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Statistical Evaluation of the Metallurgical Test Data in the ORR-PSF-PVS Irradiation Experiment

F. W. Stallmann

Prepared for the
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

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ABSTRACT

A statistical analysis of Charpy test results of the two-year Pressure Vessel Simulation metallurgical irradiation experiment was performed. Determination of transition temperature and upper shelf energy derived from computer fits compare well with eyeball fits. Uncertainties for all results can be obtained with computer fits. The results were compared with predictions in Regulatory Guide 1.99 and other irradiation damage models.

INTRODUCTION

The two-year Pressure Vessel Simulator (PVS) metallurgical irradiation experiment at the Oak Ridge Research Reactor (ORR) Poolside Facility (PSF) was performed in order to simulate, as closely as possible, the irradiation conditions in commercial reactor pressure vessels and surveillance capsules. Of primary interest was the question whether results obtained from surveillance capsule evaluations in commercial power reactors can safely be extrapolated. Since there are considerable differences in fluence rate and fluence spectrum between the pressure vessel wall and the surveillance capsules, possible effects of these factors on the irradiation damage need to be investigated. The magnitude of these effects, if any, may also be different for different types of materials, e.g., plate material vs. welds or between materials of different chemical compositions. In order to answer these questions, five capsules were irradiated in the PSF-PVS experiment, each containing metallurgical specimens of the same mix of plate and weld materials. Two of the capsules received high-fluence rates, characteristic of surveillance capsules (SSC-capsules), and the other three were irradiated to about the same total fluence but at lower fluence rates and over a longer time period (two years vs. one to two months). For a more detailed description, see Refs. 1 and 2.

In order to detect possible effects of fluence rates and spectra, a very high accuracy of the test results is required since these effects are likely to be subtle. In addition, reliable estimates of the uncertainties must be known in order not to confuse random fluctuations with physical effects. A careful statistical evaluation of the test results is therefore necessary. This includes both the determination of damage fluences and of the change in metallurgical properties. The determination of damage exposure parameter values, fluence > 1.0 MeV, fluence > 0.1 MeV, and dpa of iron, has been described elsewhere.[3] The resulting exposure parameter values are given to an accuracy better than 10% (1σ) and are used in this report. The raw Charpy test data from Ref. 1 were used for the statistical evaluation of material property changes. Other material test data (CT specimens, tensile, and compression tests) will be included in a later investigation. The primary data for assessing property damage are the changes in nil ductility temperature (NDT) and upper shelf energy. These data are obtained by fitting a suitable curve through the energy vs. test temperature plots. Eyeball fittings were used in Ref. 1. Such fits give usually reliable results, if done by an experienced investigator. It is, however, impossible to assign uncertainties to such fittings, and ambiguous cases may also depend too much on human judgment. Computer fitting has been used more recently for some investigations, primarily the hyperbolic tangent.[4] However, not all data sets fit comfortably into such a model and uncertainties may be underestimated because of the inflexibility of the model. In this report, a method was used, which was first described in Ref. 5. The method has since been generalized to include non-linear functions and is still under active development. A detailed description of the procedure is given below.

The procedure was first used to determine the NDT values at 41J (30 ft-lb), 68J (50 ft-lb), and at 0.89-mm lateral expansion for each set of specimen in the different capsules. The values obtained in this way are mostly very close to the eyeball fits in Ref. 1, and none deviated more than could be expected from the statistical uncertainties (see Tables 4 and 5). The upper shelf energy, including uncertainties, was also determined and compared to eyeball fits, with similar results (Table 6).

The same statistical procedure can be used to combine results of irradiation at different fluences and fit them to a model which relates NDT shift to a power of fluence. Several power law fits were tried involving different exposure parameters ($\phi t > 1$, $\phi t > 0.1$, dpa) and different exponents (0.3 and 0.5). None of the fits were good enough to agree with all individual measurements within uncertainties (Table 9). Attempts were also made to fit only the data from a combination of unirradiated specimen and at one or both of the SSC capsules to a power law in order to predict the results obtained in the wall capsules, as it may be done for damage predictions in commercial power reactors. The results (Table 10) could be considered acceptable for such predictions provided sufficient safety margins are imposed.

A more detailed investigation of the individual results shows, however, that the relation between fluence and damage is much more complex than a simple power (Figs. 1-6). There are definite, though subtle, differences between the short-time, high-fluence rate irradiations in the SSC capsules and the long-time, low-fluence rate irradiations in the wall capsules. These effects appear to be material dependent not only in terms of the absolute damage but also in terms of rate of changes as a function of fluence.

For this reason, no efforts have been made to fit the data to models which correlate damage with chemical composition such as the content of copper and/or nickel. No simple (e.g., bilinear) relation can adequately describe the relation between, say, copper and nickel content and ΔNDT, and there is not enough variety of test data available from this experiment to explore more complex models.

COMPUTATIONAL PROCEDURES

The procedure used in this report is an extension and refinement of the method in Ref. 5. The current program package, named CV-81, is a linear, least squares procedure, although linear combinations of nonlinear functions can be used. This method differs from the standard linear or non-linear regression analysis by allowing statistical errors not only in the dependent variables, but also in all independent variables. This means that the data are fit to a given model by adjusting all input data according to their statistical uncertainties to obtain maximum likelihood estimates for the fitting parameters assuming a Gaussian distribution. This procedure assumes that variances and covariances of all input data are known in advance and are not determined from the goodness of fit, as it is often done in standard least squares fitting procedures. For the calculations in this report, it was assumed that the test temperature was accurate to ±2°C (1σ), the Charpy energy to ±15J, and the laterial expansion to ±2 mm. The latter two figures are not primarily based on the measuring precision but are a measure for the variability within the material. In other words, if a large number of Charpy specimen of the same material are broken at the same test temperature, the statistical distribution of the results is assumed to be Gaussian with a sigma of 15J or 2 mm, respectively. This is a rather crude and, probably, conservative estimate, since the actual value depends very much on the homogeneity of the material. However, not having any data for a direct determination of the variance, an over-estimate gives at least a conservative determination of the output uncertainties without noticeably affecting the goodness of fit.

A measure for the appropriateness of the input uncertainties is given through the value of chi-square divided by the number of degrees of freedom (X^2/F). This value is expected to be one, although large fluctuations occur for small sample sizes. An X^2/F value which is much smaller than one indicates an over-estimation of the input uncertainties, an X^2/F value larger than one signifies under-estimation of variances or inconsistencies in the input data. Both cases can be found in Tables 3-5, although smaller values are more common. Even the larger values are not outside the expected fluctuation for X^2, due to small sample sizes.

In order to determine the NDT at 41J or 68J, only those test data were used for the fit which are in the transition region. A linear fit can then be used instead of the hyperbolic tangent or similar models used in other computer fitting procedures. Test data from either the upper or lower shelf region do not carry any information about NDT but may nevertheless influence its determination and uncertainties if included in the fit. The selection of data as belonging to the transition region introduces a certain element of arbitrariness in the fitting procedure. This is, however, not all bad, since it gives the needed flexibility by adding human experience to a preconceived formalism. Several selection criteria were tried; all agreed within statistical uncertainties. However, the uncertainties decrease if more points are added to the fit. In some cases, most notably for the A302-B plate and the 22NiMoCr37 forging, a quadratic instead of the linear fit may be more appropriate. Implementing quadratic fits requires a slight change in the computer program and is, for this reason, not included in this report but will be tried later. No substantial changes are expected in ΔNDT if the linear fits are replaced by quadratic ones.

Upper shelf energies were also determined by linear fits using only data from the upper shelf. Possible slopes of the upper shelf were not found to be statistically significant and, therefore, ignored. In some cases, only one or two points were tested at the upper shelf rregion, resulting in large uncertainties.

The CV-81 procedure allows one to combine unirradiated and irradiated specimen and fit the shifts of NDT or upper shelf to a power of fluence.

This was done for a variety of damage parameters and exposures. The results are discussed below.

