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Use of surveillance test results within a regulatory context

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Outline

- US legislation
  - Regulatory Guide 1.99 Revision 2 (May 1988)
  - 10 CFR Pt.50 - §50.61, App. G and H (1/1/01)
  - Future Developments: new PTS Rule (§50.61a) and Reg. Guide 1.99 Rev. 3
- Examples of other legislations
  - France: RSEM Code – Article B7212
  - Germany: KTA 3203 (6/01)

Regulatory Guide 1.99 Rev. 2
- Principle -

- The projected embrittlement* of the RPV materials (base and weld metals) corresponding to end-of-life (EOL) conditions has to be estimated and compared to the acceptable safety limits (PTS screening criteria + USE limit)
  - when surveillance data are not available: using regression correlations derived from surveillance database available at the time (late 80's)
  - when surveillance data are available: fitting Charpy shifts using the same formalism as above

*Increase of RT_{NDT} and decrease of USE

Regulatory Guide 1.99 Rev.2
- Structure -

- Regulatory position 1: Surveillance Data not available
  - Embrittlement (ART_{EOL}) is calculated using correlations which relate fast neutron fluence to material's composition (chemistry factor - Cu and Ni content)
- Regulatory position 2: Credible surveillance data available
  - Embrittlement is calculated by fitting available Charpy data ($\Delta RT_{NDT} \equiv \Delta T_{41J}$) using the same formalism as for Pos. 1 and adjusting the Chemistry Factor

Regulatory Guide 1.99 Rev.2
Pos.1: no surveillance data (I)

- 1.1 Adjusted Reference Temperature (ART)

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin}$$

  - Initial RT_{NDT} = for the unirradiated material; as defined in ASME Code Sect. III, Paragraph NB-2331

- Adjustment of reference temperature caused by irradiation

$$\Delta RT_{NDT} = CF \cdot f^{(0.28 - 0.10 \log f)}$$

Regulatory Guide 1.99 Rev.2
Pos.1: no surveillance data (II)

$$\Delta RT_{NDT} = CF \cdot f^{(0.28 - 0.10 \log f)}$$

- f (10^{19} n/cm², E > 1 MeV) = neutron fluence at defect location
- CF = chemistry factor (°F); function of copper and nickel content; different for welds and base metal (plates and forgings)

TABLE 1

CHEMISTRY FACTOR FOR WELDS, °F

Copper, Wt-%	Nickel, Wt-% 0	0.20	0.40	0.60	0.80	1.00	1.20
0	20	20	20	20	20	20	20
0.01	20	20	20	20	20	20	20
0.02	21	26	27	27	27	27	27
0.03	22	35	41	41	41	41	41
0.04	24	43	54	54	54	54	54
0.05	26	49	67	68	68	68	68
0.06	29	52	77	82	82	82	82
0.07	32	55	85	95	95	95	95
0.08	36	58	90	106	108	108	108
0.09	40	61	94	115	122	122	122
0.10	44	65	97	122	133	135	135
0.11	49	68	101	130	144	148	148
0.12	52	72	103	135	153	161	161
0.13	58	76	106	139	162	172	176
0.14	61	79	109	142	168	182	188
0.15	66	84	112	146	175	191	200
0.16	70	88	115	149	178	199	211
0.17	75	92	119	151	184	207	221
0.18	79	95	122	154	187	214	230
0.19	83	100	126	157	191	220	238
0.20	88	104	129	160	194	223	245
0.21	92	108	133	164	197	229	252
0.22	97	112	137	167	200	232	257
0.23	101	117	140	169	203	236	263
0.24	105	121	144	173	206	239	268
0.25	110	126	148	176	209	243	272
0.26	113	130	151	180	212	246	276
0.27	119	134	155	184	216	249	280
0.28	122	138	160	187	218	251	284
0.29	128	142	164	191	222	254	287
0.30	131	146	167	194	225	257	290
0.31	136	151	172	198	228	260	293
0.32	140	155	175	202	231	263	296
0.33	144	160	180	205	234	266	299
0.34	149	164	184	209	238	269	302
0.35	153	168	187	212	241	272	305
0.36	158	172	191	216	245	275	308
0.37	162	177	196	220	248	278	311
0.38	166	182	200	223	250	281	314
0.39	171	185	203	227	254	285	317
0.40	175	189	207	231	257	288	320

TABLE 2

CHEMISTRY FACTOR FOR BASE METAL, °F

Copper, Wt-%	Nickel, Wt-% 0	0.20	0.40	0.60	0.80	1.00	1.20
0	20	20	20	20	20	20	20
0.01	20	20	20	20	20	20	20
0.02	20	20	20	20	20	20	20
0.03	20	20	20	20	20	20	20
0.04	22	26	26	26	26	26	26
0.05	25	31	31	31	31	31	31
0.06	28	37	37	37	37	37	37
0.07	31	43	44	44	44	44	44
0.08	34	48	51	51	51	51	51
0.09	37	53	58	58	58	58	58
0.10	41	58	65	65	67	67	67
0.11	45	62	72	74	77	77	77
0.12	49	67	79	83	86	86	86
0.13	53	71	85	91	96	96	96
0.14	57	75	91	100	105	106	106
0.15	61	80	99	110	115	117	117
0.16	65	84	104	118	123	125	125
0.17	69	88	110	127	132	135	135
0.18	73	92	115	134	141	144	144
0.19	78	97	120	142	150	154	154
0.20	82	102	125	149	159	164	165
0.21	86	107	129	155	167	172	174
0.22	91	112	134	161	176	181	184
0.23	95	117	138	167	184	190	194
0.24	100	121	143	172	191	199	204
0.25	104	126	148	176	199	208	214
0.26	109	130	151	180	205	216	221
0.27	114	134	155	184	211	225	230
0.28	119	138	160	187	216	233	239
0.29	124	142	164	191	221	241	248
0.30	129	146	167	194	225	249	257
0.31	134	151	172	198	228	255	266
0.32	139	155	175	202	231	260	274
0.33	144	160	180	205	234	264	282
0.34	149	164	184	209	238	268	290
0.35	153	168	187	212	241	272	298
0.36	158	173	191	216	245	275	303
0.37	162	177	196	220	248	278	308
0.38	166	182	200	223	250	281	313
0.39	171	185	203	227	254	285	317
0.40	175	189	207	231	257	288	320

- Linear interpolation is permitted
- Cu% and Ni% are best-estimate values (or upper limits in specifications)

Regulatory Guide 1.99 Rev.2
Pos.1: no surveillance data (III)

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin}$$

- "Margin" (°F) has to be added to obtain conservative, upper-bound values of ART

$$\text{Margin} = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2}$$

- σ_I = standard deviation for initial RT_{NDT}; to be estimated from the precision of the test method (drop weight + Charpy); typically = 5°C
- σ_D = standard deviation for ΔRT_{NDT}; given as 28°F for welds and 17°F for base metal; needs not exceed ½ the value of ΔRT_{NDT}

Regulatory Guide 1.99 Rev.2
Pos.1: no surveillance data (IV)

