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Current Practice and Future Possibilities for Surveillance Program Design and Embrittlement Trending

Mark Kirk*, mark.kirk@nrc.gov

Component Integrity Branch, Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission

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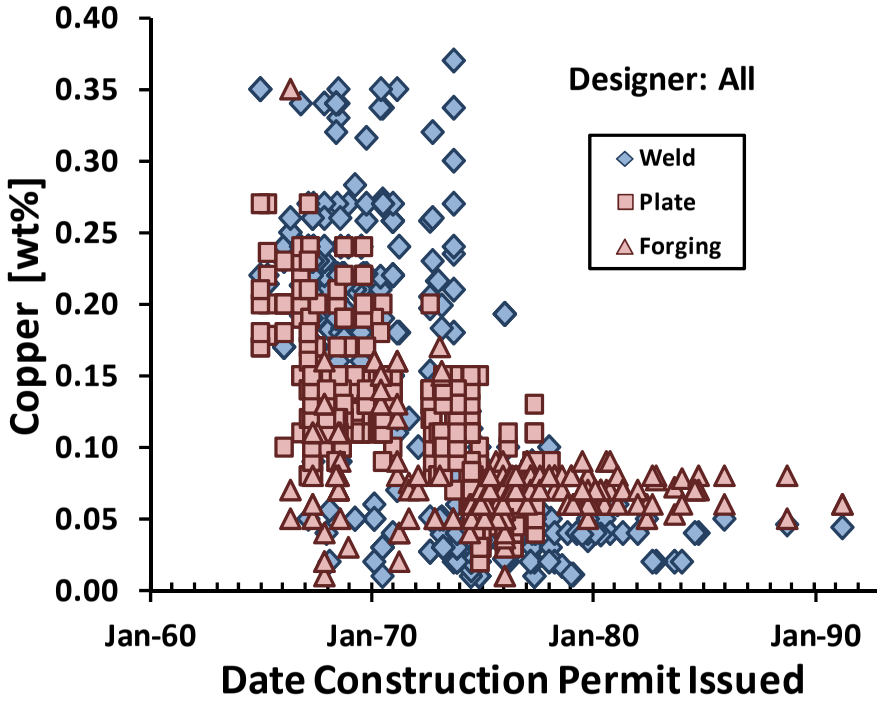
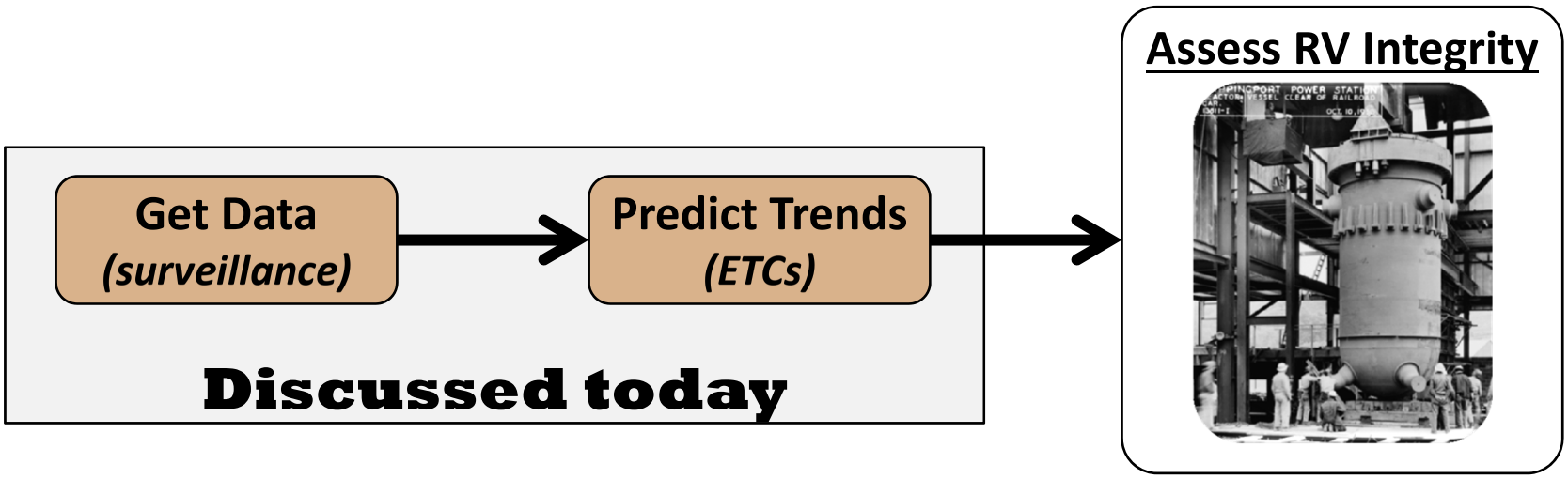
* The opinions expressed here are those of the author alone. They do not represent an official position of the NRC.

