Knowledge Gaps in Toughness and Irradiation: Lessons of the Past, Prospects for the Future

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Themes

- What can we learn from the past?
- What can we expect in the future?
  - What can we do about it?

- Answers - we need to:
  - Develop understanding
  - Find and fill gaps
  - Prepare for unexpected issues

Failure during hydro-test (chemical plant pressure vessel)

Fig. 1.12. *Failure by brittle fracture of thick-walled cylindrical pressure vessel during hydraulic test (By courtesy of John Thompson Ltd., Wolverhampton)*

Witnesses heard "a kind of dull thud".

A two tonne piece landed 45m away in a car park.

Fortunately, there was only one injury, and that was minor.

Past technical surprises (1)

- Unexpected (at least to most people) sensitivity to irradiation damage variables:
  - Impurities (copper, phosphorus, etc.)
  - Alloying elements (nickel, manganese, etc.)
  - Irradiation environment (spectrum, flux, etc.)
- Unexpected (- ditto -) phenomena:
  - No loops in steels (?)
  - Grain boundary embrittlement
  - CRPs, MNPs, UMDs, LBPs (?)
  - etc., etc,

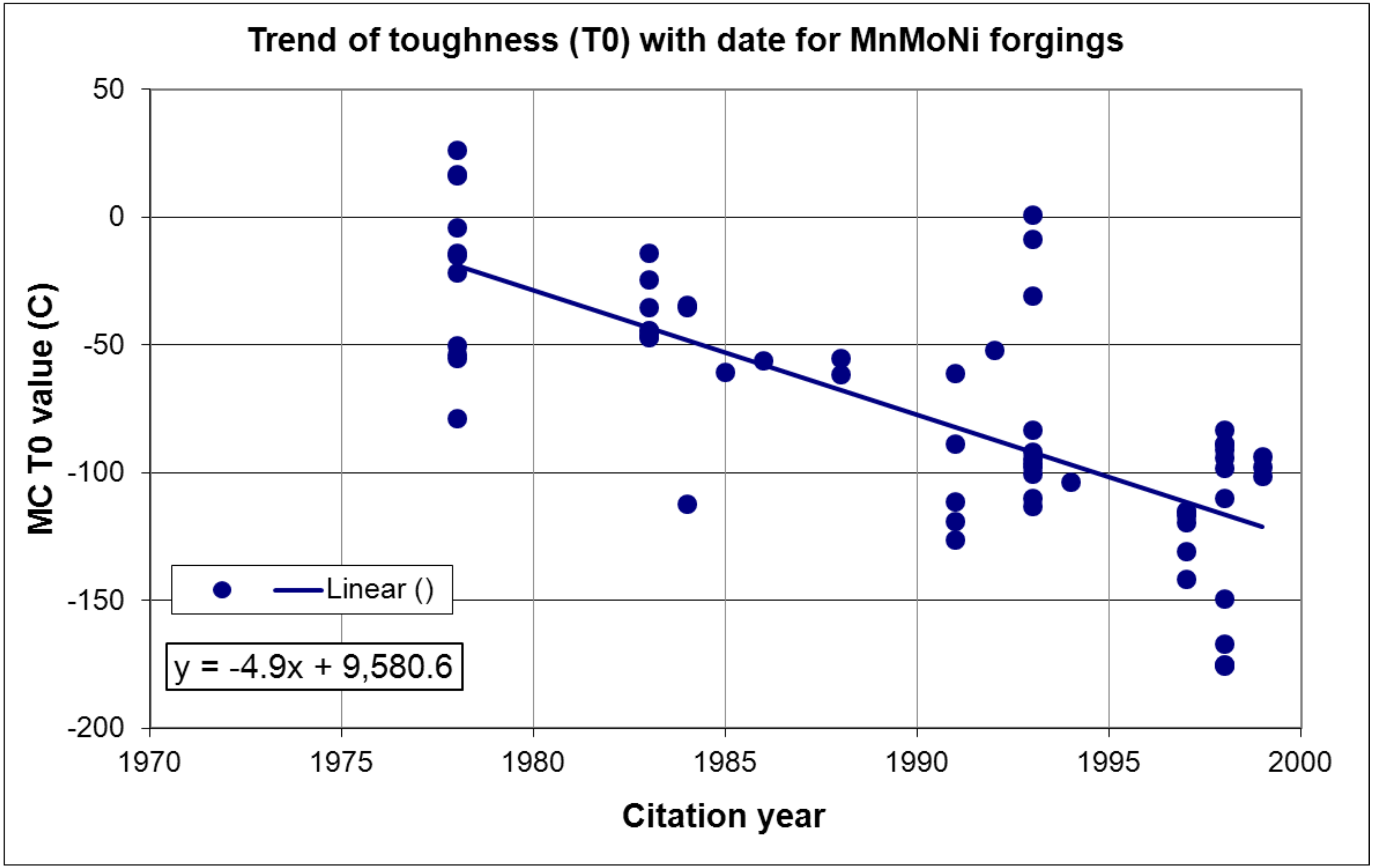
Past technical surprises (2)

