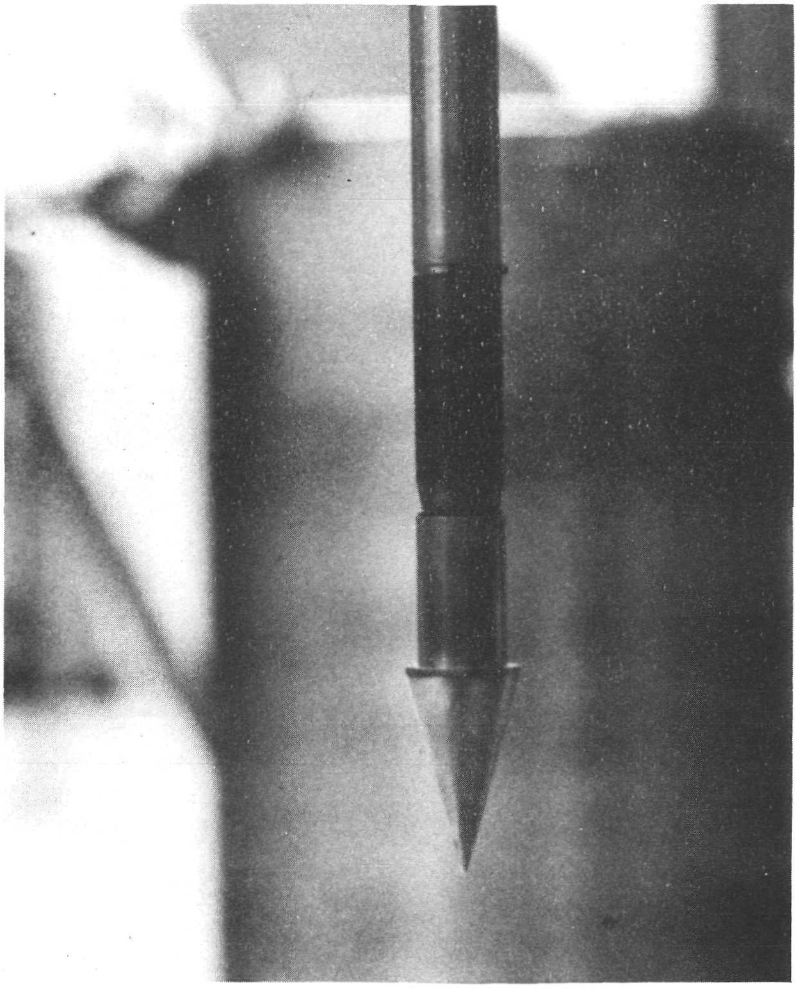

Figure C-1. - Penetrometer head.

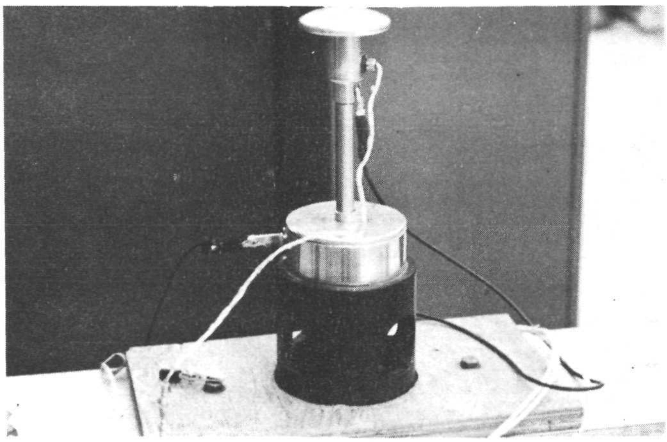

Figure C-2. - Penetrometer handle and stem.

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IRRADIATION EFFECTS ON 17-7 PH STAINLESS STEEL, A-201 CARBON STEEL, AND TITANIUM - 6-PERCENT-ALUMINUM - 4-PERCENT-VANADIUM ALLOY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1972

1. Report No. NASA TM X-2678	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IRRADIATION EFFECTS ON 17-7 PH STAINLESS STEEL, A-201 CARBON STEEL, AND TITANIUM - 6-PERCENT-ALUMINUM - 4-PERCENT-VANADIUM ALLOY		5. Report Date November 1972 6. Performing Organization Code
7. Author(s) Robert A. Hasse and Charles B. Hartley		8. Performing Organization Report No. E-7093
9. Performing Organization Name and Address Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135		10. Work Unit No. 503-25 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Irradiation effects on three materials from the NASA Plum Brook Reactor surveillance Program were determined. An increase of 105 K in the nil-ductility temperature for A-201 steel was observed at a fluence of approximately 3.1×10^{18} neutrons/cm^2 (neutron energy $E_n > 1.0$ MeV). Only minor changes in the mechanical properties of 17-7 PH stainless steel were observed up to a fluence of 2×10^{21} neutrons/cm^2 ($E_n > 1.0$ MeV). The titanium - 6-percent-aluminum - 4-percent-vanadium alloy maintained its notch toughness up to a fluence of 1×10^{21} neutrons/cm^2 ($E_n > 1.0$ MeV).

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Irradiation effects; A-201 steel; 17-7 PH stainless steel; Ti-6Al-4V alloy; Notch toughness; Nil-ductility temperature; Tensile properties	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	18	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

IRRADIATION EFFECTS ON 17-7 PH STAINLESS STEEL, A-201 CARBON STEEL, AND TITANIUM - 6-PERCENT-ALUMINUM - 4-PERCENT-VANADIUM ALLOY

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SUMMARY

The NASA Plum Brook Reactor maintains a surveillance test program for selected materials used in reactor and experiment hardware. The test results for three of these materials are presented in this report.

