Lifetime Extension Tutorial

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1 Part A

In order to estimate the reference temperature safety margins for the given samples, Eq 1 and Eq 3 were used.

$$\Delta \mathrm{RT}_{\mathrm{NDT}} = R \times \mathrm{CF} \times f \tag{1}$$
$$\mathrm{RT}_{\mathrm{NDT}} = \mathrm{RT}(U) + \Delta\,\mathrm{RT}_{\mathrm{NDT}} + M \tag{2}$$

$$\Delta \mathrm{RT}_{\mathrm{PTS}} = R \times \mathrm{CF} \times F^{0.28-0.10\ln F} \tag{3}$$
$$\mathrm{RT}_{\mathrm{PTS}} = \mathrm{RT}(U) + \Delta\,\mathrm{RT}_{\mathrm{PTS}} + M \tag{4}$$

The various parameters referenced by these equations were found as follows:

- σ_Δ was taken from the key (see Table 1)
- M was calculated using Eq 5
- CF was linearly interpolated from the chemistry tables given, using the Cu and Ni parameters given in the Charpy data source
- f was determined for $\Delta\mathrm{RT}_{\mathrm{NDT}}$ by mapping EOL fluence to the parameter f from the digitised graph given in the specification appendix, as required.

The results for these calculations can be seen in Table 2. All units given in the table are consistent with those given in the report specification.

$$M = 2\sqrt{\sigma_U^2 + \sigma_\Delta^2} \tag{5}$$

Table 1: σ_Δ values for different materials.

	Material	σ_Δ
0	Weld	28
1	Base Metal	17

2 Part B

The Cu content at the 95 % probability given by the normal distribution $\mathcal{N}(\mu = 0.213\,\mathrm{wt\%C}, \sigma = 0.02\,\mathrm{wt\%C})$ was found to be 0.245 90 wt%C, using `scipy.stats.norm.ppf(.95, mu, std)`. The calculations performed above were then repeated, with the limiting material composition modified to this value. The results of this calculation can be seen in Table 3. These results indicate that unless the copper content is known with sufficient accuracy, the reference safety margins should consider the case in which the copper content is underestimated. Increasing the copper content in this case would indicate that the component in question would not be safe to use, according to the safety reference limits.

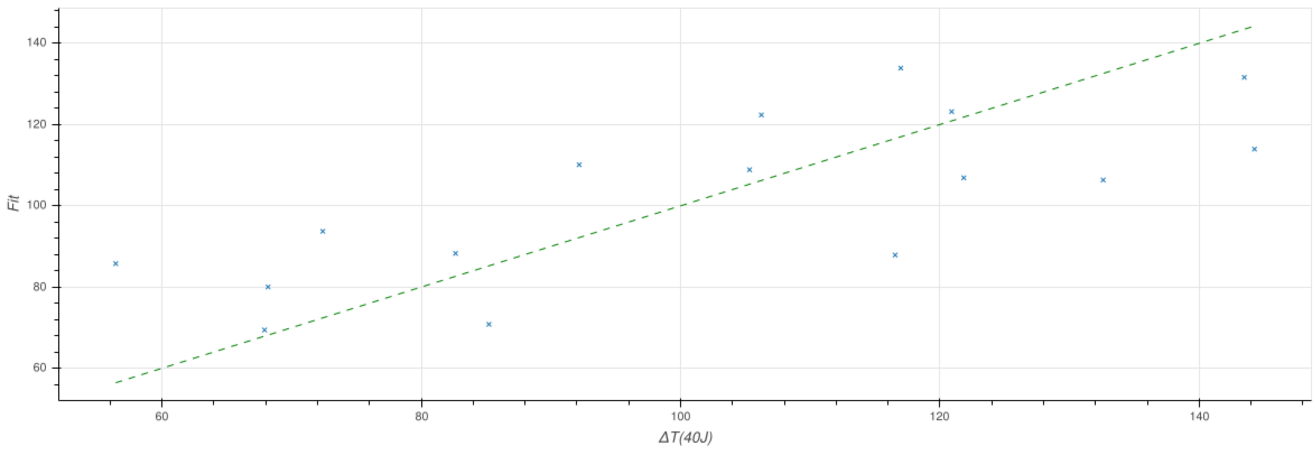
Table 2: Parameters and results from calculation of RT_{NDT} and RT_{PTS}. The value ΔTlim denotes the temperature distance to the limiting case.

