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Exploratory Assessment of Postirradiation Heat-Treatment Variables in Notch-Ductility Recovery of A5333-B Steel

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ABSTRACT

Charpy-V specimens of an A533-B steel plate irradiated at 288°C to 2.4 x 10^{19} n/cm^2 > 1 MeV were used to determine the relative effectiveness of seven different heat treatments for notch ductility recovery. The plate was selected for study because of its 0.20% copper content for high radiation embrittlement sensitivity. Heat treatment temperatures were 343°, 399°, 427° and 454°C; heat treatment times were 24, 168, 336, and 425 hours.

The experimental results indicate that full recovery can be obtained in some pressure vessel steels irradiated at 288°C using a 454°C-168h anneal. However, the effectiveness of this treatment is shown to be highly material dependent. The results also demonstrate that heat treatments yielding full upper shelf recovery may not produce full transition temperature recovery. For 399° and 454°C heat treatments, notch ductility recovery with a 24h anneal was only 11° to 14°C less than the recovery produced by a 168h anneal. On the other hand, a 454°C-24h anneal was clearly superior to a 399°C-168h anneal.

Analyses of the data suggest that at least two recovery mechanisms were contributing in the temperature range investigated.

CONTENTS

LIST OF FIGURES

EXPLORATORY ASSESSMENT OF POSTIRRADIATION HEAT TREATMENT VARIABLES IN NOTCH DUCTILITY RECOVERY OF A533-B STEEL

1. INTRODUCTION

Postirradiation heat treatment (annealing) is now a well recognized metallurgical method for the alleviation of radiation-induced embrittlement in low alloy steels (Ref. 1). The method can produce significant recovery in notch ductility and fracture toughness in terms of a lowering of the brittle/ductile transition temperature and an elevation of the upper shelf level relative to as-irradiated condition properties. Laboratory tests have shown further that irradiation with intermediate annealing can result in a smaller total irradiation effect than irradiation without annealing as illustrated in Fig. 1 (Ref. 2). At present, certain commercial power reactors are looking to annealing as a means for restoring safety margins to their pressure vessel if needed. The vessels in question were constructed with plates and welds later found to have a high sensitivity to radiation embrittlement at the service temperature (~288°C). In most cases, the high radiation sensitivity was imparted by a high content of copper in the form of an impurity (≥0.2% Cu). For some steels, representative of pre-1973 vessel construction, tests have shown that projected end-of-life fluences can produce Charpy-V (C_V) transition temperature elevations (41J index) of 150°C or more (Ref. 3, 4). Likewise, C_V upper shelf levels can be reduced to below 68J (50 ft-lb), the minimum level allowed by the code for unrestricted vessel operations (Ref. 5). Annealing would be applied in-situ in order to mitigate or wholly remove the accrued irradiation embrittlement to enable the vessel to reach its design lifetime.

Application of the method to an operating vessel will require an in-depth understanding of steel response to individual annealing time-temperature combinations and secondly, a full understanding of irradiation-annealing-reirradiation (IAR) behavior of the vessel materials. This study addresses the first issue. Recent surveys indicate that available data on recovery vs. annealing time and temperature are quite limited (Ref. 6). Data are especially sparse for annealing temperatures as high as those now being considered (up to 454°C) by potential users. Objectives of the current effort were to explore recovery kinetics and to examine annealing time and temperature variables from the view of selecting best heat treatment conditions and projecting the probable result.

2. MATERIAL

The material employed for the study was a 210 mm (8.25 in.) thick plate of A533-B steel produced by Lukens Steel Company from its vacuum treated, electric furnace melt D2819. The chemical composition of the melt and the heat treatment of the plate were:

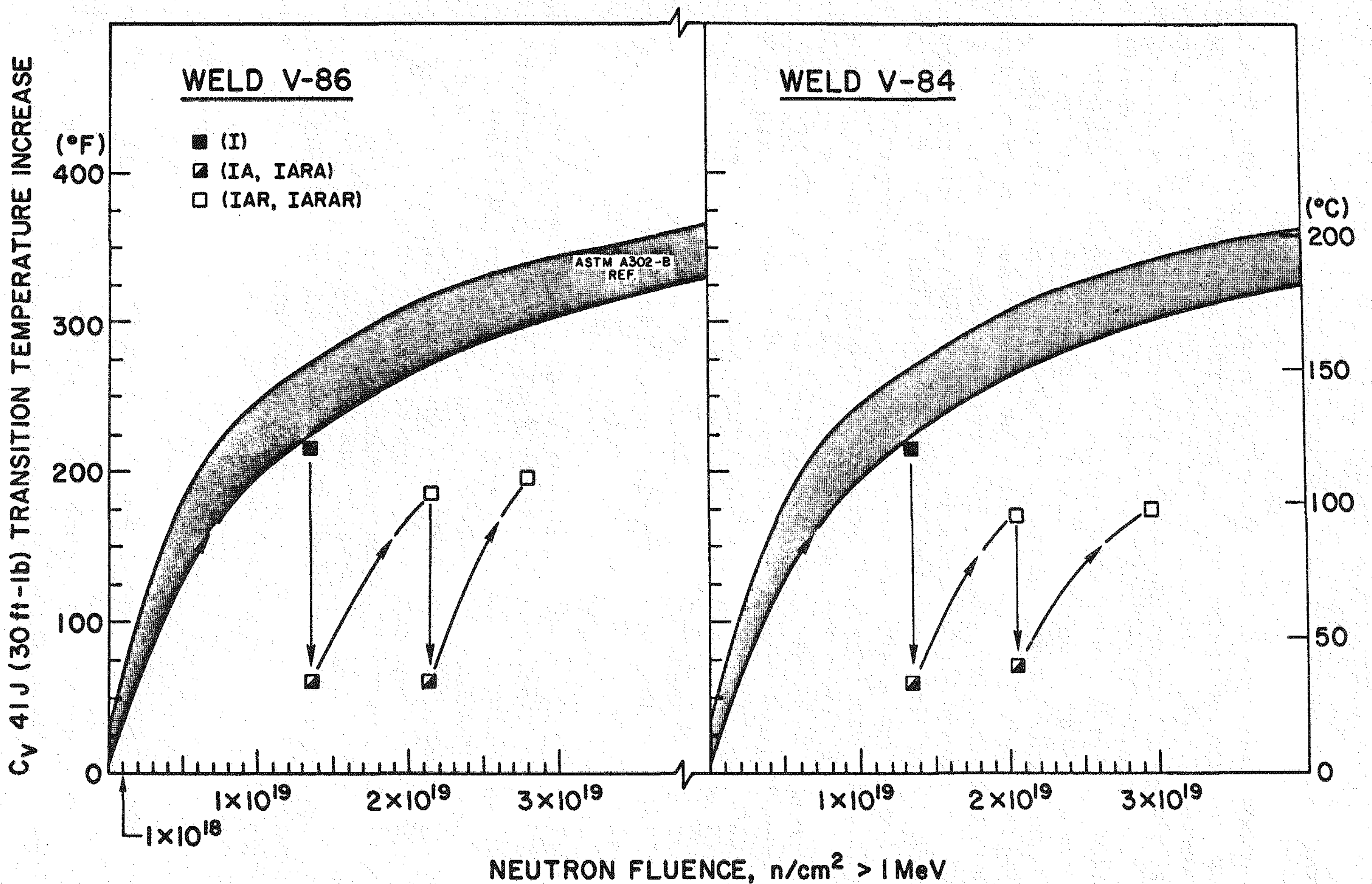

Fig. 1. Transition temperature behavior of two submerged arc welds (0.35% Cu and 0.7% Ni) with 288°C irradiatio 399°C annealing and 288°C reirradiation (two cycles). The shaded band refers to the expected data trend without intermediate annealing. Notice the smaller (total) irradiation effect when intermediate annealing was used.