Test results for 17-7 PH stainless steel show no change in yield strength up to a fast fluence of 2×10^{21} neutrons per square centimeter (neutron energy $E_n > 1.0$ MeV). The ultimate tensile strength increased approximately 20 percent, and the percent elongation taken from the load-time chart decreased approximately 30 percent. Coil springs were also irradiated and subjected to a proof test of 2×10^6 20-percent compression cycles. All springs passed the test. The maximum fast fluence was 2×10^{21} neutrons per square centimeter ($E_n > 1.0$ MeV).

Increases in the nil-ductility temperature for A-201 steel ranged from 10 K at a fluence of 1.2×10^{17} neutrons per square centimeter ($E_n > 1.0$ MeV) to 105 K at a fast fluence of 3.1×10^{18} neutrons per square centimeter.

The titanium - 6-percent-aluminum - 4-percent-vanadium alloy maintained its room-temperature notched toughness up to a fast fluence of 1×10^{21} neutrons per square centimeter ($E_n > 1.0$ MeV). The ultimate tensile strength and 0.2 percent yield strength increased by approximately 40 percent. The percent elongation taken from the load-time chart decreased by approximately 70 percent. The notched tensile strength increased slightly and then decreased. The ratio of notched to smooth tensile strength decreased from 1.53 to 1.04.

INTRODUCTION

The NASA Plum Brook Reactor (PBR) has maintained a surveillance program for selected materials used in the Reactor and its experiment hardware. This report documents the results for three of these materials: 17-7 PH stainless steel, A-201 carbon steel, and a titanium - 6-percent-aluminum - 4-percent-vanadium (Ti-6Al-4V) alloy.

Materials are selected for inclusion in the surveillance program on the basis of irradiation-effect information available at the time they are inserted in the reactor. Other materials that have been included are beryllium, Lockalloy, and a titanium-tungsten couple formed by hot isostatic pressing. A preliminary report on the beryllium program has been issued (ref. 1). The study of the effects of irradiation on the tensile properties of Lockalloy has just begun. The titanium-tungsten program is restricted to a metallographic study of the bond as a function of irradiation.

A description of the materials considered in this report is presented first along with their irradiation history and environment. The testing results and discussion are then presented. Dosimetry details are given in the appendix.

MATERIALS AND IRRADIATION HISTORY

17-7 PH Stainless Steel

The 17-7 PH stainless steel is used in the PBR in the form of coil springs and bar stock. The springs are located at the ends of the fuel elements and reflector pieces and serve to absorb hydraulic vibrations. Two types of specimens have been irradiated under the surveillance program, coil springs and tensile specimens. The specimens are described in figure 1. The manufacturer's certified analysis is given in table I.

The specimens were irradiated in the PBR reflector to a fluence of approximately 4.9×10^{20} neutrons per square centimeter (neutron energy $E_n > 1.0$ MeV) and then transferred to a core lattice position. The neutron energy spectra for these positions are given in the appendix.

The specimens were in direct contact with flowing reactor primary cooling water (PCW) during irradiation. The characteristics of the PCW are given in table II. Nominal tensile specimen bulk temperature during irradiation was 360 K.

A-201 Carbon Steel

The PBR pressure vessel was fabricated from A-201 carbon steel. The surveillance specimens irradiated under this program were cut directly from the pressure vessel. The specimens (fig. 2) were subsize V-notch specimens broken in the Izod manner. The manufacturer's certified analysis of the material is given in table III.

The specimens were sealed inside stainless-steel containers filled with helium. The specimens were originally irradiated near the pressure vessel wall at a fast flux of approximately 10^6 neutrons per square centimeter per second ($E_n > 1.0$ MeV). Specimen temperature was 308 K at this location. After irradiation in this location for about 6 years, the specimens were moved closer to the core and irradiated in a flux of approximately 9×10^{10} neutrons per square centimeter per second ($E_n > 1.0$ MeV). Maximum specimen temperature at this location was calculated as 360 K.

Titanium - 6-Percent-Aluminum - 4-Percent-Vanadium Alloy

The Ti-6Al-4V alloy was used in experiment facility hardware. The property of concern was notched toughness as a function of neutron dose. Accordingly, the notched-to smooth-tensile-strength ratio was used as a measure of the embrittlement. The analysis of this material is given in table IV.

The specimens (fig. 3) were irradiated in the same manner as the 17-7 PH specimens, that is, in contact with the PCW. They were irradiated in a reflector position up to 2.5×10^{20} neutrons per square centimeter ($E_n > 1.0$ MeV) and then transferred to a core lattice position. Nominal bulk temperature during irradiation was 340 K.

RESULTS AND DISCUSSION

17-7 PH Stainless Steel

The tensile specimens were tested with a crosshead speed of 0.51 centimeter per minute. The test results are given in table V. The ultimate tensile strength increased slightly up to a fluence of approximately 3×10^{20} neutrons per square centimeter ($E_n > 1.0$ MeV). No increases were observed above this fluence. A corresponding decrease in total elongation was also observed. No changes were detectable in the 0.2 percent yield strength. Small changes may have been obscured by the data scatter. In general, the data are consistent with those for other precipitation-hardened martensitic steels (ref. 2).

The proof test for the springs consisted of repeatedly compressing the springs 0.63 centimeter. A test was considered successful if the spring completed 2×10^6 cycles. All specimens passed the test. The maximum fast fluence was 2×10^{21} neutrons per square centimeter ($E_n > 1.0$ MeV).

A-201 Carbon Steel

The results of the impact tests are given in table VI and figures 4 and 5. Changes in the ductile to brittle transition temperature are given in terms of the temperature at the midrange energy value from the impact tests. Comparison of these results with other data reported in the literature (e.g., ref. 3) would be complicated and uncertain. For a comprehensive treatment of the various parameters, the work being done by the Naval Research Laboratories on pressure vessel steels should be consulted.

