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REPORT NO. RN-S-0365

REVIEW OF HIGH-TEMPERATURE RADIATION EMBRITTLEMENT
OF ENGINEERING ALLOYS

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REVIEW OF HIGH-TEMPERATURE RADIATION EMBRITTLEMENT
OF ENGINEERING ALLOYS

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ABSTRACT

The known characteristics and the theoretical studies of high-temperature radiation embrittlement are reviewed. This embrittlement is attributed primarily to the presence of helium, which results from the thermal-neutron $B^{10} (n, \alpha) Li^7$ reaction; however, many details of the embrittlement mechanism are not understood. A compilation of mechanical-property radiation test data is presented for several high-temperature alloys.

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NOTE: Figures and tables for the main text are in Sections V,B and V,C, respectively. (See Contents, above.)

I. INTRODUCTION

Numerous recent investigations have demonstrated that nuclear radiation can result in severe embrittlement of high-temperature alloys when they are tested at temperatures above 1000°F after being irradiated either at or below the test temperature. This embrittlement appears as a reduction in elongation both in tensile tests and in stress-rupture tests. In stress-rupture tests, the time to rupture is decreased substantially. These tests have usually been performed at dose levels of 10^{20} to 10^{21} nvt (with thermal- and fast-neutron doses being about equal). In a few tests performed at doses of 10^{16} to 10^{18} nvt, embrittlement has still occurred to a lesser degree. These lower doses include the range of exposure to which many parts of the NERVA engine are subjected. Within the reactor, some components are subjected to slightly higher doses, approximately 10^{19} nvt. This report covers experimental and theoretical studies of the radiation embrittlement often observed in high-temperature tensile and stress-rupture tests of irradiated alloys. Experimental data have been compiled to document the character and magnitude of ductility losses in a wide variety of high-temperature alloys.

The report is also intended to be a reference document on recent radiation-effects data regarding mechanical properties. The more familiar types of radiation-effects data, for moderate test temperatures (usually near room temperature), are compiled in Appendix C. The data include the most recent information reported in technical journals and government reports (up to June 1966).

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II. CONCLUSIONS AND RECOMMENDATIONS

The mechanisms of high-temperature radiation embrittlement are reasonably well understood, but many missing details preclude quantitative predictions of how serious embrittlement may be in untested alloys. For example, total boron content cannot be correlated with damage sensitivity for some alloys because boron also affects properties that are independent of radiation phenomena. Grain size and special heat treatments affect damage sensitivity in ways not completely understood. Studies of exposure, temperature, and strain-rate thresholds are too limited to justify the prediction of design properties in most alloys.

It is recommended that prospective NERVA materials that will be subjected to neutron exposures of greater than 10^{16} nvt (thermal) and to concurrent or subsequent stresses at temperatures above 1000°F (540°C) be subjected to exposures one or two decades greater than anticipated for the operating environment. Of interest in such tests would be boron content, grain size, precipitate distribution, and chemistry of residual elements. To the extent feasible, the influence of these variables should be determined so that, if necessary, a particular alloy may be modified to improve radiation resistance. If severe embrittlement of an alloy results, the postirradiation properties might be improved by chemistry changes, prior cold work, or modified heat treatments. Current materials of interest in this program that are known to have marginal properties after irradiation include Inconel X-750, Inconel 718, Waspalloy, and René 41.

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III. CHARACTERISTICS OF HIGH-TEMPERATURE RADIATION EMBRITTLEMENT

High-temperature embrittlement, unlike low-temperature radiation embrittlement, which is observed after irradiation and tensile testing at low or moderate temperature, is irreversible and correlates with the thermal-neutron dose rather than with the fast-neutron dose^{1*}. Low-temperature ductility losses are accompanied by increases in yield strength and ultimate strength, whereas yield strengths and stress-strain relationships remain relatively unchanged in testing at sufficiently high temperature. Only the ductility is significantly reduced. Typical data comparing the effects of post-irradiation test temperatures are shown in Figures 1 and 2. An irradiation temperature in the range of 110 to 1150°F (40 to 620°C) is not an important variable in high-temperature embrittlement³⁵. The magnitude of reduction in hot ductility is highly sensitive to strain rate^{2,7,13,17,18}, with the reduction effect being greater at the lower strain rates. For example, the true uniform strain of Hastelloy N is reduced from 32% to 13% when irradiated at 1290°F to an exposure of 9×10^{20} nvt (thermal) and tested at 1290°F at a strain rate of 1.2 in./in./min; whereas, at a strain rate of 0.002 in./in./min, the true uniform strain is reduced from 20% to 5.6%. Tensile strengths are reduced somewhat because total elongation is reduced, the magnitude of reduction depending on the strain rate. In stress-rupture tests, rupture strengths (for fixed time to rupture) are lower, but the major changes are in loss of ductility^{9,19}. Failure is predominately intergranular^{9,13,17,19}. Enhanced precipitation also appears to occur within the grains¹³.

There are two primary differences in the radiation effects at test temperatures below 1000°F and at temperatures above 1000°F. First, postirradiation annealing removes the embrittlement observed in testing at temperatures below 1000°F. For irradiation above 1000°F, postirradiation annealing temperatures as high as 1900 and 2400°F do not increase the ductility^{2,7}. The second

*Throughout the main text and the appendixes of this report, superior numerals indicate items in the List of References unless other use (such as for an exponent) is obvious.

major difference is dependence of the magnitude of ductility loss on thermal-neutron dose rather than fast-neutron dose for materials tested above 1000°F. Below this temperature, the mechanical-property changes depend primarily on fast flux dose.

Low-temperature radiation effects result from high-energy neutrons colliding with atoms and displacing them from their normal lattice positions, thereby disturbing the local crystalline arrangement. These disturbances consist of interstitial atoms and vacancies as well as interstitial and vacancy complexes. The mobility of interstitials is high at room temperature, and their migration results in substantial annealing as they return to vacancies or go to grain boundaries and dislocations. At slightly higher temperatures, the vacancies have high mobilities and likewise disappear at vacancy sinks such as grain boundaries or dislocations. At still higher temperatures, normal diffusion processes will relieve the local strains associated with interstitial or vacancy complexes.

The only damage that can remain after the above annealing is that resulting from transmutations. For doses below about 10^{20} nvt (thermal), the major transmutation reaction in boron-containing alloys is $B^{10} + n \rightarrow He^4 + Li^7$, or $B^{10}(n, \alpha)Li^7$. The thermal-neutron cross section for the $B^{10}(n, \alpha)Li^7$ reaction is 3840×10^{-24} sq cm. Natural boron contains 18.8% of the B^{10} isotope. Although current theories differ in details, all ascribe the primary source of high-temperature ductility loss to the $B^{10}(n, \alpha)$ reaction, even when the boron content of alloys is less than 10 ppm by weight.

IV. MECHANISMS OF EMBRITTLEMENT

The effect of temperature and time is to allow segregation of transmutation products at microstructural positions that significantly affect ductility. The transmutation product considered to be most important by most authors is helium, a neutral alpha particle, produced by reaction of thermal neutrons* with boron-10^{1,14,15,16}. Helium is insoluble in nickel and iron-base metals; it forms no chemical bond with these elements and is gaseous at temperatures of concern. As a result, the effect of the helium atom on mechanical properties can be appreciable even when present in only trace quantities (10^{-8} atom fraction). Fast-neutron (n, α) reactions with other elements may also be important^{20,21}. At high fast-neutron doses (above 10^{20} nvt) and low boron contents (≤ 1 ppm), most helium atoms are produced by fast-neutron (n, α) reactions.

A. THEORY OF BARNES¹⁵ AND ROWCLIFFE¹³

Several similar explanations for helium embrittlement have been presented. The first detailed explanation was that of Hyam and Summer (1962)¹⁴ and R. S. Barnes (1964)¹⁵. Further direct support for this theory for a stainless steel was provided by Rowcliffe (1966)¹³. In this explanation, low-ductility fracture is explained in terms of stress-induced growth of grain-boundary helium bubbles. These bubbles grow under an increasing applied stress until a critical size is reached beyond which the internal helium pressure decreases at a slower rate than the surface tension that restrains this pressure. The bubbles then grow continuously, without further increase in stress, at a rate determined by the supply of thermally created vacancies. A crack is thus nucleated that eventually results in intergranular failure. Rowcliffe, by means of electron-transmission microscopy, showed that this effect occurs in a 20%Cr-25%Ni-Ti stainless-steel alloy. Helium bubbles within a narrow size range (45 ± 10 Å in diameter) were observed to lie along grain boundaries. Postirradiation annealing at 750°C increased the size to 55 ± 15 Å. Tensile testing at 750°C altered the distribution by increasing the bubble size to a

*See Appendix A for comparison between fast and thermal neutron flux on production of helium.

maximum of several hundred Angstrom units. Bubbles of similar size also appeared along dislocations within the grains. The number of small-size bubbles was also reduced. Calculations showed that, although many bubbles were observable (down to approximately 20-Å diameter), only a small fraction of the total helium was visible in the form of bubbles. Hence most of the helium remains as isolated atoms at defects in the matrix or resides in bubbles smaller than 20 Å in diameter. This explanation fails quantitatively since the stress predicted as necessary for bubble growth is much greater than that observed experimentally.

B. THEORY OF MOTEFF, ROBERTSHAW, AND KINGSBURY⁹

In this explanation the effects of boron on the mechanical properties of unirradiated material are considered as an indication of boron location in alloys. Boron has been found by many investigators to significantly influence the creep-rupture properties of many high-temperature alloys^{9,22-28}. Metallographic studies of iron- and nickel-base alloys have shown that boron influences microstructures both by decreasing the solubility of carbon and by segregation at grain boundaries with consequent decrease in grain-boundary diffusion²⁴. Boron, by promoting intragranular precipitation of M_6C , reduces massive grain-boundary precipitation of $M_{23}C_6$, suppresses cellular precipitation, and increases ductility²³. Creep-rupture properties at high temperature may be significantly improved by 10 to 20 ppm of boron added to precipitation-hardening alloys²⁷. This improvement was found to be due to the ability of zirconium, boron, and optimum amounts of boron plus zirconium, in that order of effectiveness, to retard structural deterioration at the grain boundaries. Approximately 0.001-wt% natural boron increases the elongation and time to rupture by factors of more than four over materials containing no boron. Increasing the amount of boron to 0.010 wt% provides a further twofold improvement²⁷. For irradiated specimens, variation of boron content from 0.0009 to 0.010 wt% can increase the stress-rupture life by a factor of six. On the basis of information such as the above, Moteff, Robertshaw, and Kingsbury conclude that irradiation-induced embrittlement of complex heat-resistant alloys is the result of the presence of a high concentration of boron in the grain boundaries*

*See Appendix B for a discussion of boron grain-boundary segregation and consequent heavier damage in this region.

and along dislocations in combination with the high thermal-neutron cross section for the $B^{10} (n, \alpha) Li^7$ reaction. This reaction may lead to the following sequence of effects⁹:

(1) Atom displacements are caused by the recoiling Li nucleus and alpha particles in the grain boundary. Total displacements caused by this mechanism are estimated to be an order of magnitude greater than those produced by fast neutrons.

(2) Small vacancy clusters are formed, which, together with helium atoms, condense onto grain boundaries, subgrain boundaries, dislocations, and nearby precipitates. Dislocation loops are formed, grow rapidly, and may form dislocation networks. Additional precipitates (carbides, nitrides, borides) are also formed in the local regions of lattice disorder.

(3) These small precipitates, dislocation loops, networks, and small helium gas bubbles lying along the periphery of the boundary would impede dislocation movement and pin some of the dislocations, thereby significantly reducing slip within the grain. Grain-boundary sliding would also be reduced. As a result of the reduction in slip within the grains and of grain-boundary sliding, total specimen elongation will be greatly reduced. A further possibility is that the large amount of lattice disorder caused by the $B^{10} (n, \alpha) Li^7$ reaction in regions close to grain boundaries may furnish additional sites for boron atoms to occupy. The result would be a reduction in the number of boron atoms in the grain boundary, where they play their major role in determining the creep-rupture properties of high-temperature alloys. This latter possibility would be more important for alloys containing less than approximately 0.001 wt% boron.

In the above explanation, helium-bubble formation, by itself, is not of prime importance. The major damage mechanism is a high concentration of lattice disorder and a subsequent immobilizing of this disorder by small

precipitates, helium gas bubbles, and dislocation networks. The grain boundary region thus becomes highly strain resistant, and failure then occurs by fracture along the grain boundary.

C. THEORY OF MARTIN AND WEIR

Martin and Weir also point out that the damage that causes low ductility and increased strength at low deformation temperature is different from the damage that causes low ductility at high temperature. The effect of irradiation does not correlate with fast-neutron exposures, but rather with thermal-neutron dose^{29,30}. Postirradiation heat treatments that anneal the low-temperature irradiation effects^{31,32} do not improve the ductility at elevated temperature. From these and other results they conclude that the elevated-temperature effect

- (1) is due to thermal-neutron exposure,
- (2) results in little change in strength characteristics,
- (3) does not anneal at temperatures up to 1750°F, and
- (4) results in low ductility by promoting early initiation and propagation of grain-boundary fracture.