RESULTS

Six different materials were contained in each of the six irradiation capsules. These were the A-302-B and A-533-B plate materials, the 22NiMoCr37 and the A-508-3 forgings, and two submerged arc welds, codes EC and R, respectively. Summaries of the materials properties and chemical composition are given in Tables 1 and 2. They were irradiated in two simulated surveillance capsules, SSC1 and SSC2, to nominal fluences (ϕ > 1.0 MeV) of 2 and $4 \cdot 10^{19}$ n/cm^2, respectively, and in three wall capsules corresponding to the inner surface (0-T) and quarter and half thicknesses (1/4 T and 1/2 T), to nominal fluences of 4, 2, and $1 \cdot 10^{19}$ n/cm^2, respectively. The actual fluences received vary from specimen to specimen but are generally within $\pm$10% of the mean for each group of specimen. The mean values are listed in Table 3. (For more details, see Ref. 3.) The raw Charpy test data, both from irradiated and unirradiated specimens, are published in Ref. 1. These were processed by a generalized Charpy Fitting Code CV81 as described above. NTD values were determined at 41J (30 ft-lb), 68J (50 ft-lb), and at 0.89-mm lateral expansion. These values were obtained for each group of specimen in each irradiation capsule and for the unirradiated specimen. The results are summarized in Tables 4 and 5. Only data from the transition region were chosen for this evaluation. This was done by excluding test data with energies above 80% of the maximum Charpy energy and restricting the temperature range so that exceptionally low values from the upper shelf are excluded. The remaining points are then fitted to a straight line whose intersection with the 41/68J or 0.89-mm point determines the corresponding transition temperatures. These values are, in some cases, above the upper shelf level and are then, of course, meaningless. The results are most reliable if data points are both above and below the transition point and preferably clustered around this point. Exceptions in which all data points are either below or above the transition point are noted in the table.

Upper shelf values (see Table 5) are similarly obtained by restricting the data points to temperatures above the transition region, leaving some intermediate data points in the "no man's land." Since no slopes of the upper shelf could be detected, the upper shelf values are simply the energy averages for the selected data sets. Most sets included only very few data points which accounts for the relatively large uncertainties in Table 6. The SSC1 data for the A302-B plate appear to have two different upper shelf levels for the left and right side of the capsule. These are also from two different layers of the plate which seems to be the reason for the difference since the irradiation conditions are almost identical.

The computer-derived values in Tables 4 through 6 agree very well with the determinations of the Materials Engineering Associates, Inc.'s (MEA) report. There are a few instances where statistical and "intuitive" values differ, but these are ambiguous cases and the differences are not large.

CORRELATION BETWEEN FLUENCE AND DAMAGE

Table 7 summarizes the changes in transition temperature and upper shelf energy as calculated from the individual fits. The uncertainties are combinations in the sum-of-squares sense. These values are compared in Table 8 with predictions prescribed by the NRC Reg. Guide 1.99. Additional comparisons were made with planned revisions of the Reg. Guide which are published in the Minutes of the January 1984 ASTM E10.02 Subcommittee Meeting.[6] Results are given in °F, since both the old and the revised Reg. Guides are given in this temperature scale. The 41J NDT values were used for comparison, since the other values are not available for some specimen, although the Reg. Guide specifies 68J or 0.89 mm. The present Reg. Guide is based on a chemistry factor multiplied by the square root of a fluence term $f = [\phi t > 1.0 \text{ MeV } 10^{19}/\text{neutrons/cm}^2]$. This fluence dependency does not agree with materials test data bases. The revised formula is based on work by G. L. Guthrie[7] on 177 data points of power reactor surveillance results. The fluence dependency is given as $f^{(0.28-0.10 \log f)}$, where f is the same fluence term. The term f can also be given in units of dpa, namely f = dpa/0.0162, according to a private communication by G. L. Guthrie. The term $[f = \phi t > 0.1 \text{ MeV}]/3.71$ neutrons/cm^2, based on the average $\phi t > 0.1/\phi t > 1.0$ ratio, was also tried, in order to determine whether the choice of different damage parameters improves the predictions.

As can be seen in Table 8, the predictions of the revised Reg. Guide are more uniform, although less conservative, than the old predictions. The nickel values of weld code R are outside the table for the revised Reg. Guide, so that extrapolation was necessary. The prediction is still much too low, which places this material in a separate category. No large differences are found in the predictions based on different damage parameters. However, $\phi t > 0.1$ MeV gives consistently the least uniform prediction. In any event, the comparisons in Table 3 show that even the revised prediction formula gives only rather crude estimates, and fairly large safety margins are needed if the prediction is based on fluence and chemistry alone. Further sophistication is unlikely to improve the situation by much. The reason is that other factors, such as heat treatment, influence the irradiation embrittlement, leading to large data scatter in the data bases.[7]

Embrittlement predictions for reactor pressure vessels are not necessarily made on the basis of the Reg. Guide. Tests on metallurgical specimen in the surveillance capsules provide additional information, and it is resonable to expect that the surveillance data can be used for a more reliable prediction of radiation damage. In order to do this, a functional relation between fluence and damage must be established first, since the pressure vessel is exposed to a wide range of fluences which may be different from those in the surveillance capsule. Secondly, there may be differences in damage between surveillance capsule and pressure vessel because of differences in fluence rate and neutron spectrum. To answer the first question, least squares fits were performed to the Charpy data relating NDT to powers 0.5 and 0.3 of the fluence. The CV-81 procedure can perform this task using the raw Charpy data taking into account individual differences in fluence. The results are listed in Table 9. As can be expected from Guthrie's formula, the exponent 0.3 gives the better fit. There are no significant differences in the goodness of fit for the different exposure parameters. Dpa was chosen for the subsequent investigation, since it is based on a physical, though very much simplified, damage mechanism.

In Table 10, the fluence function $(dpa)^{.3}$ was fitted to sets of test specimen consisting of

1. all sets of a particular material

2. wall capsules only

3. SSC1 capsule plus unirradiated specimen

4. SSC1 and SSC2 capsules plus unirradiated specimen.

The NDT shifts resulting from these fits were calculated for the average dpa values received by the corresponding sets in the different irradiation capsules and compared to the NDT shifts obtained from individual fits in Table 4. Uncertainties for fits obtained from multiple sets are not listed in this table. The calculation, though possible, is rather time consuming. Moreover, all multiple set uncertainties are smaller than the ones for individual fits because of the larger data sets involved.

The fits 3 and 4 are used to predict the NDT shifts from individual fits and the differences are listed. These predictions simulate predictions in the pressure vessel wall based on surveillance specimen and are substantially better than those obtained from the Reg. Guide 1.99 (Table 8). They should be acceptable for embrittlement predictions in pressure vessels. Inclusion of SSC2 improves the prediction only for the two forgings and not much even there. Differences in the fits between sets 2 and 4 point to differences in the irradiation damage at different fluence rates. The differences are mostly slight, not exceeding the uncertainties and appear to be material dependent. These differences are more clearly seen in the graphs in Figs. 1-6, where the shifts of NDT and upper shelf energy are plotted in the log-log scale against dpa. These graphs show that a single power law with a fixed exponent cannot be used as an universally valid description of the correlation between fluence and damage. The slopes in these graphs are different for different fluences, different fluence rates (SSC vs. wall), and different materials. An explanation for this different behavior, if at all possible, can only be given by more detailed theoretical studies and verification through results from a larger number of irradiation experiments in test reactors and surveillance capsules.

It should be noted that the fluence rates and irradiation times in the SSC1 and SSC2 capsules are quite different from those in surveillance capsules and more typical of test reactor irradiations. Thus, the predictions in Table 10 may not be representative of predictions of pressure vessel wall embrittlement from surveillance results, although the latter may actually be more reliable. The larger discrepancies in the weld code R are probably due to the large absolute shifts and may not represent a qualitatively different behavior. Check of the irradiation temperature history shows[8] that the specimen of code EC in the SSC2 capsule were exposed to an irradiation temperature of about 300°C, which is 12°C higher than the nominal temperature of 288°C. Thus, the NDT shift at 288°C for these specimen should be higher than the value of 123°C, although it is impossible to say by how much. This brings this particular NDT shift more in line with the other measurement. No other irradiation temperature anomalies were found.