Chemical Composition (Wt. %)

C	Mn	P	S	Si	Ni	Mo	Cu
.22	1.40	.010	.008	.19	.63	.54	.20

Heat Treatment

Austenitization:	885-913°C (1625-1675°F) for 0.5 h per in. (min.) and water quenched.
Tempering:	671°C (1240°F) for 0.5 h per in. (min.) and water quenched.

The plate was chosen primarily for its relatively high copper content. As stated above, copper content of 0.20% or more has a pronounced detrimental effect on 288°C radiation embrittlement resistance and has proven to be a critical factor in the high radiation sensitivity of some vessel materials. C_v specimens were taken from the quarter thickness location in the plate in the transverse (TL-weak) orientation. Specimens for preirradiation and postirradiation determinations were removed from adjacent locations to assure that initial properties were the same.

3. MATERIAL IRRADIATION

The specimens were irradiated in a single capsule in the water-cooled reactor at the State University of New York (SUNY) at Buffalo. Irradiation temperatures were controlled at 288°C ±8°C and were monitored continuously by 24 thermocouples attached to the specimens. The total irradiation time was 741 hours. The average neutron fluence was 2.4×10^{19} n/cm^2, E > 1 MeV. based on a calculated neutron spectrum (Ref. 7) and analysis of iron neutron dosimeter wires placed within the specimen array. The average fluence, E > 0.1 MeV, was 7.0×10^{19}m/cm^2. The variation in neutron fluence (min./max.) over the length of the assembly was about 13 percent. For fluence balancing across the width of the experiment, the unit was rotated 180° in the reactor core piece at mid-exposure.

4. POSTIRRADIATION TESTING AND HEAT TREATMENT

C_v specimen tests were performed using a remotized impact tester calibrated against specimen standards supplied by the Army Mechanics and Materials Research Center. Postirradiation heat treatments were performed using a recirculating air furnace. The furnace maintained specimen temperatures within ± 3°C of the set point temperature in each case. Specimens for each annealing set were chosen at random from the experiment. Heat treatment temperatures ranged from 343°C (650°F) to 454°C (850°F); annealing times ranged from 24h to 425h.

5. RESULTS

Experimental results are illustrated in Figs. 2 through 5 and are summarized in Table 1. The irradiation treatment, as noted in Fig. 2, produced a C_v 41J transition temperature elevation of 128°C (230°F) and a decrease in C_v upper shelf energy (USE) level of 45J (33 ft-lb). The magnitudes of the observed irradiation effects are consistent with the copper content and fluence level of the plate, based on earlier observations (Ref. 5).

The annealing data permit several important observations. First, heat treatment conditions capable of producing full upper shelf recovery may be incapable of producing full transition temperature recovery. This is illustrated by the 399°C-24h and the 399°C-168h data and has been seen with other steels (Ref. 2, 6). Secondly, full transition temperature recovery along with full (projected) upper shelf recovery was obtained with the 454°C-168h anneal. Note however that a 24h period at this temperature did not achieve full recovery although the difference is small. A third observation is that the difference between 24h and 168h anneals, in terms of transition recovery, is also small for the lower annealing temperature of 399°C. Lastly, the 399°C-168h anneal was almost as effective as the 427°C-168h anneal; on the other hand, the data for the 427°C-168h anneal vs. the 454°C-168h anneal show a much larger difference.

6. DISCUSSION

The effectiveness of the 454°C-168h annealing treatment observed here (full recovery) is quite different from that found by MEA for two A302-B plates irradiated in the same reactor to a slightly higher fluence (~2.6 x 10^{19} n/cm^2). In the latter case (Ref. 8), transition recovery was not 100 percent. Jointly, the findings indicate that the temperature condition for the development of full transition temperature recovery is material dependent.

The third and fourth observations listed above suggest the existence of more than one recovery mechanism. The active temperature range for one mechanism appears to extend from 343°C to 399°C or 427°C while activation of the second mechanism requires a temperature of 454°C minimum. The possibility of separate, but overlapping recovery mechanisms has been proposed by Pachur (Ref. 9) and is supported by his observations of hardness recovery trends in irradiated and annealed pressure vessel steels. The present results provide a partial experimental confirmation of the existence of multiple mechanisms. Further experimentation to isolate the phenomena is in order. Also, it is clear that the relationship of steel composition and exposure history to recovery mechanisms and their temperature ranges of activity needs more study.