European Commission

Presentation Overview

- **Surveillance program design**
  - Early developments: USA, 1960 to 1970
  - Evolution of ASTM requirements
  - A partial survey of current national practices outside of the USA
  - Some ideas for further consideration
- **Embrittlement trending (ETCs)**
  - Trend curves: traditional curves & recent developments
  - Current activities in ASTM

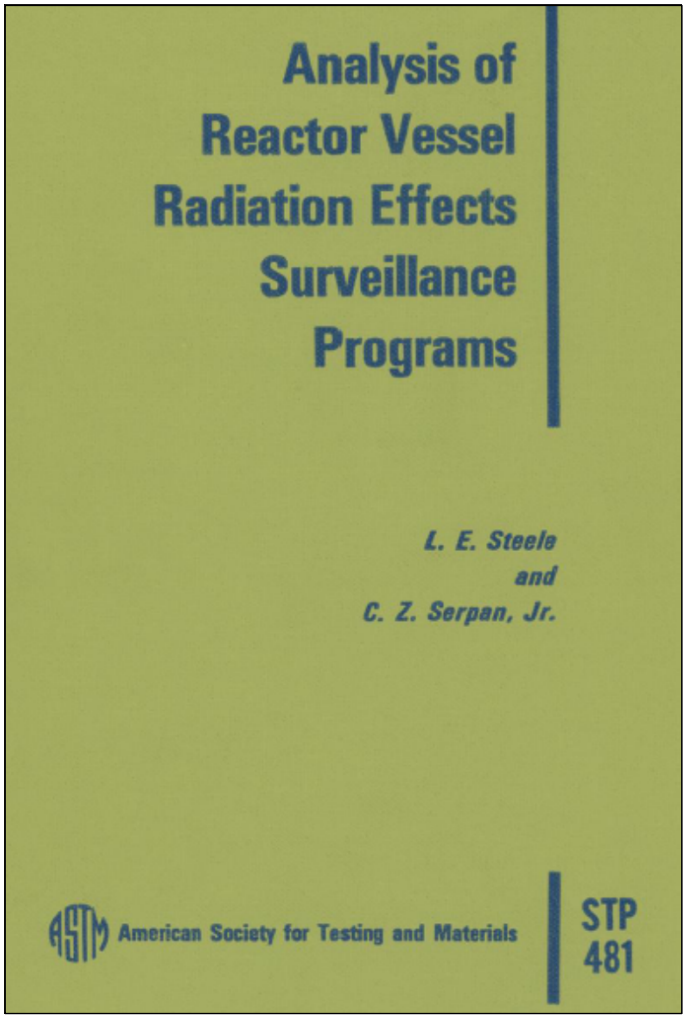




Surveillance Program Design

USA: 1960 to 1970

- **Excellent review of lessons learned from the 1st 10 years of commercial nuclear power in the USA**
- **Critique of the 5 then existing reactor surveillance programs that had produced surveillance data**
  - Big Rock Point 67MW GE BWR (stop 97)
  - Yankee Rowe 185MW (W) PWR (stop 92)
  - Dresden 1 210MW GE BWR (stop 78)
  - Elk River 58MW AC BWR (stop 68)
  - Humbolt Bay 200MW GE BWR (stop 76)
- **Insights regarding origins and bases of ASTM E185 recommendations & guidance**



Surveillance Program Design

USA: 1960 to 1970, Review of Surveillance Programs from ASTM STP-481

Specimens

- Predominantly Charpy & Tensile
- Elk River had fatigue specimens
- Limited fracture toughness specimens

Materials Tested

- Elk River: No "actual vessel materials", but many research materials
- Yankee Rowe: Surveillance plate heat treated differently than vessel plate, no weld, capsules fell off
- Some CMMs, some without
- Some HAZ, some without

Irradiation Conditions

- Capsules: wall (most important), accelerated, & thermal
- Under-estimate of flux and fluence (Dresden & Big Rock) showed value of archive materials
- Lead factor – low value preference
  - Placement *"at the vessel wall"*
  - Located *"at positions to test the effects in the actual environment"*

Sampling Strategy

- Properties evaluated: (T_{41J}, USE, YS, UTS, …)
- Number of measurements made highly variable
- Dresden: ID & OD sampling, not ¼t
- No commentary on capsule pull schedule
- Preference for actual plant exposure

Surveillance Program Design

ASTM STP-481: "A good surveillance program should include the following"

- **"irradiation of the steel (plate, weld, HAZ) from the actual pressure vessel"**
  - "from the core-region shell courses. Steel from … shell courses not in the flux field need not be used"
  - "should receive the same heat treatment as the vessel plate"
  - "The surveillance weldment should duplicate the fabrication practice for longitudinal seam weld"
- **"utilize an irradiation location and condition which duplicates as closely as possible the physical and nuclear conditions of the vessel"**
  - "The most critical location to a RPV surveillance program is that one nearest to the vessel wall."
  - "The differences in neutron spectrum between the vessel cladding interface and the surveillance exposure locations may be important. … The closer the surveillance exposure location is to the pressure vessel wall, the smaller spectral variations become."