CONCLUSIONS

Statistical analysis of materials test data from irradiation experiment is necessary in order to arrive at reliable conclusions from such experiments. Computer fitting of Charpy data is desirable and feasible provided sufficiently flexible fitting models are used. The evaluation of the PSF metallurgical experiment shows that damage prediction on the basis of chemistry and fluence alone, such as the Reg. Guide 1.99, is not very reliable since individual differences in the material generate large data scatter. Prediction on the basis of test results for a given material in surveillance capsules or test reactors are much more reliable and are sufficient for practical applications. The accurate evaluation of materials test results with uncertainties provides also the opportunity for more detailed studies of the damage mechanism and for testing damage models.

REFERENCES

1. J. R. Hawthorne and B. H. Menke, Light Water Reactor Pressure Vessel Surveillance Dosimetry Improvement Program: Postirradiation Notch Ductility and Tensile Strength Determinations for PSF Simulated Surveillance and Through-Wall Specimen Capsules, NUREG/CR-3457, MEA-2026, U.S. Nuclear Regulatory Commission, Washington, DC, 1983.

2. J. R. Hawthorne, B. H. Menke, and A. L. Hiser, Light Water Reactor Pressure Vessel Surveillance Dosimetry Improvement Program: Notch Ductility and Fracture Toughness Degradation of A 302-B and A 533-B Reference Plates from PSF Simulated Surveillance and Through-Wall Irradiation Capsules, NUREG/CR-3295, MEA-2017, U.S. Nuclear Regulatory Commission, Washington, DC, 1983.

3. F. W. Stallmann, Determination of Damage Exposure Parameter Values in the PSF Metallurgical Irradiation Experiment, NUREG/CR-3814, ORNL/TM-9166, U.S. Nuclear Regulatory Commission, Washington, DC, 1984.

4. W. Oldfield, "Fitting Curves to Toughness Data," Journal of Testing and Evaluation, JTEVA, Vol. 7, No. 6, 1979, pp. 326-333.

5. F. W. Stallmann, Curve Fitting and Uncertainty Analysis of Charpy Impact Data, NUREG/CR-2408, ORNL/TM-8081, U.S. Nuclear Regulatory Commission, Washington, DC, 1982.

6. P. N. Randall, "Regulatory Position," Attachment to the Minutes of the ASTM E10.02 Meeting, (draft), San Diego, CA, January 1984.

7. G. L. Guthrie, "Charpy Trend Curves Based on 177 PWR Data Points," LWR-PV-SDIP Quarterly Progress Report, April - June 1983, NUREG/CR-3391, Vol. 2, NRC, Washington, DC, 1983.

8. W. N. McElroy et al., "Pressure Vessel Benchmark Facility for LWR Metallurgical Testing of Reactor Pressure Vessel Steels (ORR-PSF)," LWR-PV-SDIP Quarterly Progress Report, April 1982 - June 1982, NUREG/CR-2805, Vol. 2, NRC, Washington, DC, 1982.

Table 1. Materials

Material	Heat code	Supplier	Thickness (mm)	Yield[a] strength (MPa)	Heat treatment
A302-B (ASTM reference plate)	F23	NRL	152	482	899°C-6 h, water quenched 649°C-6 h, air cooled
A533-B (HSST plate 03)	3PS, 3PT, 3PU	NRL	305	454	843-899°C-4 h, water quenched 649-677°C-4 h, air cooled 607-636°C-20 h, furnace cooled
22NiMoCr37 forging	K	KFA	295	407	Not reported to MEA or ORNL
A508-3 forging	MO	MOL	238	462	900-955°C-12.8 h, air cooled 630-665°C-14 h, furnace cooled 610°C >10°C-24 h, furnace cooled
Submerged arc weld (single vee type, A533-B base plate)	EC	EPRI	235	456	621°C ± 28°C-50 h, furnace cooled
Submerged arc weld (single vee type, A533-B base plate)	R	Rolls-Royce & Assoc., Ltd.	160	489	920°C ± 15°C-6 h, water spray quenched 600°C-6 h, air cooled 600°C-36 h, air cooled 650°C-6 h, air cooled

Table 2. Chemical compositions (wt-%)

Material	Code	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Sn	Ti	V
A302-B (ASTM Ref. Plate)	F23	0.24	0.23	1.34	0.011	0.023	0.11	0.51	0.18	0.04	0.20	0.037	0.015	0.001
A533-B (HSST Plate 03)	3PS, 3PT, 3PU	0.20	0.25	1.26	0.011	0.018	0.10	0.45	0.56	----	0.12	-----	-----	-----
22NiMoCr37 Forging	K	0.18	0.16	0.72	0.009	0.004	0.45	0.63	0.96	0.031	0.12	-----	-----	-----
A508-3 Forging	MO	0.20	0.28	1.43	0.008	0.008	----	0.53	0.75	0.031	0.05	-----	-----	>0.1
A533-B S/A Weld	EC	0.11	0.52	1.57	0.007	0.011	0.02	0.48	0.64	0.008	0.24	0.004	<0.01	0.005
A533-B S/A Weld	R	0.05	0.45	1.54	0.009	0.008	0.12	0.34	1.58	0.01	0.23	0.006	0.003	0.01

Table 3. Average fluences for the different sets of Charpy specimens

Pos.	F23	3PT/3PU	K	MO	EC	R
	Material code					
	$\phi t > 1.0$ (10^{19} n/cm^2)					
SSC1	2.59	2.32	1.75	1.93	1.87	2.46
SSC2	5.38	4.83	3.64	4.02	3.90	5.13
0-T	3.95	3.59	2.71	2.95	2.88	3.81
1/4 T	2.16	1.95	1.47	1.60	1.60	2.12
1/2 T	1.03	0.94	0.71	0.77	0.77	1.02
	$\phi t > 0.1$ (10^{19} n/cm^2)					
SSC1	7.46	6.61	5.69	6.32	6.11	7.07
SSC2	15.35	13.63	11.70	13.02	12.59	14.56
0-T	11.44	10.20	8.77	9.65	9.45	10.97
1/4 T	8.13	7.13	6.11	6.84	6.82	7.95
1/2 T	5.27	4.60	3.97	4.45	4.48	5.21
	dpa (10^{-2})					
SSC1	3.86	3.44	2.77	3.07	2.97	3.66
SSC2	7.96	7.11	5.72	6.34	6.14	7.57
0-T	6.06	5.46	4.40	4.80	4.71	5.83
1/4 T	3.70	3.28	2.64	2.92	2.92	3.62
1/2 T	2.11	1.87	1.51	1.67	1.68	2.09

Table 4. NDT values determined at 41J (30 ft-lb) and 68J (50 ft-lb), respectively

	χ^2	41J NDT (°C)	Std. dev. (°C)	41J-NDT MEA (°C)	68J NDT (°C)	Std. dev. (°C)	68J-NDT MEA (°C)
A-302-B							
Unirr.	0.1	-6	± 9	-4	24	±13	21
SSC1	0.2	72	± 8	78	108	±12	99
SSC2	0.3	88	± 8	90	(125)*	±20	104
0-T	0.2	71	± 7	77	(111)	±17	96
1/4 T	0.3	59	±18	63	(133)	±83	85
1/2 T	0.02	46	± 8	46	(81)	±15	77
A-533-B							
Unirr.	0.2	-5	± 6	-1	23	± 6	24
SSC1	0.7	66	± 8	60	94	±11	88
SSC2	0.4	79	± 8	80	109	± 8	107
0-T	0.2	66	±13	74	(115)	±24	102
1/4 T	0.3	64	± 6	68	88	± 5	93
1/2 T	0.2	47	± 7	52	75	± 6	79
22NIMOCR37							
Unirr.	2.5	-79	±17	-65	-55	± 5	-57
SSC1	0.9	(-27)	±14	-4	2	± 8	4
SSC2	1.4	30	± 8	29	59	± 6	49
0-T	1.1	2	±11	7	35	± 6	29
1/4 T	1.2	-13	±14	13	27	± 8	24
1/2 T	0.7	-13	± 7	-9	16	± 5	13
A-508-3							
Unirr.	1.8	-58	± 4	-54	-43	± 3	-45
SSC1	3.6	-43	± 4	-34	-30	± 3	-29
SSC2	1.0	-19	± 5	-15	-5	± 3	-6
0-T	0.3	-31	± 3	-29	-19	± 2	-20
1/4 T	0.5	-35	± 4	-34	-23	± 3	-26
1/2 T	3.1	-36	± 5	-40	-19	± 3	-34
Submerged arc weld (EC)							
Unirr.	0.14	-20	± 8	-18	30	±17	21
SSC1	0.02	92	±32	90	(196)	±120	-
SSC2	0.05	103	±60	101	(187)	±60	-
0-T	0.08	105	±50	96	(194)	±171	-
1/4 T	0.12	76	±16	76	(148)	±59	-
1/2 T	0.10	74	±19	71	(145)	±65	-
Submerged arc weld (R)							
Unirr.	1.2	-89	± 5	-79	-63	± 3	-68
SSC1	0.05	141	±11	143	196	±21	188
SSC2	0.06	220	±38	210	(308)	±100	-
0-T	0.11	205	±15	207	(273)	±40	-
1/4 T	0.13	181	±25	177	(265)	±74	210
1/2 T	0.2	156	±44	160	(231)	±44	199

*Values in parentheses are obtained by extrapolation and may be unreliable.