By noting²⁹ that no change in ductility is observed between irradiated and unirradiated specimens that fracture transgranularly, they consider that elevated-temperature irradiation affects only the fracture at grain boundaries. The thermal-neutron boron (n, α) reaction is considered most likely to cause embrittlement by producing helium at the grain boundary. This grain-boundary helium in turn affects nucleation of cracks at the grain boundary. On the basis of the amount of helium necessary for embrittlement of beryllium³³ (2.07×10^{-3} atom fraction) and the amount of helium required for embrittlement of Hastelloy N³⁰ (approximately 1×10^{-5} atom fraction), grain-boundary segregation of boron need not be very large, even when the average boron concentration is only a few parts per million. Qualitative support for the B(n, α) reaction is provided by the fact that an irradiation temperature between 120

and 1300°F is not an important variable³⁵. This implies that phase transformations during irradiation that are dependent on solid-state diffusion are not important.

Martin and Weir point out that ductility loss is more severe at low strain rates. This effect arises because low ductility and intergranular failure normally tend to occur at low strain rates even without the influence of elevated-temperature irradiation. The addition of a high-temperature irradiation environment accentuates sensitivity to strain rate. The explanation of Martin and Weir for the mechanism of intergranular fracture is based on a model proposed by Zener³⁴ in which the grain boundary is assumed to be a viscous region in an elastic matrix. The viscous region deforms as the shear stress is applied and tensile stresses are concentrated at the ends of the boundary. Once the fracture stress is exceeded, a wedge-type crack is nucleated at the boundary ends (triple point) and is propagated on further increase in shear stress. The amount of intergranular fracture is reduced at high strain rates because the shear stress for flow in the viscous boundary is highly sensitive to strain rate.

Since the stress necessary to nucleate a crack is approximately inversely proportional to the square root of the length of the sliding interface^{17,34}, it follows that greater ductility should be observed for small-grained material than for large-grained material. Martin and Weir found this to be the case for both unirradiated and irradiated material. For the irradiated material, reduction in grain size for a given concentration of boron increases ductility for two reasons. First, the stress required for nucleation of a crack is increased and, second, the helium concentration at the grain boundary is reduced because of the larger boundary surface areas. These two effects could not be quantitatively separated, but the reduced ductility after irradiation was shown to be primarily associated with a reduction in grain-boundary sliding before crack nucleation. Deformation of the grains and crack widening were reduced to a much lesser extent.

D. SUMMARY OF CHARACTERISTICS AND MECHANISMS

Present knowledge about elevated-temperature irradiation embrittlement of metals and alloys may be summarized as follows:

(1) Normal or low-temperature radiation damage mechanisms are replaced by elevated-temperature radiation damage mechanisms at temperatures above roughly half the absolute melting temperature of an alloy.

(2) The effect of this elevated-temperature radiation damage on mechanical properties cannot be removed by normal annealing--in contrast to low-temperature radiation damage effects.

(3) Elevated-temperature radiation damage manifests itself as loss of ductility and premature intergranular fracture.

(4) When an alloy normally fails intergranularly, irradiation prior to test can almost completely suppress ductility.

(5) Neutron irradiation at elevated temperatures affects fracture at grain boundaries.

(6) Thermal neutrons, through the $B^{10} (n, \alpha) Li^7$ reaction, cause the observed loss of ductility (see Figure 23).

(7) Recoiling Li and α fragments probably cause about ten times as much lattice disorder in the grain boundary region as fast neutrons cause in the matrix of an alloy.

(8) For alloys that fracture intergranularly, the stress required to nucleate a crack is inversely proportional to the square root of grain size and is sensitive to the strain rate. At high strain rates, little stress can

be concentrated at grain-boundary intersections. At low strain rates, deformation by grain-boundary sliding occurs, which in turn causes stress concentrations at grain boundary intersections and, ultimately, crack nucleation. The effect of $B^{10} (n, \alpha) Li^7$ reaction in the grain boundary region is to reduce the stress necessary to nucleate a crack and increase the sensitivity of stress concentration to strain rate. The helium atoms form small bubbles (approximately 20-Å diameter) along grain boundaries, in dislocations, and act as barriers to dislocation movement in the grain boundary region. The result is a reduction in amount of grain-boundary sliding before cracks are nucleated and propagated.

(9) Thermal-neutron-dose threshold for the detectable loss in ductility depends on the boron concentration, but the ratio of thermal-neutron dose to natural boron concentration appears to be about 10^{15+1} nvt:1 ppm (wt) natural boron. For alloys with very low ductility, the threshold thermal-neutron dose is probably less, and, for relatively ductile materials, it is probably more.

E. METHODS OF MITIGATION

The basic cause of elevated-temperature embrittlement is the thermal-neutron $B^{10} (n, \alpha) Li^7$ nuclear reaction--at neutron doses less than about 10^{22} nvt. Since the boron resides primarily at grain boundaries, any metallurgical treatment that will reduce this concentration will make the alloy more resistant to radiation damage¹. This method must be used with caution, because boron, in the absence of radiation, may have beneficial effects on ductility that can be lost. One way to achieve this result is to decrease the grain size for a given average boron content². A second way is to make alloys with a very low boron content.

A third way is to add elements to the alloy or modify its heat treatment so that the boron will not be tied up within the grain and a more uniform distribution⁴ will be achieved.

A fourth way is to add elements that render the grain boundary more ductile in spite of the boron (n, α) reaction at the grain boundaries. Titanium additives have been used successfully in some cases (not all) to reduce the magnitude of high-temperature irradiation embrittlement for a given thermal flux dose.

Probably the simplest procedure for reduction of susceptibility to elevated-temperature irradiation embrittlement is to use an alloy in its most ductile condition at its operating temperature.

V. COLLECTION OF EXPERIMENTAL DATA FOR SEVERAL ALLOYS

Large quantities of radiation test data have been surveyed, and selected data are presented in the figures of Section V,B and the tables of Section V,C. General comments and alloy comparisons are made in Section V,A. Included are tensile data and stress-rupture data. The alloys and property data collected are listed in Table 1. Nominal chemical compositions for these alloys are given in Table 2. Specific data collected are shown in Tables 3 and 4. Table 3 contains tensile data for test temperatures above room temperature. Only the data for test temperatures of 930°F (500°C) or higher are pertinent to the present discussions. Table 4 contains stress-rupture data, including elongation when available.

Although some attempt was made to include material histories and test conditions, such information is missing in many instances. When additional details or more recent data are needed on these subjects, the REON Materials Department (7720) will provide assistance.

Appendix C contains tensile test data for tests performed at or near room temperature after irradiation. These data are presented as reference data and are pertinent to this report only to illustrate the nature of low-temperature radiation effects and to indicate that, in the case of high irradiation temperatures, metallurgical changes can occur that are not directly related to the intergranular fractures involved in high-temperature radiation effects.

In the tables and figures, and in Appendix C, there is often no distinction made between thermal and fast neutrons. When no such distinction is made, the fast and thermal fluxes can generally be assumed to be of the same order of magnitude. If the property data presented are to be used for design purposes, the original sources or their authors should be consulted for additional details on flux spectrum, boron content, and strain rate. Unless specified otherwise, strain rates are low, approximately 0.002 in./in./min for high-temperature tests. In the case of low-temperature tests, the properties are not sensitive

to strain rate. Boron contents are presented when known; however, they must be viewed with caution in many instances, since only a few laboratories appear to have the experience and facilities to make accurate boron analyses.

A. GENERAL COMMENTS AND COMPARISON OF DATA

1. Austenitic Stainless Steels

Reduction in elongation due to high-temperature irradiation of 304 stainless steel is appreciable. Data given in Reference 70 show that creep during neutron irradiation severely reduces the rupture life of annealed 304 stainless steel, as shown below.

Temperature, °C	Stress, psi	% Creep Strain to Failure		Rupture Time, hr	
		In Reactor	Out of Reactor	In Reactor	Out of Reactor
650	20,000	8 to 9	25 to 26	150	570
550	30,000	3 to 4	8	770	4500

The fast (or thermal) neutron dose was between 10^{19} and 10^{21} nvt. Steady-state creep rates were unchanged, as shown in Figure 21.

Type-316 stainless steel shows a 50% loss in elongation to about 16 to 33% as compared with about 58% when tested at 750°C after 6×10^{19} nvt. Very limited data at 700°C after 2 to 3×10^{19} nvt show no change in uniform elongation compared with that for unirradiated controls.

Type-347 stainless steel also shows a typical ductility loss of about 50% when tested above 500°C. Since its initial ductility is high, it is still useful after irradiation.

Extensive data for A-286 are available. This alloy shows severe ductility loss. Uniform elongation at about 540 to 650°C drops from about 36% to about 5% after irradiation to a dose of 7×10^{20} nvt ($E \geq 1$ Mev). Stress-rupture tests show that significant ductility loss occurs after only

10^{15} nvt. In comparison with 304, 316, and 347 stainless steel, this alloy seems to be more susceptible to high-temperature radiation damage.

For the 20Cr-25Ni-Nb stabilized stainless steel, considerable scatter is shown in tensile-test elongation after various fast flux doses. However, there appears to be a general downward trend from about 50% elongation to about 10% elongation as the fast-neutron dose increases to 10^{21} nvt. This same general trend appears in the in-reactor stress-rupture data. Over very long times (low stresses and large total doses), the time to rupture at a given stress tends to be less than in out-of-reactor tests.

2. Nickel-Base Alloys

Inconel X (Inconel X750) shows severe loss of ductility. At about 1000°F (550°C) elevated-temperature tensile elongation goes from about 21% for controls to essentially zero at 2×10^{20} nvt. Stress-rupture tests show the same severe loss of ductility and consequent reduced time to rupture.

At temperatures of 1200 to 1300°F (650 to 700°C) Inconel (Inconel 600) also shows a large loss in ductility. Uniform elongation drops from 20% for controls to about 5% after a dose of 3 to 6×10^{20} nvt ($E \geq 1$ Mev) at tensile-test temperatures of 650 and 700°C.

Inconel 625, on the other hand, shows very little loss in ductility at doses of 2×10^{21} nvt at a tensile-test temperature of 650°C.

Inconel 702 also shows little ductility change due to fast-neutron doses of up to 10^{21} nvt at 700°C. Incoloy 800 shows about a 50% loss in ductility at 3×10^{20} nvt ($E \geq 1$ Mev).

Hastelloy R-235 shows a 60 to 70% loss in ductility at a test temperature of 700°C after a total fast flux dose of 10^{20} nvt.

Hastelloy X and Hastelloy X-280 show definite losses in tensile-test uniform elongation at test temperatures above about 1200°F (650°C). These losses appear to be somewhat affected by irradiation temperature as well as tensile-test temperatures. A portion of the ductility loss is due to the normal degradation of Hastelloy X. However, the alloy still shows significant high-temperature irradiation damage. Uniform elongation declines from about 45 to 50% in the unirradiated condition to about 5% at 2×10^{20} nvt at 1290°F (700°C). The threshold of high-temperature radiation damage is at about 10^{15} nvt as determined by the time to rupture and the elongation at rupture in stress-rupture tests. At long times (about 1000 hr) in stress-rupture tests, curves for irradiated and unirradiated specimens appear to coincide. This would imply that high-temperature radiation damage is removable by very-long-time annealing.

Considerable information exists for Hastelloy N; 940°F (500°C) appears to be the threshold temperature for reduced elongation to occur in elevated-temperature tensile tests after 10^{20} to 10^{21} nvt ($E \geq 1$ Mev). Maximum loss of uniform elongation appears to be at a test temperature of 1200°F (650°C). For instance, an elongation of 20 to 30% for the unirradiated condition is reduced to 5% or less after 10^{21} nvt. Results of stress-rupture tests also indicate a marked reduction in time to rupture due to irradiation. However, at long times (about 1000 hr) to rupture (low stresses), the irradiated and unirradiated stress-rupture curves appear to coincide.

The final alloy for which sufficient data exist to permit conclusions is René 41. The high-temperature tensile-test data show that the threshold temperature for irradiation-induced loss in ductility is about 1200°F (650°C). At 1600°F (870°C), severe ductility loss occurs after a neutron dose of 5×10^{19} nvt, whereas at 1200°F (650°C), little ductility loss is shown. Again from stress-rupture tests, the fast-flux (roughly equivalent to thermal-flux dose) threshold for significant loss in ductility is less than 10^{15} nvt (see Figure 22). The irradiated stress-rupture curves appear to coincide with the unirradiated curves at rupture times greater than 1000 hr. This result is similar to that for Hastelloy X; that is, annealing for very long times appears to remove much of the elevated-temperature irradiation damage.