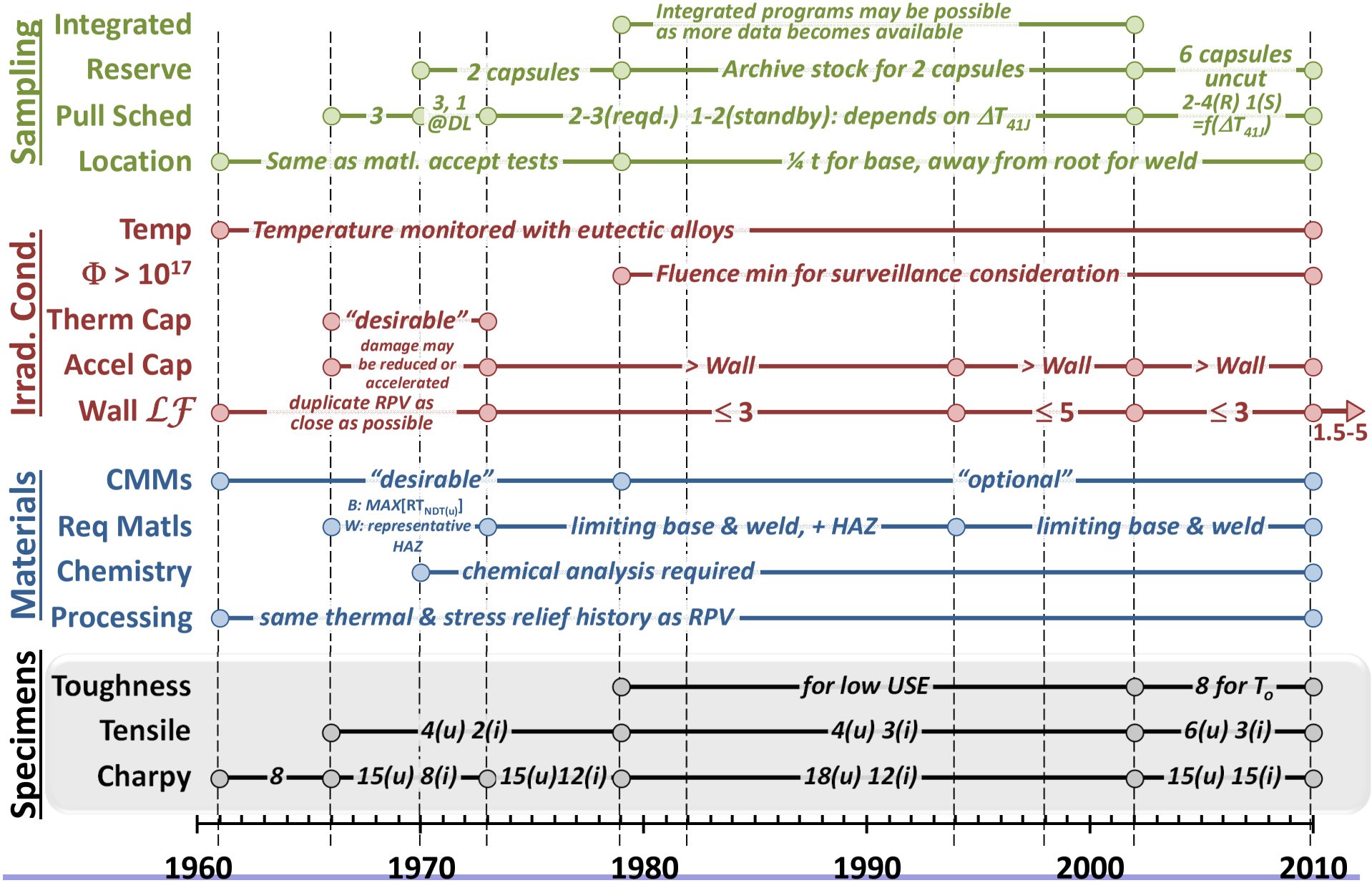
Surveillance Program Design

ASTM STP-481: Other Recommendations

- **Regarding ¼t sampling**
  - Dresden 1 samples "were taken from representative steel, but from both the top and bottom plate surfaces. The effect of the expected superior microstructure in the plate surfaces versus the plate ¼ thicknesses (wherein the material characteristics are judged for contractual acceptance), is not well -known and always will be the cause for uncertainty."
- **Regarding pull schedule**
  - One vessel wall capsule after a year or two
  - One vessel wall capsule after about five years
- **Regarding temperature monitors**
  - "Reliance will thus have to be placed upon the results of inspecting low melting point alloys. These do not give [a] precise temperature measurement … but no other recourse is available."
  - "The contribution provided by knowing the temperature is for interrelating the surveillance results with experimental test reactor trends and thereby projecting results to future years."
  - "Temperature monitoring is also important to assure that the specimens are exposed at temperatures which truly represent the vessel."