	Identity	Material	σ_Δ	M	f	CF	$\Delta\,RT_{NDT}$	RT_{NDT}	$\Delta\,RT_{PTS}$	RT_{PTS}	$\Delta T(\mathrm{lim})$
0	D-3803-1	Plate	17	34.000	1.196	158.95	190.076	219.076	184.072	213.072	56.928
1	D-3803-2	Plate	17	34.000	1.196	160.40	191.810	195.810	185.751	189.751	80.249
2	D-3803-3	Plate	17	34.000	1.196	157.50	188.342	217.342	182.393	211.393	58.607
3	D-3804-1	Plate	17	34.000	1.196	128.80	154.022	188.022	149.157	183.157	86.843
4	D-3804-1	Plate	17	34.000	1.196	131.00	156.653	160.653	151.705	155.705	114.295
5	D-3804-1	Plate	17	34.000	1.196	82.00	98.057	107.057	94.960	103.960	166.040
6	2-112 A/C	Axial Weld	28	65.513	1.123	230.15	258.431	267.944	255.248	264.761	5.239
7	3-112A/C	Axial Weld	28	65.513	1.123	217.10	243.777	253.291	240.775	250.288	19.712
8	3-112A/C	Axial Weld	28	65.513	1.123	230.15	258.431	267.944	255.248	264.761	5.239
9	9-112	Circumf...Weld	28	65.513	1.205	225.20	271.458	280.972	262.019	271.532	28.468

Table 3: Parameters and results from calculation of RT_{NDT} and RT_{PTS}, using modified compositions. The value ΔTlim denotes the temperature distance to the limiting case.

	Identity	Material	σ_Δ	M	f	CF	$\Delta\,RT_{NDT}$	RT_{NDT}	$\Delta\,RT_{PTS}$	RT_{PTS}	$\Delta T(\mathrm{lim})$
0	D-3803-1	Plate	17	34.000	1.196	158.950	190.076	219.076	184.072	213.072	56.928
1	D-3803-2	Plate	17	34.000	1.196	160.400	191.810	195.810	185.751	189.751	80.249
2	D-3803-3	Plate	17	34.000	1.196	157.500	188.342	217.342	182.393	211.393	58.607
3	D-3804-1	Plate	17	34.000	1.196	128.800	154.022	188.022	149.157	183.157	86.843
4	D-3804-1	Plate	17	34.000	1.196	131.000	156.653	160.653	151.705	155.705	114.295
5	D-3804-1	Plate	17	34.000	1.196	82.000	98.057	107.057	94.960	103.960	166.040
6	2-112 A/C	Axial Weld	28	65.513	1.123	242.809	272.645	282.159	269.287	278.801	-8.801
7	3-112A/C	Axial Weld	28	65.513	1.123	217.100	243.777	253.291	240.775	250.288	19.712
8	3-112A/C	Axial Weld	28	65.513	1.123	242.809	272.645	282.159	269.287	278.801	-8.801
9	9-112	Circumf...Weld	28	65.513	1.205	225.200	271.458	280.972	262.019	271.532	28.468

Figure 1: Plot of single dose $\Delta T_{40\,\mathrm{J}}$ against fit using Eq 8.



3 Part C

Each data set from the collection given in the specification was fit with a sigmoid function of the form

$$E = a + b \tanh \frac{T - T_0}{c}\,. \tag{6}$$

The value for $T_{40\,\mathrm{J}}$ was then determined from the inverse sigmoid function

$$c \,\mathrm{atanh}\, \frac{E - a}{b}\,, \tag{7}$$

using these fit parameters.
The value $\Delta T_{40\,\mathrm{J}}$ was then determined for each data set as the difference of $T^{i}_{40\,\mathrm{J}}$ and $T^{0}_{40\,\mathrm{J}}$, the individual and unirradiated start of life parameters respectively (see Table 4).
Finally, a dose damage relationship function of the form

$$\Delta T_{40\,\mathrm{J}} = A + B F_T \sqrt{D_{\mathrm{eff}}} \tag{8}$$
$$F_t = 1.2 - 0.00106 T_{\mathrm{irr}}\,, \tag{9}$$