B. FIGURES

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TABLE 1

ALLOYS CONSIDERED AND TYPES OF MECHANICAL-PROPERTY DATA COLLECTED

<u>Alloy</u>	<u>Boron Content, wt%</u>	<u>Strain Rate, in./in./min</u>	<u>UTS</u>	<u>0.2% YS</u>	<u>El.</u>	<u>Stress Rupture</u>	<u>Reference</u>
304 SS	-	-	X	X	X	-	4,7,18,38-39,43,59
	0.00022	-	X	X	X	-	17
	0.0002	-	X	X	X	-	17
	0.0002	-	X	X	X	-	29
	-	-	-	-	X	-	40
304L SS	0.0008	-	X	X	X	-	37
304L SS(0.02wt%C)	0.0008	-	-	-	X	-	41,42
(0.06wt%C)	0.0008	-	-	-	X	-	41,42
304L SS+0.15Ti	0.0008	-	-	-	-	X	41
316 SS	-	-	X	X	X	-	5,43
316L SS	-	-	X	X	X	-	5
347 SS	-	-	X	X	X	-	4,14,31,32,43
	0.004	0.02	X	X	X	-	29
348 SS	0.0008	-	X	X	X	-	37
	-	-	X	X	X	-	37,38,39,59
	-	-	-	-	X	-	40
A-286	0.005	-	X	X	X	-	39
	-	-	X	X	X	-	61
	0.004	-	-	-	-	X	19
	0.0009	-	-	-	-	X	36
	0.010	-	-	-	-	X	36
	0.0051	-	-	-	-	X	4
	0.010	-	-	-	X	X	55
	0.00085	-	-	-	X	X	75
	0.0044	-	-	-	X	X	75
	0.0050	-	-	-	X	X	75
Fe-Cr-Al	-	-	X	X	X	-	4

TABLE 1 (Cont.)

<u>Alloy</u>	<u>Boron Content, wt%</u>	<u>Strain Rate, in./in./min</u>	<u>UTS</u>	<u>0.2% YS</u>	<u>El.</u>	<u>Stress Rupture</u>	<u>Reference</u>
Fe-Cr-Al-Y	-	-	X	X	X	-	4
20Cr-25Ni-Cb	0.0005,	-	X	X	X	X	5
Stabilized	0.0003	-	-	-	X	-	18
	0.0005,	-	-	-	X	-	18
	0.0003	-	-	-	X	-	18
	0.0001≤	X	-	-	X	X	54
AM350 SS (stabilized)	-	-	X	X	X	-	38,59
AM 355 SS	-	-	X	X	X	-	44
406 SS	-	-	X	X	X	-	43
410 SS	-	-	X	X	X	-	38,39,40,59,61,62,63
Ni-270	-	-	X	X	X	-	40
Ni-330	-	-	X	X	X	-	40,67
"A" Nickel	-	-	X	X	X	-	66
Hastelloy C	-	-	X	X	X	-	46
Hastelloy N	-	-	X	X	X	-	5,40,42,45,46
	0.004	-	X	X	X	-	30,58
	-	-	-	-	-	X	40,47,48,57
	-	-	-	-	X	X	56
Hastelloy R-235	-	-	X	X	X	-	5,43,45,46,68
Hastelloy X	0.0005	-	X	X	X	-	49,68
& Hastelloy X-220	-	-	X	X	X	-	5,40,42,43,45,46,64
	-	0.2,2.0, 20.0	-	-	X	-	69
	-	-	X	X	X	X	50
	-	-	-	-	-	X	4,41
Inconel 600	0.001	-	X	X	X	-	40,42,43
	-	-	X	X	X	-	5,46,68,59
Inconel 625	0.001	-	X	X	X	-	43,45,46,50
	-	-	X	X	X	-	5

TABLE 1 (Cont.)

<u>Alloy</u>	<u>Boron Content, wt%</u>	<u>Strain Rate, in./in./min</u>	<u>UTS</u>	<u>0.2% YS</u>	<u>El.</u>	<u>Stress Rupture</u>	<u>Reference</u>
Inconel 702	-	-	X	X	X	-	5,43,45,68,64,65
Inconel 718	-	-	X	X	X	-	5,45,46,51
Inconel X-750	-	-	-	-	X	X	60,75
	-	-	X	X	X	-	59,60,64,65
Incoloy 800	-	-	X	X	X	-	40,42,46
Rene 41	0.005, 0.008	-	X	X	X	-	49
	0.0046	-	-	-	-	X	19
	0.0045, 0.0041	-	-	-	-	X	4

TABLE 2

NOMINAL CHEMICAL COMPOSITIONS OF STAINLESS STEELS AND NICKEL-BASE SUPERALLOYS

Alloys	Fe	Cr	Ni	Mo	Max Co	Max Mn	Max Al	Ti	Zr	Max Cu	Cb+Ta	Max C	Max Si	Max P	Max S	V	W	B
<u>Austenitic Stainless Steels</u>																		
304 SS	67.0	19.0	10.0	0.50		2.00				0.50		.08	1.00	.04	.03			
316 SS	65.3	17.0	12.0	2.50		2.00						.08	1.00	.045	.03			
347 SS	65.0	18.0	11.5	0.50		2.00				0.50	10xC (min)	.08	1.00	.04	.03			
348 SS**	65.0	18.0	11.5	0.50	0.20	2.00				0.50	10xC ⁺ (min)	.08	1.00	.04	0.030			
A 286	53.0	15.0	25.5	1.25		2.00	0.35	2.10				.08	1.00	.04	.03	0.30		.001-
20Cr-25Ni-1.Cb Stabilized*SS ⁽¹⁾	52.0	21.0	25.0	0.01		0.67		0.01			0.7	0.025	0.59					.010
<u>Ferritic Stainless Steels</u>																		
406 SS	81.0	13.0	0.2			0.35	4.0					0.12	0.36	0.018	0.014			
<u>Nickel-Based Alloys</u>																		
Inconel X-750 (Inconel X)	7.00	15.5	71.0			1.00	1.00	2.50		0.50	1.00	0.08	0.50		0.01			
Inconel 600 ⁺⁺ (Inconel)	7.20	15.8	76.0			0.20				0.10 (Typ)		0.04 (Typ)	0.20 (Typ)		0.007			
Inconel 625*	3.00	22.0	62.0	9.00		0.15					4.00 (Typ)	0.05 (Typ)	0.30 (Typ)	0.005				
Inconel 702 ⁺⁺	.35	15.6	79.5			.05 (Typ)	3.40	0.70		0.10 (Typ)		0.04 (Typ)	0.20 (Typ)					
Inconel 800 (Incoloy) ⁺⁺	46.0	20.5	32.0			0.75 (Typ)		1.00		0.15 (Typ)		0.04 (Typ)	0.35 (Typ)		0.007			
Hastelloy R-235 ⁺⁺⁺	8.00	15.5	65.0	5.50	2.25 (Typ)	0.25 (Typ)	2.00 (Typ)	2.50				0.10 (Typ)	0.50 (Typ)					
Hastelloy X	19.0	22.0	44.0	9.00	2.50	1.00	0.50 (Al+Ti)					0.15	1.00	0.03	0.02		1.00 (Max)	
Hastelloy X-280	19.0	22.0	47.0	9.0	0.60 (Typ)	0.75						0.15	0.53				0.40 (Typ)	
Hastelloy N (Inor 8)	5.00 (max)	7.0	68.0	16.50	0.20	.80	0.50 (Al+Ti)			0.35		0.08	1.00	0.01	0.02		0.50 (Max)	0.01 (Max)
Rene 41***	1.80	19.0	54.0	10.0	11.0 (Typ)		1.50 (Typ)	3.10				0.1	.3					.005

(Data Verified Against NERVA Materials Properties Data Book Unless Otherwise Indicated)

(1) Reference (5)

* All Values nominal.

** Data from Stainless and Heat-Resisting Steels, AISI, Apr 1963*** Data from High-Temperature High-Strength Alloys, A7SI, Feb 1963.

+ Cb + Ta 1.5 max (Ta 0.10 max)

++ Source: Huntington Alloys Index of Government and Engineering Society Specifications, Inco, Feb 1962.

+++ Haynes High-Temp Alloys, Sept. 1962.

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TABLE 3

IRRADIATION EFFECTS, ELEVATED-TEMPERATURE
TENSILE TESTS

AUSTENITIC STAINLESS STEELS

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Table 3

304 STAINLESS STEEL

Refer- ence	Total Flux n/cm ²	Irradiation Temperature C	Test Temperature C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
17	None	-	842	9.6		36.0		
	2x10 ²⁰ 2x10 ¹⁹ slow 2x10 ¹⁹ fast	20-30	842	10.7		10.9	.0002	
	None	-	842	10.3		6.8	"	
	2x10 ²⁰ 2x10 ¹⁹ slow 2x10 ¹⁹ fast	20-30	842	10.8		4.2	"	
	None	-	842	9.2		22.5	"	
	2x10 ²⁰ 2x10 ¹⁹ slow 2x10 ¹⁹ fast	20-30	842	9.4		7.8	"	
7	7x10 ²⁰	550	843	18.9	20.2	2.7	.0002	
	"	550	843	17.2	18.5	2.2	"	
	"	550	843	9.9	15.7	7.4	"	
	"	550	843	9.5	14.9	3.9	"	
	None	-	843	9.7	15.2	16.5	"	
29	-	-	399	13.4	62.5	52.8	.0002	
	-	-	"	14.0	62.4	49.6	"	
	-	-	"	12.6	54.2	39.7	"	
	-	-	454	13.2	61.4	47.9	"	
	-	-	"	11.5	58.5	47.5	"	
	-	-	"	13.3	55.0	39.1	"	
	-	-	704	9.5	29.0	50.7	"	
	-	-	704	10.9	30.6	52.2	"	

Table 3, Continued

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
29	-	-	704	11.2	31.5	55.4	.0002	
continued	-	-	843	9.3	14.0	47.4	"	
	-	-	843	9.8	15.3	44.9	"	
	-	-	"	9.7	15.2	25.1	"	
	7x10 ²⁰	130	399	45.0	64.2	33.2	.0002	
	"	375	"	23.0	64.0	39.4	"	
	"	593	"	18.2	84.1	44.2	"	
	"	169	454	72.8	76.0	15.1	"	
	"	350	"	41.0	66.4	26.5	"	
	"	456	"	24.4	63.0	45.9	"	
	"	704	"	14.8	50.4	30.8	"	
	"	180	704	-	38.0	15.2	"	
	"	704	"	10.8	31.2	21.0	"	
	"	183	843	9.5	14.0	7.5	"	
	"	347	"	9.0	15.2	7.5	"	
	"	704	"	11.5	14.7	10.8	"	
43	None	-	700	39	42	25		
	9x10 ¹⁴	20-30	"	47	48	25		
37	None	-	300	22.5	66.8	43.6	.0008	
	4.1x10 ¹⁹	290	300	47.8	74.6	26.6	"	

Table 3, Continued

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
38	4.07x10 ¹⁹	290	300	47.8	74.6	24.1	.0008	
	9.20x10 ¹⁹	"	"	53.5	76.5	24.9	"	
17	None	-	704	18.9		52.9	.00022	
	2x10 ²⁰ 2x10 ¹⁹ slow	50	"	19.7		41.4	"	
	2x10 ¹⁹ fast							
	None	-	"	18.7		58.2	"	
	2x10 ²⁰ 2x10 ¹⁹ slow	50	"	18.9		41.7	"	
	2x10 ¹⁹ fast							
	None	-	"	15.3		35.2	"	
	2x10 ²⁰ 2x10 ¹⁹ slow	50	"	14.8		19.1	"	
	2x10 ¹⁹ fast							
	None	-	"	13.4		39.2	"	
	2x10 ²⁰ 2x10 ¹⁹ slow	50	"	12.8		22.8	"	
	2x10 ¹⁹ fast							
	None	-	"	11.5		11.0	"	
	2x10 ²⁰ 2x10 ¹⁹ slow	50	"	11.8		10.0	"	
	2x10 ¹⁹ fast							
	None	-	"	10.4		30.3	"	
	2x10 ²⁰ 2x10 ¹⁹ slow	50	"	-		18.8	"	
	2x10 ¹⁹ fast							
	None	-	842	9.2		45.4	"	
	2x10 ²⁰ 2x10 ¹⁹ slow	20-30	"	10.2		15.8	"	
	2x10 ¹⁹ fast							
	None	-	"	9.4		47.1	"	

Table 3, Continued

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
17	2x10 ²⁰ 2x10 ¹⁹ slow fast	20-30	842	10.9		16.2	.0002	
	None	-	"	9.5		28.0	"	
	2x10 ²⁰ 2x10 ¹⁹ slow fast	20-30	"	10.7		9.7	"	
42	-	-	842	-	-	39.0	0.0008	
	-	-	842	-	-	25.6	"	
	3.5x10 ²⁰	700	650	-	-	28.0	"	
	"	800	"	-	-	29.9	"	
	"	900	"	-	-	12.4	"	
	"	700	704	-	-	23.0	"	
	"	800	"	-	-	13.3	"	
	"	900	"	-	-	6.4	"	
	"	700	775	-	-	9.1	"	
	"	800	"	-	-	7.2	"	
	"	900	"	-	-	2.9	"	
	"	700	842	-	-	6.7	"	
	"	800	"	-	-	4.0	"	
	"	900	"	-	-	2.2	"	

Table 3, Continued

316 STAINLESS STEEL

Refer- ence	Total Flux n/cm^2	Irradiation Temperature $^{\circ}\text{C}$	Test Temperature $^{\circ}\text{C}$	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
5	-	-	750	12.5	27.8	56.5	.0012	
	5.8×10^{20} fast	650	"	16.8	28.7	16.5	.0012	
	5.0×10^{20} slow							
	-	-	"	10.0	23.5	59.4	.00013	
	5×10^{19} fast	45	"	8.5	23.2	26.3	.00013	
	1.5×10^{20} slow							
43	4.7×10^{19} fast	650	"	13.0	25.3	33.3	.00013	
	1.1×10^{20} slow							
43	None	-	700	13	36	48		
	2.53×10^{19}	650	"	25	67	46		