- **Manufacturing and operational issues**
  - Underclad cracking
  - Segregation in large forgings
  - External corrosion (Davis Besse)
  - Hydrogen flaking (Doel3, Tihange 2)
  - etc.
- **The solution of these issues relied on good understanding of materials degradation and structural integrity assessment (SIA)**

Past technical improvements

- **Some examples:**
  - **“Better” materials**
  - **Better analysis methods:**
    - **Fracture Mechanics**
    - **Finite Element Analysis**
    - **Master Curve / Unified Curve**
  - **Better Non-Destructive Examination techniques**
  - **Better testing methods**
    - **Mechanical: small fracture toughness, reconstitution**
    - **Microstructural: AP, SANS, FIB …**
  - **Better computers enabling MS/MP models**

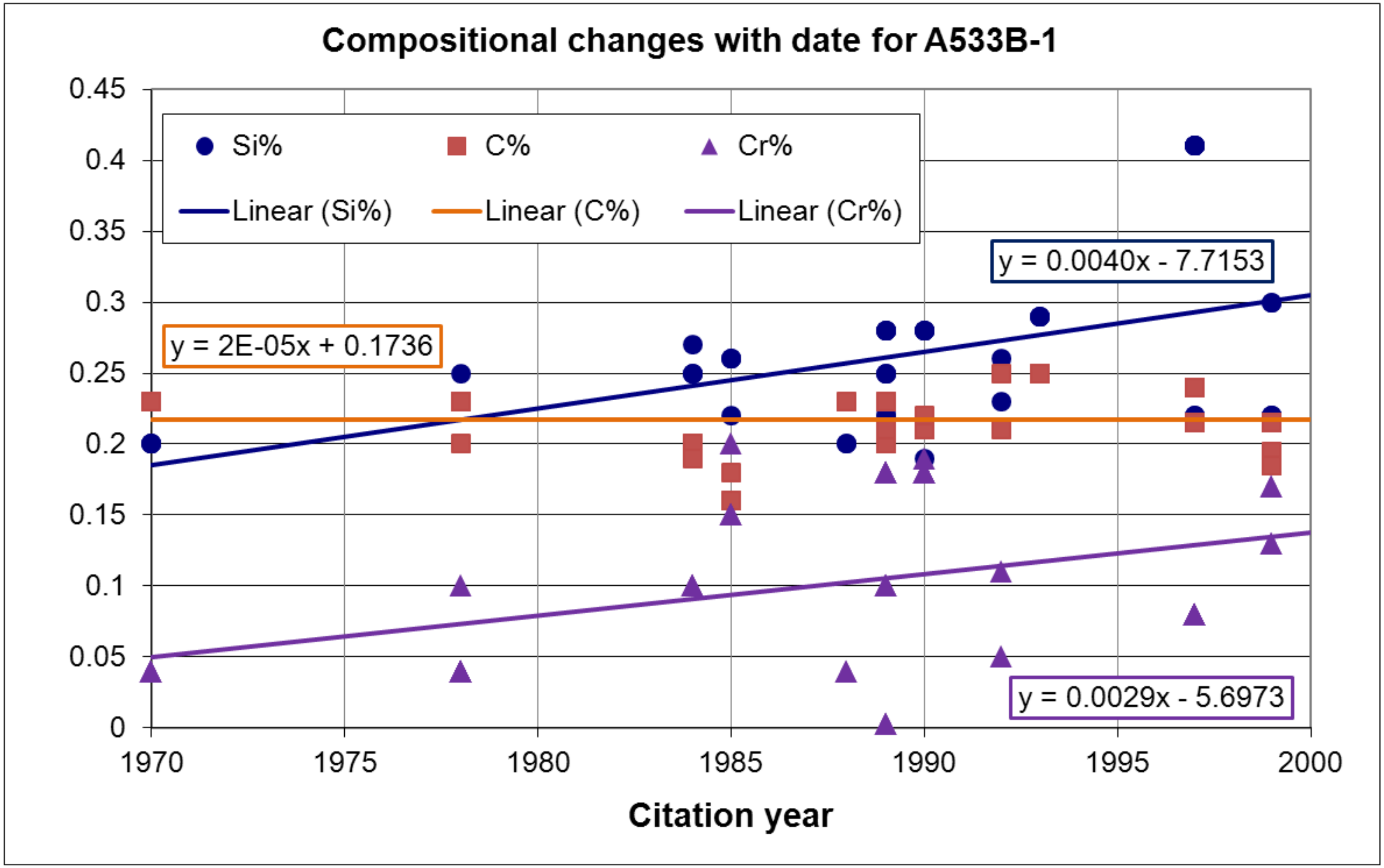
Improvement in toughness with date



A508-2; A508-3; 20NiMoCr26; 22NiMoCr37

Data compiled by Mark Kirk

Compositional changes with date



Materials have changed

Past and Future

1960
Calder Hall # 4
60MWe
40 years

2010
EPR
1650 MWe
60 years?

2060
??R
????? MWe
??? years

Changes in past 50 years

- Larger, thicker RPVs (forgings)
- Changes to steelmaking and fabrication practice
- Changes to supply routes (including mineral sources)
- International collaboration
- Increasingly tight regulation (demonstrable safety)
- Losing experienced staff
- Changes in the ways that organizations work
- Need to extend RPV life (due to nuclear hiatus)