Surveillance Program Design

ASTM E185: Evolution of requirements from 1961 to today



Surveillance Program Design

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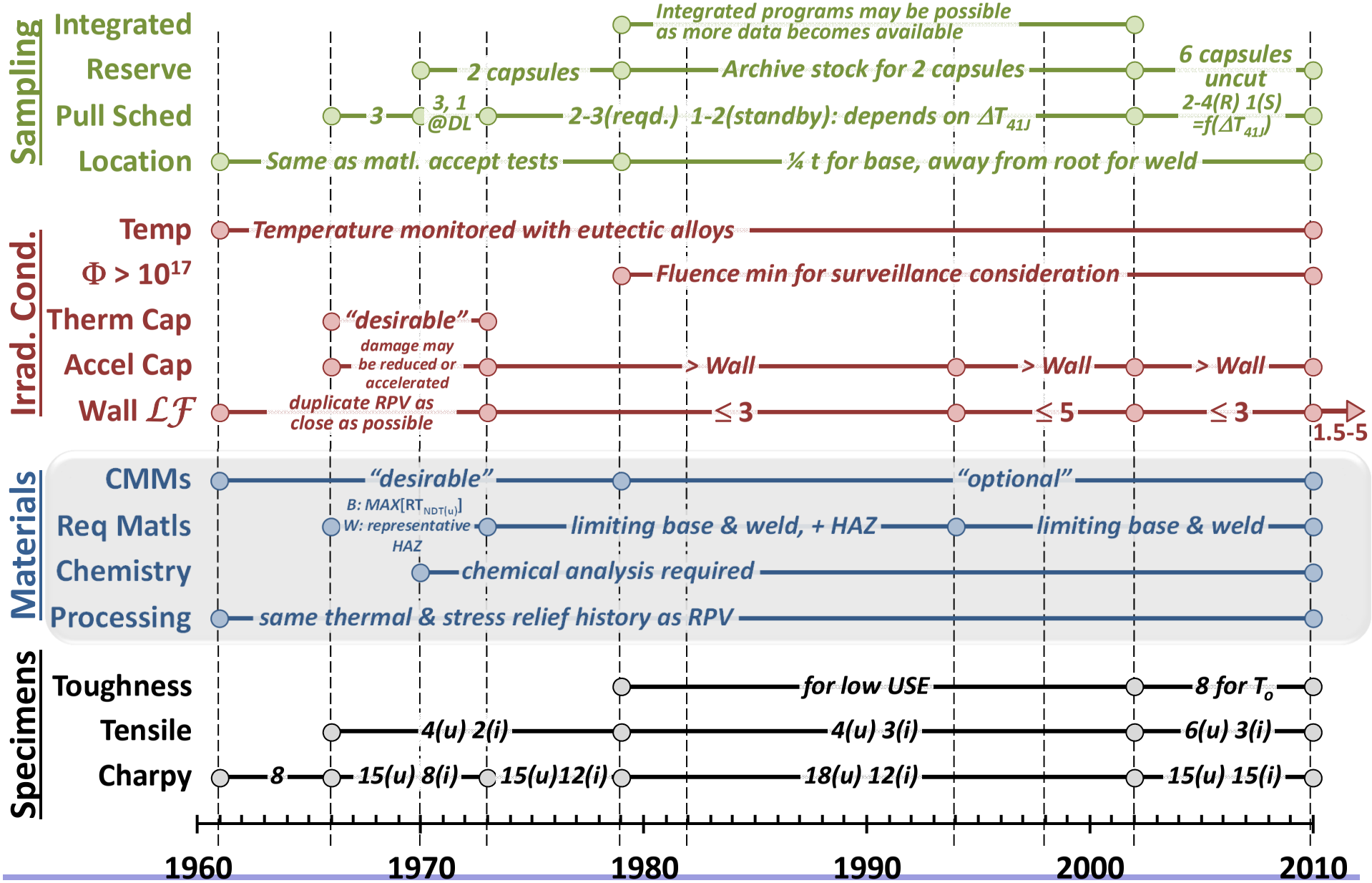

Surveillance Program Design

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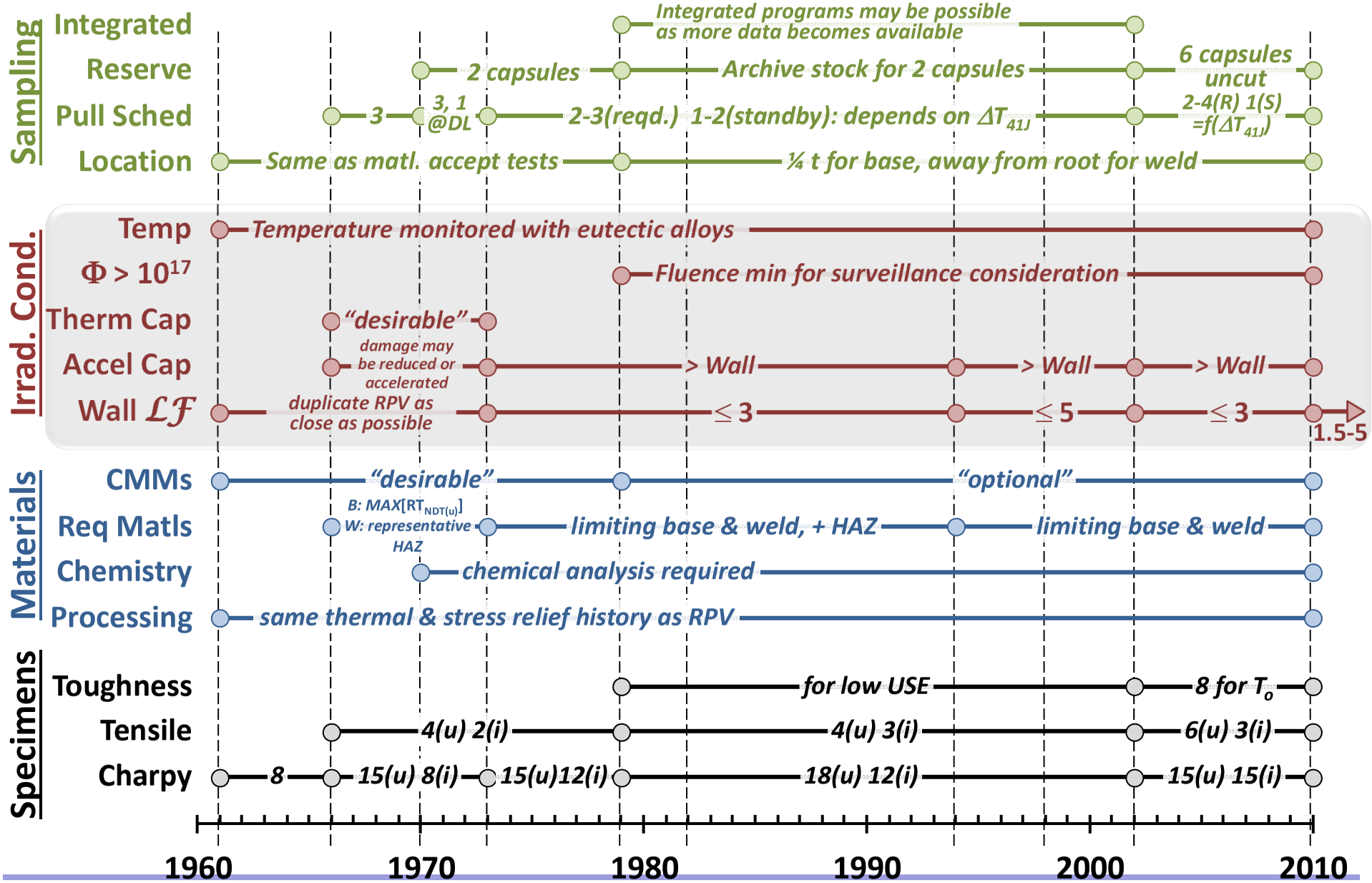