The midrange energy values from these impact tests have not been correlated to a nil-ductility temperature (NDT) for the full-size pressure-vessel plate. At best, the impact data indicate at what fluence significant shifts in the NDT begin to occur. On this basis, areas of the pressure vessel accumulating a fluence greater than 5×10^{17} neutrons per square centimeter ($E_n > 1.0$ MeV) would be potentially susceptible to brittle failure.

Titanium - 6-Percent-Aluminum - 4-Percent-Vanadium Alloy

The specimens of Ti-6Al-4V alloy were pulled with a crosshead speed of 0.51 centimeter per minute. The testing results for this material are given in table VII and figure 6. For a notch sharpness of 18, this alloy did not approach notch sensitivity at room temperature until approximately 10^{21} neutrons per square centimeter ($E_n > 1.0$ MeV). (The notch sharpness is defined as one-half the bar diameter divided by the notch radium a/r.) For higher values of a/r, the material would probably become notch sensitive more rapidly (ref. 4).

SUMMARY OF RESULTS

The effect of reactor irradiation on 17-7 PH stainless steel, A-201 carbon steel, and a titanium - 6-percent-aluminum - 4-percent-vanadium (Ti-6Al-4V) alloy has been determined. The following results were obtained:

1. Test results for 17-7 PH stainless steel showed no change in the yield strength at a fast fluence of 2×10^{21} neutrons per square centimeter (neutron energy $E_n > 1.0$ MeV). The ultimate tensile strength increased approximately 20 percent. Total elongation based on crosshead travel decreased about 30 percent. Coil springs irradiated to the same fluence passed the proof test of 2×10^{6} 20-percent compression cycles.

2. Increases in the nil-ductility temperature for A-201 carbon steel ranged from 10 K at a fast fluence of 1.2×10^{17} neutrons per square centimeter ($E_n > 1.0$ MeV) to 105 K at a fast fluence of 3.1×10^{18} neutrons per square centimeter.

3. The alloy Ti-6Al-4V was irradiated to a fast fluence of 1×10^{21} neutrons per square centimeter ($E_n > 1.0$ MeV). The notched- to smooth-tensile-strength ratio decreased from 1.53 to 1.04. The ultimate and yield strengths increased approximately

40 percent. The percent elongation taken from the crosshead travel decreased about 70 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 14, 1972,
503-25.

APPENDIX - NEUTRON SPECTRA AND DOSIMETRY

Lattice and Reflector Positions for 17-7 PH Stainless Steel and Titanium - 6-Percent-Aluminum - 4-Percent-Vanadium Alloy

The relative integral and differential neutron flux energy spectra are given in figures 7 to 10. These spectra were obtained by using the SAND II computer code with 9 to 13 detectors. The detectors generally covered the energy region of 0.4 eV to 10 MeV.

The fast neutron fluence ($E_n > 1.0$ MeV) was monitored by using nickel dosimeter wires. The thermal neutron fluence was monitored with cobalt (Co) wires by using a cross section of 37.2 barns for the Co^{59} (n, γ) Co^{60} reaction. The neutron fluence ($E_n > X$) may be determined by using the reported values for fast fluence ($E_n > 1.0$ MeV) and the values of relative integral flux φ from figures 8 and 10. Thus,

$$\text{neutron fluence } (E_n > X) = \frac{\varphi(E_n > X) \times \text{fast fluence } (E_n > 1.0)}{\varphi(E_n > 1.0)}$$

The uncertainties in the fluence values are given in table VIII. The higher uncertainties for the reflector positions are the result of the fact that no dosimeter wires were included in many of the earlier irradiations in these positions. Fluences for these irradiations were calculated from data obtained during irradiations in which dosimeters were included. Thus, for the 17-7 PH and titanium alloys, the uncertainties in the lower fluences are those given for the reflector positions. The uncertainties for the higher fluences approach those given for the lattice positions.

Irradiations of A-201 Carbon Steel

The neutron spectrum for $E_n > 1.0$ MeV (fig. 11) was determined by irradiating various threshold detectors at the position were the specimens were irradiated. The spectrum for $E_n > 0.1$ MeV was obtained from one-dimensional calculations normalized by the $E_n > 1.0$ MeV flux. The threshold detectors used were titanium, aluminum, nickel, and indium.

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TABLE I. - COMPOSITION 17-7 PH

STAINLESS STEEL

Element	Tensile specimens[a]	Springs[b]
	Concentration, wt. %	
Carbon	0.064	0.073
Manganese	.64	.77
Surfur	.010	.012
Phosphorus	.019	.019
Silicon	.49	.49
Chromium	17.11	17.04
Nickel	7.29	7.28
Aluminum	1.24	1.09
Iron	Balance	Balance

[a]Condition indicated by tensile properties was intermediate between R-100 and RH-950 (ref. 5).
[b]Condition, CH-900 (ref. 5).

TABLE II. - PRIMARY-COOLING-

WATER PROPERTIES

Property	Nominal value
Conductivity, μmho/cm	0.8
pH	6.3
Pressure, N/cm^2	1.12×10^6
Temperature, K	338

TABLE III. - COMPOSITION

OF A-201 CARBON STEEL

Element	Concentration, wt. %
Carbon	0.20
Manganese	.80
Phosphorus	.04
Silicon	.20
Sulfur	.05
Iron	Balance

TABLE IV. - COMPOSITION

OF Ti-6Al-4V ALLOY

[Hardness, 57 (30 kg, braile indenter.]