Extension of the 399°C heat treatment to very long times (>3 weeks) did not result in full recovery for the A533-B steel investigated here. This observation supports earlier assumptions, based on limited data, that extension of the annealing time past 168h does not produce sufficient additional transition recovery to be worthwhile. That is, a heat treatment of 168 hours duration is about optimum for many if not most steels. For temperatures higher than 399°C, the present results suggests that a shorter annealing time, such as 96 hours, may constitute the optimum in terms of maximum benefit for that temperature.

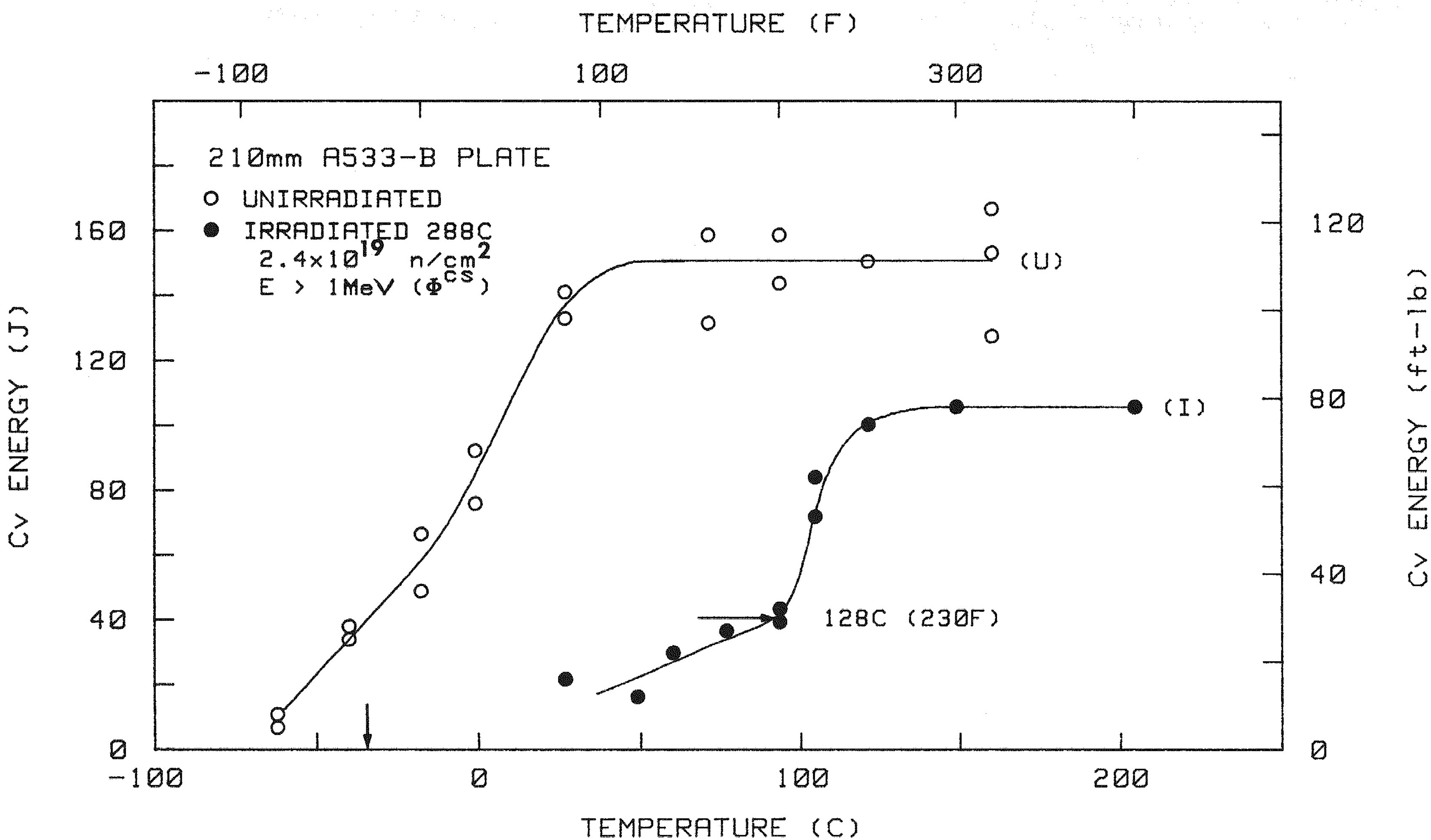

Fig. 2. Notch ductility behavior of the A533-B plate before and after 288°C irradiation. The magnitudes of the transition temperature elevation and the reduction in upper shelf energy (large) are consistent with the copper content of the plate and the fluence level.