Table 3, Continued

347 STAINLESS STEEL

<u>Refer- ence</u>	<u>Total Flux n/cm²</u>	<u>Irradiation Temperature °C</u>	<u>Test Temperature °C</u>	<u>.2% Yield (Ksi)</u>	<u>U. T. S. (Ksi)</u>	<u>Elonga- tion (%)</u>	<u>Boron Content wt %</u>	<u>Comments</u>
14	-	-	700	33.0	43.0	34.0		
	2.53x10 ¹⁹	650	"	39.0	68.0	27.0		
	-	-	"	42.0	45.0	24.0		
	9x10 ¹⁹	20-30	"	45.0	46.0	43.0		
29	7 x 10 ²⁰	160	400	73.5	76.0	9.8	.0004	
	"	409	"	31.0	71.5	24.8		
	"	593	"	27.4	66.7	19.0		
	"	160	593	43.2	59.2	22.0		
	"	399	"	45.2	60.4	20.4		
	"	593	"	44.7	57.8	14.6		
	-	-	400	48.8	66.8	23.5		
	-	-	"	46.8	66.3	23.4		
	-	-	"	48.8	67.1	21.0		
	-	-	"	39.0	63.0	22.3		
	-	-	593	43.1	60.0	23.0		
	-	-	"	43.8	60.1	23.7		
	-	-	"	42.7	60.1	25.1		
	-	-	"	43.1	59.4	20.5		
	-	-	704	39.0	45.3	25.2		
	-	-	"	36.6	44.3	25.0		
	-	-	"	32.5	39.4	34.9		

Table 3, Continued
347 STAINLESS, Continued

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U. T. S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
4	-	-	315	28	68.5	35.5		
	5.7x10 ²¹	50	"	81	83.5	15.5		
	-	-	"	28	68.5	35.5		
	1.2x10 ²²	50	"	86	88	12.5		
59	-	-	700	33	43	34		
	3.0x10 ¹⁹	650	"	39	62	27		
31,32	-	-	400	36.5	67.6	26.2		
"	2.0x10 ²¹	50	"	62.5	66.7	13.5		
"	-	-	"	36.5	67.7	26.2		
"	4.5x10 ²¹	50	"	65.4	69.3	11.5		
"	-	-	315	36.5	67.7	26.2		
"	6.1x10 ²¹	50	"	71.8	73.3	12.5		
"	-	-	400	45.0	75.0	48.0		
"	2.1x10 ²¹	250	"	103.0	103.0	4.5		
"	-	-	"	45.0	75.0	48.0		
"	5.1x10 ²¹	390	"	115.0	115.0	1.5		
"	-	-	"	45.0	75.0	48.0		
"	6.9x10 ²¹	400	"	120.0	120.0	3.5		
"	-	-	"	45.0	75.0	48.0		
"	2.3x10 ²¹	370	"	115.3	115.3	4.2		

Table 3, Continued

<u>Refer- ence</u>	<u>Total Flux n/cm²</u>	<u>Irradiation Temperature °C</u>	<u>Test Temperature °C</u>	<u>.2% Yield (Ksi)</u>	<u>U. T. S. (Ksi)</u>	<u>Elonga- tion (%)</u>	<u>Boron Content wt %</u>	<u>Comments</u>
31,32	-	-	400	45.0	75.0	48.0		
"	3.7x10 ²¹	400	"	123.0	123.5	4.2		
"	-	-	"	45.0	75.0	48.0		
"	6.5x10 ²¹	400	"	123.6	125.8	4.1		

Table 3, Continued

348 STAINLESS STEEL

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U. T. S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
38	5.07x10 ¹⁹	280	300	46.5	71.4	23.4		
	"	"	"	44.0	71.5	23.7		
	1.24x10 ²⁰	"	"	52.3	73.0	22.0		
	"	"	"	53.1	74.5	19.8		
37	None	-	300	28.9	65.4	33.3	.0008	
	5.1x10 ¹⁹	290	"	47.2	73.1	25.3	"	
	None	-	"	28.2	63.0	34.1	"	
	5.1x10 ¹⁹	290	"	45.1	69.2	26.4	"	

Table 3, Continued
A-286 STAINLESS STEEL

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt %	Comments
60	-	-	650	102.5	109.5	36.0		
	7.0x10 ²⁰	90	"	91.0	111.0	2.5		
	-	-	540	107.4	136.0	10.5		
	7.0x10 ²⁰	90	"	111.0	130.0	6.3		

Table 3, Continued

20Cr-25Ni-Nb STABILIZED SS

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
5	-	-	750	18.2	27.6	55.5	.0005 ↓	
	3.8x10 ¹⁸	Room Temp.	"	18.5	26.4	48.3		
	3.7x10 ¹⁵	"	"	16.4	27.2	29.1		
	5.4x10 ¹⁹	"	"	17.5	28.0	29.3		
	-	-	850	13.2	14.2	56.4		
	3.8x10 ¹⁸	Room	"	13.1	14.4	41.1		
	3.7x10 ¹⁵	"	"	14.6	15.8	38.6		
	5.4x10 ¹⁹	"	"	14.8	16.2	37.6		
18	5.8x10 ¹⁸	?	750			48		
	-	-	"			55		
	1.9x10 ¹⁶	?	"			29		
	7.4x10 ¹⁶	?	"			18		
	-	-	"			47		
	3x10 ¹⁹	?	"			20		
	3x10 ¹⁹	?	"			14		
	5x10 ²⁰	?	"			9		

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FERRITIC STAINLESS STEELS

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Table 3, Continued

406 STAINLESS STEEL

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
43	None	-	700	14	14	74		
	2.53x10 ¹⁹	650	"	31	42	54		
	None	-	"	11	12	68		
	9x10 ¹⁹	20-30	"	12	13	120		

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NICKEL-BASE ALLOYS

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Table 3, Continued

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	<u>INCONEL X</u>		Elonga- tion (%)	Boron Content wt %	Comments
				.2% Yield (Ksi)	U.T.S. (Ksi)			
60	-	-	535	91.5	147.0	19.7		
	2x10 ²⁰	<100	"	131.0	138.0	0		
	"	"	"	131.0	137.0	0		
	-	-	650	86.8	131.0	21.5		
	2x10 ²⁰	<100	"	101.7	106.0	0		
	"	"	"	-	80.0	-		

Table 3, Continued

INCONEL 600

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
5	-	-	700	28	46	29.0		
	2.53x10 ¹⁹	650	"	32	60	17.0		
	1.21x10 ²⁰	"	"	32	28	5.0		
43	-	-	700	65	67	11		
	9x10 ²⁰	20-30	"	72	72	21		

Table 3, Continued

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	<u>INCONEL 600</u>		Elonga- tion (%)	Boron Content wt%	Comments
				.2% Yield (Ksi)	U.T.S. (Ksi)			
68	-	-	700	28.0	46.0	29.0		
	3x10 ¹⁹	650	"	33.0	60.0	16.0		
	1.5x10	"	"	33.9	28.0	4.0		
43	None	-	700	28	46	29	.001	
	2.53x10 ¹⁹	650	"	32	70	16	"	
	1.21x10 ²⁰	"	"	32	33	3	"	
40	None	-	650	27.96	53.76	16.74	.001	
	None	-	"	21.62	50.20	18.70	"	
	None	-	"	16.41	47.24	22.37	"	
	1.91x10 ²⁰	740	"	26.50	34.25	2.49	"	
	"	"	"	25.23	34.26	2.84	"	
	"	"	"	15.00	29.43	7.62	"	
	None	-	650	18.66	59.2	36.86	"	
	1.57x10 ²⁰	280	"	26.42	37.21	10.35	"	
	5.68x10 ²⁰	"	"	29.14	42.58	3.18	"	
42	5.68x10 ²⁰	280	650	48.13	56.15	3.30	.001	
	"	"	"	60.62	67.10	2.08	"	

Table 3, Continued

INCONEL 625

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
50	-	-	300	94.19	149.49	8.3	.001	
	9.2x10 ¹⁹	740	"	100.00	143.68	6.19	"	
	-	-	"	91.5	140.20	8.99	"	
	1.9x10 ²⁰	740	"	85.23	128.12	5.29	"	
	-	-	650	80.00	112.00	8.17	"	
	9x10 ¹⁹	-	"	72.14	96.77	4.81	"	
	-	-	"	84.57	124.62	10.45	"	
	9x10 ¹⁹	-	"	66.15	96.65	6.62	"	
	-	-	"	83.58	129.60	9.05	"	
	-	-	"	84.57	124.60	10.45	"	
	1.71x10 ²¹	50	"	107.94	125.66	7.16	"	
	-	-	"	80.00	112.00	8.17	"	
	9.2x10 ¹⁹	740	"	72.14	96.77	4.81	"	
	9.2x10 ¹⁹	"	"	66.15	96.65	6.62	"	
42	-	-	650	85.3	133.8	5.0	.001	
	1.03x10 ²⁰	280	"	73.9	101.1	8.34	"	
	3.2x10 ²⁰	"	"	85.1	109.1	9.1	"	
	5.68x10 ²⁰	"	"	88.6	108.6	13.2	"	
	1.46x10 ²¹	"	"	45.41	52.11	4.52	"	

Table 3, Continued

INCONEL 702

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
68	-	-	700	87.0	95.0	5		
	3.0x10 ¹⁹	650	"	56.0	65.0	5		
	1.5x10 ²⁰	"	"	9.0	22.0	4		
43	-	-	700	75	84	13		
	9x10 ²⁰	20-30	"	60	60	20		
5	-	-	700	88	94	5.5		
	2.53x10 ¹⁹	650	"	57.5	65	6.5		
	1.21x10 ²⁰	650	"	5.0	11.0	6.0		
43	None	-	700	87	95	5		
	2.53x10 ¹⁹	650	"	55	65	5		
	1.21x10 ²⁰	"	"	55	21	17		

Table 3, Continued

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	<u>INCOLOY 800</u>		Elonga- tion (%)	Boron Content wt%	Comments
				.2% Yield (Ksi)	U.T.S. (Ksi)			
40	None	-	650	32.63	60.26	15.75		
	1.91x10 ²⁰	740	"	25.64	37.54	3.70		
	None	-	"	25.74	54.70	17.88		
	1.91x10 ²⁰	740	"	18.56	35.15	7.63		
	None	-	"	22.86	53.32	15.84		
	1.91x10 ²⁰	740	"	12.63	28.79	9.59		
42	1.54x10 ²⁰	280	650	13.89	37.27	23.37		

Table 3, Continued

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	<u>HASTELLOY R-235</u>		Elonga- tion (%)	Boron Content wt%	Comments
				.2% Yield (Ksi)	U.T.S. (Ksi)			
5	-	-	700	85	127	18.5		Heat Treat 750°C
	2.53x10 ¹⁹	750	"	85	119	8.0		
	1.21x10 ²⁰	"	"	87	88	4.0		
43	None	-	700	99	104	31		Mill annealed
	9x10 ²⁰	20-30	"	92	93	23		
	None	-	700	85	127	19		Heat Treat 650°C
	2.53x10 ¹⁹	650	"	85	117	7		
	1.21x10 ²⁰	"	"	87	88	4		
68	-	-	700	85	128.0	19.0		Heat Treat 650°C
	3.0x10 ¹⁹	650	"	85	117.0	7.0		
	1.5x10 ²⁰	"	"	86.0	90.0	5.0		

Table 3, Continued

HASTELLOY X

Refer- ence	Total ₂ Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
49	7 x 10 ¹⁹	540	540	31.4	83.0	53.6	.0005	
	"	540	"	30.9	88.3	46.5	"	Solutioned
	"	650	"	42.0	90.6	34.3	"	
	"	540	650	32.2	73.7	22.2	"	
	"	650	"	29.2	76.5	34.1	"	Solutioned
	"	870	"	33.1	85.0	25.7	"	
	"	870	870	25.75	35.75	9.8	"	
	"	870	"	27.2	38.0	19.1	"	Solutioned
	-	-	540	27.7	88.0	32.5	"	
	-	-	"	26.0	79.0	43.3	"	
	-	-	"	35.8	94.0	53.1	"	
	-	-	"	22.8	81.9	49.3	"	Solutioned
	-	-	650	31.4	77.0	29.0		
	-	-	"	25.8	72.9	37.9	"	Solutioned
	-	-	870	19.0	31.4	46.0	"	
	-	-	"	23.6	28.1	49.1	"	Solutioned
43	None	-	700	36	70	39		
	9x10 ²⁰	20-30	"	42	56	3		
	None	-	700	36	72	48		
	2.53x10 ¹⁹	650	"	42	64	13		
	1.21x10 ²⁰	"	"	40	58	9		
68	-	-	700	35.0	71.0	48.0	"	
	3.0x10 ¹⁹	650	700	23.0	87.0	24.0	"	
	1.5x10 ²⁰	"	"	20.0	40.0	5.0	"	