➢ 1.2 Charpy Upper-Shelf Energy

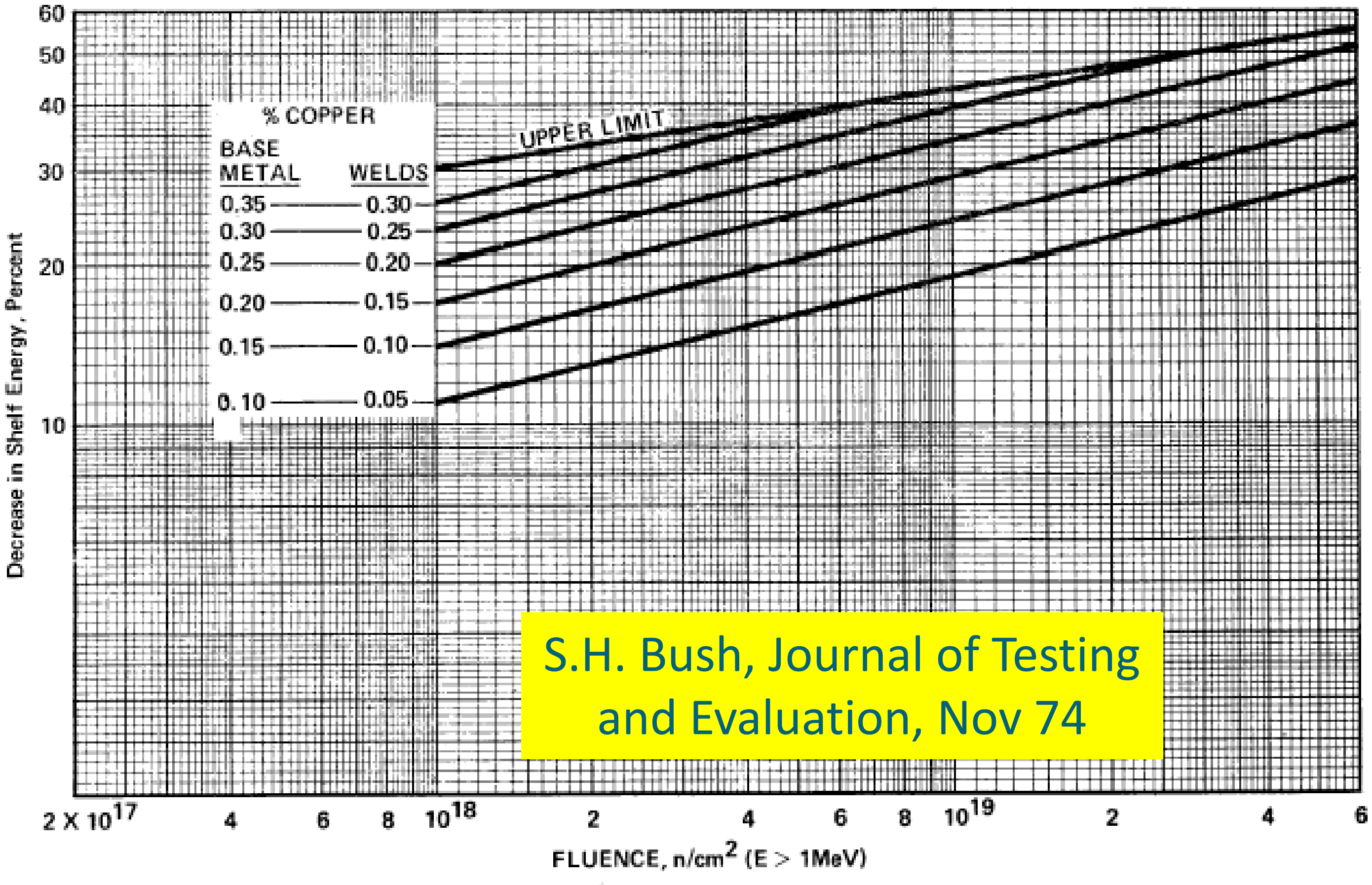


FIGURE 2 Predicted Decrease in Shelf Energy as a Function of Copper Content and Fluence

- Linear interpolation is permitted

Regulatory Guide 1.99 Rev.2
Pos.1: no surveillance data (V)

- Limits of applicability
  - Grades of SA-302, 336, 533 and 508 steels having minimum specified yield strengths of 50,000 psi (345 MPa) and their welds and heat affected zones
  - Nominal irradiation temperature of 550°F (288°C)
    - temperatures below 525°F (274°C) produce greater embrittlement
    - temperatures above 590°F (310°C) produce less embrittlement
    - temperature correction factor should be justified
  - Application to fluence, Cu or Ni levels beyond the ranges specified should be justified

Regulatory Guide 1.99 Rev.2
Pos.2: available surveillance data (I)

2.1 Adjusted Reference Temperature (ART)

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin}$$

$$\Delta RT_{NDT} = CF \cdot f^{(0.28 - 0.10 \log f)}$$

- CF isn't based on Cu/Ni, but established by fitting available surveillance data ($\Delta RT_{NDT} \leftrightarrow \Delta T_{41J}$) using a least-squares method
- In the calculation of the Margin, σ_D may be cut in half

- If $ART_{Pos2} > ART_{Pos1}$, Pos.2 should be used
- If $ART_{Pos2} < ART_{Pos1}$, either may be used

Regulatory Guide 1.99 Rev.2
Pos.2: available surveillance data (II)

- 2.2 Charpy Upper Shelf Energy
  - Experimental ΔUSE values can be plotted and fitted with a line parallel to existing lines
- Criteria for credibility of surveillance data
  1. Surveillance materials should be limiting in terms of radiation embrittlement
  2. Scatter of Charpy data should allow to unambiguously determine T_{41J} and USE
  3. When two or more surveillance sets are available, their scatter about the best-fit line (Pos.2) should not exceed 56°F (31°C) for welds and 34°F (19°C) for base metal
  4. Capsule temperature should match vessel wall temperature within ±25°F (14°C)
  5. Data for reference material should be within the scatter band of its data base

Safety against pressurized thermal shock (PTS) events - 10 CFR Ch. I (1/1/01) -

- PTS event: *event or transient in PWR's causing severe overcooling (thermal shock) concurrent with or followed by significant pressure in the reactor vessel*
- RT_{PTS}: (adjusted) reference temperature (RT_{NDT}) evaluated for the EOL fluence

$$RT_{PTS} = \text{Initial } RT_{NDT} + \Delta RT_{NDT,f=EOL} + \text{Margin}$$

- PTS Screening Criterion: value of RT_{PTS} above which the plant cannot continue to operate without justification

Fracture toughness requirements - 10 CFR Ch. I (1/1/01) -

§ 50.61

$$RT_{PTS} < \text{PTS Screening Criterion}$$

- where: **PTS Screening Criterion = 270 °F (132 °C)**
  for plates, forgings and axial welds
  PTS Screening Criterion = 300 °F (149 °C)
  for circumferential welds