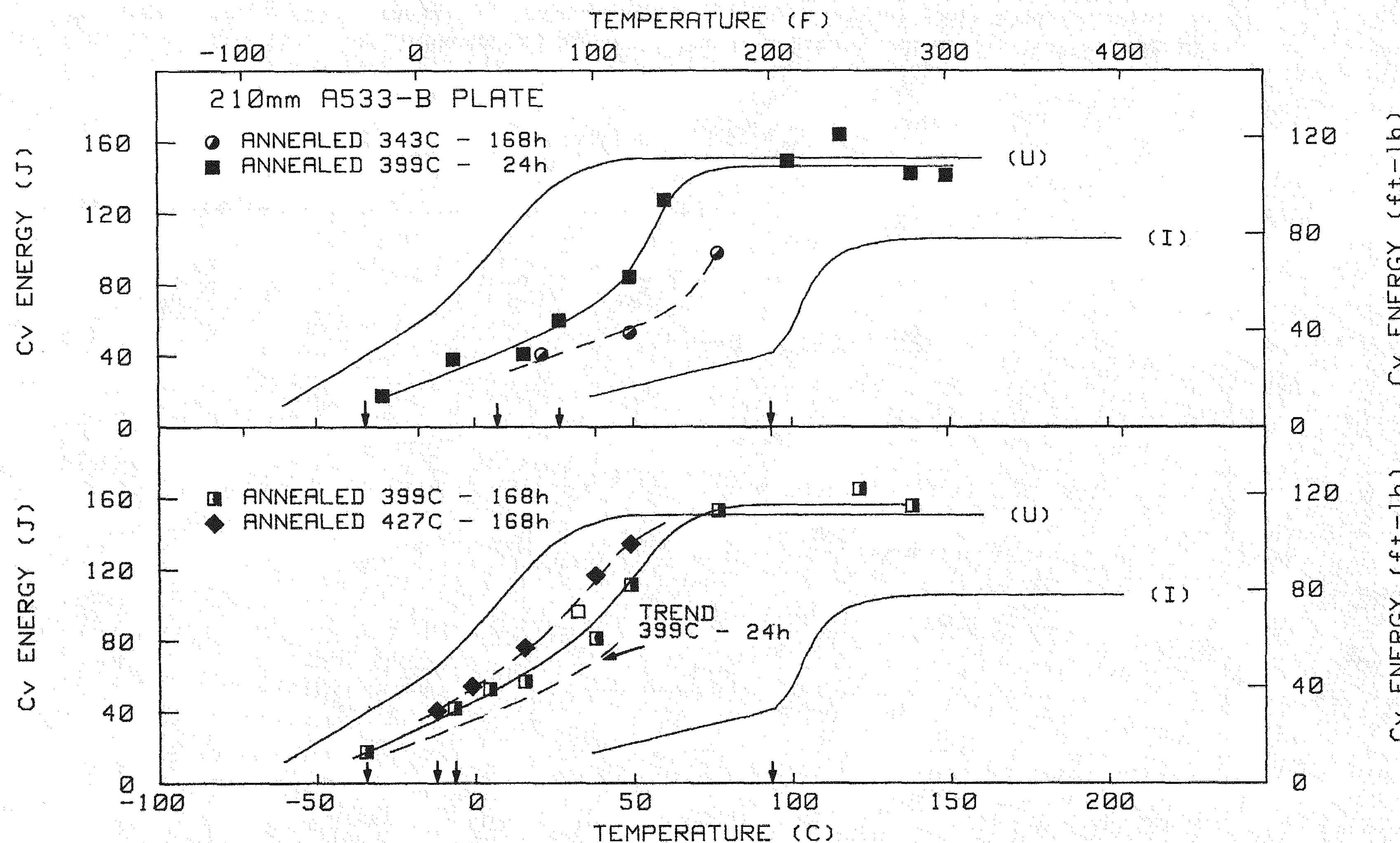

Fig. 3. Notch ductility behavior of the A533-B plate after postirradiation heat treatment at 343°C for 168h and at 399°C for 24 h (upper graph) and after postirradiation heat treatment at 399°C for 168h and at 427°C for 168h (lower graph). The trend curves for the unirradiated and as-irradiated condition are reproduced from Fig. 2 in both graphs for reference.