was fit to the irradiated and doubly irradiated groups using a linear least squares solver with a residual function (see Fig 1, Fig 2), and the parameters tabulated per–group (see Table 5). To handle doubly irradiated samples, it was assumed that the irradiation process is linear, and hence the expression $F_T \sqrt{D_eff}$ was replaced with the sum of that from each dose. The fit values were tabulated in see Table 4. In an exploration of the research surrounding the Charpy test for irradiated samples, it was found that a particular form of the dose damage relationship outlined above may be used to maximise the a likelihood function whose form permits the inclusion of both the single and doubly irradiated data sets into the solving procedure. It was, however, outside of the scope of this project. It was observed in the double dose group that in plotting the fit and estimated values for $\Delta T_{40\,\mathrm{J}}$, a slightly curved could be observed. This suggests that the fit function does not correctly model the data, as expected.

Figure 2: Plot of double dose $\Delta T_{40\,\mathrm{J}}$ against fit using Eq 8.

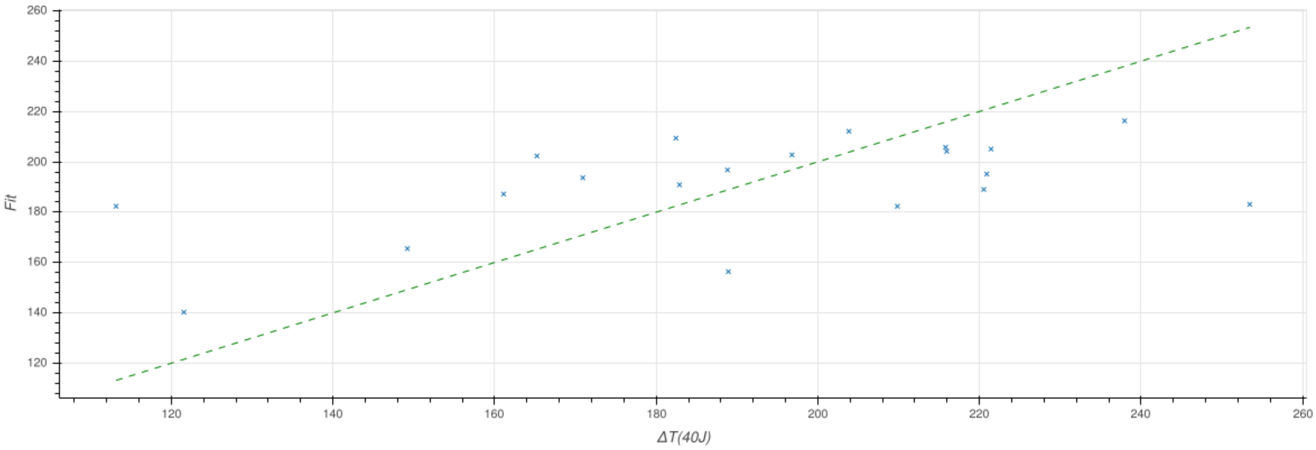


Table 4: Estimated $T_{40\,\mathrm{J}}$ and relative $T_{40\,\mathrm{J}}$ from data set.