Table 3, Continued

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	(%/min) Strain Rate Comments	Solution Anneal
69	Control	-	538	33.6	-	42.2	-	2	"
	1x10 ²⁰	50	538	36.6	-	42.4	-	2	"
	Control	-	650	35.1		35.4	-	2	"
	1x10 ²⁰	50	650	35.8		18.9	-	2	"
	Control	-	760	31.4		7.5	-	2	"
	1x10 ²⁰	50	760	34.6		8.0	-	2	"
	Control	-	871	30.7		3.7	-	2	"
	1x10 ²⁰	50	871	29.7		3.7	-	2	"
	"	50	650	31.3		32.6	-	20	"
	"	50	650	33.3		12.0	-	0.2	"
	"	50	760	31.6		15.3	-	20.0	"
	"	50	760	33.4		5.7	-	0.2	

Table 3, Continued

Reference	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	<u>HASTELLOY X-280</u>		Elonga- tion (%)	Boron Content wt%	Comments
				.2% Yield (Ksi)	U.T.S. (Ksi)			
45	-	-	700	35	72	48		
	2.53x10 ¹⁹	650	"	42	87	24		
	1.21x10 ²⁰	"	"	40	25-58	5		
40	None	-	650	40.00	85.53	15.02		Solution annealed
	1.91x10 ²⁰	740	"	34.69	67.35	5.76		"
42	1.03x10 ²⁰	280	650	25.88	48.74	10.67		Solution annealed
	1.57x10 ²⁰	"	"	26.84	52.63	14.75		"
	3.2x10 ²⁰	"	"	31.680	56.44	14.32		"
	1.91x10 ²⁰	740	"	34.69	67.35	5.76		"
40	None	-	650	31.07	80.04	52.10		Solution Annealed
	1.03x10 ²⁰	280	"	25.88	48.74	10.67		"
	1.57x10 ²⁰	280	"	26.84	32.63	14.75		"
	3.20x10 ²⁰	280	"	31.68	56.44	14.32		"

Table 3, Continued

HASTELLOY N

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2%Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
58	7x10 ²⁰ fast 9x10 ²⁰ slow ↓	700	300	36.0	154.3	42.2	.004	
		-	300	40.7	147.0	37.9	"	
		700	400	35.0	146.9	40.2	"	
		-	400	40.7	153.0	39.3	"	
		700	500	35.8	129.5	35.3	"	
		-	500	35.8	144.0	42.4	"	
		700	600	32.5	82.4	11.8	"	
		-	600	36.2	109.0	26.7	"	
		700	700	31.0	53.4	8.0	"	
		-	700	34.1	102.8	30.8	"	
		700	800	28.5	38.4	3.7	"	
		-	800	30.9	59.9	12.2	"	
		700	700	30.5	44.2	6.3	"	
		700	900	23.5	23.5	0.6	"	
		-	900	21.8	22.2	1.2	"	
13	3.5x10 ²⁰ slow	625	750	-	-	7		
	1.5x10 ²⁰ fast		Argon	-	-			
	-		750	-	-	65		
			Argon					
40	1.9x10 ²⁰	740	300	36.75	67.32	14.31		
	"	740	650	30.20	36.53	3.78		
	None	-	650	31.98	82.54	30.5		Solution Treated
	8.26x10 ²⁰	50	650	44.6	52.67	6.09		"

Table 3, Continued

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
40	1.00x10 ²¹	50	650	43.37	50.65	3.51		Solution Treated
	None	-	650	25.77	57.82	20.22		"
	1.03x10 ²⁰	280	650	29.79	50.52	12.71		"
	1.46x10 ²¹	"	"	19.64	19.78	.30		"
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42	1.03x10 ²⁰	fast	280	29.79	50.52	12.71		
	1.46x10 ²¹	fast	"	19.64	19.78	0.3		
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Table 3, Continued

RENE 41

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)	Boron Content wt%	Comments
49	-	(650)	650	132.0	190.2	13.0	0.005- 0.0041	1175 solution anneal
	1.1x10 ²⁰ (4.5x10 ¹⁹)	650	650	131.2	170.2	8.2	0.0041	+ 100hr at 650
	-	(870)	650	114.2	180.2	4.1	"	1175 sol. anneal + 100 hr 870
	5x10 ¹⁹ (3x10 ¹⁹)	870	650	125.4	165.1	4.3	"	"
	-	(870)	870	49.9	73.9	24.8	"	"
	5x10 ¹⁹ (3x10 ¹⁹)	870	870	50.5	55.8	2.8	"	"
	-	(650)	650	130.6	191.8	12.1	"	1065 Sol. Anneal + 650°C 100 hr
	1.1x10 ²⁰ (4.5x10 ¹⁹)	650	650	144.2	181.2	5.2	"	"
	-	(870)	870	40.6	64.9	22.7	"	+870-100 hr
	5x10 ¹⁹ (3x10 ¹⁹)	870	870	32.6	36.3	2.95	"	
	-	(540)	540	94.8	130.0	10.3	.008- .0045	1175 Sol. Anneal + 540 - 100 hr
	7x10 ¹⁹ (3x10 ¹⁹)	540	540	103.7	137.1	17.9	"	"
	-	(650)	650	102.4	143.5	12.5	"	650- 100 hr
	5x10 ¹⁹ (4.5x10 ¹⁹)	650	650	106.0	138.0	8.1	"	

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TABLE 4
STRESS-RUPTURE TESTS

AUSTENITIC STAINLESS STEELS

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Table 4

20Cr-25Ni-Nb STABILIZED

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
5	-	-	650	17.5	66.4	.		
	-	-	"	12.6	387.0			
	-	-	"	10.5	907			
	-	-	"	17.5	111			
	-	-	"	12.6	884			
	-	-	"	10.5	2353			
	7x10 ¹³	Reactor Ambient	"	17.5	63			
	"	"	"	12.6	288			
	"	"	"	10.5	692			
	"	"	"	17.5	54			
	"	"	"	17.6	260			
	"	"	"	10.5	1056			

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
41	-	-	815	9.8	1.45	49.0		
	-	-	"	8.4	4.6	42.7		
	-	-	"	7.0	16.9	32.1		
	-	-	"	5.6	25.9	28.5		
	-	-	"	4.9	95.0	29.7		
	-	-	"	3.5	735.0	18.1		
	-	-	815	12.6	.31			
	-	-	"	10.5	1.35			
	-	-	"	8.4	8.9			
	-	-	"	6.3	60.0			
	-	-	"	5.3	248.0			
	1x10 ¹⁹	50	650	21.1	11.3			
	"			17.6	79.0			
	"			21.1	14.8			
	"			17.6	50.8			

Table 4, Continued

A-286 STAINLESS STEEL

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress ₂ kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4	-	-	540	77.3	84	2.5	.0051	
	-		"	77.3	44	5.6		
	-	-	"	70.3	127	3.6		
	-	-	"	73.9	39	3.3		
	-	-	"	70.3	143	3.0		
	-	-	"	63.3	434	6.8		
	-	-	"	52.9	457	-		
	-	-	"	66.9	234	2.6		
	-	-	650	49.2	14	4.1		
	-	-	"	42.2	37	7.5		
	-	-	"	40.5	86	6.8		
	-	-	"	37.2	190	11.4		
	-	-	"	35.2	273	11.4		
	7x10 ¹⁹ _{fast}	540	540	49.2	3431	1		
	3x10 ¹⁹ _{slow}	"	"	56.3	1372	1		
	"	"	"	66.9	56	1		
	"	"	"	73.9	17	2		
	"	"	"	66.9	54	1		
	"	"	"	59.8	62	1		
	"	"	"	66.9	311	0.7		
	"	"	"	73.9	17	1.0		
	"	"	"	59.8	334	1.3		

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Table 4, Continued

Reference	Total Flux n/cm ²	Irrad. Temp. °C	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4	1.1x10 ²⁰ fast	650	650	31.6	12	1	.0051	
	5x10 ¹⁹ slow			38.7	11	1	"	
	"			31.6	30	1	"	
	"			28.2	113	1	"	
	"			28.2	81	1	"	
	"			31.6	48	1	"	
	1.1x10 ²⁰ fast	650	650	31.6	25	1	.0075	
	5x10 ¹⁹ slow			21.1	154	2	"	
	"			21.1	285	2	"	
	"			31.6	23	1	.0052	
	1.1x10 ²⁰ fast			28.2	47	1	"	
	"			24.7	46	1	"	
	"			35.2	20	2	.0043	
	"			31.6	37	2	"	
	"			35.2	52	2	"	
	"			26.0	71	2	"	
	"			26.0	45	2	"	
	"			21.1	241	3	"	
19	-	-	650	42.2	36	19.1	.0040	
	-	-	"	38.7	87	33.4		
	-	-	"	35.2	98	13.1		
	-	-	"	31.6	343	30.1		
	-	-	"	35.2	123	13.4		

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
19	8.3x10 ¹⁴	650	650	35.2	152	8.6	.0040	
	"	"	"	38.7	42	7.1		
	"	"	"	38.7	32	6.7		
	"	"	"	35.2	109	8.1		
	"	"	"	35.2	76	8.4		
	2.7x10 ¹⁶	"	"	35.2	28	2.3		
	"	"	"	31.6	40	2.5		
	"	"	"	26.0	400	3.4		
	"	"	"	31.6	60	2.7		
	"	"	"	35.2	26	2.8		
	1.1x10 ²⁰	"	"	35.2	20	2.0		
	"	"	"	31.6	37	2.0		
	"	"	"	35.2	52	2.0		
	"	"	"	26.0	71	2.0		
	"	"	"	26.0	45	2.0		
	"	"	"	21.1	241	3.0		
55	-	-	660	35.2	456.7	14.2	.010	
	-	-	"	38.7	191.9	10.5	"	
	-	-	"	42.1	98.8	21.5	"	
	-	-	"	49.2	15.7	12.3	"	
	-	-	"	35.4	305.9	11.2	.00085	
	-	-	"	35.2	647.6	15.5	"	
	-	-	"	38.7	194.5	7.7	"	

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
55	-	-	660	42.5	106.3	17.7	.00085	
	-	-	"	49.2	23.3	17.3	"	
	4.9x10 ¹⁹	80	"	38.7	252.1	3.2	.010	
	"	"	"	42.7	76.9	2.3	"	
	"	"	"	49.2	22.4	3.1	"	
	"	"	"	35.2	58.9	1.8	.00085	
	"	"	"	38.7	46.4	3.0	"	
	"	"	"	42.2	18.0	1.9	"	
	"	"	"	49.2	4.6	2.6	"	
36	-	-	660	42.5	106.3	17.7	.0051	
	4.9x10 ¹⁴	Reactor Ambient	"	42.2	18.0	1.9	"	
	-	-	"	42.1	98.8	21.5	"	
	4.9x10 ¹⁹	Reactor Ambient	"	42.7	76.9	2.3	"	

NICKEL-BASE ALLOYS

BLANK

Table 4, Continued

HASTELLOY N

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
56	1.2x10 ²⁰ fast	650	648.8	26.37	21.78	2.2		
	"	"	"	31.64	6.96	3.1		
	"	"	"	35.16	0.77	7.6		
	"	"	815.6	5.273	388	2.5		
	"	"	"	6.117	188.91	3.5		
	"	"	"	7.734	41.84	2.7		
	"	"	"	7.734	18.02	1.2		
	"	"	"	9.843	16.23	4.6		
	"	"	"	7.734	22.46	1.2		
	"	"	"	14.84	1.31	1.7		
	-	-	648.8	24.61	760.5	34.3		
	-	-	"	24.61	842.1	15.2		
	-	-	"	"	759.4	12.7		
	-	-	"	24.37	239.8	11.2		
	-	-	"	28.12	177.1	9.6		
	-	-	"	35.16	38.0	13.4		
	-	-	815.6	7.734	144.43	12.6		
	-	-	"	"	264.75	24.3		
	-	-	"	9.843	47.13	11.8		
	1.2x10 ²⁰ fast	650	468.8	12.66	>1994	-		
	"	"	"	21.09	94.85	-		
	"	"	"	24.61	49.87	1.1		
	"	"	"	"	51.18	1.3		
	"	"	"	"	64.5	1.4		
	"	"	"	24.61	61.1	2.6		

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
47	-	-	650	24.8	1000			
	-	-	"	30.0	200			
	-	-	"	35.2	50			
40	-	-	"	24.8	850			
	-	-	"	24.8	760			
	-	-	"	26.5	230			
	-	-	"	28.0	180			
	-	-	"	35.2	38			
	1x10 ²⁰	650	"	21.1	96			
	"	"	"	24.5	50			
	"	"	"	26.5	23			
	"	"	"	31.5	7			
	"	"	"	35.2	.75			
	"	"	"	24.5	50			
48	None		816	4.3	3000			
	"		"	5.0	2000			
	"		"	6.1	1000			
	"		"	7.7	400			
	"		"	10.2	100			
	"		"	14.2	10			
	"		"	15.4	5			

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm	Irrad. Temp. °C	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
40	None		816	7.6	145			
	"		"	9.8	48			
	10 ²⁰	650	"	5.2	400			
	"	"	"	6.1	190			
	"	"	"	7.8	42			
	"	"	"	9.8	17			
	"	"	"	14.9	1.4			