App. G

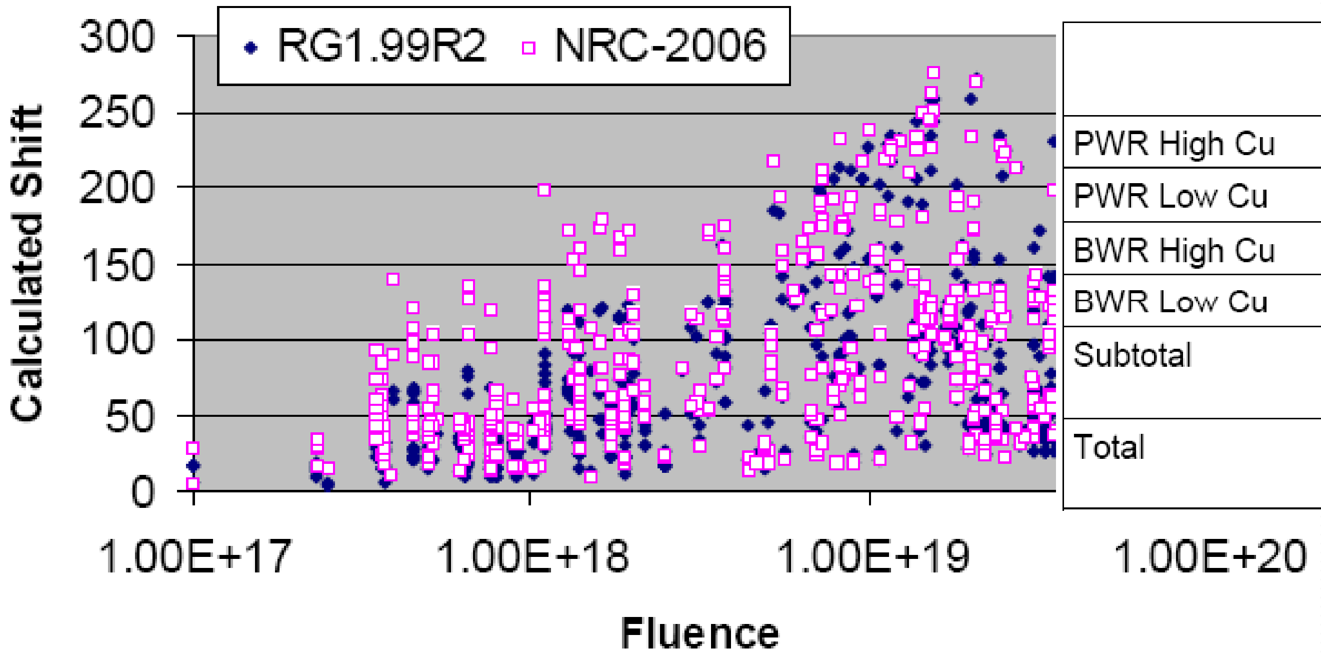
USE ≥ 75 ft-lb (102 J) (initially)

USE ≥ 50 ft-lb (68 J) (throughout the RPV life)

- If requirements are not fulfilled:
  - flux reduction programs
  - thermal annealing treatment of the vessel

Revised PTS rule (50.61a) and embrittlement correlation

- US-NRC has developed an updated embrittlement correlation (Eason, Odette, Nanstad, Yamamoto - EONY), based on mechanistic understanding and more extensive data base (936 data points)
- This will be implemented in the revised regulation



	Calibration set	Validation set	Remaining SRM data
PWR High Cu	440	45	
PWR Low Cu	219	23	
BWR High Cu	124	11	
BWR Low Cu	27	1	
Subtotal	775	80	81 (out of 107)
Total	936 (8 outliers and 4 data with unusual irradiations are excluded)		

Regulatory Guide 1.99 Rev.3 Embrittlement correlation (I)

$$TTS = MDterm + CRPterm$$

Irradiation T (°F)

$$MDterm = A\left(1 - 0.001718\,T_c\right)\left(1 + 6.130\,PMn^{2.471}\right)\sqrt{\phi t_e}$$

$$A = \begin{cases} 1.140x10^{-7} & for\ forgings \\ 1.561x10^{-7} & for\ plates \\ 1.417x10^{-7} & for\ welds \end{cases}$$

P and Mn contributions acknowledged

Effective fast fluence

$$\phi t_e = \begin{cases} \phi t & for\ \phi \geq 4.3925 \times 10^{10} \\ \phi t \left(\dfrac{4.3925 \times 10^{10}}{\phi}\right)^{0.2595} & for\ \phi < 4.3925 \times 10^{10} \end{cases}$$

Flux

Regulatory Guide 1.99 Rev.3 Embrittlement correlation (II)

Effective Cu content

$$CRP\ term = B\left(1+3.77Ni^{1.191}\right)f\left(Cu_e, P\right)g\left(Cu_e, Ni, \phi t_e\right)$$

$$B = \begin{cases} 102.3 \quad for\ forgings \\ 102.5 \quad for\ plates\ in\ non-CE\ mfg.\ vessels \\ 135.2 \quad for\ plates\ in\ CE\ mfg.\ vessels \\ 155.0 \quad for\ welds \\ 128.2 \quad for\ SRM\ plates \end{cases}$$

Standard Reference Materials

$$g\left(Cu_e, Ni, \phi t_e\right) = \frac{1}{2} + \frac{1}{2}\tanh\left[\frac{\log_{10}\left(\phi t_e\right) + 1.139Cu_e - 0.448Ni - 18.120}{0.629}\right]$$

Regulatory Guide 1.99 Rev.3 Embrittlement correlation (III)

$$f(Cu_e, P) = \begin{cases} 0 \quad for\ Cu \le 0.072 \\ [Cu_e - 0.072]^{0.6679} \quad for\ Cu > 0.072\ and\ P \le 0.008 \\ [Cu_e - 0.072 + 1.359(P - 0.008)]^{0.6679} \quad for\ Cu > 0.072\ and\ P > 0.008 \end{cases}$$

$$Cu_e = \begin{cases} 0 \quad \text{for } Cu \le 0.072 \text{ wt\%} \\ Cu \quad \text{for } Cu > 0.072 \text{ wt\%} \end{cases}$$

