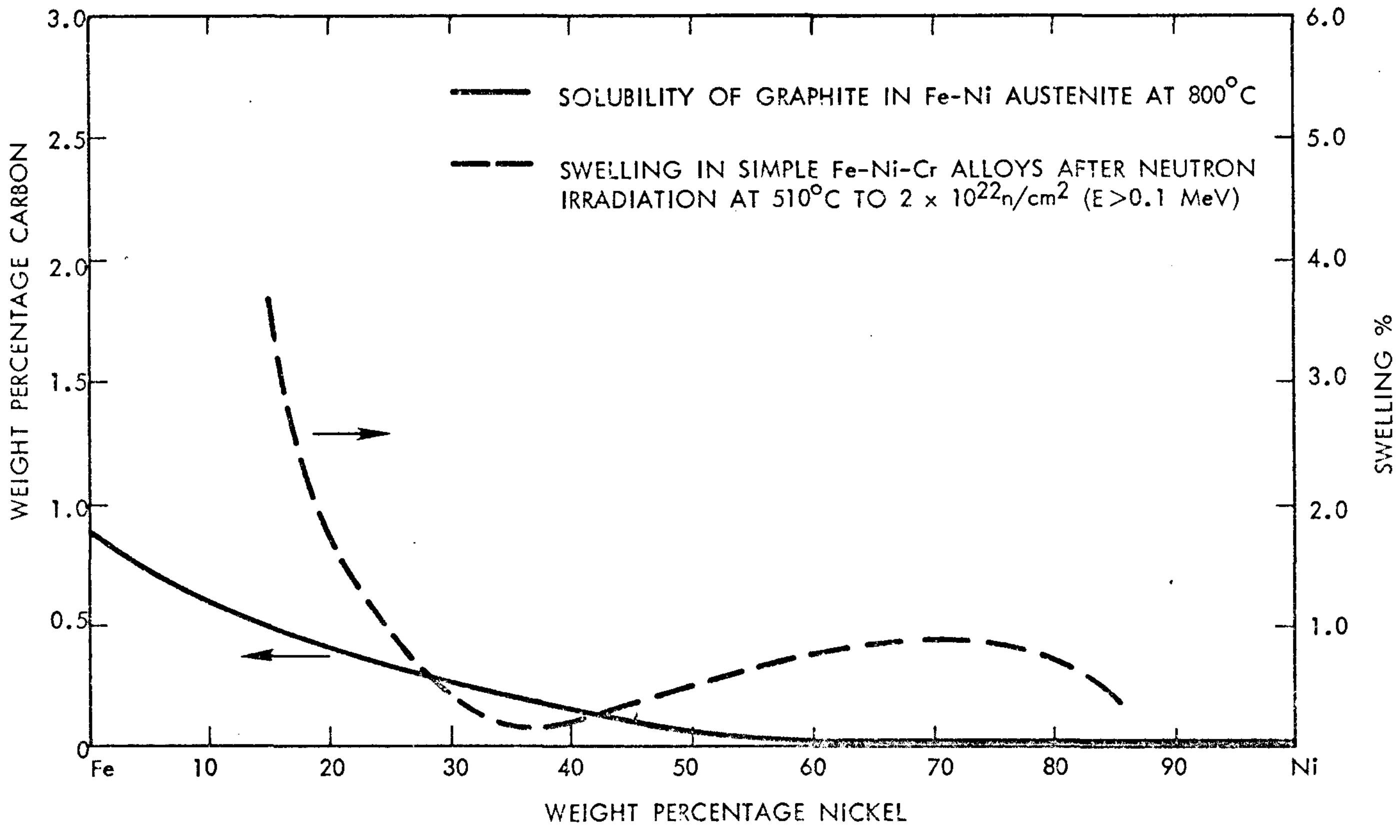

HEDL 7710-151.3