Surveillance Program Design

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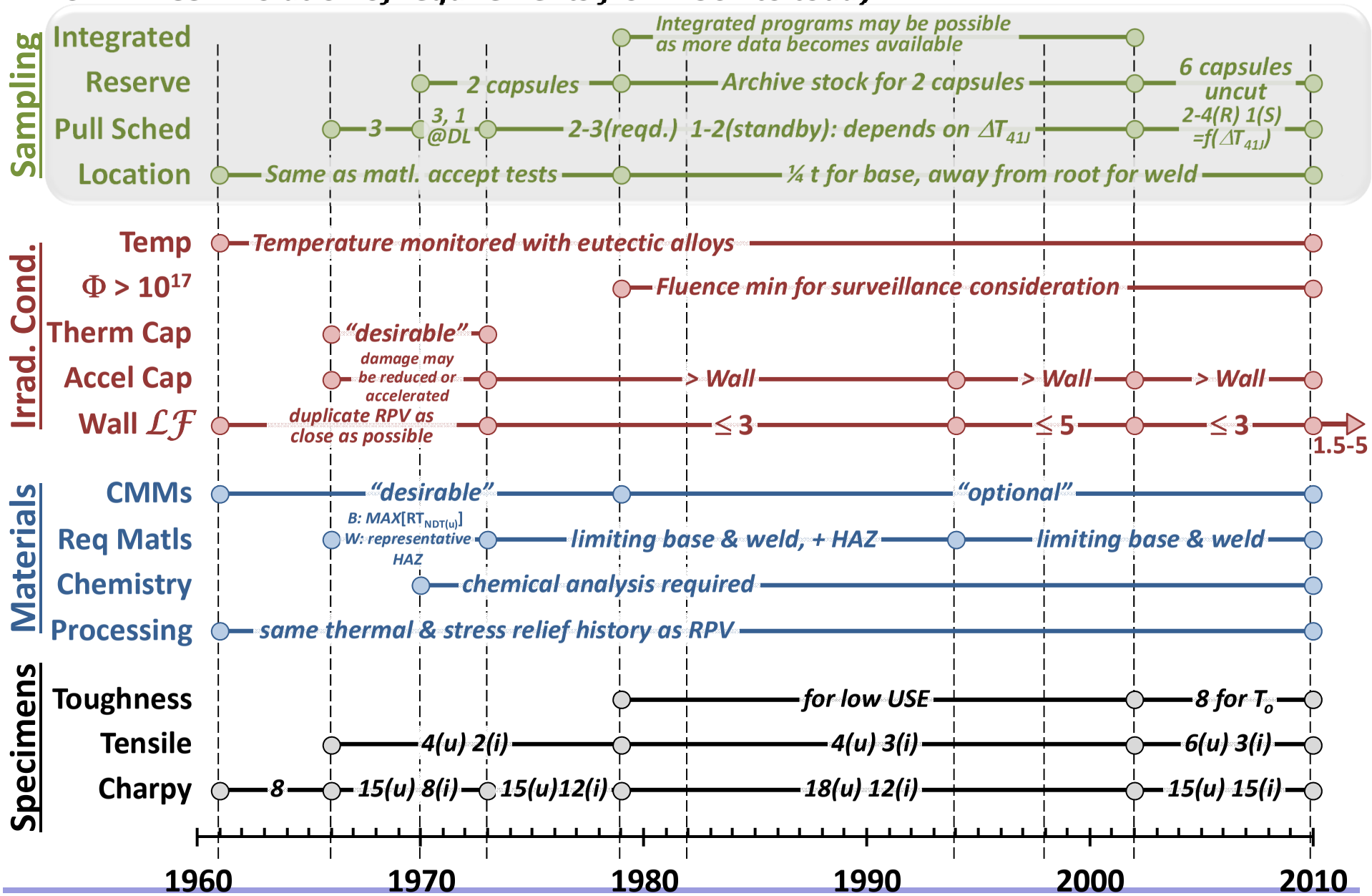


Surveillance Program Design

Modern Surveillance Requirements – an Incomplete International Survey

- **Fracture toughness tests now required or recommended**
  - ASTM E185 (2002)
  - Germany: KTA 3203 (2001)
  - Switzerland: ENSI-B01/d (2011)
  - Japan: has FT in PWR capsules. CRIEPI investigating 0.15T C(T) for LTO.
  - AREVA: EPR surveillance program
  - Westinghouse: AP-1000
  - SCK·CEM: "Enhanced" surveillance (also includes property to property correlations)
  - Czech Republic WWER
- **Lead Factor Limits**
  - ASTM E185: varies from 3 to 5, changes over the years
  - KTA 3203 (Germany): 1.5 to 12
  - Czech Republic supplemental surveillance: up to 5
  - France: 0.5 - 4
  - Japan: PWRs < 3, BRWs ≈>5
  - Spain: 0.8 - 12
  - Hungary: 12-18 validated by "extended surveillance" at lower lead factors