Table 5. NDT values determined at 0.89-mm lateral expansion

	χ^2	NDT 0.89 mm (°C)	Std. dev. (°C)	NDT 0.89 mm MEA (°C)
A-302-B				
Unirr.	0.08	8	6	7
SSC1	0.3	94	8	97
SSC2	0.5	100	8	99
0-T	0.3	(95)*	15	90
1/4 T	0.3	(80)	14	74
1/2 T	0.06	64	8	63
A-533-B				
Unirr.	2.4	2	5	13
SSC1	0.8	87	8	82
SSC2	0.4	93	5	99
0-T	0.2	93	9	93
1/4 T	0.8	76	4	85
1/2 T	0.4	59	5	66
22NIMOCR37				
Unirr.	3.0	-61	6	-59
SSC1	2.3	15	4	7
SSC2	0.7	56	6	49
0-T	1.2	36	4	24
1/4 T	4.2	32	6	24
1/2 T	0.7	13	5	10
A-508-3				
Unirr.	1.1	-48	4	-45
SSC1	3.4	-30	3	-29
SSC2	1.6	-10	3	-6
0-T	0.5	-22	3	-20
1/4 T	0.8	-25	3	-26
1/2 T	3.5	-29	4	-34
Submerged arc weld (EC)				
Unirr.	0.4	-8	8	-9
SSC1	0.05	(136)	34	110
SSC2	0.3	130	17	113
0-T	0.07	(163)	66	113
1/4 T	0.1	(110)	20	105
1/2 T	0.1	(121)	42	105
Submerged arc weld (R)				
Unirr.	1.8	-69	3	-73
SSC1	0.2	191	17	185
SSC2	0.2	(283)	64	-
0-T	0.06	(295)	56	-
1/4 T	0.2	(252)	58	205
1/2 T	0.2	201	22	194

*Values in parentheses are obtained by extrapolation and may be unreliable.

Table 6 Summary of upper shelf evaluations

	χ^2	Upper shelf energy (J)	Std. dev. (J)	MEA determination (J)
A-302-B				
Unirr.	0.14	107	± 5	108
SSC1	0.5	84	± 8	86 (77/94)
SSC2	0.04	74	± 7	75
0-T	0.2	82	± 8	80
1/4 T	0.3	78	± 8	81
1/2 T	0.04	81	± 8	81
A-533-B				
Unirr.	0.4	147	± 7	150
SSC1	0.4	119	± 8	115
SSC2	0.11	107	±11	106
0-T	0.06	105	±11	106
1/4 T	3.6	107	±11	-
1/2 T	0.13	125	± 9	125
22NIMOCR37				
Unirr.	0.08	204	±11	203
SSC1	0.6	157	±11	160
SSC2	0.04	135	±11	135
0-T	0.14	161	±11	161
1/4 T	0.01	156	±11	156
1/2 T	0.2	164	± 9	164
A-508-3				
Unirr.	5.2	237	± 8	212
SSC1	0.14	205	±11	205
SSC2	0.04	200	±11	201
0-T	1.6	208	± 9	219
1/4 T	0.06	230	±11	233
1/2 T	0.8	211	±11	211
Submerged arc weld (EC)				
Unirr.	0.04	90	± 6	92
SSC1	0.08	57	±11	58
SSC2	1.1	57	±11	50
0-T	0.05	56	± 9	54
1/4 T	0.1	59	±11	58
1/2 T	0.6	60	±11	58
Submerged arc weld (R)				
Unirr.	0.04	178	±11	178
SSC1	0.002	80	±11	90
SSC2	0.02	55	±11	57
0-T	-	68	±15	54
1/4 T	0.03	70	± 9	69
1/2 T	0.07	80	± 9	80

Table 7. Summary of radiation damage determinations for the Charpy specimen

	$\phi t > 1.0$ MeV ($n/cm^2 \cdot 10^{19}$)*	$\phi t > 0.1$ MeV ($n/cm^2 \cdot 10^{19}$)	dpa (°C)	ΔNDT 41J (°C)	Std. dev. (°C)	ΔNDT 68J (°C)	Std. dev. (°C)	ΔNDT 0.89 mm (°C)	Std. dev. (°C)	Upper shelf drop (J)	Std. dev. (°C)
A-302-B											
SSC1	2.59	7.46	3.86	78	±12	84	±17	86	±10	23	± 8
SSC2	5.38	15.35	7.96	94	±11	(101)**	±15	92	±10	33	± 6
O-T	3.95	11.44	6.06	77	±10	(87)	±20	(77)	±16	25	± 7
1/4 T	2.16	8.13	3.70	65	±18	(109)	±83	(72)	±15	29	± 6
1/2 T	1.03	5.27	2.11	52	±10	(57)	±17	56	±10	26	± 7
A-533-B											
SSC1	2.32	6.61	3.44	71	±11	71	±12	85	± 9	28	±11
SSC2	4.83	13.63	7.11	84	±10	86	±11	91	± 7	40	±13
O-T	3.59	10.20	5.46	71	±13	(92)	±25	91	±10	42	±13
1/4 T	1.95	7.13	3.28	69	± 9	65	± 7	74	± 6	40	±13
1/2 T	0.94	4.60	1.87	52	±10	52	± 8	57	± 7	22	±13
22NIMOCR37											
SSC1	1.75	5.69	2.77	(52)	±16	57	±11	78	± 7	47	±16
SSC2	3.64	11.70	5.72	109	±14	114	±10	117	± 8	69	±16
O-T	2.71	8.77	4.40	81	±16	90	±10	97	± 7	43	±16
1/4 T	1.47	6.11	2.64	66	±18	82	±11	93	± 8	48	±16
1/2 T	0.71	3.97	1.51	66	±13	71	± 9	74	± 8	40	±15
A-508-3											
SSC1	1.93	6.32	3.07	15	± 7	13	± 5	18	± 5	32	±14
SSC2	4.02	13.02	6.34	39	± 7	38	± 5	38	± 5	37	±14
O-T	2.95	9.65	4.80	27	± 7	24	± 5	26	± 5	29	±11
1/4 T	1.60	6.84	2.92	23	± 6	20	± 5	23	± 5	7	±14
1/2 T	0.77	4.45	1.67	22	± 7	24	± 6	21	± 6	26	±14
Submerged arc weld (EC)											
SSC1	1.87	6.11	2.97	112	±33	(166)	±120	(142)	±35	33	±14
SSC2	3.90	12.59	6.14	123	±60	(157)	-	138	±20	33	±14
O-T	2.88	9.45	4.71	125	±50	-	-	(171)	±66	34	±11
1/4 T	1.60	6.82	2.92	96	±18	-	-	(118)	±22	31	±14
1/2 T	0.77	4.48	1.68	94	±20	(136)	±65	(129)	±42	26	±14
Submerged arc weld (R)											
SSC1	2.46	7.07	3.66	230	±12	259	±21	260	±17	98	±15
SSC2	5.13	14.56	7.57	309	±38	-	-	352	±64	123	±15
O-T	3.81	10.97	5.83	294	±15	-	-	(364)	±56	110	±15
1/4 T	2.12	7.95	3.62	270	±25	-	-	(321)	±58	108	±14
1/2 T	1.02	5.21	2.09	242	±44	-	-	270	±22	98	±14

*neutrons/$cm^2 \cdot 10^{19}$.