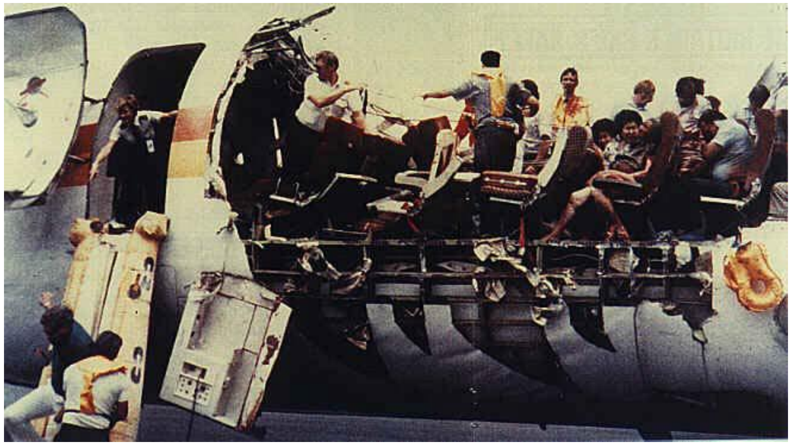
Changes in next 50 years

- Much the same?
- Always moving beyond experience

Engineering failures

Tay Bridge Disaster

Titanic



Aloha Airlines Flight 243

Disaster theory

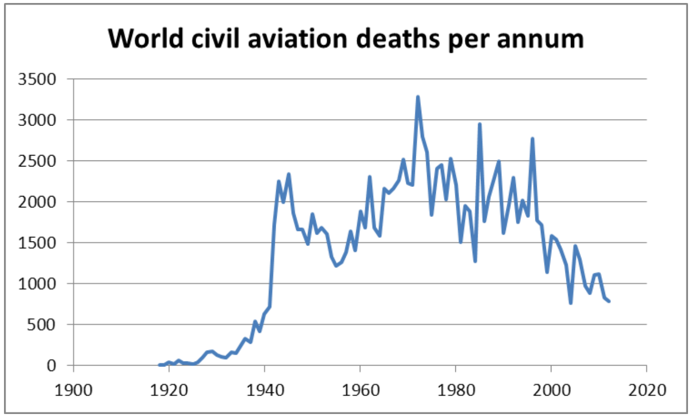
- **Unforeseeable (?)**
  - **Natural accident theory**
  - **Epistemic accidents**
- **Foreseeable**
  - **Failures of foresight**
    - **In the UK TAGSI four-legged safety case, the fourth leg, forewarning of failure (through surveillance, development