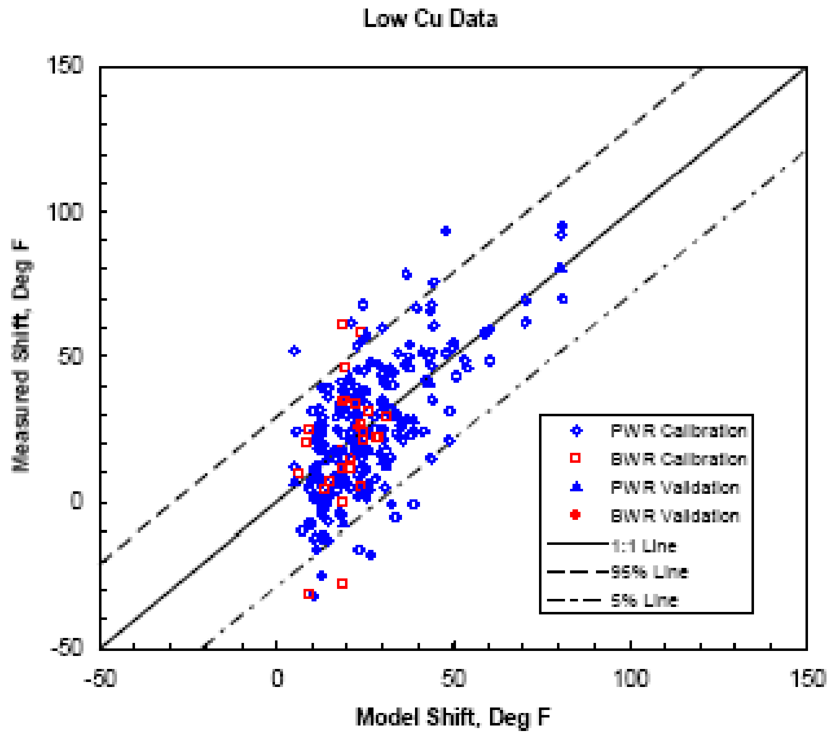
Threshold for Cu effects

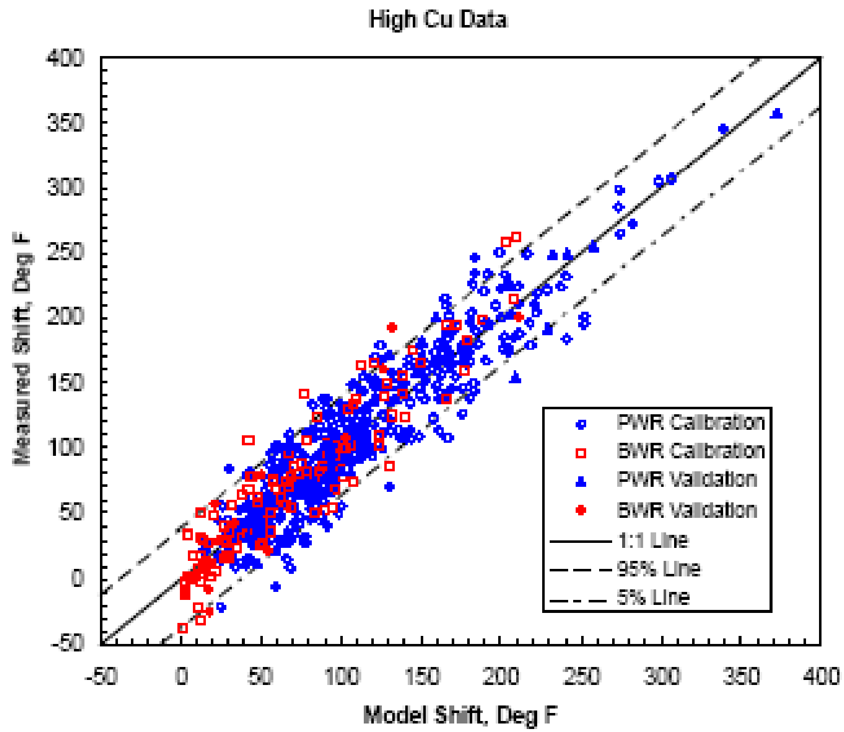
Saturation Cu effects

$$Max(Cu_e) = \begin{cases} 0.370 \quad for\ Ni < 0.5\ wt\% \\ 0.2435 \quad for\ 0.5 \le Ni \le 0.75\ wt\% \\ 0.301 \quad for\ Ni > 0.75\ wt\%\ \ (all\ welds\ with\ L1092\ flux) \end{cases}$$

Regulatory Guide 1.99 Rev.3 Embrittlement correlation (IV)

Model predictions vs measured shifts





Revised PTS rule (10 CFR §50.61a) (1)

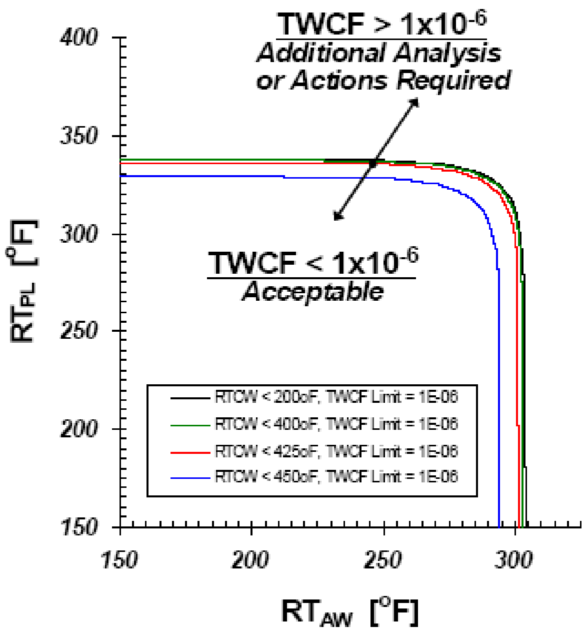
Total through-wall cracking frequency in a vessel

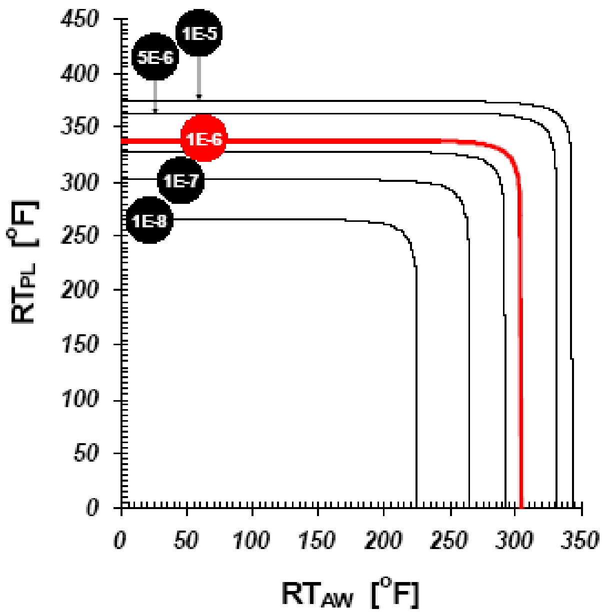
$$TWCF_{TOTAL} = TWCF_{AXIAL-WELD} + \alpha_{PL} \cdot TWCF_{PLATE} + TWCF_{CIRC-WELD}$$

$$TWCF_{AXIAL-WELD} = 4\text{x}10^{-26} \cdot \exp\{0.0585 \cdot (RT_{AW} + 459.69)\}$$

$$\alpha_{PL} = 1.7, \qquad TWCF_{PLATE} = 4\text{x}10^{-29} \cdot \exp\{0.064 \cdot (RT_{PL} + 459.69)\}$$