Table 4, Continued

HASTELLOY X

Refer- ence	Total Flux ₂ n/cm	Irrad. Temp. oC	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4	5x10 ¹⁹ fast 4x10 ¹⁹ slow	650	650	31.6	7.6	6.0	.0005	
"	"	"	"	28.2	36.0	5.0	"	
"	"	"	"	28.2	19.0	4.8	"	
"	"	"	"	19.7	783	4.0	"	
"	"	"	"	19.7	799	10.3	"	
"	"	"	"	24.7	352	9.8	"	
"	"	"	"	31.6	19.0	15.4	"	
"	"	"	"	28.2	34	17.0	"	
"	"	"	"	24.7	235	19.0	"	
"	"	"	"	28.2	57	11.8	"	
	1.1x10 ²⁰ fast 5x10 ¹⁹ slow	"	"	28.2	124	14.3	.0010	
"	"	"	"	22.5	1081	14.2	"	
"	"	"	"	35.2	14.8	12.9	"	

Table 4, Continued

HASTELLOY X-280

Refer- ence	Total Flux ₂ n/cm	Irrad. Temp. °C	Test Temp. °C	Stress ₂ Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
41	-	-	870	5.6	.7	27		
	-	-	"	4.2	3.9	32.9		
	-	-	"	2.8	7.3	26.5		
	-	-	"	1.75	36.0	19.0		
	-	-	"	1.0	250.0	24.1		
	-	-	1150	3.5	.4	24.7		
	-	-	"	2.8	.6	23.5		
	-	-	"	2.1	2.0	23.4		
	-	-	"	1.7	4.3	19.8		
	-	-	"	.9	21.0	23.0		
	-	-	"	.6	65.0	10.8		
	-	-	"	3.5	114.0	14.2		
	-	-	"	.2	340.0	14.2		
	None	-	650	31.6	99.8	26.5		
	"	-	650	24.6	509.1	23.3		
	"	-	732	19.7	42.1	40.8		
	3.6x10 ¹⁹	?	650	28.1	136.8	17.1		
	"	?	650	24.6	215.4	9.0		
	"	?	650	31.6	44.4	8.2		
	"	?	732	15.5	123.8	10.6		
	"	?	732	19.7	15.7	5.3		
	"	?	732	19.7	38.4	29.9		

1 Kg/mm² = 1.422 Ksi

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm ²	Irrad. Temp. °C	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4	-	-	540	63.3	.6	42.0		
	-	-	"	52.9	28	30.5	.0005	
	-	-	"	42.2	800	19.0	"	
	-	-	"	49.2	45	24.9	"	
	-	-	"	42.2	218	31.0	"	
	-	-	"	52.9	21	39.6	"	
	-	-	"	49.2	62	34.4	"	
	-	-	"	38.8	762	24.2	"	
	-	-	650	31.6	44	27.0	"	
	-	-	"	24.7	287	16.4	"	
	-	-	"	38.7	9	19.5	"	
	-	-	"	28.2	130	47.9	"	
	-	-	"	24.7	330	34.6	"	
	-	-	"	31.6	58	31.6	"	
	7x10 ¹⁹ fast 3x10 ¹⁹ slow	540	540	42.2	22	20.7		
	"	"	"	48	7.2	28.0		
	"	"	"	31.6	852	10.0		
	"	"	"	36.6	179	16.3		
	"	"	"	42.2	34	22.1		
	"	"	"	36.6	230	19.6		
	"	"	"	39.4	73	29.4		

Table 4, Continued

RENE 41

Refer- ence	Total Flux ₂ n/cm	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4, 50	5x10 ¹⁹	615	650	63.2	40	1.6		
"	"	"	"	57.6	110	2.0		
"	"	"	"	63.2	3	1.7		
"	"	"	"	56.2	1.5	0.9		
"	"	"	"	49.2	7.4	1.6		
	1.1x10 ²⁰	630	650	66.8	26	-		
"	"	"	"	80.9	8.2	1.2		
"	"	"	"	74.5	23	0.9		
"	"	"	"	74.5	49	1.2		
"	"	"	"	63.2	23	1.2		
"	"	"	"	63.2	66	1.1		
"	"	"	"	63.2	165	1.0		
	5x10 ¹⁹	815	650	80.8		4.0		
"	"	"	"	70.3	201	1.1		
"	"	"	"	74.5	73	3.9		
"	"	"	870	17.6	13	0		
"	"	"	"	14.06	11	1		
"	"	"	"	10.5	526	4.8		
"	"	"	"	14.0	23	4.1		
"	"	"	"	12.3	415	2.9		
"	"	"	"	7.0	258	3.8		
"	"	"	"	17.5	0.5	1.0		
"	"	"	"	10.5	7.7	2.4		

Table 4, Continued

Reference	Total Flux ₂ n/cm	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4, 50	5x10 ¹⁹	815	870	14.0	19.0	8.2		
	"	"	"	17.5	2.6	0.7		
	"	"	"	10.5	46	1.2		
	"	"	"	14.0	10	1.8		
	"	"	"	7.0	346	2.5		
	"	"	"	10.5	249	2.1		
	"	"	"	17.5	7	0.7		
	"	"	"	7.0	4191	2.2		
	"	"	"	12.0	223	1.9		
	"	"	"	17.6	4	1.1		
	"	"	"	10.5	32	1.2		
	"	"	"	7.0	1035	2.3		
19	8.3x10 ¹⁹	650	650	87.9	64	2.1	.0046	
	"	"	"	84.4	220	1.4	"	
	"	"	"	80.9	150	1.3	"	
	"	"	"	91.4	57	2.3	"	
	"	"	"	84.4	148	1.2	"	
	2.7x10 ¹⁶	"	"	87.9	17	2.1	"	
	"	"	"	84.4	98	1.4	"	
	"	"	"	80.9	85	.8	"	
	"	"	"	84.4	60	1.1	"	
	"	"	"	77.4	77	1.1	"	
	1.1x10 ²⁰	"	"	75.0	63	1.0	"	

Table 4, Continued

Reference	Total Flux n/cm ²	Irrad. temp. °C	Test temp.	Stress Kg/mm ²	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
19	1.1x10 ²⁰	650	650	66.8	110	1.2	.0046	
	"	"	"	80.9	27	1.1	"	
	"	"	"	80.9	92	1.4	"	
	"	"	"	66.8	186	1.4	"	
	"	"	"	63.3	434	-	"	
	-	-	"	70.3	1192	7.5	"	
	-	-	"	75.2	637	9.0	"	
	-	-	"	80.9	230	9.1	"	
	-	-	"	87.9	83	7.4	"	
	-	-	"	92.8	46	3.7	"	
	-	-	"	70.3	910	4.0	"	
4	-	-	650	70.3	149	4.8	.0045	
	-	-	"	80.9	22	4.8	"	
	-	-	"	70.3	46	4.4	"	
	-	-	"	70.3	207	1.3	"	
	-	-	"	70.3	426	3.0	"	
	5x10 ¹⁹ 4x10 ¹⁹ fast slow	650	650	66.9	28	1.5	"	
	"	"	"	63.3	75	1.1	"	
	"	"	"	59.8	32	1.6	"	
	"	"	"	59.8	141	1.3	"	
	"	"	"	66.9	54	1.3	"	

Table 4, Continued

Refer- ence	Total Flux ₂ n/cm	Irrad. Temp. °C	Test temp.	Stress ₂ Kg/mm	Time to Rupture (h)	Elonga- tion %	Boron Content wt%	Comments
4	1.1x10 ²⁰ fast 5x10 ¹⁹ slow	650	650	75	63	1.0	.0041	
	"	"	"	66.9	110	1.2	"	
	"	"	"	80.9	27	1.1	"	
	"	"	"	80.9	92	1.4	"	
	"	"	"	66.9	186	1.4	"	
	"	"	"	63.3	434	-	"	

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APPENDIX A

COMPARISON BETWEEN FAST- AND THERMAL-NEUTRON
FLUX PRODUCTION OF HELIUM^{42,74}

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Appendix A

Because the neutron flux of most of the reactor test facilities used for radiation damage studies has a predominant thermal-neutron component, the application of test data obtained in these environments to component designs for reactor systems in which the neutron spectrum consists primarily of fast neutrons must be considered with extreme caution. For instance, hydrogen and helium atoms can significantly affect the mechanical properties of metals, and the rates of formation of these atoms depend greatly on the neutron spectrum and the flux level, in addition to the presence of elements with large neutron cross sections for the (n,p) or (n, α) reactions.

About 50% of the neutrons in a typical water-moderated-core (ETR, MTR, ORR) spectrum have energies below 25 Kev. About 81% of the $B^{10}(n,\alpha)Li^7$ reactions will be caused by the 17% of neutrons having energies below 0.4 ev (subcadmium component). The number of helium atoms produced by the $B^{10}(n,\alpha)Li^7$ reaction with neutrons having energies greater than 1.0 Mev is within a factor of two for the case of the watt fission spectrum and the water-moderated-core spectrum and represents only 2×10^{-4} of the helium-atom production for the entire neutron energy range of the water-moderated spectrum.

Fast-neutron (n, α) and (n,p) reactions generally occur above neutron energies of 1 Mev. Fast-neutron interactions producing hydrogen and helium occur with Fe, Ni, Ti, Cr, Al, N_2 , and Si--essentially all of the major elements found in structural alloys. For instance, the $Ni^{58}(n,p)Co^{58}$ reaction with fission-spectrum neutrons will be the key contributor of hydrogen in the nickel-base alloys. The $Fe^{56}(n,p)Mn^{56}$ and $Fe^{56}(n,\alpha)Cr^{53}$ reactions will contribute significantly to hydrogen and helium production, respectively, in iron-base alloys. Nitrogen also appears to have a large (n, α) fast-neutron cross section. For Hastelloy X, about 0.06-atom-percent nitrogen will contribute 15% of the helium atoms as compared with 56% for nickel in a fast-neutron spectrum. With the exception of the $B^{10}(n,\alpha)Li^7$ reaction, the helium and hydrogen production rates will generally be within a factor of two for most reactor spectra when normalized to unit flux for those neutrons above 1 Mev.

Appendix A

Production of helium and hydrogen by thermal- and fast-neutron dose is compared for a nickel-base alloy (Hastelloy X) and an iron-base alloy (A-286) in Figure 1. Figure 1 indicates that the helium production rate resulting from fast-neutron reactions will be greater than that resulting from the thermal-neutron $B^{10}(n,\alpha)Li^7$ reaction when the ratio of fast flux to thermal flux is greater than about 200. When the fast flux is equal in magnitude to the thermal flux, the fast flux will produce more helium atoms than the thermal flux after a fast-neutron dose of about 7×10^{22} to 2×10^{23} neutrons/cm². For total fast-neutron doses below about 10^{22} neutrons/cm² (again assuming equivalence of fast and thermal neutron fluxes), the fast-neutron contribution to helium production is negligible.

Appendix A

Figure 1 Production of Helium Atoms in Hastelloy X and A-286 Alloys as a Function of Neutron Dose 42, 74

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APPENDIX B

BORON SEGREGATION AT
GRAIN BOUNDARIES^{42,74}

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Appendix B

Calculations by Myers⁷¹ showed that boron (n, α) reactions contribute about 4.5% of the displaced atoms caused by fast-neutron collisions in iron-base alloy containing about 0.003 wt% (about 0.016 atomic percent) natural boron, assuming the thermal-neutron flux is equal to the fast-neutron flux. In considering a similar calculation of the displacements in the grain boundary region caused by boron segregation at the grain boundaries, the boron concentration must be estimated.

Theoretical calculations⁷² of the concentration of boron in the grain boundaries of an iron-base alloy may be obtained by using the equation⁷³

$$n_2^b = \frac{n_2 \exp(Q/RT)}{(1 - n_2) + n_2 \exp(Q/RT)},$$

where n_2 is the atom fraction of boron in the material and n_2^b is the atom fraction of boron in the grain boundary.

Values of n_2^b are plotted as a function of n_2 for various temperatures in Figure 1. With an activation energy of $Q = 13.2$ Kcal/gm-mole and a temperature of 1200°F (650°C), the above equation yields a value of $n_2^b = 0.16$ for $n_2 = 0.011$ atom%. The boundary therefore contains 16-atom-percent boron, or 1400 times as much as in the grain. At this temperature, however, the boron mobility may not be high enough for equilibrium segregation. If the heat-treatment temperature is used as the point at which equilibrium segregation exists (say about 900°C), $n_2^b \approx 0.042$ or 4.2 atom percent. This concentration is still 360 times greater than that in the grains.

Such a grain-boundary boron concentration results in 94.4% of the atomic displacements being due to the boron (n, α) reaction in the grain boundary region and only 5.6% being due to fast-neutron atom displacements.