Series	A	B	C	T_0	D_1^T	D_1^F	T_1	D_2^T	D_2^F	T_2	$T_{40\,\mathrm{J}}$	$\Delta T_{40\,\mathrm{J}}$
Start of Life	61.52	37.87	29.26	26.73	0.0	0.0	0.0	0.0	0.0	0.0	7.85	0.0
RPV 515	17.21	18.16	38.62	8.97	36.1	6.09	198.0	0.0	0.0	0.0	nan	nan
RPV 514	47.81	34.1	3.44	93.87	66.5	8.5	198.0	0.0	0.0	0.0	93.06	85.21
RPV 508	160.0	145.99	22.53	101.96	71.3	0.34	190.0	0.0	0.0	0.0	75.76	67.91
RPV 14	40.88	33.48	43.35	77.16	84.7	11.78	198.0	0.0	0.0	0.0	76.03	68.18
RPV 510	36.55	29.85	69.11	82.46	89.0	27.61	198.0	0.0	0.0	0.0	90.49	82.64
RPV 13	42.93	19.27	1.15	124.58	102.3	14.7	198.0	0.0	0.0	0.0	124.4	116.55
RPV 12	53.02	38.37	41.6	94.95	105.5	26.89	198.0	0.0	0.0	0.0	80.25	72.4
RPV 507	53.18	43.51	75.19	87.78	110.4	0.54	190.0	0.0	0.0	0.0	64.28	56.42
RPV 512	45.47	36.54	77.56	152.14	141.1	30.97	198.0	0.0	0.0	0.0	140.45	132.59
RPV 513	46.8	23.52	25.62	137.31	149.9	24.75	198.0	0.0	0.0	0.0	129.69	121.84
RPV 511	40.77	20.64	16.43	152.73	159.6	38.29	198.0	0.0	0.0	0.0	152.12	144.27
RPV 7	35.37	30.58	55.58	104.69	180.3	0.87	190.0	0.0	0.0	0.0	113.17	105.32
RPV 506	43.37	26.52	29.99	103.86	184.5	0.87	190.0	0.0	0.0	0.0	100.03	92.18
RPV 10	185.74	197.53	233.96	350.0	186.1	45.85	198.0	0.0	0.0	0.0	128.76	120.91
RPV 502	35.03	35.44	72.77	103.8	228.7	1.33	190.0	0.0	0.0	0.0	114.08	106.23
RPV 503	57.68	30.39	39.62	177.68	265.6	1.33	190.0	0.0	0.0	0.0	151.33	143.48
RPV 504	43.76	17.62	12.82	127.61	275.1	1.33	190.0	0.0	0.0	0.0	124.83	116.98
I20L(B)	36.63	17.62	0.02	121.02	105.5	26.89	198.0	668.0	47.9	189.0	121.02	113.17
I20L(B)...Set	30.36	26.06	84.43	184.93	105.5	26.89	198.0	668.0	47.9	189.0	217.69	209.84
I30B_1	132.87	135.01	339.22	477.02	141.1	30.97	198.0	901.0	45.0	280.0	190.73	182.88
I20(H)B_1	174.62	221.87	537.38	602.0	141.1	30.97	198.0	943.0	61.7	186.0	223.8	215.95
I20(H)T_1	40.21	35.5	101.31	224.26	141.1	30.97	198.0	981.0	59.6	188.0	223.66	215.81
I30A_1	129.87	114.8	166.16	403.67	141.1	30.97	198.0	1005.0	46.4	286.0	228.76	220.9
513_3	0.0	132.64	450.0	56.71	149.9	24.75	198.0	369.0	22.6	311.0	196.78	188.93
I20L(T)_1	36.25	19.62	54.75	217.79	149.9	24.75	198.0	693.0	44.8	190.0	228.38	220.53
513_2	600.0	579.57	102.83	470.28	149.9	24.75	198.0	765.0	44.6	292.0	261.3	253.44
103_1	0.0	72.6	102.01	105.74	154.5	29.85	198.0	761.0	42.9	260.0	168.97	161.12
10_3	27.37	33.46	53.19	108.29	189.6	1.12	190.0	157.0	9.7	275.0	129.4	121.55
28_3	37.57	15.93	30.75	152.34	192.1	1.12	190.0	436.0	23.6	282.0	157.06	149.21
71_2	42.23	17.18	25.84	182.15	207.7	1.12	190.0	853.0	46.5	273.0	178.77	170.92
I25H(B)	35.0	25.24	104.04	208.4	237.7	1.22	190.0	902.0	59.6	227.0	229.28	221.43
I30A_2	30.6	23.72	75.81	172.86	237.7	1.22	190.0	1005.0	46.4	286.0	204.65	196.79
I20L(T)_2	31.45	26.7	77.61	170.92	241.0	1.22	190.0	693.0	44.8	190.0	196.67	188.82
I20H(B)_2	31.31	26.74	65.01	189.78	241.0	1.22	190.0	943.0	61.7	186.0	211.69	203.84
I20H(T)_2	35.11	32.03	83.88	232.89	265.6	1.33	190.0	981.0	59.6	188.0	245.81	237.96
I30B_2	34.43	21.09	60.72	156.65	275.1	1.33	190.0	901.0	45.0	280.0	173.09	165.24
I25(H)T	31.61	32.28	140.03	153.02	275.1	1.33	190.0	946.0	58.5	242.0	190.29	182.43

Table 5: Dose damage relationship fit parameters (see Eq 8).

Group	A	B
Single	2.547	8.360
Double	28.125	3.473