Surveillance Program Design

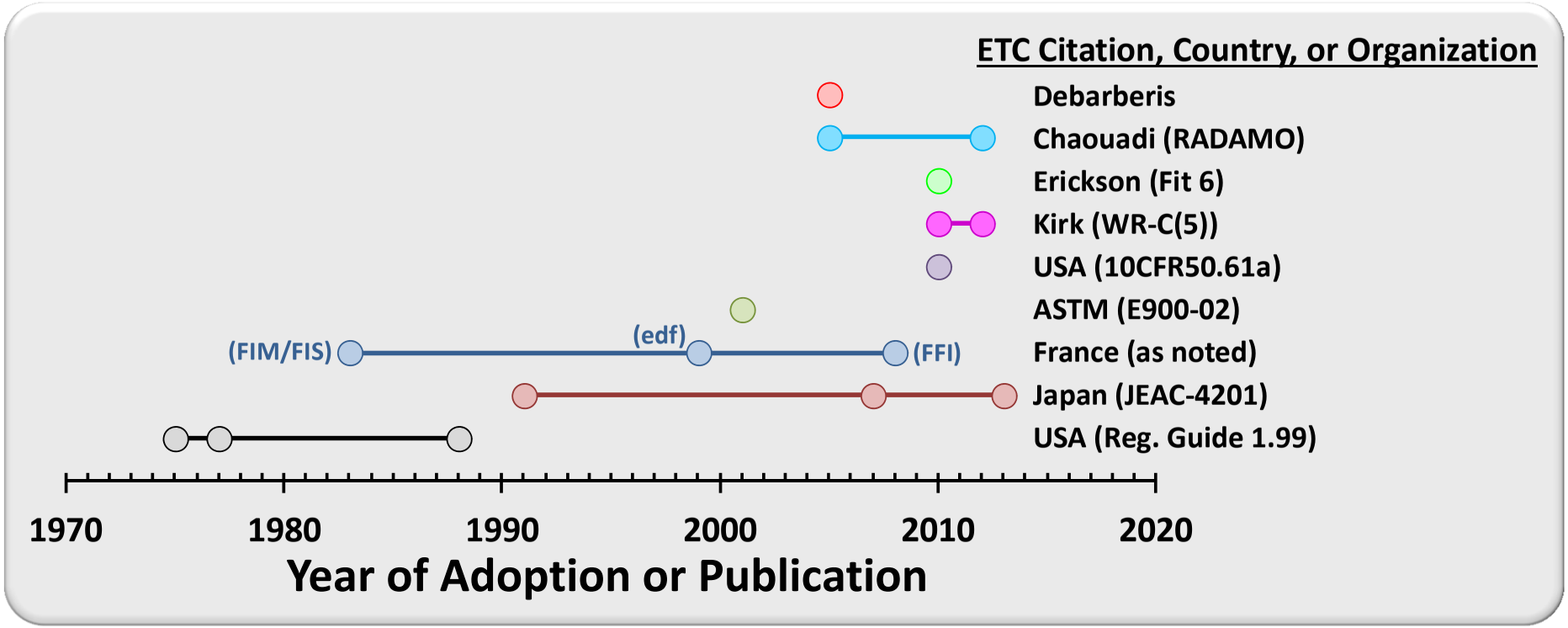
Some Ideas for Further Discussion

- **Early detection/warning of embrittlement**
  - Lead factor limits (typically < 5)
  - Limits on high exposures (typically < 2x EOL fluence)
- **Optimized use of surveillance volume**
  - Non-transition temperature tests, &/or non-limiting materials
  - Specimen inserts
  - Developing interpretations of data
    - arrest information from instrumented Charpy
    - CVN master curve
- **Integrated *vs*. plant specific surveillance**

Embrittlement Trend Curves

Background

- **Many ETCs have been introduced in the last ≈decade**



Embrittlement Trend Curves

Background

- Many ETCs have been introduced in the last ≈decade
- **Despite considerable differences between**
  - Mechanism *vs.* data preference,
  - fitting functions,
  - fit data sets, and
  - variables used

	Single Term									
Curve ID	**Fluence**	**Flux**	**Temp.**	**Cu**	**Ni**	**P**	**Mn**	**Si**	**C**	**PF**
Todeschini, FFI	X			X	X	X				2
RR-UCSB	X	X	X	X	X	X	X	X	X	2
RG 1.99 R2	X			X	X					2

	Low Cu Term										HIgh Cu Term									
Curve ID	**Fluence**	**Flux**	**Temp.**	**Cu**	**Ni**	**P**	**Mn**	**Si**	**C**	**PF**	**Fluence**	**Flux**	**Temp.**	**Cu**	**Ni**	**P**	**Mn**	**Si**	**C**	**PF**
E900-02	X		X								X			X	X					4
10CFR50.61a	X	X	X			X	X			3	X	X		X	X	X				5
Kirk, WR-C(5)Rev.1	X		X		X	X	X			3	X		X	X	X	X	X			3
Erickson, Fit 6	X		X		X	X	X				X		X	X	X					
JEAC4201-2007	X	X	X	X	X						X	X	X	X	X					
RADAMO	X		X		X						X		X	X	X	X				