Element	Concentration, wt. %
Aluminum	6.3 to 7.5
Vanadium	4.1 to 4.5
Iron	0.08 to 0.12
Carbon	0.02
Nitrogen	0.009 to 0.01
Oxygen	0.15 to 0.17
Hydrogen	50 to 80 ppm
Titanium	Balance

TABLE V. - TENSILE PROPERTIES OF IRRADIATED 17-7 PH STAINLESS STEEL

[All specimens passed spring proof test of 2×10^6 cycles.]

Thermal fluence, neutrons/cm^2	Fast fluence ($E_n > 1.0$ MeV), neutrons/cm^2	0.2 Percent offset yield strength, N/m^2	Ultimate tensile strength, N/m^2	Total elongation,[a] percent
0	0	[b]9.10×10^8	[c]11.6×10^8	21
$.27\times10^{21}$	$.23\times10^{20}$	10.1	12.4	19
.38	.33	9.51	12.4	18
1.7	1.4	8.47	12.6	16
2.4	1.9	8.55	12.7	16
2.6	2.2	8.75	13.1	15
3.3	3.1	9.24	13.4	15
5.2	4.9	9.04	13.5	15
8.9	11	8.75	13.4	14
17	21	9.75	13.7	14

[a]Calculated from load-time chart.
[b]Range, 8.3×10^8 to 9.7×10^8 N/m^2.
[c]Range, 11.3×10^8 to 11.9×10^8 N/m^2.

TABLE VI. - TEST RESULTS FOR A-201 CARBON STEEL

Thermal fluence, neutrons/cm^2	Fast fluence ($E_n > 1.0$ MeV), neutrons/cm^2	Nil-ductility temperature,[a] NDT, K	Change in nil-ductility temperature, ΔNDT, K
0	0	238	---
$.62\times10^{18}$	1.2×10^{17}	248	10
2.9	4.9	273	35
8.4	16	283	45
16	31	343	105

[a]Temperature at midrange energy value from impact tests.

TABLE VII. - TEST RESULTS FOR Ti-6Al-4V ALLOY

Thermal fluence, neutrons/cm^2	Fast fluence, ($E_n > 1.0$ MeV), neutrons/cm^2	0.2 Percent offset yield strength, N/m^2	Ultimate tensile strength, N/m^2		Total elongation,[b] percent	Notched- to smooth-tensile-strength ratio
			Smooth	Notched[a]		
0	0	1.09×10^{9}	1.10×10^{9}	1.69×10^{9}	10.0	1.53
$.25\times10^{20}$	$.22\times10^{19}$	1.14	1.19	1.71	7.0	1.44
2.3	2.0	1.28	1.30	1.78	4.4	1.37
3.7	3.1	1.25	1.27	1.72	4.9	1.35
9.6	7.7	1.34	1.35	1.76	4.2	1.30
73	97	1.54	1.55	1.62	3.0	1.04

[a]Notch sharpness a/r, 18.
[b]Calculated from load-time chart.

TABLE VIII. - UNCERTAINTIES

(95 PERCENT CONFIDENCE)

IN NEUTRON FLUENCES

Neutron energy, E_n, MeV	17-7 PH and Ti-6Al-4V		A-201
	Lattice	Reflector	
	Uncertainty in fluence, percent		
≤ 1.0	±40	±50	±60
Thermal	±10	±30	±30
≥ 1.0	±25	±40	±40

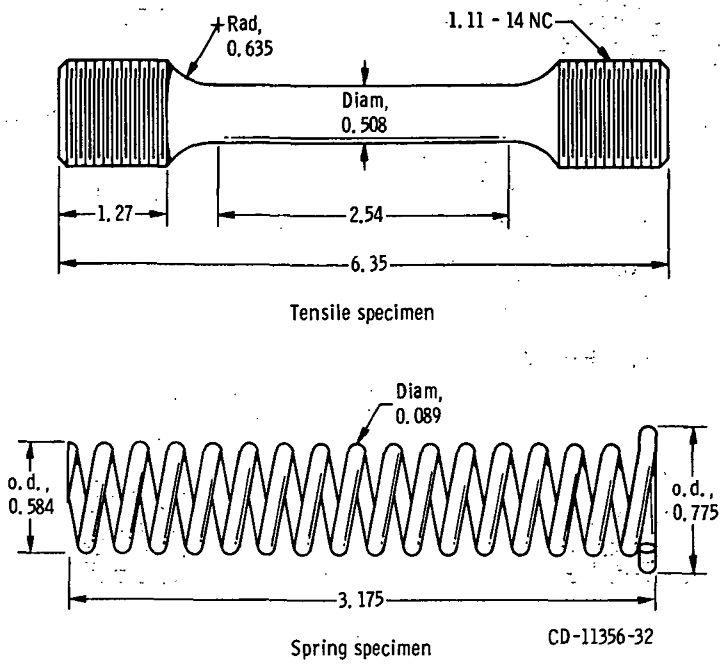


Figure 1. - 17-7 PH stainless steel test specimens. (Dimensions in centimeters.)