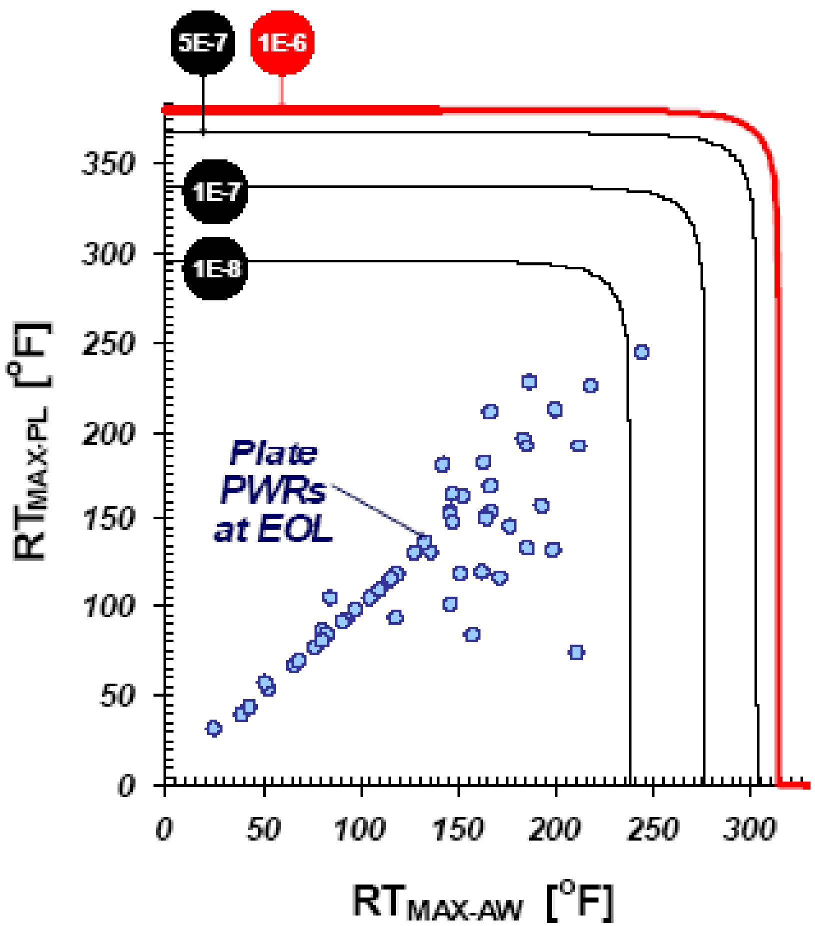
$$TWCF_{CIRC-WELD} = 3\text{x}10^{-27} \cdot \exp\{0.051 \cdot (RT_{CW} + 459.69)\}$$

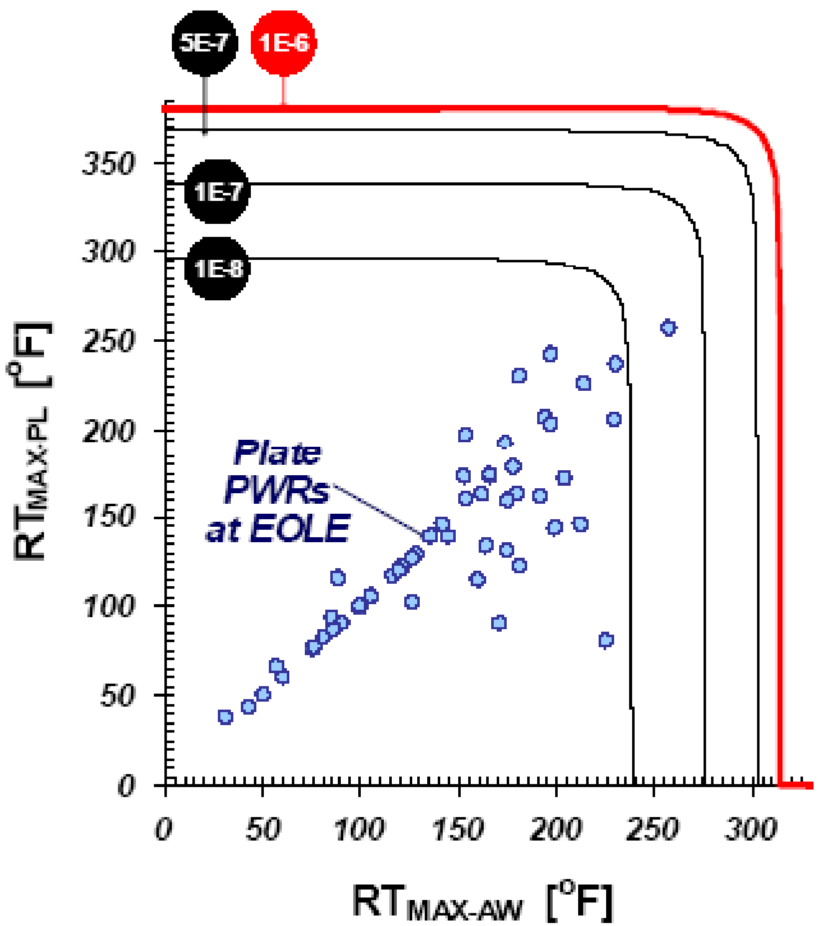




Revised PTS rule (10 CFR §50.61a) (2)

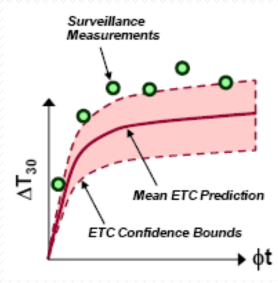
Assessment of US PWR's at EOL (40 years, 32 EFPY)



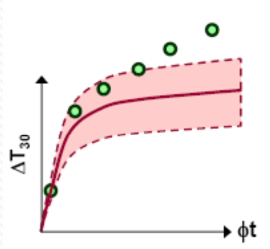


Revised PTS rule
Evaluation of surveillance data

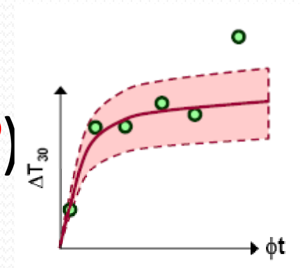
- Surveillance programs results shall be evaluated <u>provided there are at least three capsules evaluated</u>
- Purpose: determine whether the surveillance data show a **significantly** different trend than predicted by the model
- Criteria to evaluate deviations between data and model (consistency check):



  - Type A deviations (*are data uniformly offset from the model?*)
  - Type B deviations (*does the offset increase with fluence?*)



  - Type C deviations (*can outliers be identified?*)



Revised PTS rule
Surveillance data consistency check (1)

- Type A deviations (data uniformly offset from the model)

mean residual

$$\bar{r} = \frac{1}{n}\sum_{1}^{n}\left(\Delta T_{41J(meas)} - \Delta T_{41J(calc)}\right)$$

$$\bar{r} \leq r_{MAX,heat} = 2.33\frac{\sigma}{\sqrt{n}}$$

standard deviation of the residuals about the model for a relevant material group