Embrittlement Trend Curves

Background

- Many ETCs have been introduced in the last ≈decade
- Despite considerable differences between
  - mechanism *vs.* data preference,
  - fitting functions,
  - fit data sets, and
  - variables used
- **All equations model the same phenomena**
  - similar radiation environments
  - similar RPV steels
- **ASTM E10.02 is therefore evaluating recent ETCs using**
  - a common data set
  - statistical evaluation metrics

  for possible use in E900

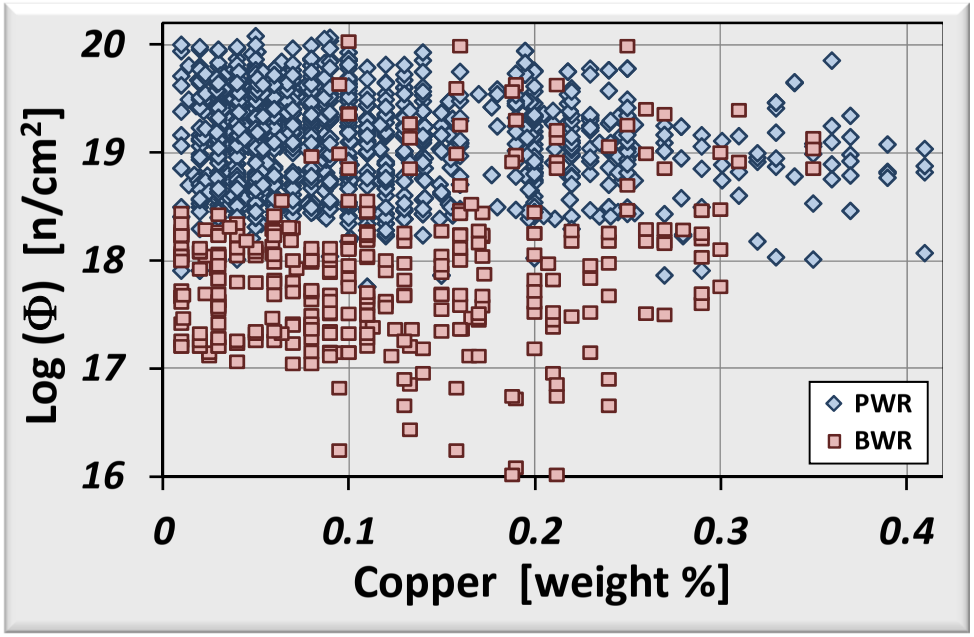
Embrittlement Trend Curves

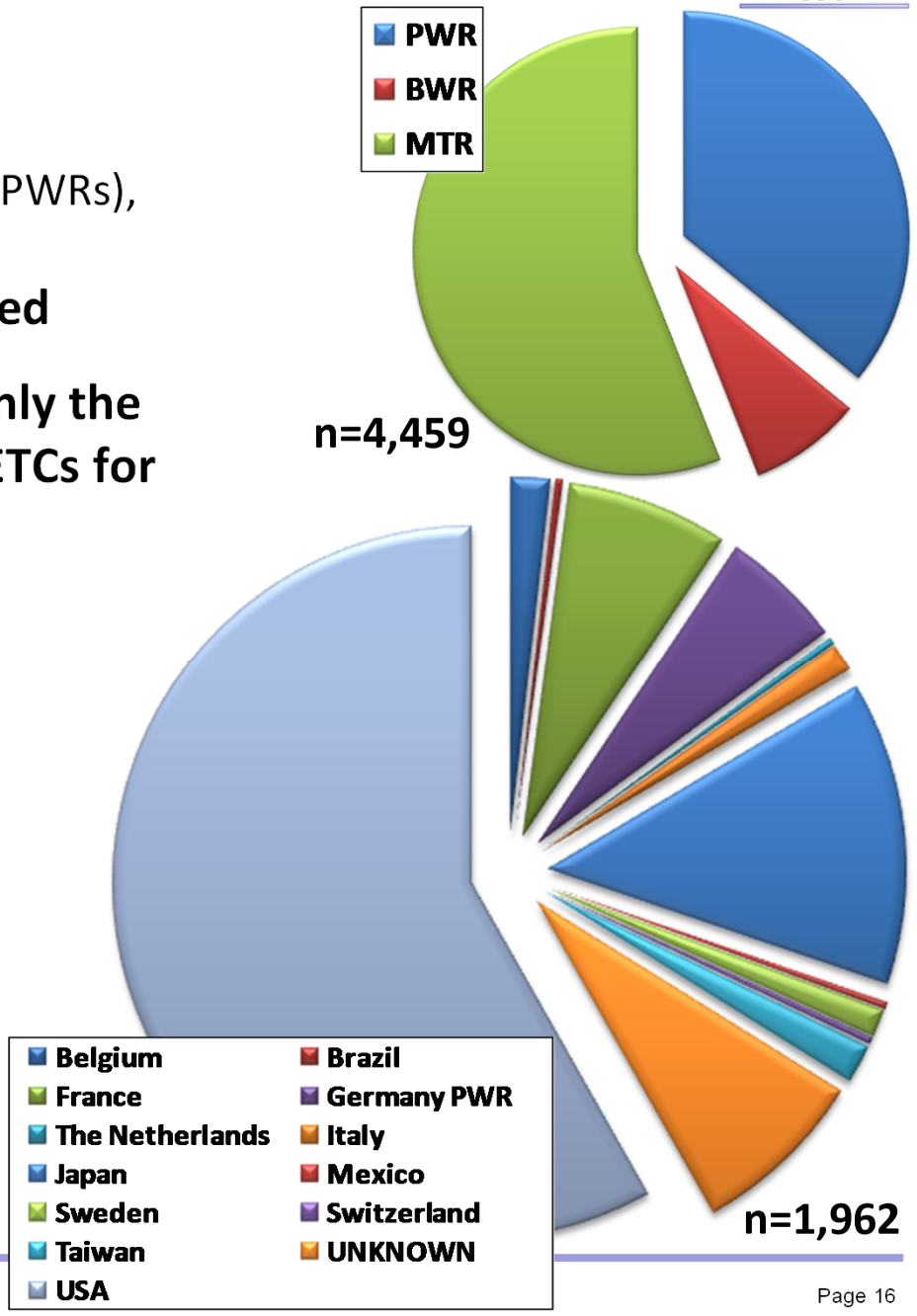
E10.02 Evaluation – Common Data Set

- **Data from**
  - National surveillance programs (PWRs & PWRs),
  - Material test reactors (MTRs)