**Values in parentheses are obtained by extrapolation and may be unreliable.

Table 8. Comparison of ΔNDT values predicted by Reg. Guide 1.99 and CV81 fit of measurements

	CV81 value °F	Predicted values: present guide $\phi t>1$ °F	Predicted values: revised guide $\phi t>1$ °F	Predicted values: revised guide dpa °F	Predicted values: revised guide $\phi t>.1$ °F	Difference (Reg. Guide - CV81): present guide $\phi t>1$ °F	Difference (Reg. Guide - CV81): revised guide $\phi t>1$ °F	Difference (Reg. Guide - CV81): revised guide dpa °F	Difference (Reg. Guide - CV81): revised guide $\phi t>.1$ °F
A302-B									
SSC1	140	282	128	126	121	+142	- 12	- 14	- 19
SSC2	169	406	144	143	139	+237	- 25	- 26	- 30
0-T	139	346	138	137	132	+207	- 1	- 2	- 7
1/4-T	117	277	127	125	124	+160	+ 10	+ 8	+ 7
1/2-T	94	178	102	110	112	+ 80	+ 8	+ 16	+ 18
A533-B									
SSC1	128	145	102	100	96	+ 17	- 26	- 28	- 32
SSC2	151	210	116	114	111	+ 59	- 35	- 37	- 40
0-T	128	180	111	109	105	+ 52	- 17	- 19	- 23
1/4-T	124	133	98	99	98	+ 9	- 26	- 27	- 26
1/2-T	94	92	82	86	88	- 2	- 12	- 8	- 6
22NIMOCR37									
SSC1	103	111	99	99	96	+ 8	- 4	- 4	- 7
SSC2	205	161	115	114	112	- 44	- 90	- 91	- 93
0-T	162	141	109	107	106	- 21	- 53	- 55	- 56
1/4-T	148	102	95	98	98	- 46	- 53	- 56	- 56
1/2-T	128	71	77	84	88	- 57	- 51	- 44	- 40
A508-3									
SSC1	23	56	37	36	36	+ 33	+ 14	+ 13	+ 13
SSC2	68	80	42	42	41	+ 12	- 26	- 26	- 27
0-T	43	69	40	40	39	+ 26	- 3	- 3	- 4
1/4-T	36	51	35	36	36	+ 15	- 1	0	0
1/2-T	43	35	29	31	33	- 8	- 14	- 12	- 10
Sub. Arc Weld (EC)									
SSC1	201	273	211	210	205	+ 72	+ 10	+ 9	+ 4
SSC2	221	395	243	242	238	+174	+ 22	+ 21	+ 17
0-T	225	341	231	231	225	+116	+ 6	+ 6	0
1/4-T	173	254	203	209	210	+ 81	+ 30	+ 36	+ 37
1/2-T	169	176	167	182	189	+ 7	- 2	+ 13	+ 20
Sub. Arc Weld (R)									
SSC1	414	298	390	384	370	-116	- 24	- 30	- 44
SSC2	556	431	443	437	425	-127	-113	-119	-131
0-T	529	362	423	419	405	-157	-106	-110	-124
1/4-T	486	277	379	383	379	-209	-107	-103	-107
1/2-T	435	192	316	335	344	-243	-119	- 99	- 81

Table 9. 41-J transition temperature increase for individual fits and for various fluence dependent functions

	Individual fits CV81 (°C)	MEA (°C)	$[\phi t>1]^{.5}$ (°C)	$[\phi t>1]^{.3}$ (°C)	$[\phi t>.1]^{.5}$ (°C)	$[\phi t>.1]^{.3}$ (°C)	$[dpa]^{.5}$ (°C)	$[dpa]^{.3}$ (°C)
A-302-B								
SSC1	78	82	64	67	61	68	62	69
SSC2	94	94	92	84	87	84	89	85
0-T	77	81	78	76	74	77	77	78
1/4 T	65	67	58	63	63	69	60	68
1/2 T	52	50	40	51	51	61	46	57
A-533-B								
SSC1	71	61	61	65	59	62	60	63
SSC2	84	81	88	81	85	77	86	78
0-T	71	75	76	73	73	71	75	72
1/4 T	69	69	56	61	61	64	59	62
1/2 T	52	53	38	49	49	56	44	52
22NIMOCR37								
SSC1	(52)	61	55	57	56	65	55	66
SSC2	109	94	79	72	80	81	80	82
0-T	81	72	69	66	71	75	71	76
1/4 T	66	78	50	54	58	67	54	65
1/2 T	66	56	34	43	47	59	41	55
A-508-3								
SSC1	15	20	22	23	22	21	22	20
SSC2	39	39	33	28	32	26	32	25
0-T	27	25	28	26	27	24	28	23
1/4 T	23	20	21	22	23	22	22	20
1/2 T	22	14	14	18	19	19	17	17
Submerged arc weld (EC)								
SSC1	112	108	102	111	102	100	102	104
SSC2	123	129	147	138	147	125	146	130
0-T	125	114	127	126	128	114	129	120
1/4 T	96	94	95	106	108	104	101	104
1/2 T	94	89	66	85	87	91	77	88
Submerged arc weld (R)								
SSC1	230	222	229	250	227	239	228	243
SSC2	309	289	330	311	327	297	329	303
0-T	294	286	285	285	284	273	288	280
1/4 T	270	256	212	238	240	247	226	242
1/2 T	245	239	147	191	194	218	171	205

Table 10. 41J ΔNDT predictions obtained from least squares fits of different specimen sets using the fluence function $f = [dpa]^{.3}$

	Individual fits			Combined fits $[dpa]^{0.3}$ fit				Difference surveillance-individual	
						Surveillance			
	dpa (10^{-2})	CV81 (°C)	Std. Dev. (°C)	All caps. + unirr. (°C)	Wall caps. only (°C)	SSC1 plus unirr. (°C)	SSC1+2 plus unirr. (°C)	SSC1 only (°C)	SSC1 + SSC2 (°C)
A-302-B									
SSC1	3.86	78	±12	69	63	77	76	- 1	- 2
SSC2	7.96	94	±11	85	79	96	94	+ 2	0
0-T	6.06	77	±10	78	73	88	87	+11	+10
1/4 T	3.70	65	±18	68	63	76	75	+11	+10
1/2 T	2.11	52	±10	57	53	64	63	+12	+11
A-533-B									
SSC1	3.44	71	±11	63	61	67	66	- 4	- 5
SSC2	7.11	84	±10	78	76	83	82	- 1	- 2
0-T	5.46	71	±13	72	70	77	76	+ 6	+ 5
1/4 T	3.28	69	± 9	62	60	66	65	- 3	- 4
1/2 T	1.87	52	±10	52	51	56	55	+ 4	+ 3
22NIMOCR37									
SSC1	2.77	(52)*	±16	66	59	53	70	- 1	+18
SSC2	5.72	109	±14	82	73	67	87	-42	-22
0-T	4.40	81	±16	76	68	62	80	-19	- 1
1/4 T	2.64	66	±18	65	58	53	69	-13	+ 3
1/2 T	1.51	66	±13	55	49	45	58	-21	- 8
A-508-3									
SSC1	3.07	15	± 7	20	22	13	21	- 2	+ 6
SSC2	6.34	39	± 7	25	27	16	26	-23	-13
0-T	4.80	27	± 7	23	25	14	24	-13	- 3
1/4 T	2.92	23	± 6	20	21	12	21	-11	- 2
1/2 T	1.67	22	± 7	17	18	11	18	-11	- 4
Submerged arc weld (EC)									
SSC1	2.97	112	±33	104	105	103	101	- 9	-11
SSC2	6.14	123	±60	130	130	128	126	+ 5	+ 3
0-T	4.71	125	±50	120	120	119	116	- 6	- 9
1/4 T	2.92	96	±18	104	104	103	101	+ 7	+ 5
1/2 T	1.68	94	±20	88	88	87	85	- 7	- 9
Submerged arc weld (R)									
SSC1	3.66	230	±12	243	263	224	222	- 6	- 8
SSC2	7.57	309	±38	303	327	280	277	-19	-22
0-T	5.83	294	±15	280	302	259	256	-35	-38
1/4 T	3.62	270	±25	242	262	224	222	-46	-48
1/2 T	2.09	245	±44	205	222	189	188	-56	-57

*Values in parentheses are obtained by extrapolation and may be unreliable.