Material Group	σ [°F]	Number of available data points					
		3	4	5	6	7	8
Welds, for Cu > 0.072	26.4	35.5	30.8	27.5	25.1	23.2	21.7
Plates, for Cu > 0.072	21.2	28.5	24.7	22.1	20.2	18.7	17.5
Forgings, for Cu > 0.072	19.6	26.4	22.8	20.4	18.6	17.3	16.1
Weld, Plate or Forging, for Cu ≤0.072	18.6	25.0	21.7	19.4	17.7	16.4	15.3

Revised PTS rule
Surveillance data consistency check (2)

- Type B deviations (measurements differ by an amount that increases with fluence)

$$T_{SURV} = \frac{m}{se(m)}$$

m: slope of the linear fit of residuals vs LOG_{10} fluence

$se(m)$: standard error associated with m

$$T_{SURV} \le T_{MAX}$$

Number of available data points (n)	T_{MAX}
3	31.82
4	6.96
5	4.54
6	3.75
7	3.36
8	3.14
9	3.00
10	2.90
11	2.82
12	2.76
14	2.68
15	2.65

Student's T distribution (significance level = 1%)

Revised PTS rule
Surveillance data consistency check (3)

➢ <u>Type C deviations</u> (existence of outliers)

Largest normalized residual r^*_{MAX}
Second largest normalized residual $r^*_{MAX,2}$

$$r^* = \frac{r}{\sigma}$$

σ: population standard deviation

$$r^*_{MAX} \leq r^*_{TH}$$
$$r^*_{MAX,2} \leq r^*_{TH,2}$$

Number of available data points (n)	Second largest allowable normalized residual value (r_{TH2}*)	Largest allowable normalized residual value (r_{TH}*)
3	1.55	2.71
4	1.73	2.81
5	1.84	2.88
6	1.93	2.93
7	2.00	2.98
8	2.05	3.02
9	2.11	3.06
10	2.16	3.09
11	2.19	3.12
12	2.23	3.14
13	2.26	3.17
14	2.29	3.19
15	2.32	3.21

Surveillance data consistency check (4)
Application to US operating PWR's

Plant Name	Heat ID	Product Form	Population σ [°F]	Number of ΔT_{30} Values	Heat Fails these Deviation Tests		
					A - Mean Test	B - Slope Test	C - Outlier Test
San Onofre 3	PSO301	Plate	18.6	3	FAIL		FAIL
D.C. Cook 2	PCK201	Plate	21.2	8	FAIL		
Beaver Valley 1	PBV101	Plate	21.2	8	FAIL		FAIL
Callaway	WCL101	Weld	18.6	4	FAIL		FAIL
Surry 1	WSU101	Weld	26.4	3	FAIL		FAIL
Indian Point 2	PIP203	Plate	21.2	3	FAIL		
Sequoyah 1	FSQ101	Forging	19.6	8	FAIL		
Sequoyah 1	WSQ101	Weld	26.4	4	FAIL		
Sequoyah 1	WSQ201	Weld	26.4	4			FAIL

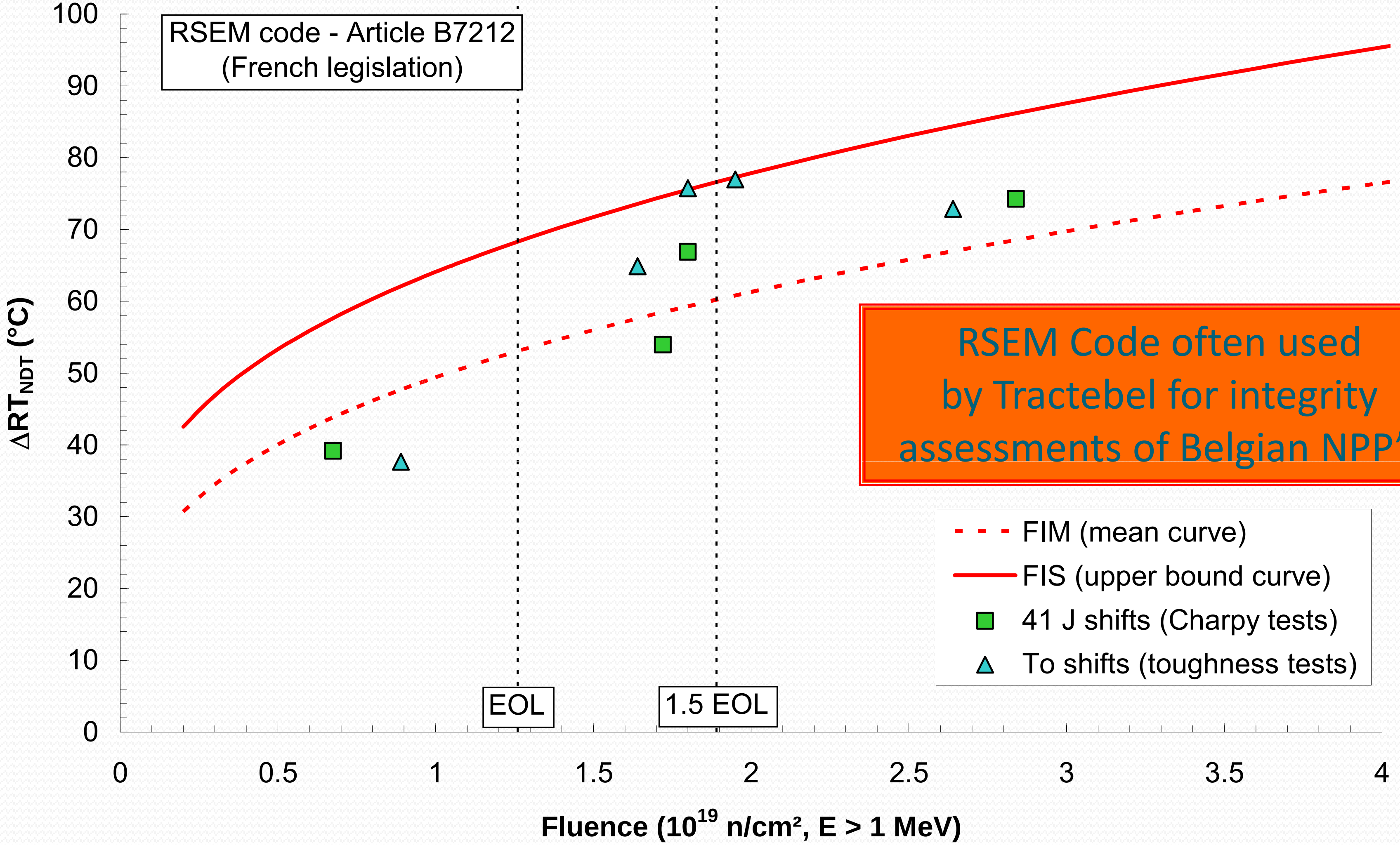
M. EricksonKirk, B. Elliott, L. Abramson, "Statistical Procedures for Assessing Surveillance Data for 10 CFR 50.61a," June 9, 2008