  has been collated, QA checked, & stored

- **E10.02 subcommittee agreed to use only the PWR & BWR data in its evaluation of ETCs for the next revision of E900**

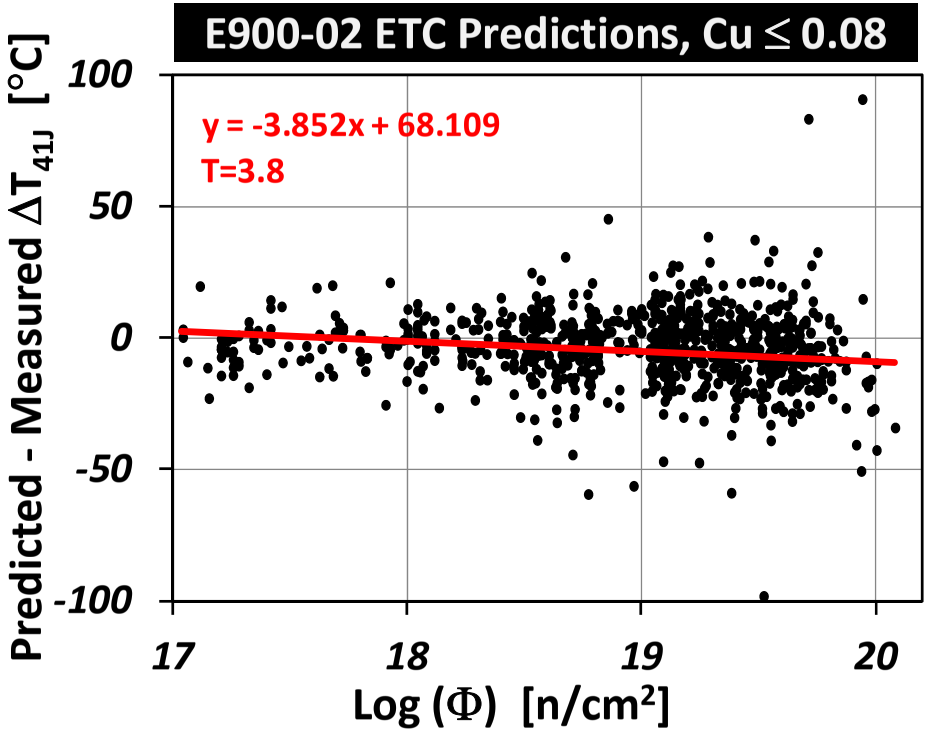




Embrittlement Trend Curves

E10.02 Evaluation – Statistical Evaluation Metrics

- **Statistical metrics evaluate ETCs for**
  - Central tendency
  - Scatter
  - Residual trends
  - Likelihood
  - AICc
- **Evaluation can be made of any data set or subset**



		E900-02	10CFR50.61a	WR-C(5)R1	EdF 900 MW	E-Fit 6	JEAC 4201-2007(PVP13)	RR / UCSB	RG1.99 Rev2	RADAMO
	Deltas vs Best ETC									
CENTRAL TENDENCY	Mean Residual [R]	4.25	3.00	2.68	1.11	0.68	0.00	2.94	0.32	0.81
	T test on Mean R	6.33	4.50	4.30	1.80	0.76	0.00	4.83	0.12	1.15
VARIABLE TRENDS	Slope	3.12	3.47	3.39	4.03	0.82	0.00	0.53	4.78	5.06
	T test on Slope	2.95	3.42	3.58	4.62	0.61	0.00	0.42	4.58	5.58
	% Difference from Best ETC									
SCATTER	RMSD	36.5%	31.5%	24.3%	16.1%	30.4%	0.0%	22.7%	34.6%	21.0%
CENTRAL TENDENCY	ln(L)	9.1%	11.6%	0.0%	2.3%	4.3%	2.6%	10.9%	42.1%	10.3%
& SCATTER	mean [ln(L)]	9.1%	11.6%	0.0%	2.3%	4.3%	2.6%	10.9%	42.1%	10.3%
COMBINED	AICc	8.5%	11.5%	0.0%	1.7%	4.0%	2.3%	10.3%	41.3%	10.1%

Embrittlement Trend Curves

E10.02 Evaluation – Recent & Upcoming Steps

Date	Venue	Item
19th October 2013	the internet	Data & evaluation tool distributed to E10.02 members
27th-28th January 2014	Houston, Texas	Meeting to discuss members' evaluations, and agree (?) on ETC to ballot in E900 revision
???	the internet	Ballot of E900 revision
9th-10th June 2014	Jackson Hole, Wyoming	Meeting to resolve (?) negatives on E900 ballot
14th -18th September 2014	Avignon, France	Paper presenting results of E10.02 evaluation