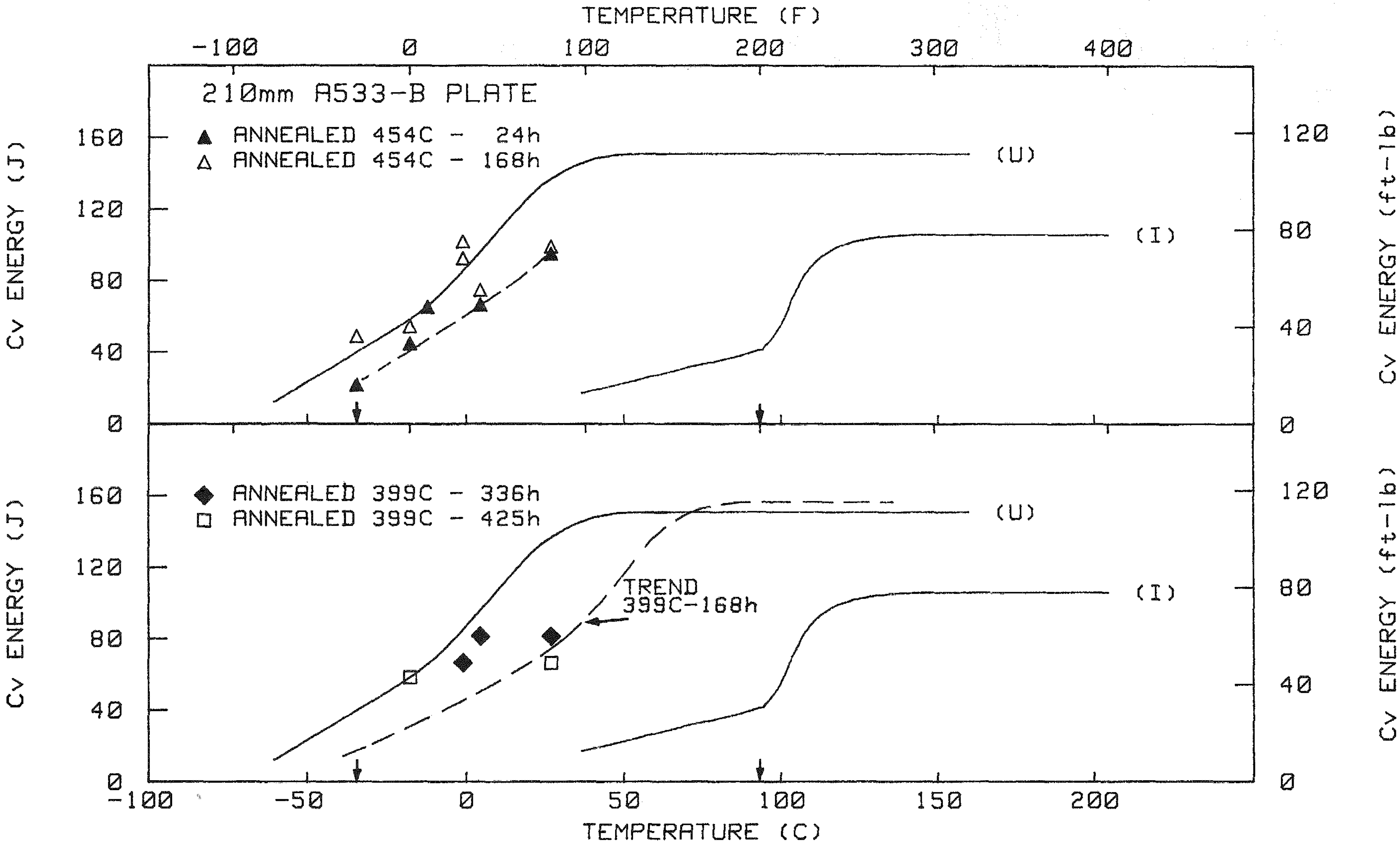

Fig. 4. Notch ductility behavior of the A533-B plate after postirradiation heat treatment at 454°C (upper graph) and after postirradiation heat treatment at 399°C (lower graph). In the upper graph the dashed line summarizes the data trend for 454°C-24h annealing. In the lower graph, the data suggest some additional recovery (small) with the extension of the heat treatment to very long times (336 hr or 425h).