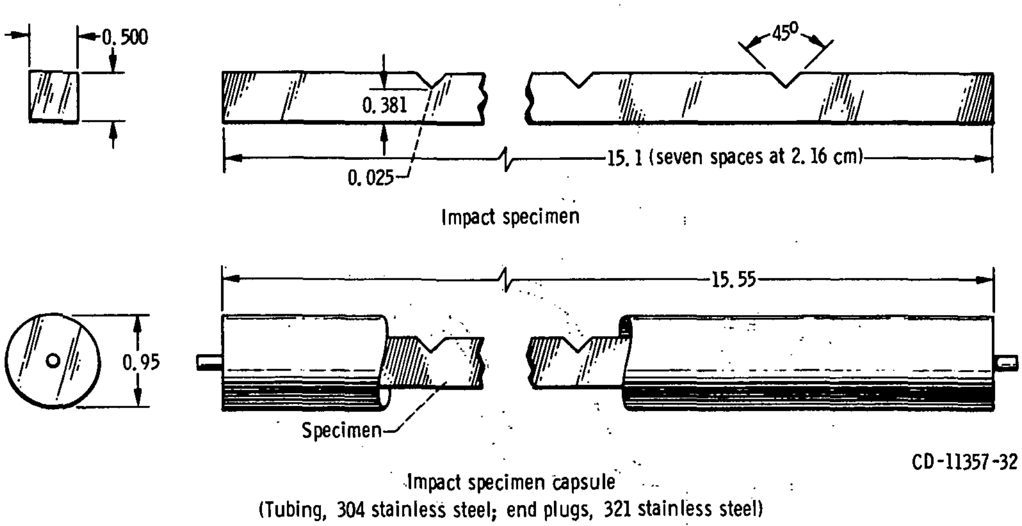
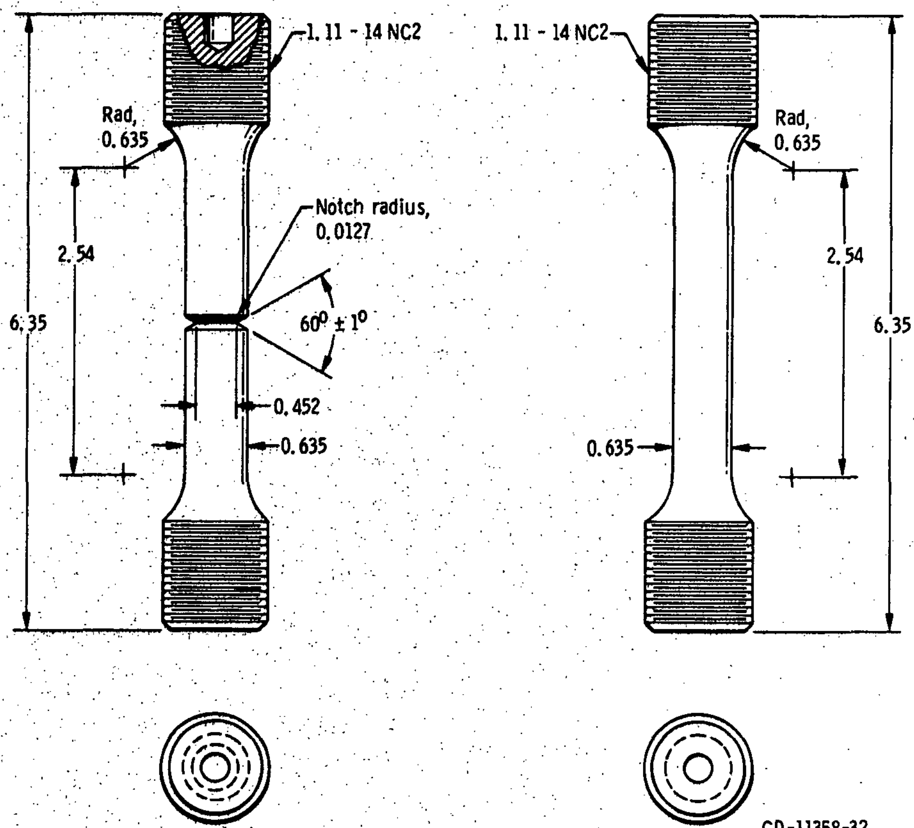


Figure 2. - A-201 impact specimen. (Dimensions in centimeters.)



Notched tensile specimen

Smooth tensile specimen

Figure 3. - Ti-6Al-4V specimens. (Dimensions in centimeters.)

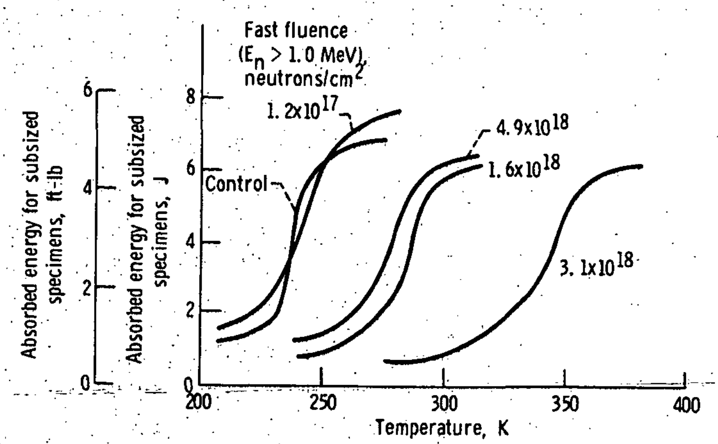


Figure 4. - Notched impact properties of A-201 steel.

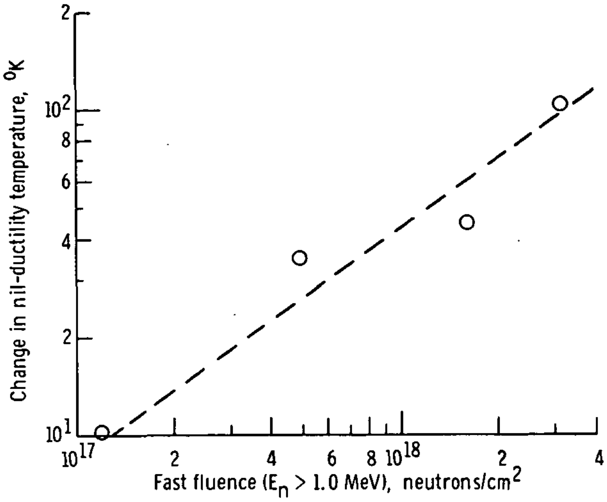


Figure 5. - Change in nil-ductility temperature for A-201 carbon steel.