Other national legislations
France – RSEM Code, article B7212

$$\Delta RT_{NDT} = 8 + \left[24 + 1537\left(P - 0.008\right) + 238\left(Cu - 0.08\right) + 191\ CuNi^2\right]\left(\frac{f}{10^{19}}\right)^{0.5}$$

- The formula represents an upper bound
- It is applicable for fluences between 2×10^{18} and 8×10^{19} n/cm^2 (E > 1 MeV)
- Irradiation temperature must be between 275 and 300 °C
- The regulation does not allow to use plant-specific surveillance data (RG 1.99 Pos.2 philosophy) instead of the predictive formula; surveillance data must fall below the upper bound curve
- There is no provision for Charpy USE variations

Safety case according to the French legislation (RSEM Code)



RSEM Code often used by Tractebel for integrity assessments of Belgian NPP's

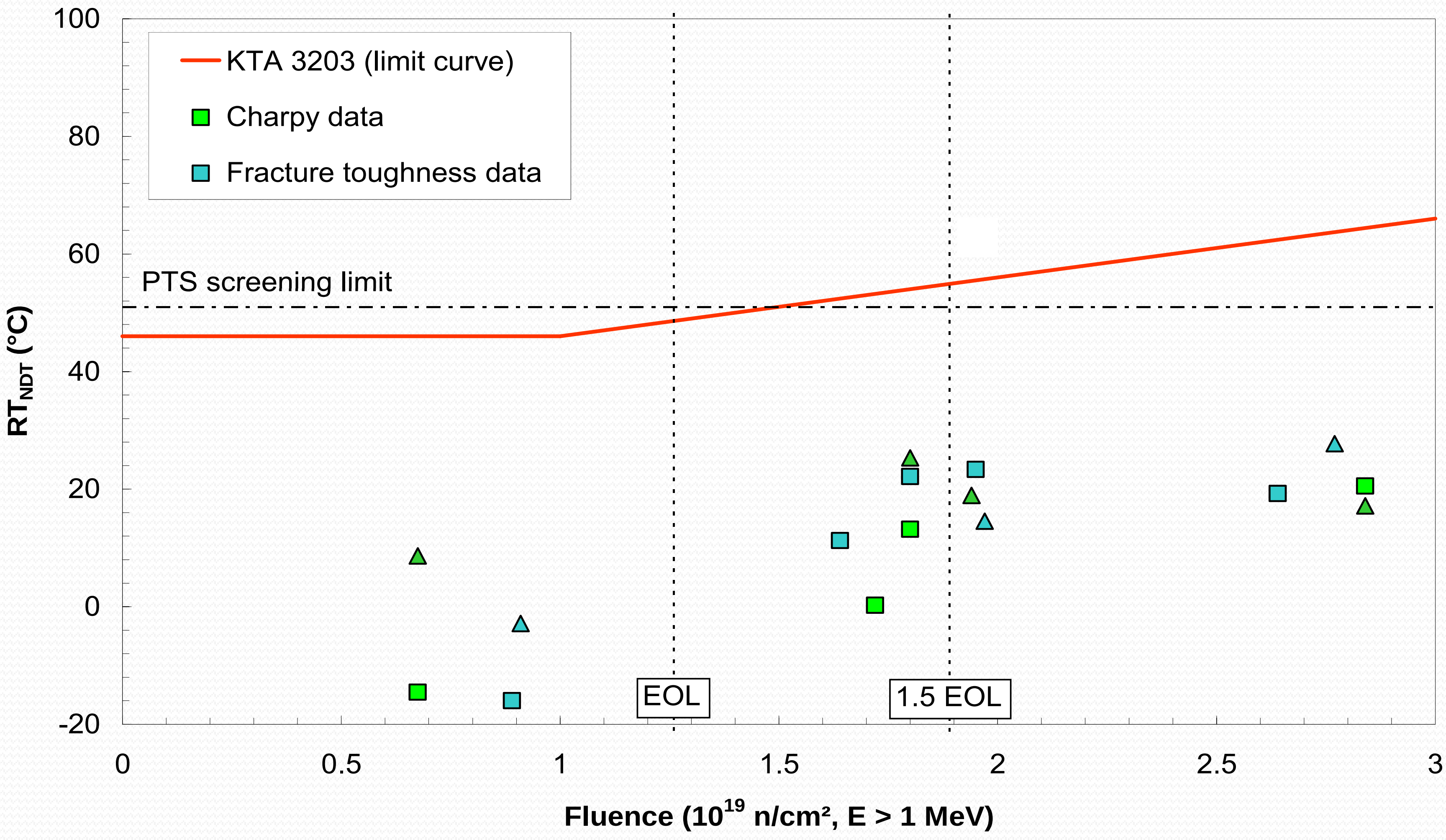
Other national legislations
Germany – KTA 3203 (6/01)

- Below 1×10^{17} n/cm² (E > 1 MeV), no irradiation effect is expected and no irradiation surveillance program is required
- Between 1×10^{17} and 1×10^{19} n/cm², the limit value of the reference temperature RT_{NDT} is:

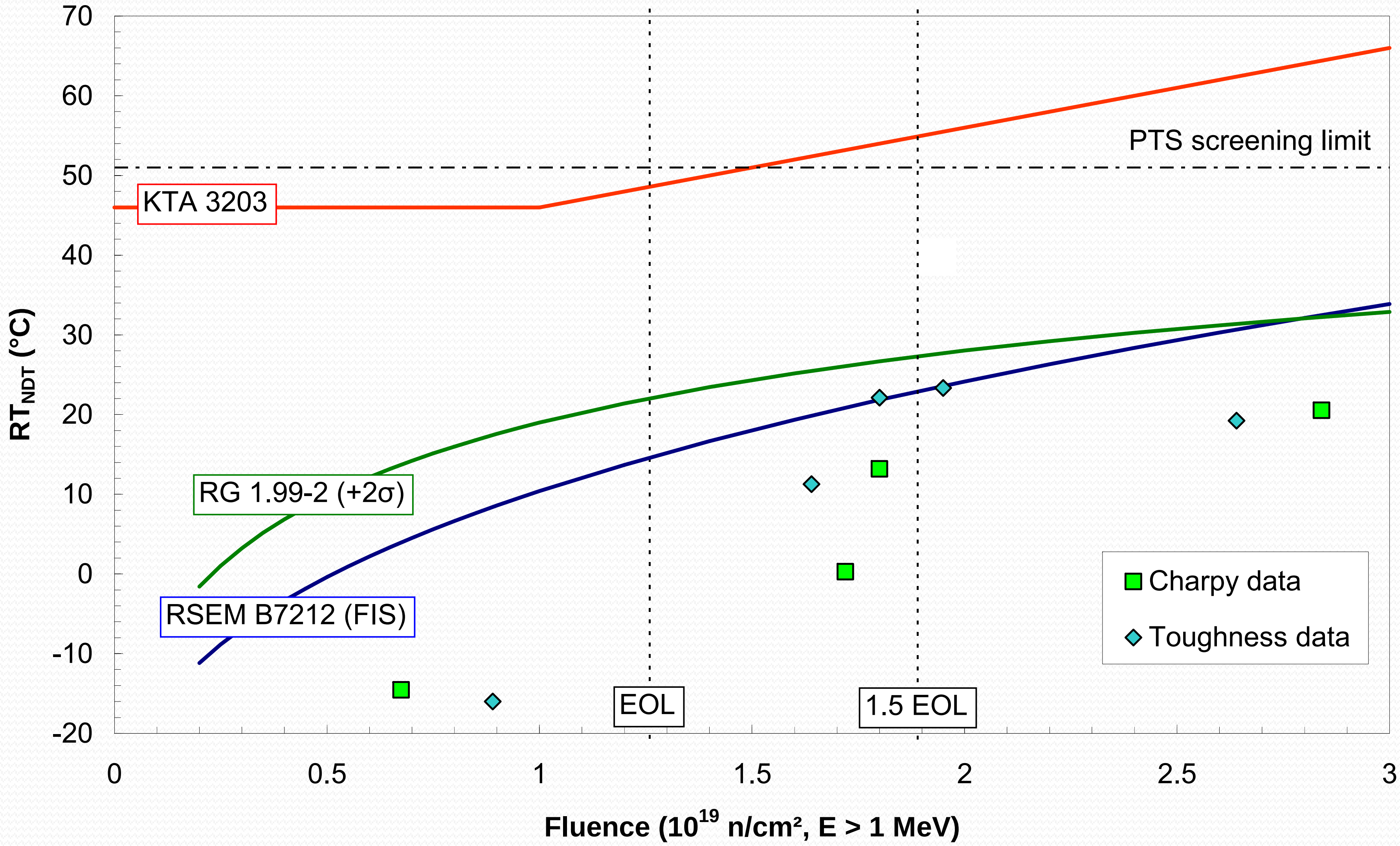
$$RT_{limit} = 40\ °C$$

- Above 1×10^{19} n/cm², RT_{limit} increases linearly with a slope of 2×10^{18} °C/(n/cm²)
- Throughout the RPV life, the reference temperature for the surveillance materials (calculated exactly as in the US legislation) has to remain below RT_{limit}
- **Rules are indipendent of chemical composition**

Safety case according to the German legislation (KTA)



Comparison between different national regulations (US – F – D)



ASME Code Sect. III, Div. 1 – NB 2331
Establishment of reference temperature RT_{NDT}

1. Determine nil-ductility transition temperature by drop weight tests ⇨ NDT
2. Perform Charpy tests and establish full transition curves for absorbed energy and lateral expansion ⇨ T_{68J}, $T_{0.89mm}$
3. Reference temperature RT_{NDT} is defined as the highest between:
   - NDT
   - $T_{Cv} = T_{68J} – 33$ °C
   - $T_{Cv} = T_{0.89mm} – 33$ °C

Reg. Guide 1.99 Rev. 2
Fluence factor

G.L. Guthrie, NUREG/CR-3391, Apr 84
G.R. Odette, EPRI NP-3319, Jan 84

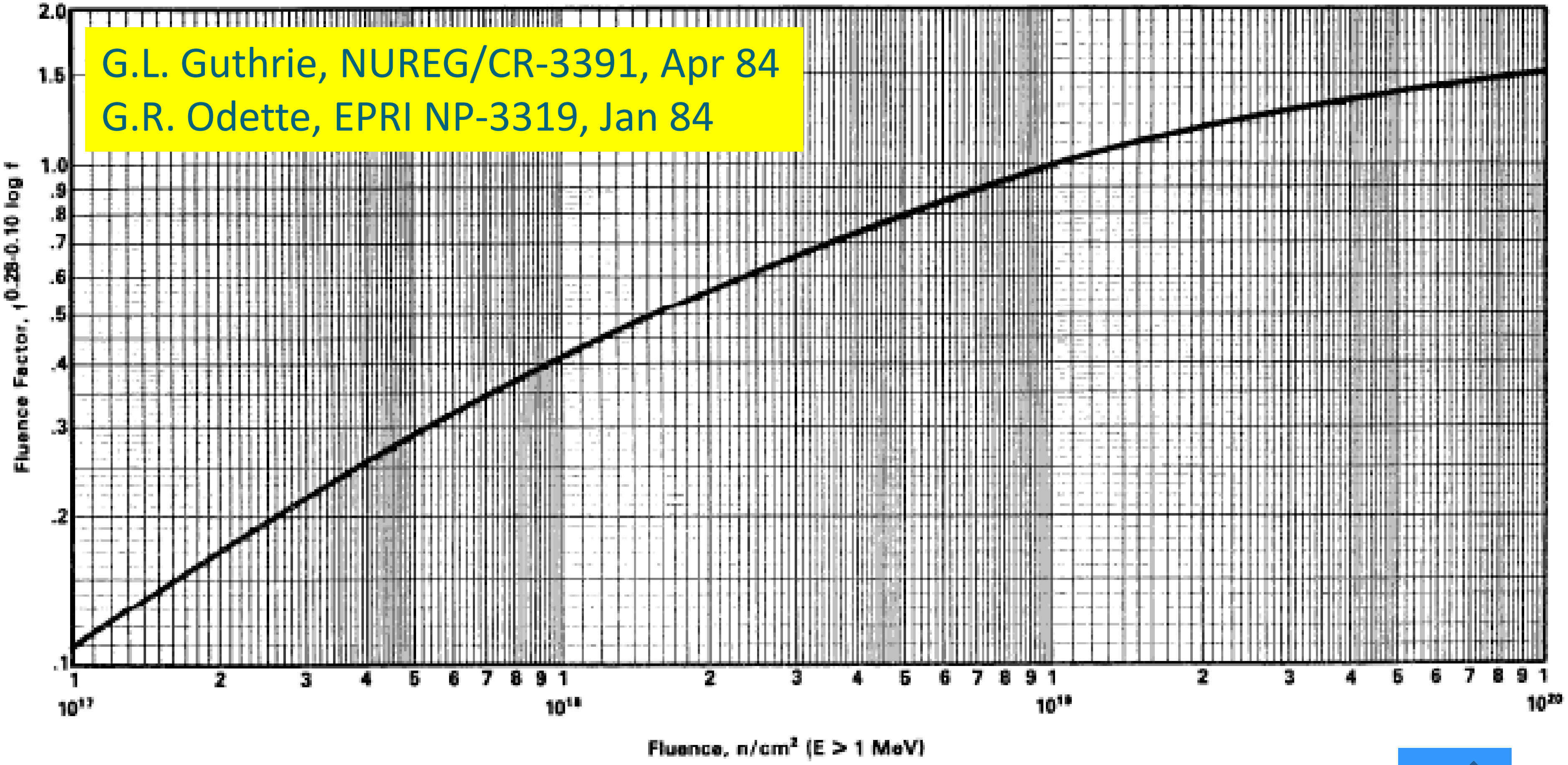


FIGURE 1 Fluence Factor for Use in Equation 2, the Expression for ΔRT_{NDT}

Reg. Guide 1.99 Rev. 2
Position 2 – Fitting of surveillance data