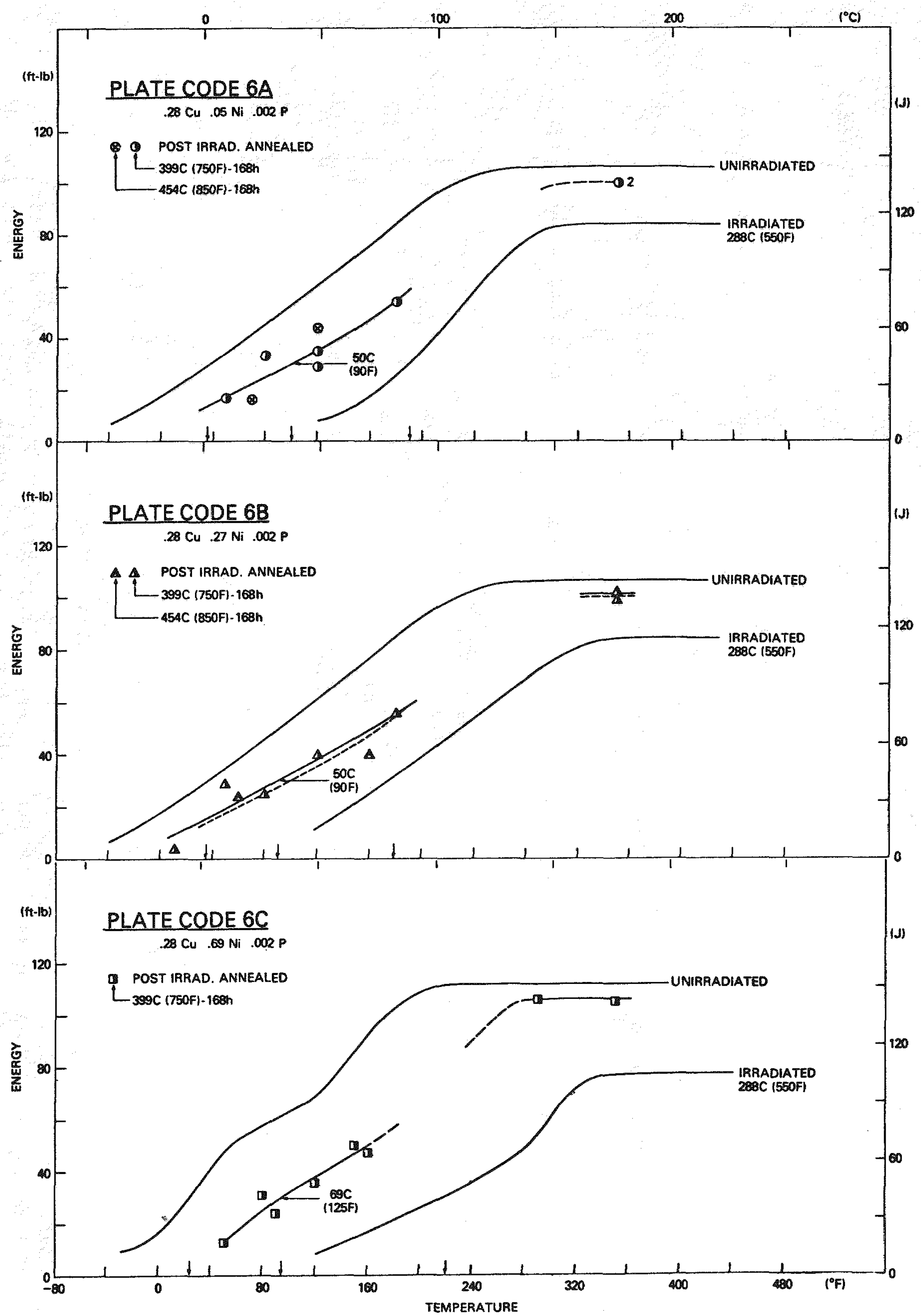

Fig. 5. Recovery in notch ductility observed for three plates of A302-B and A533-B steel after 288°C irradiation followed by postirradiation heat treatment at 399°C for 168h or by postirradiation heat treatment at 454°C for 168h. The plates were from the same 3-way split steel melt. Notice that the 454°C heat treatment did not produce full transition temperature recovery in either case.

Table 1. Charpy-V Test Results

Condition	C_v 41J Temperature				C_v Upper Shelf Energy			
	Actual		Change[a]		Actual		Change[a]	
	°C	°F	Δ°C	Δ°F	J	ft-lb	ΔJ	%
Unirradiated	-34	-30	--	--	150	111	--	--
As irradiated	93	200	128	230	106	78	45	30
Annealed 343°C-168h	27	80	67	120	(not determined)			
Annealed 399°C -24h	7	45	86	155	146	108	41	91
Annealed 399°C-168h	-7	20	100	180	156	115	>45[b]	>100[b]
Annealed 427°C-168h	-12	10	106	190	(not determined)			
Annealed 454°C-24h	-18	0	111	200	(not determined)			
Annealed 454°C-168h	-34	-30	128[b]	230[b]	(not determined)			
Annealed 399°C-336h or 425h	-7[c]	<20[c]	<100	<180	(not determined)			

[a] irradiation effect or amount of recovery by heat treatment

[b] full recovery

[c] data did not extend below 65J (40 ft-lb)

7. CONCLUSIONS

Primary observations and conclusions drawn from this study are:

- Full recovery in notch ductility can be obtained for some but not all 288°C irradiated materials by a 454°C-168 postirradiation anneal. The nature of the metallurgical dependency is not known at this time.

- Postirradiation annealing conditions producing full upper shelf recovery in 288°C irradiated materials may be incapable of concurrently producing full transition temperature recovery. A sufficiently high annealing temperature appears to be the key requirement for full transition recovery.

- For the material investigated and 399°C or 454°C annealing temperatures, a 24 hour heat treatment proved almost as effective as a 168 hour heat treatment. On the other hand, a 454°C-24h heat treatment was more effective than a 399°C-168h heat treatment.

- At least two recovery mechanisms may exist. One mechanism is active in the range of 343°C to 399°C or 427°C; activiation of the second mechanism appears to require a temperature of 454°C, minimum.

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17. KEY WORDS AND DOCUMENT ANALYSIS
A533-B Steel; Annealing; Embrittlement Relief; Low Alloy Steels; Notch Ductility; Nuclear Reactors; Pressure Vessels; Properties Recovery; Postirradiation Heat Treatment; Radiation Embrittlement.

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