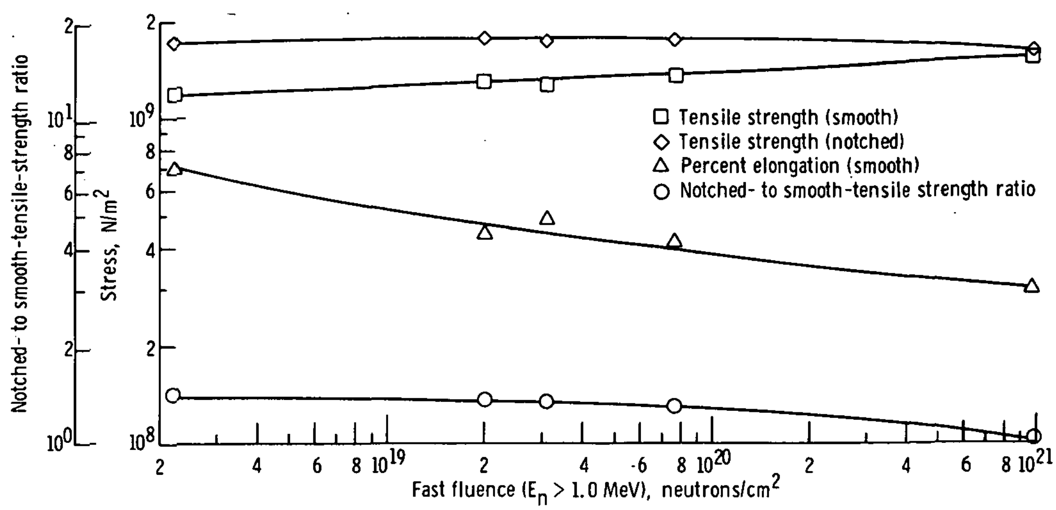
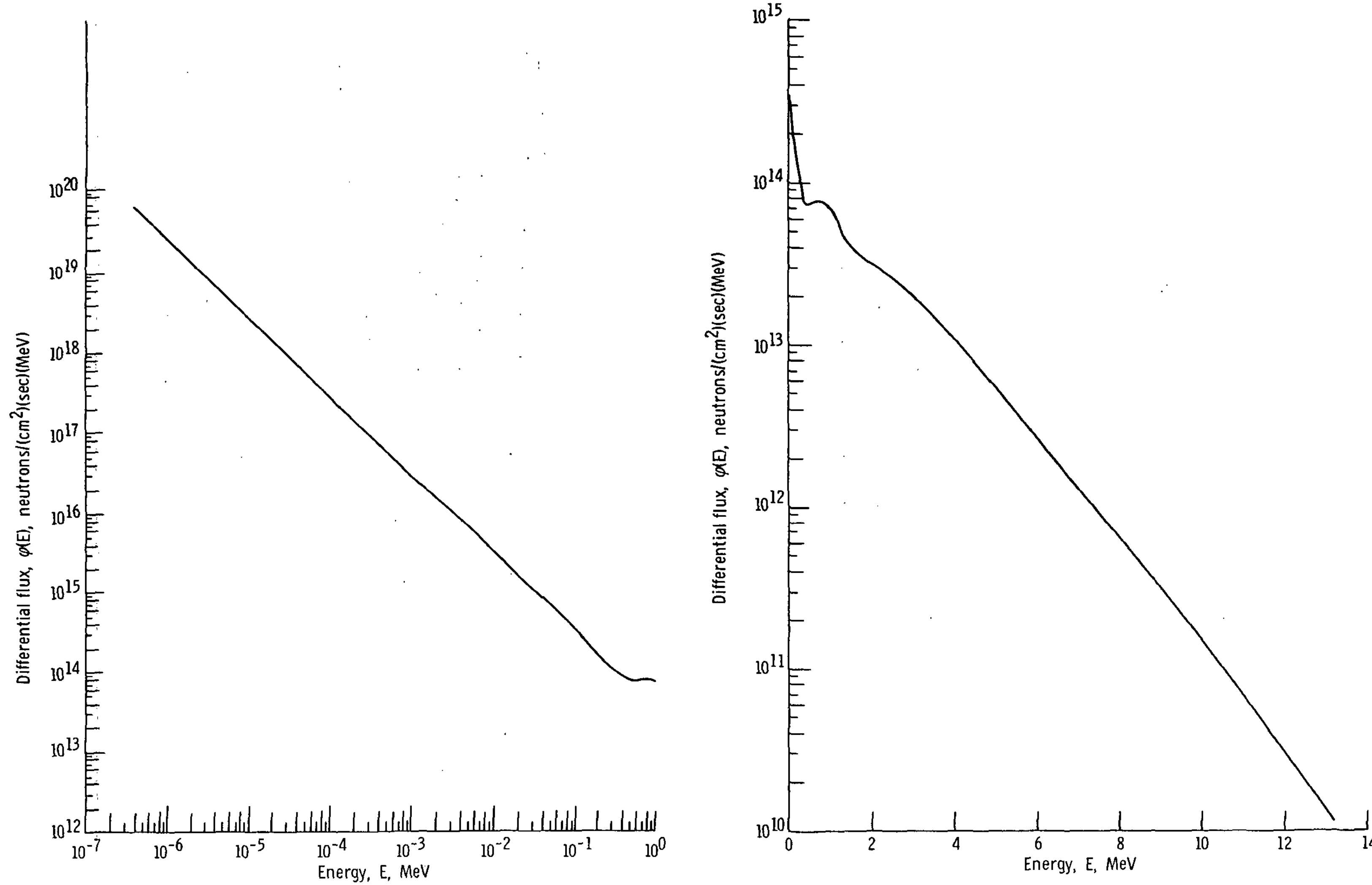


Figure 6. - Test results for Ti-6Al-4V alloy.