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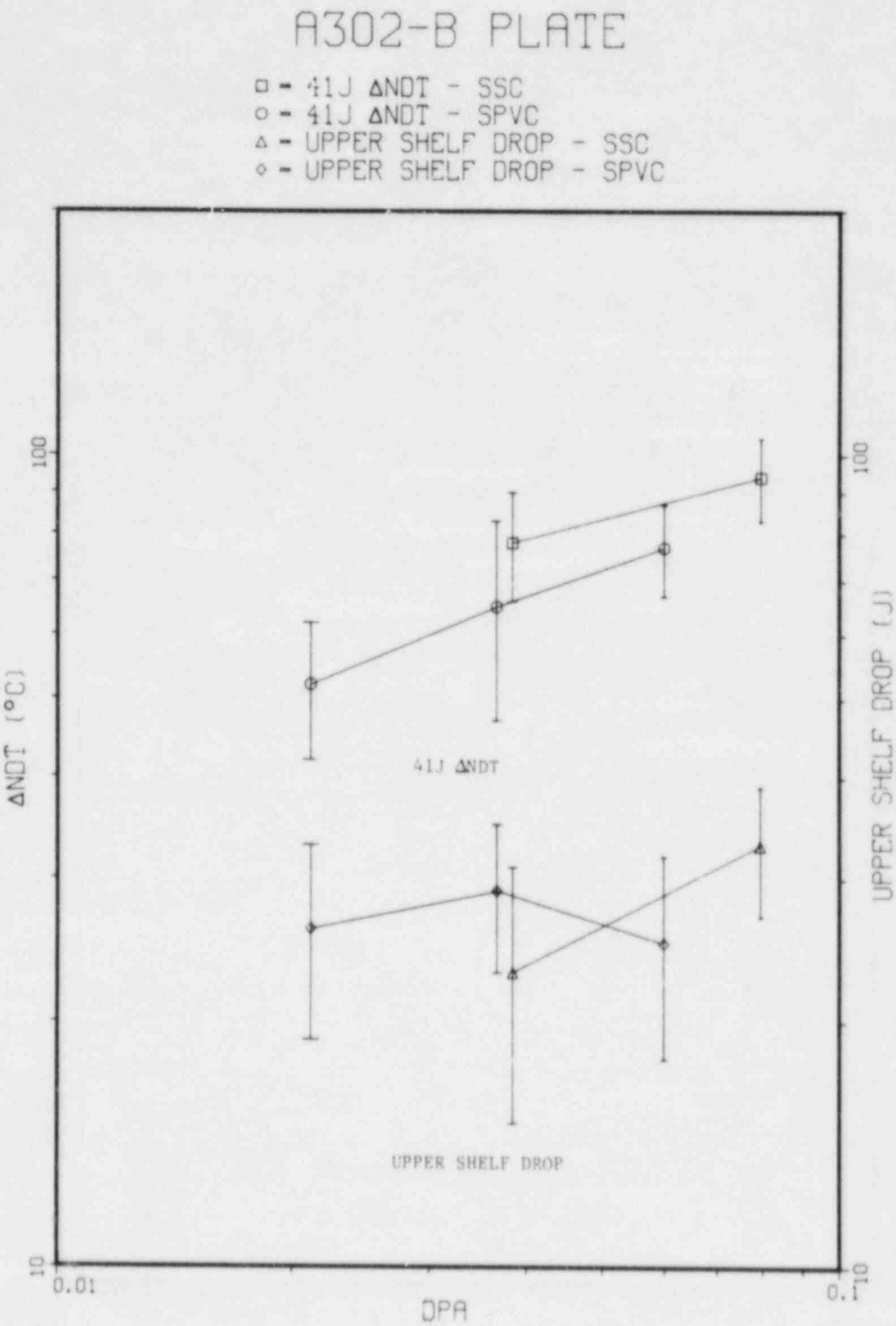

Fig. 1. ΔNDT and upper shelf drop vs. dpa, A302-B plate.

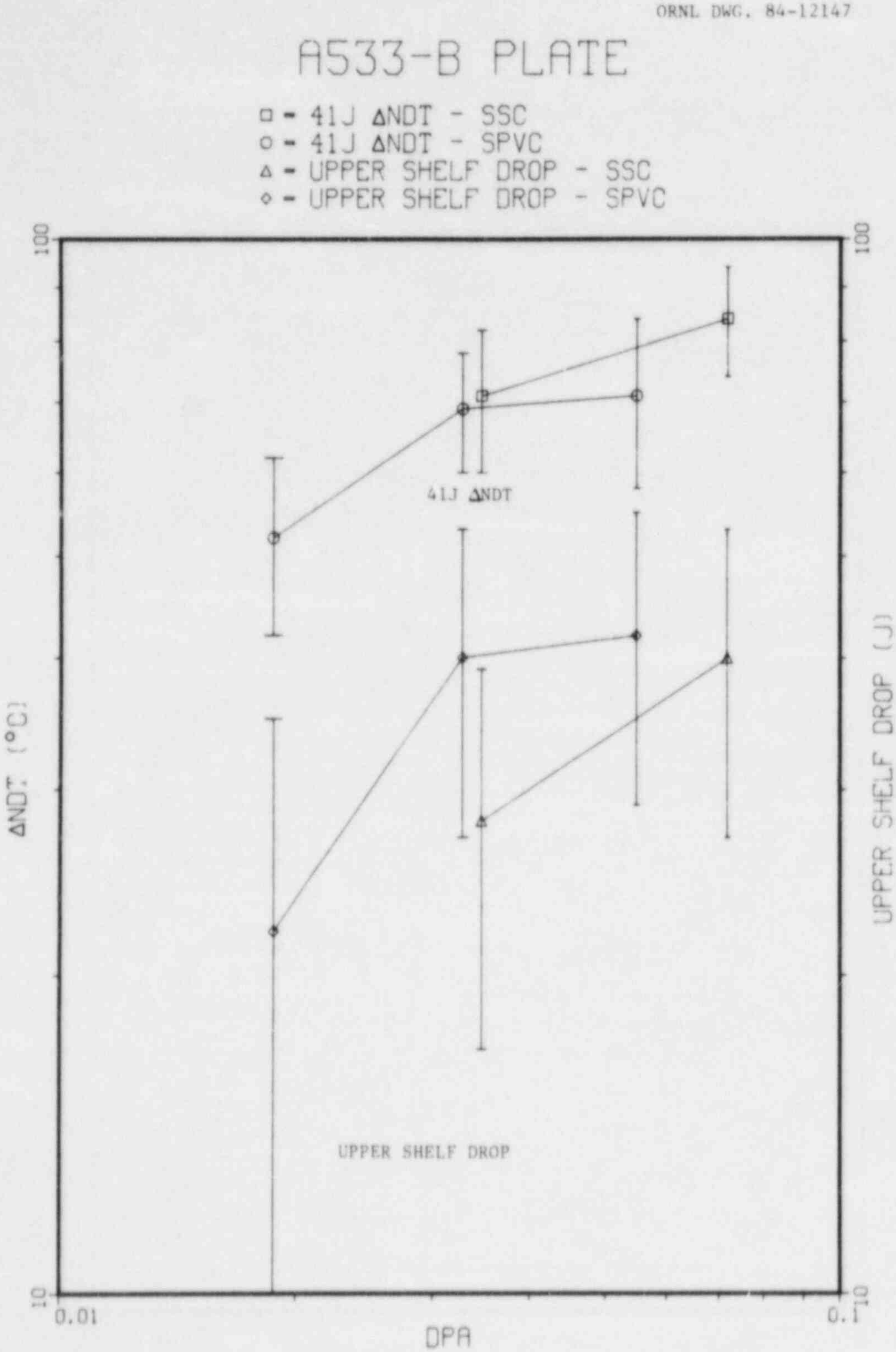

Fig. 2. ΔNDT and upper shelf drop vs. dpa, A533-B plate.