Appendix B

Figure 1 Grain-Boundary Boron Atom Fraction as a Function of Matrix Boron Atom Fraction for Various Temperatures⁷³

APPENDIX C

LOW-TEMPERATURE TENSILE TESTS OF
IRRADIATED ALLOYS

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Appendix C

AUSTENITIC STAINLESS STEELS

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Appendix C
304 STAINLESS STEEL

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
59	-	-	RT	32.5	90.3	77.1
	4.1x10 ¹⁹	260-290	"	63.3	100.7	54.5
	-	-	"	32.4	89.4	74.3
	9.2x10 ¹⁹	260-290	"	73.2	104.1	55.1
	-	-	"	35.6	97.7	89.5
	7.1x10 ²⁰	260-290	"	114.1	126.1	24.4
	-	-	"	35.1	98.1	85.5
	1.4x10 ²¹	260-290	"	136.4	136.4	8.0
	-	-	"	32.8	91.3	72.6
	1.4x10 ²¹	260-290	"	151.5	153.0	9.1
	-	-	"	38.0	91.4	84.6
	1.8x10 ²⁰	260-290	"	90.4	113.1	39.7
	-	-	"	32.7	90.2	89.6
	3.5x10 ²⁰	260-290	"	96.5	112.6	36.7
	-	-	"	-	-	-
	5.3x10 ¹⁹	260-290	"	70.4	101.3	49.5
43	None	-	20	77	112	38
	9x10 ¹⁹	20-30	"	132	132	13
29	-	-	204	16.3	62.0	52.3
	7x10 ²⁰ fast	169	20	88.0	105.4	50.6
	9x10 ²⁰ slow					
	"	290	"	41.3	87.6	66.4
	"	704	"	29.8	80.2	78.6

Appendix C

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
29	7x10 ²⁰ fast	447	204	27.6	63.8	41.7
	9x10 ²⁰ slow					
	-		20	26.0	86.0	89.8
	-		"	26.4	85.3	89.5
	-	-	"	25.2	85.3	85.0
38	4.07x10 ¹⁹	280	RT	63.3	100.7	77.8
	9.20x10 ¹⁹	"	"	73.2	104.1	47.6
	7.1x10 ²⁰	"	"	114.1	216.1	17.5
	1.43x10 ²¹	"	"	136.4	136.4	0.5
	1.45x10 ²¹	"	"	151.5	153.0	0.9
	1.77x10 ²⁰	"	"	90.4	113.1	31.3
	3.46x10 ²⁰	"	"	96.5	112.6	30.4
	5.3x10 ¹⁹	"	"	70.4	101.3	40.5
	-	-	RT	32.5	91.1	78.8
39	1.1x10 ²⁰	50	RT	85.1	85.1	-
7	7x10 ²⁰	290	20	41.3	87.6	55.4
	"	"	20	25.8	31.2	77.9
	None	-	20	26.4	85.3	83.5

Appendix C
347 STAINLESS STEEL

Refer- ence	Total ₂ Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
43	None	-	20	53	100	44
	2.53x10 ¹⁹	650	"	40	95	37
	None	-	"	66	101	39
	9x10 ¹⁹	20-30	"	115	117	19
29	-	-	20	60.2	96.0	45.6
	-	-	"	63.4	98.3	43.8
	-	-	"	52.0	97.5	48.6
	7x10 ²⁰ fast	160	20	112	117.4	28.0
	9x10 ²⁰ slow					
	"	399	"	83.2	109.5	30.7
	"	760	"	43.1	93.5	45.4
	"	160	"	85.6	88.5	13.5
	"	399	"	68.0	81.2	16.4
4	-	-	RT	35.0	89.0	63.0
	5.7x10 ²¹	50	"	98.0	112.0	33.5
	-	-	"	35.0	89.0	63.0
	1.2x10 ²²	50	"	106.5	112.5	31.0
	-	-	"	53.0	100	44.0
	3.0x10 ¹⁹	650	"	52.0	95	39.0
31,32	-	-	RT	56.6	92.0	57.0
	1.9x10 ²¹	265	RT	132.0	135.0	4.3
	-	-	"	56.6	92.0	57.0

Appendix C

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
31,32	3.9x10 ²¹	330	RT	143.0	145.0	6.5
	-	-	"	56.6	92.0	57.0
	7.1x10 ²¹	390	"	143.0	149.0	10.3
	-	-	"	56.6	92.0	57.0
	1.7x10 ²¹	280	"	130.0	134.0	6.5
	-	-	"	56.6	92.0	57.0
	5.6x10 ²¹	355	"	139.5	144.8	10.6
	-	-	"	56.6	92.0	57.0
	3.3x10 ²¹	390		143.0	147.0	9.4

Appendix C

348 STAINLESS STEEL

Reference	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
59	-	-	RT	38.9	91.6	58.9
	5.1x10 ¹⁹	260-290	"	56.1	97.2	49.6
	-		"	38.9	93.9	54.4
	5.1x10 ¹⁹	260-290	"	56.5	99.3	45.4
	-	-	"	38.4	92.5	57.3
	1.2x10 ²⁰	260-290	"	63.0	100.3	49.9
	-	-	"	38.2	89.2	60.5
	1.2x10 ²⁰	260-290	"	64.3	103.2	45.7
	-	-	"	39.5	91.0	66.9
	5.5x10 ²⁰	260-290	"	95.8	111.5	20.9
	-	-	"	38.2	91.6	60.5
	5.5x10 ²⁰	260-290	"	101.0	116.9	23.6
	-	-	"	38.1	88.2	64.2
	1.1x10 ²¹	260-290	"	155.0	156.0	5.3
	-	-	"	38.9	92.3	60.8
	1.1x10 ²¹	260-290	"	150.0	153.7	7.1
	-	-	"	39.2	91.6	58.5
	1.3x10 ²¹	260-290	"	145.0	148.7	5.9
	-	-	"	39.1	93.1	149.6
	1.3x10 ²¹	260-290	"	147.4	58.0	6.3
	-	-	"	39.5	91.9	57.5
	1.2x10 ²⁰	260-290	"	81.9	114.3	37.1

Appendix C

Reference	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
59	-	-	"	38.2	91.5	110.0
	1.2x10 ²⁰	260-290	"	82.1	53.1	37.5
	-	-	"	38.3	90.2	69.8
	3.8x10 ²⁰	260-290	"	93.1	114.3	32.6
	-	-	"	38.1	90.7	68.8
	3.8x10 ²⁰	260-290	"	92.2	138.0	29.5
	1.3x10 ²⁰	"	"	72.1	102.9	37.5
	1.2x10 ²⁰	"	"	73.6	104.5	41.1
38	5.07x10 ¹⁹	280	RT	56.1	97.2	42.7
	"	"	"	56.5	99.3	39.9
	1.24x10 ²⁰	"	"	63.0	100.3	42.0
	"	"	"	64.3	103.2	38.5
	5.5x10 ²⁰	"	"	95.8	111.5	14.0
	"	"	"	101.0	116.9	17.9
	1.1x10 ²¹	"	"	155.0	156.0	0.6
	"	"	"	150.8	153.7	2.1
	1.32x10 ²¹	"	"	145.0	148.7	1.1
	"	"	"	147.4	149.6	0.9
	1.17x10 ²⁰	"	"	81.9	114.3	31.4
	"	"	"	82.1	110.0	28.0
	3.85x10 ²⁰	"	"	93.1	114.3	26.3
	"	"	"	92.2	138.0	23.2
	1.28x10 ²⁰	"	"	72.1	102.9	31.3

Appendix C

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
38	1.22x10 ²⁰	280	RT	73.6	104.5	33.4
	-	-	"	57.8	89.5	58.0
	-	-	"	37.0	89.4	49.5
39	1.1x10 ²⁰	50	RT	89	97.8	27.7
37	5.5x10 ²⁰	290	RT	75.8	81.8	8.2
	5.5x10 ²⁰	290	"	78.0	83.0	7.7

Appendix C
350 STAINLESS STEEL

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
59	-	-	RT	114.0	183.0	16.4
	4.0x10 ¹⁹	260-290	"	162.0	227.0	18.6
	-	-	"	114.4	185.1	18.2
	4.0x10 ¹⁹	260-290	"	137.8	219.8	18.2
	-	-	"	117.0	187.4	18.5
	9.6x10 ¹⁹	260-290	"	169.2	240.6	17.8
	-	-	"	118.7	195.8	19.4
	9.6x10 ¹⁹	260-290	"	150.7	228.6	18.3
	-	-	"	112.6	184.9	21.3
	1.1x10 ²⁰	260-290	"	160.7	242.4	15.6
	-	-	"	93.0	184.9	20.1
	1.1x10 ²⁰	260-290	"	160.3	236.7	16.0
	-	-	"	160.6	189.5	15.5
	1.0x10 ²⁰	260-290	"	218.4	244.1	10.8
	-	-	"	120.8	183.6	20.1
	3.1x10 ²⁰	260-290	"	152.2	218.0	12.2
	-	-	"	115.0	180.3	21.6
	3.1x10 ²⁰	260-290	"	152.0	233.2	14.4
	-	-	"	114.0	181.6	19.6
	1.5x10 ²⁰	260-290	"	163.3	243.2	15.9
	-	-	"	111.0	181.9	20.0
	1.5x10 ²⁰	260-290	"	171.8	232.1	13.7
	-	-	"	118.9	187.3	20.4

Appendix C

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
59	3.2x10 ²⁰	260-290	RT	137.9	244.3	16.4
	-	-	"	102.9	191.3	21.1
	3.2x10 ²⁰	260-290	"	143.2	239.5	14.6
38	1.84x10 ²⁰	280	RT	190.2	240.3	13.6
	2.55x10 ²⁰	"	"	186.4	238.5	13.9
	3.2x10 ²⁰	"	"	145.2	244.3	13.8
	3.2x10 ²⁰	"	"	137.9	239.5	12.4
	1.52x10 ²⁰	"	"	163.3	243.2	12.9
	"	"	"	171.8	232.1	11.3
	3.1x10 ²⁰	"	"	152.2	218.0	10.0
	"	"	"	152.0	233.2	12.6
	9.56x10 ¹⁹	"	"	169.2	240.6	15.5
	"	"	"	150.7	228.0	15.9
	4.0x10 ¹⁹	"	"	162.0	227.3	15.7
	"	"	"	137.8	219.8	15.9
	1.14x10 ²⁰	"	"	160.7	242.4	13.9
	"	"	"	160.3	236.7	13.6
	-	-	"	62.5	203.1	15.2

Appendix C

20Cr-25Ni-Nb STABILIZED STAINLESS STEEL

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
5	-	-	RT	30.7	76.8	48.2
	3.7x10 ¹⁵ 2.2x10 ¹⁰	fast th	RT	"	37.5	42.2
	3.8x10 ¹⁸ 7.6x10 ¹⁸	fast th	"	"	54.5	31.6
	1.0x10 ¹⁹ 2.6x10 ¹⁹	fast th	"	"	66.0	28.4

MARTENSITIC STAINLESS STEELS

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Appendix C
410 STAINLESS STEEL

Refer- ence	Total Flux n/cm^2	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
62	-	-	RT	38.0	59.5	32.5
	1.2×10^{20}	50	"	89.0	92.0	15.3
59	-	-	"	38.0	67.8	26.0
61	6.0×10^{19}	265	"	56.5	85.5	23.9
59	4.5×10^{19}	265	"	67.0	85.0	19.5
61	4.2×10^{19}	265	"	56.0	77.5	27.7
59	1.0×10^{20}	"	"	75.2	89.8	20.7
61	4.9×10^{19}	265	"	57.0	78.0	26.2
59	1.0×10^{20}	"	"	92.9	97.3	8.8
61	5.6×10^{19}	265	"	59.0	78.0	25.0
59	2.4×10^{20}	"	"	105.8	106.2	4.6
61	7.2×10^{19}	265	"	60.0	80.5	26.6
59	2.5×10^{20}	"	"	108.2	108.2	4.0
61	8.3×10^{19}	265	"	61.0	80.0	26.0
	-	-	"	147.7	177.0	20.0
62	1.1×10^{19}	35	"	171.2	194.0	17.0
59	3.7×10^{19}			58.7	72.7	18.0
62	1.0×10^{20}	35	"	182.8	201.0	15.0
	2.9×10^{20}	35	"	188.9	204.7	14.0
	3.3×10^{20}	35	"	175.5	225	17.0

Appendix C

Refer- ence	Total ₂ Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
63	1.2x10 ¹⁹	35	RT	175.5	225	17.0
	1.5x10 ²⁰	35	"	198.0	223	11.0
38	4.5x10 ¹⁹	280	RT	67.0	95.0	15.1
	1.05x10 ²⁰	"	"	75.2	89.8	13.8
	1.01x10 ²⁰	"	"	92.5	97.3	4.6
	2.4x10 ²⁰	"	"	105.8	106.2	0.5
	2.5x10 ²⁰	"	"	108.2	108.2	0.3
	3.7x10 ¹⁹	"	"	58.7	72.7	12.7
	-	-	"	35.9	66.6	21.1
40	2.5x10 ²⁰	100	RT	82.4	-	0.4
	None	-	"	38	70	34
	2.5x10 ²⁰	100	"	-	115	3
	None	-	"	-	100	6

FERRITIC STAINLESS STEELS

BLANK

Appendix C
406 STAINLESS STEEL

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
43	None	-	20	59	78	23
	9x10 ¹⁹	20-30	"	89	93	13
	None	-	"	67	89	23
	2.53x10 ¹⁹	650	"	70	91	25