(a) Energies between 10^{-7} and 10^{0} MeV.

(b) Energies between 0 and 14 MeV.

Figure 7. - Differential flux spectrum for lattice.

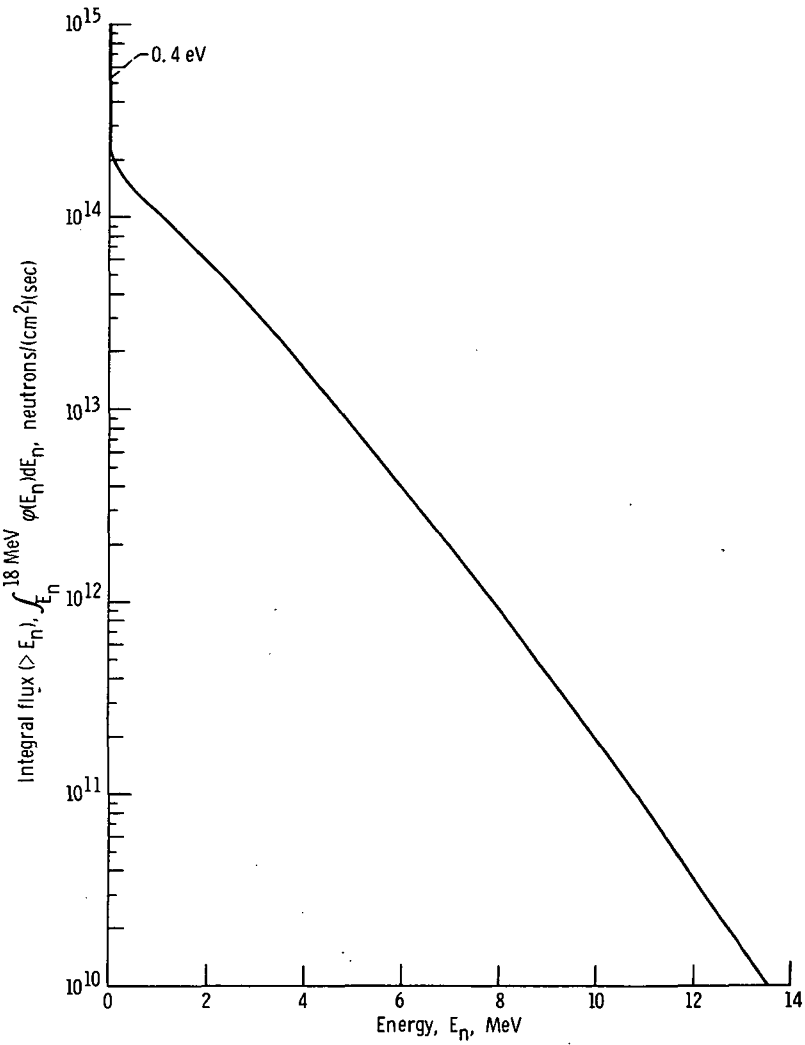
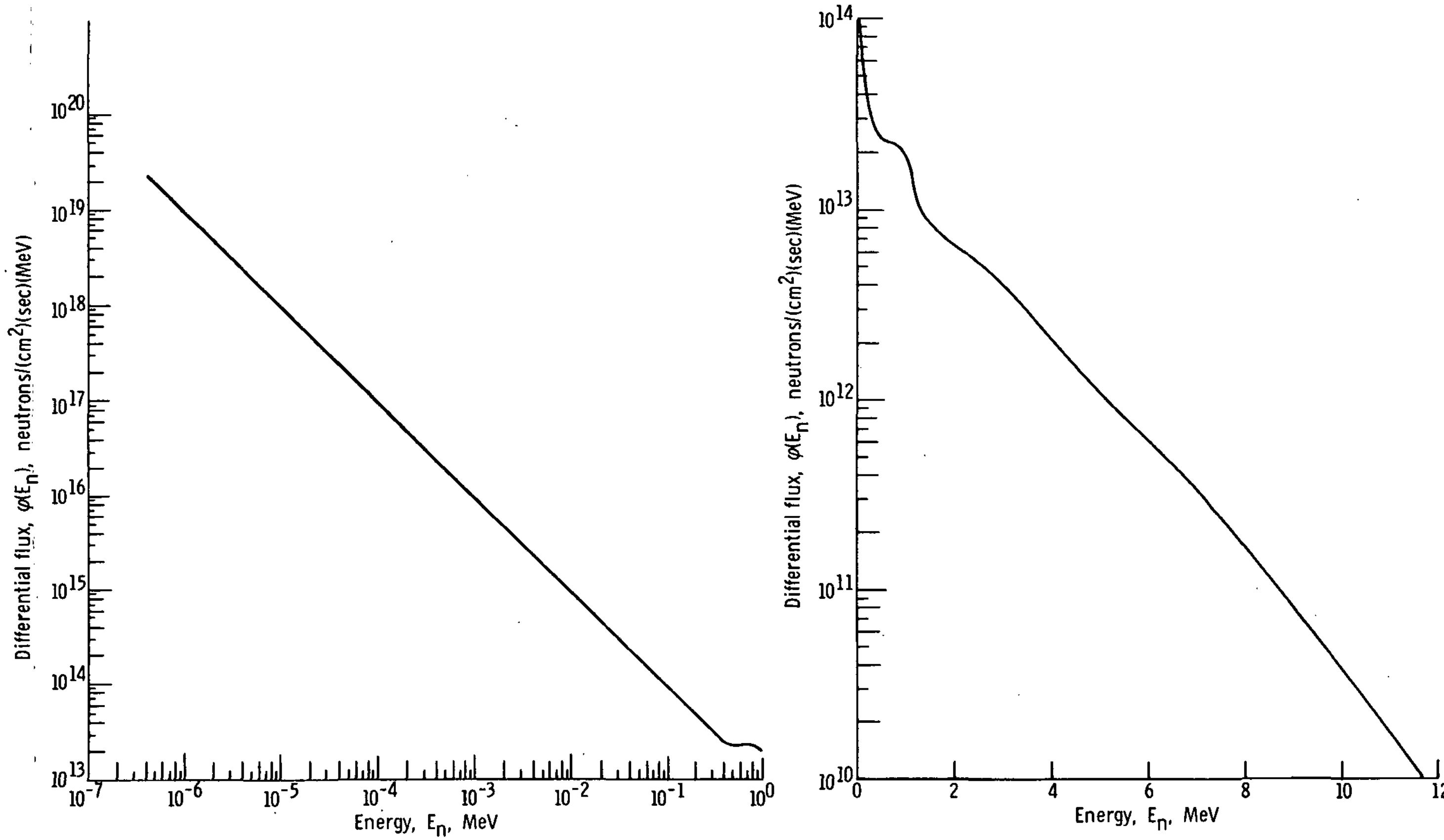