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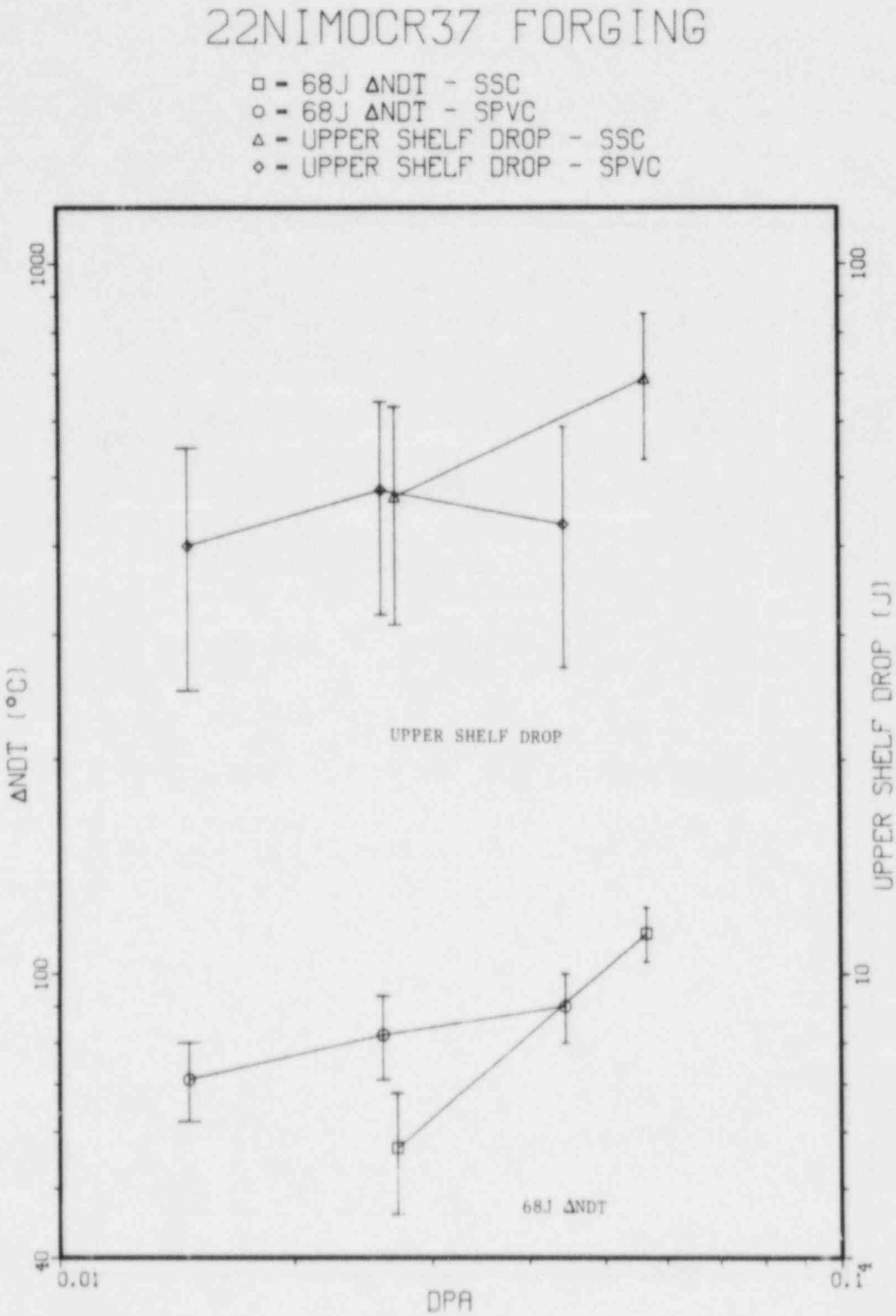

Fig. 3. ΔNDT and upper shelf drop vs. dpa, 22NiMoCr37 forging.

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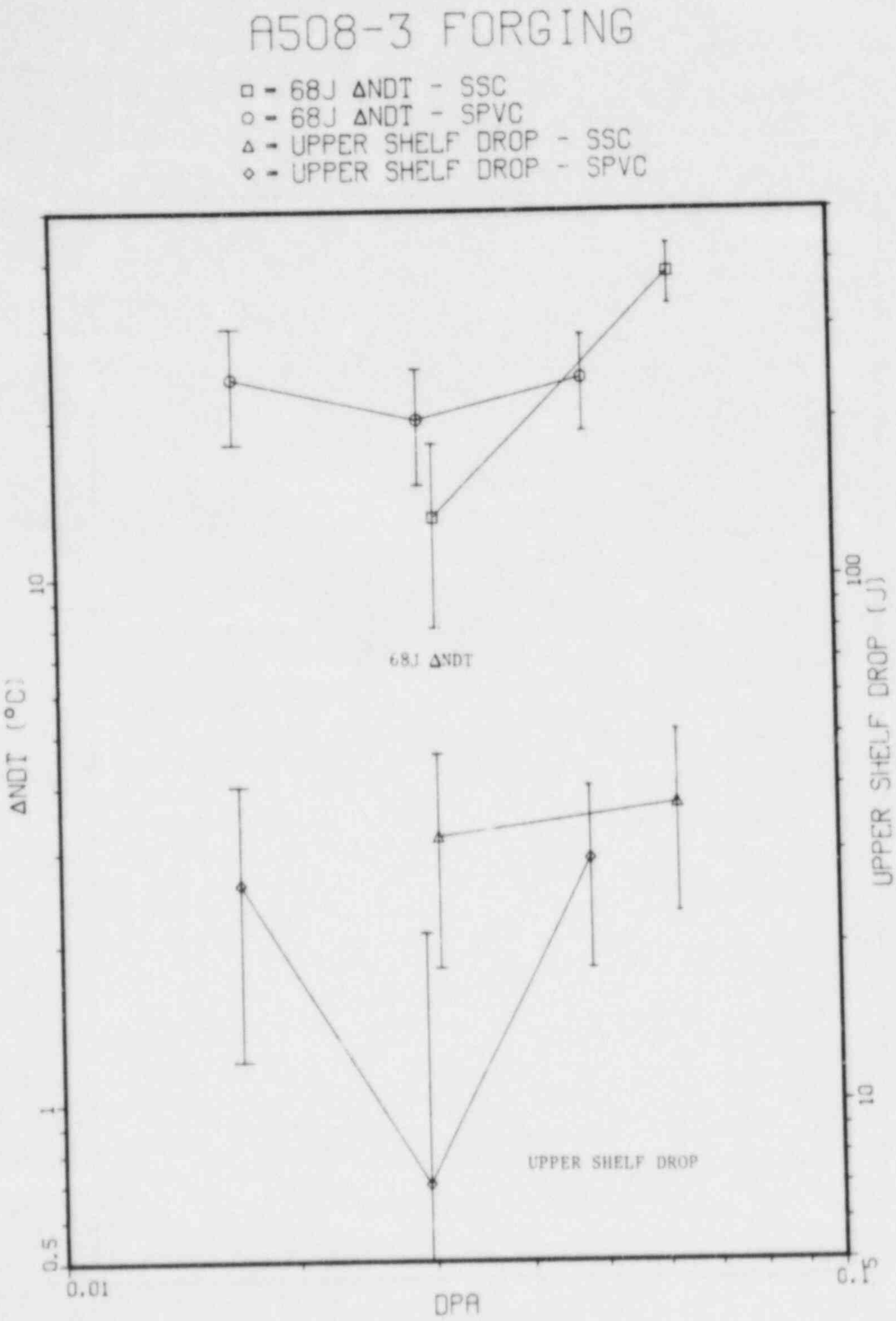

Fig. 4. ΔNDT and upper shelf drop vs. dpa, A508-3 forging.