BLANK

NICKEL-BASE ALLOYS,
LOW TEST TEMPERATURES

BLANK

Appendix C
NICKEL 330

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
40	1.1x10 ²¹	100	RT	-	108	-
	"	"	"	-	125	-
	"	"	"	-	152	-
	1.3x10 ²¹	"	"	-	106	-
	"	"	"	-	124	-
	1.2x10 ²¹	"	"	-	163	-
	"	"	"	-	164	-
	"	"	"	-	161	-
	1.8x10 ²¹	"	"	-	161	-
	"	"	"		147	-
	"				112	-
67	-	-	RT	45.8	63.4	36.0
	7.8x10 ²⁰	<100	"	95.6	95.6	10.0
	9.0x10 ²⁰	"	"	98.6	98.6	11.0
	1.13x10 ²¹	"	"	101.3	101.3	8.0
	-	-	"	52.5	66.5	-
	7.8x10 ²⁰	<100	"	108.6	108.6	-
	-	-	"	67.2	87.5	34.0
	1.13x10 ²¹	<100	"	145.0	145.0	5.0
	-	-	"	80.0	97.4	-
	1.13x10 ²¹	<100	"	163.0	163.0	-

Appendix C

Ni 270

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
.40	2.5×10^{20}	100	RT	64.1	-	6
	None	-	"	26.1	43.4	50
	2.5×10^{20}	100	"	-	73.6	3
	None	-	"	-	55.7	14

Appendix C

"A" NICKEL

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
66	-	-	RT	25.0	60.0	38.0
	9.5x10 ¹⁷	<100	"	30.0	60.0	34.0
	5.0x10 ¹⁸	"	"	37.0	61.0	35.0
	8.8x10 ¹⁸	"	"	42.0	60.0	28.0
	4.9x10 ¹⁹	"	"	55.0	65.0	22.0
	6.1x10 ¹⁹	"	"	61.0	71.0	18.0
	7.5x10 ¹⁹	"	"	63.0	70.0	21.0
	-	-	"	17.1	62.5	33.0
	2.4x10 ²⁰	<100	"	77.7	95.5	17.0
	4.0x10 ²⁰	"	"	91.2	106.0	17.0
	2.4x10 ²⁰	"	"	82.8	85.7	23.0
	4.0x10 ²⁰	"	"	61.2	89.0	13.0
	-	-	200	21.0	55.0	35.0
	9.5x10 ¹⁷	2100	"	27.0	55.0	27.5
	5x10 ¹⁸	"	"	31.0	55.0	24.0
	8.8x10 ¹⁸	"	"	36.0	56.0	26.0
	4.9x10 ¹⁹	"	"	48.0	56.0	18.0
	6.1x10 ¹⁹	"	"	52.0	60.0	18.0
	7.5x10 ¹⁹	"	"	46.0	59.0	12.5

Appendix C

INCONEL X

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
64	-	-	RT	120.3	184.3	23.0
	8x10 ¹⁸	<100	"	154.5	172.6	18.0
			"	170.8	174.0	13.0
			"	171.5	172.2	12.0
	-	-	"	103.2	170.1	28.0
	8x10 ¹⁸	<100	"	143.3	165.1	22.0
	1.6x10 ²⁰	"	"	158.6	161.3	14.0
	2.9x10 ²⁰	"	"	163.2	165.0	10.0
60	-	-	"	114.0	169.0	23.2
	2.0x10 ²⁰	<100	"	157.0	162.0	6.4
69	-	-	"	53.0	109.8	56.0
	1.3x10 ²⁰	50	"	105.0	121.2	35.0
	-	-	"	40.2	98.2	63.0
	1.2x10 ²⁰	50	"	75.4	104.0	52.0
	1.3x10 ²⁰	"	"	93.5	117.4	56.0
	-	-	"	121.9	138.0	33.0
	1.3x10 ²⁰	50	"	150.0	152.7	21.5
	7.5x10 ¹⁹	300	"	59.7	111.9	69.5
	3.0x10 ¹⁹	250	"	76.5	115.6	49.0
	7.5x10 ¹⁹	300	"	73.6	116.1	48.5
	3.0x10 ¹⁹	250	"	117.4	146.8	32.5
	3.0x10 ¹⁹	250	"	65.5	110.2	64.0

Appendix C

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
65	-	-	RT	163.3	203.4	22.0
	1.8x10 ²⁰	<100	"	194.6	195.7	12.0
	5.9x10 ²⁰	"	"	205.5	205.5	11.0
	2.2x10 ²¹	"	"	201.1	201.2	11.0
	3.5x10 ²¹	"	"	194.8	197.9	12.0
	8.5x10 ²⁰	"	"	174.0	180.5	12.0
	1.4x10 ²¹	"	"	169.0	178.0	10

Appendix C
INCONEL 600

Refer- ence	Total ₁ Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
59	-	-	RT	138.3	143.3	12.0
	1.3x10 ²⁰	50	"	169.9	169.9	9.0
	-	-	"	36.3	90.5	53.0
	7.5x10 ¹⁹	300	"	53.3	99.2	55.0
5	-	-	RT	36	95	42.0
	2.53x10 ¹⁹	650	"	37	94	43.0
	1.21x10 ²⁰	"	"	35	94	37.0
43	None	-	20	31	80	61
	9x10 ²⁰	20-30	"	133	135	15

Appendix C

INCONEL 625

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
42	-	-	RT	93.5	150.12	36.44
	9.8x10 ¹⁹ fast	50	"	124.58	149.72	29.29
	1.84x10 ²⁰	"	"	138.35	147.51	23.13
	4.61x10 ²⁰	"	"	125.48	151.46	28.06
	7.5x10 ²⁰	"	"	160.6	161.6	8.43
	-	-	"	102.09	158.5	39.2
	5.3x10 ¹⁹	280	"	118.1	169.8	38.21
	1.28x10 ²⁰	"	"	110.2	153.4	40.34
	1.51x10 ²⁰	"	"	107.21	151.99	37.78
	2.55x10 ²⁰	"	"	106.0	150.1	44.69
	7.71x10 ²⁰	"	"	100.0	136.3	47.03
	8.27x10 ²⁰	"	"	117.63	148.16	31.48
	-	-	"	54.3	70.7	27.3
	9.2x10 ¹⁹	580	"	172.1	199.4	17.6
	-	-	"	92.6	134.9	10.8
	9.2x10 ¹⁹	740	"	113.9	156.8	12.1
46	5x10 ¹⁹	280	RT	118.45	170.0	38.2
	"	580	"	172.1	199.3	17.58
	"	740	"	113.8	156.8	12.01

Appendix C

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
5	-	-	RT	102	160	34
	5.88x10 ¹⁹	280 H ₂ O	"	110	151	36
	7.2x10 ¹⁹	"	"	116	155	34
	1.1x10 ²⁰	"	"	97	145	46
	1.8x10 ²⁰	"	"	110	152	40
	5x10 ²⁰	"	"	108	150	44
50	-	-	RT	81.94	106.28	5.92
	-	-	"	92.61	134.94	10.82
	9x10 ¹⁹ fast	740	"	100.35	128.00	6.44
	"	"	"	113.80	156.80	12.09
	-	-	RT	93.0	150.0	36.0
	9.8x10 ¹⁹	50	"	124.0	150.0	29.5
	1.84x10 ²⁰	"	"	137.0	151.0	23.0
	4.61x10 ²⁰	"	"	123	145.0	28.0
	7.64x10 ²⁰	"	"	159	165.0	8.5
	-	-	"	101	159.5	38.5
	5.3x10 ¹⁹	280	"	119	170.0	38.0

Appendix C

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
50	1.57x10 ²⁰	280	RT	108	151.0	34.5
	2.55x10 ²⁰	"	"	106.5	150.0	45.0
	7.71x10 ²⁰	"	"	100.5	137.0	45.5
	8.27x10 ²⁰	"	"	119.0	149.5	31.0
	-	-	"	135	178.0	27.0
	9.2x10 ¹⁹	580	"	174	200.0	17.0
	-	-	"	90.5	132	11.5
	9.2x10 ¹⁹	740	"	112.0	157.5	13.5

Appendix C

INCONEL 702

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
54	-	-	RT	42.6	94.9	67.0
	5.0x10 ¹⁹	<100	"	101.1	113.1	50.0
	1.8x10 ²⁰	"	"	120.3	121.5	41.0
	2.9x10 ⁷⁰	"	"	128.8	130.0	36.0
65	-	-	RT	90.5	145.3	44.0
	8.5x10 ²⁰	<100	"	-	172.0	13.0
	1.4x10 ²¹	"	"	171.5	171.5	14.0
68	-	-	"	97.0	155.0	26.0
	3.0x10 ¹⁹	650	"	98.0	154.0	31.0
	1.5x10 ²⁰	"	"	100.0	138.0	15.0
5	-	-	RT	96	155	27.5
	2.53x10 ¹⁹	fast 650	"	98	154	31.5
	1.21x10 ²⁰	fast "	"	100	139	14.0
43	None	-	20	97	155	27
	2.53x10 ¹⁹	650	"	97	154	31
	1.21x10 ²⁰	"	"	99	138	14
	None	-	"	79	145	33
	9x10 ²⁰	20-30	"	138	138	11

Appendix C
INCONEL 718

Refer- ence	Total Flux n/cm^2	Irradiation Temperature $^{\circ}C$	Test Temperature $^{\circ}C$	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
5	-	-	RT	160	187	37.0
	4.5×10^{19}	280 H_2O	"	180	194	9.0
	5.8×10^{19}	"	"	192	204	13.0
	7.2×10^{19}	"	"	167	183	8.0
	1.1×10^{20}	"	"	143	165	17.0
	5.4×10^{20}	"	"	156	180	9.0
46	5×10^{19}	280	"	190.1	209.3	12.2
	"	580	"	194.1	212.0	14.1
	"	740	"	82.9	124.0	9.1

Appendix C

HASTELLOY X

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
43	None	-	20	52	116	30
	2.53x10 ¹⁹ fast	650 in	"	33	108	34
	1.21x10 ²⁰	He	"	46	105	25
	None	-	"	55	116	34
	9x10 ²⁰	20-30	"	106	130	23
49	-	-	25	43	105.0	60.0
	-	-	"	52.1	113.0	28.3
	-	-	"	48.1	112.3	25.5
	-	-	"	44	109.0	46.6
	1.5x10 ²⁰ fast	540	"	56.2	108.2	52.6
	"	650	"	59.9	112.5	39.8
	"	870	"	43.8	111.4	32.3
	"	540	"	44	108.2	44.7
68	-	-	RT	53.0	118.0	30.0
	3.0x10 ¹⁹	650	"	38.0	109.0	34.0
	1.5x10 ²⁰	"	"	46.0	105.0	25.0
64	-	-	RT	49.4	112.5	52.0
	5.0x10 ¹⁹	<100	"	100.2	129.3	50.
	1.8x10 ²⁰	"	"	104.0	130.7	43.0
	2.5x10 ²⁰	"	"	106.3	131.0	42.0
	3.6x10 ²⁰	"	"	116.0	135.9	39.0

Appendix C
HASTELLOY X-280

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
5	-	-	RT	53	115	30
	2.53x10 ¹⁹ fast	650	"	37.5	108	34
	1.21x10 ²⁰	"	"	45.0	103	25.5
40	5x10 ¹⁹ fast	280	RT	72.1	118.5	40.3
	"	740	"	55.6	124.87	26.5

Appendix C
HASTELLOY R-235

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
5	-	-	RT	90	158	17
	2.53x10 ¹⁹	650	"	97	159	19
	1.21x10 ²⁰	"	"	92	143	13
46	5x10 ¹⁹	280	RT	110.58	143.43	34.45
	"	580	"	110.05	146.98	32.77
	"	740	"	108.18	113.17	1.04
68	-	-	RT	90.0	158.0	16.0
	3.0x10 ¹⁹	650	"	96.0	159.0	18.0
	1.5x10 ²⁰	"	"	95.0	143.0	13.0
43	None	-	20	91	158	17
	2.53x10 ¹⁹	650	"	97	159	19
	1.21x10 ²⁰	"	"	91	143	13
	None	-	20	99	168	28
	9x10 ²⁰	20-30	"	175	232	15

Appendix C
HASTELLOY N

Refer- ence	Total Flux n/cm ²	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
58	9x10 ²⁰ slow	700	20	46.3	168.6	42.3
	7x10 ²⁰ fast					
	-	-	20	45.5	166.5	40.6
	Irrad.	700	100	43.9	159.5	40.1
	-	-	100	43.9	161.0	40.3
	Irrad.	700	200	39.4	150.6	40.3
	-	-	200	40.7	157.5	41.9
40	5x10 ¹⁹	280	RT	39.93	107.34	67.33
	"	740	"	43.00	75.50	18.90
	1.91x10 ²⁰	740	"	50.25	81.28	10.95
5	-	-	RT	41	104	62
	4.5x10 ¹⁹	?	"	72	115	52
	1.2x10 ²⁰	?	"	75	118	56
	1.84x10 ²⁰	?	"	90	134	57
	5.4x10 ²⁰	?	"	80	117	50

Appendix C

RENE 41

Refer- ence	Total ₂ Flux n/cm	Irradiation Temperature °C	Test Temperature °C	.2% Yield (Ksi)	U.T.S. (Ksi)	Elonga- tion (%)
49	1.5x10 ²⁰	650	26	141.6	181.1	13.0
	"	870	"	120.2	141.7	1.4
	-	-	26	102.4	145.5	11.6
	-	-	"	117.0	137.0	3.3
	1.5x10 ²⁰	540	"	111.6	133.2	7.5
	"	650	"	94.5	159.7	21.9
	"	"	"	121.0	139.0	6.1
	-	-	"	150.7	199.0	9.9
	-	-	"	135.1	161.3	2.0