Figure 8. - Integral flux spectrum for lattice.



(a) Energies between 10^{-7} and 10^{0} MeV.

(b) Energies between 0 and 12 MeV.

Figure 9. - Differential flux spectrum for reflector.

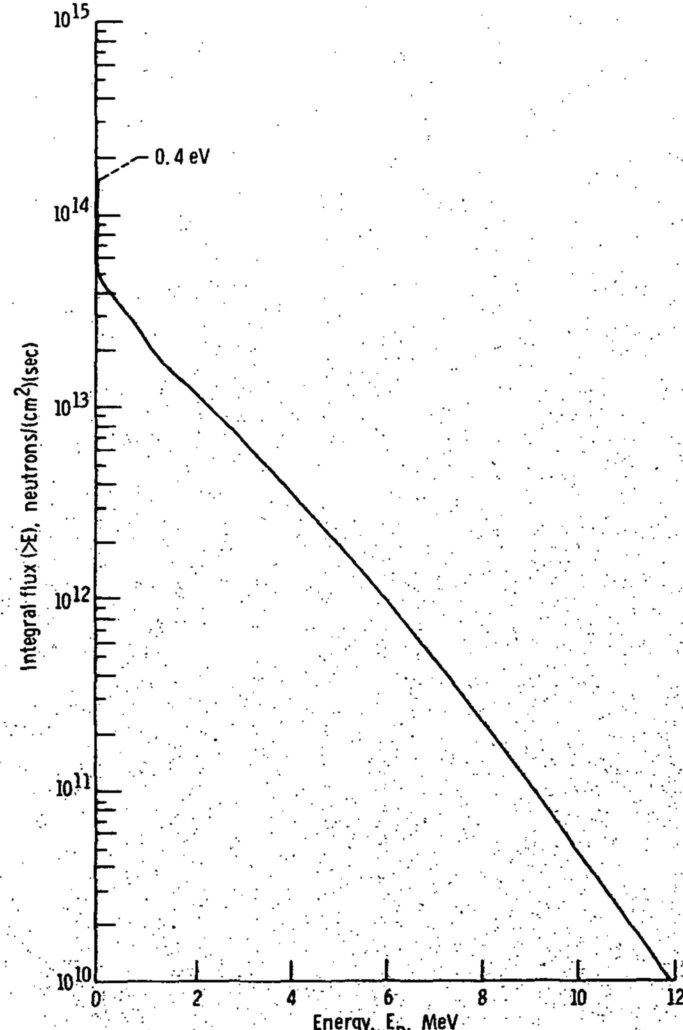


Figure 10. - Integral flux spectrum for reflector.

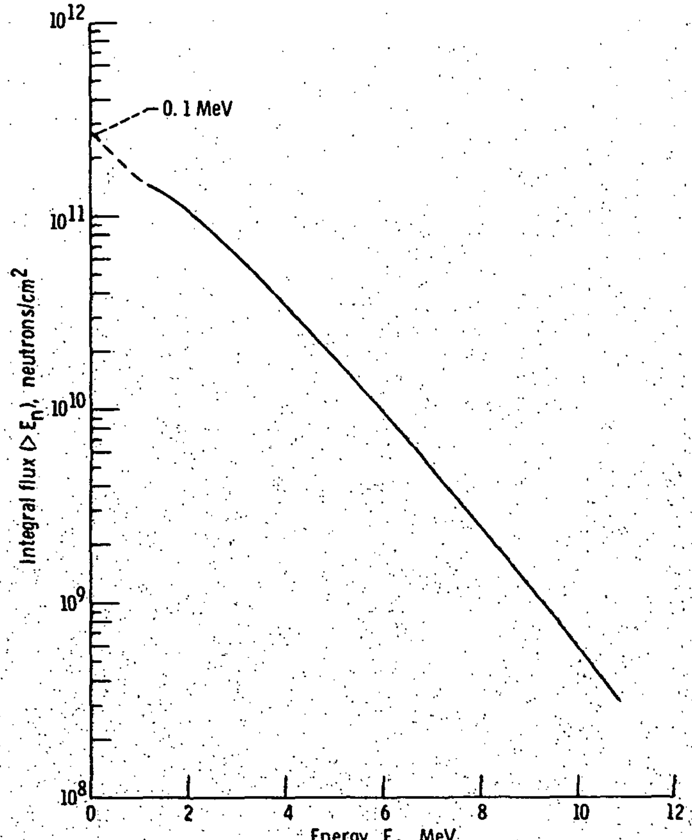


Figure 11. - Integrated neutron flux energy spectra for A-201 carbon steel irradiations.

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