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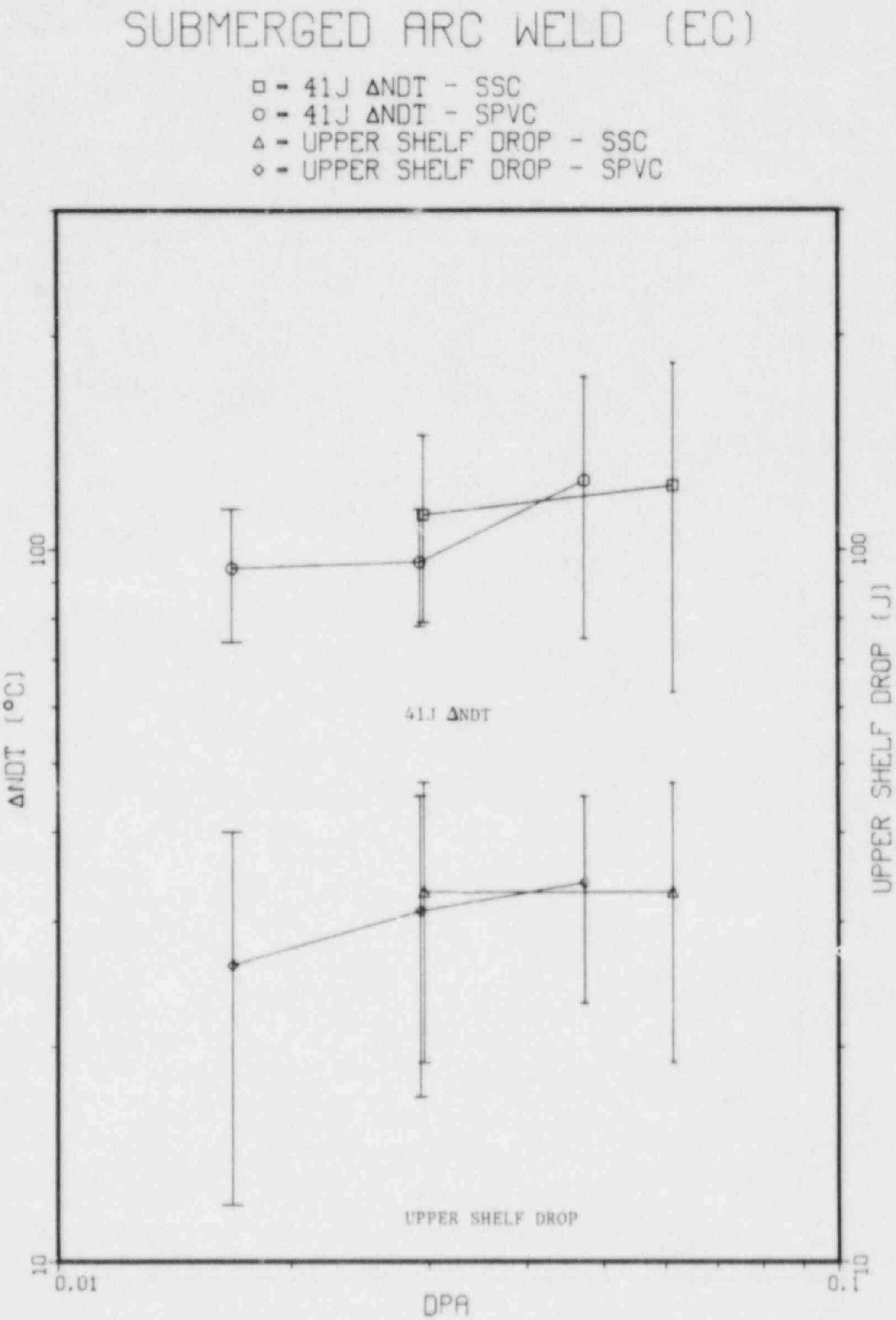

Fig. 5. ΔNDT and upper shelf drop vs. dpa, submerged arc weld (EC).

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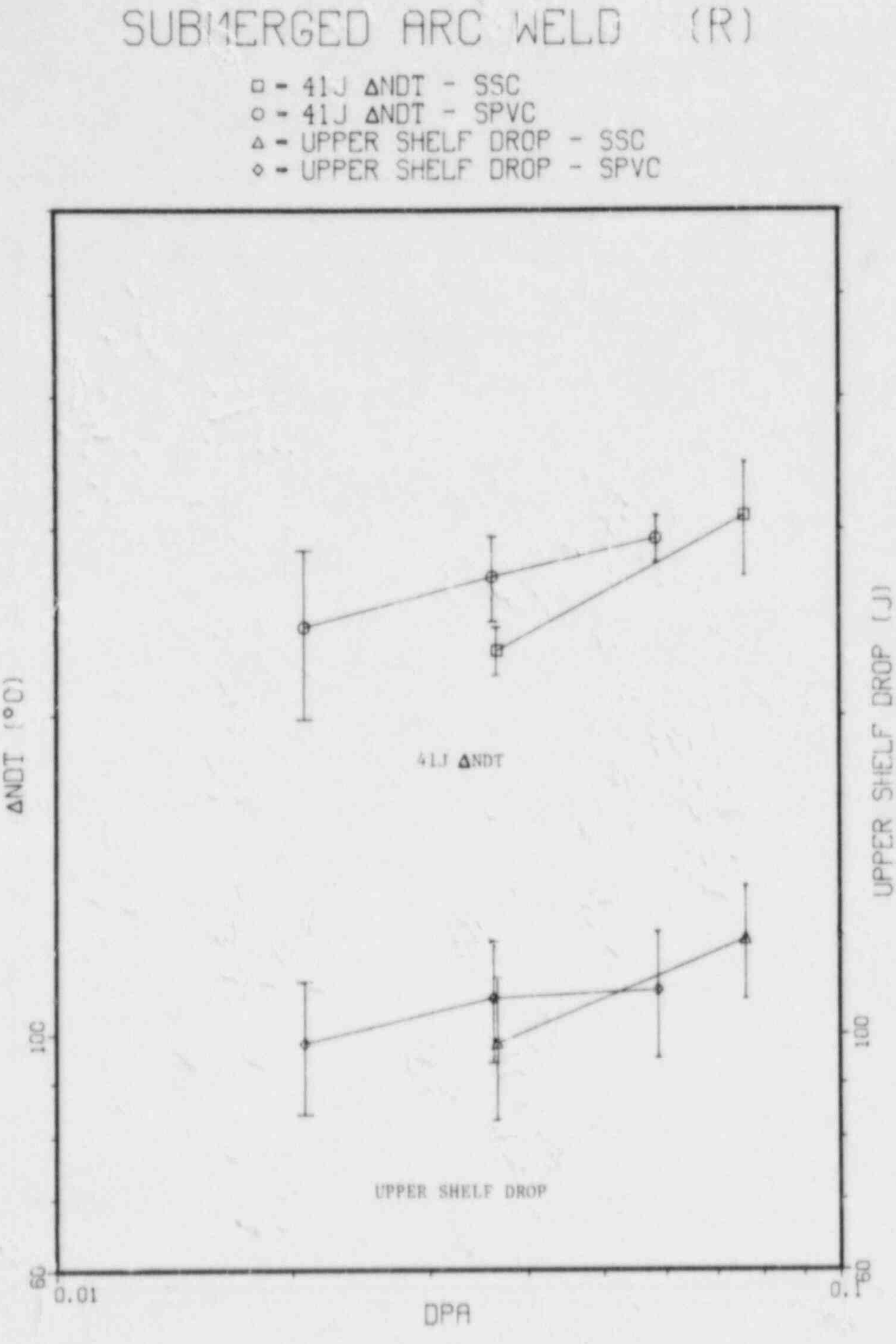

Fig. 6. ΔNDT and upper shelf drop vs. dpa, submerged arc weld (R).

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A statistical analysis of Charpy test results of the two-year Pressure Vessel Simulation metallurgical irradiation experiment was performed. Determination of transition temperature and upper shelf energy derived from computer fits compare well with eyeball fits. Uncertainties for all results can be obtained with computer fits. The results were compared with predictions in Regulatory Guide 1.99 and other irradiation damage models.

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