of knowledge, etc.), is intended to provide protection against such failures**

Anatomy of a Disaster: Why Some Accidents Are Unavoidable, John Downer Discussion Paper No: 61, Centre for Analysis and Risk Regulation, London School of Economics, March 2010

Causes of failure when engineers were at fault

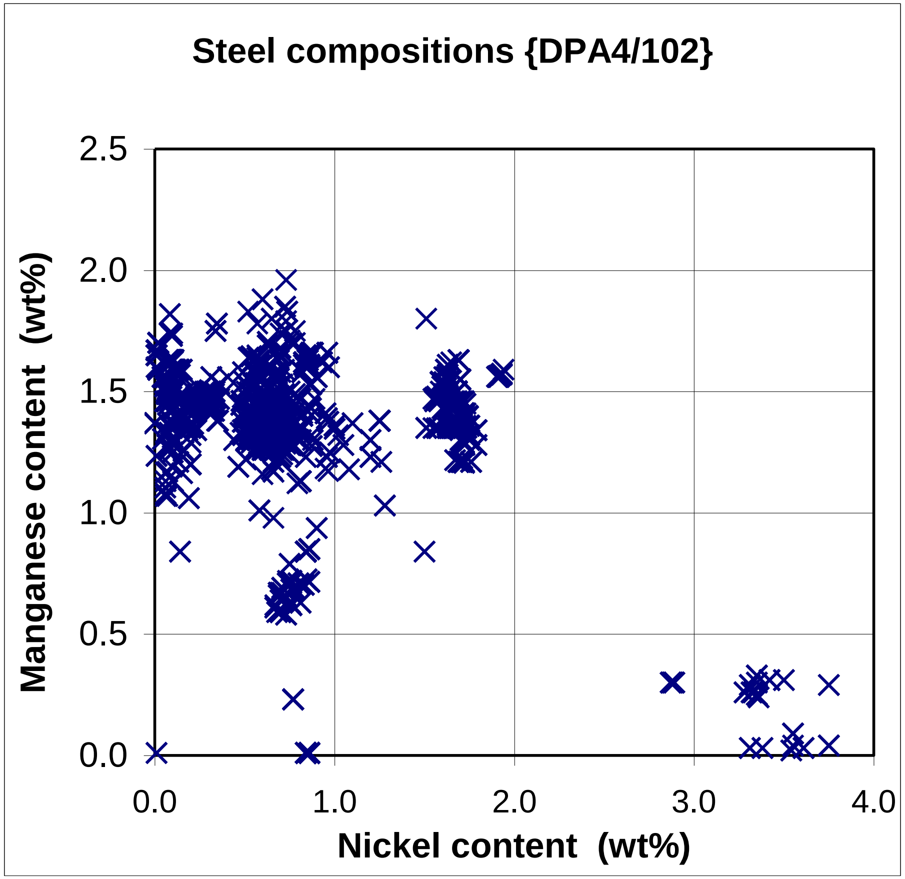
Swiss Federal Institute of Technology, Zurich, analysis in 1976 of 800 cases of structural failure in which 504 people were killed; causes were:

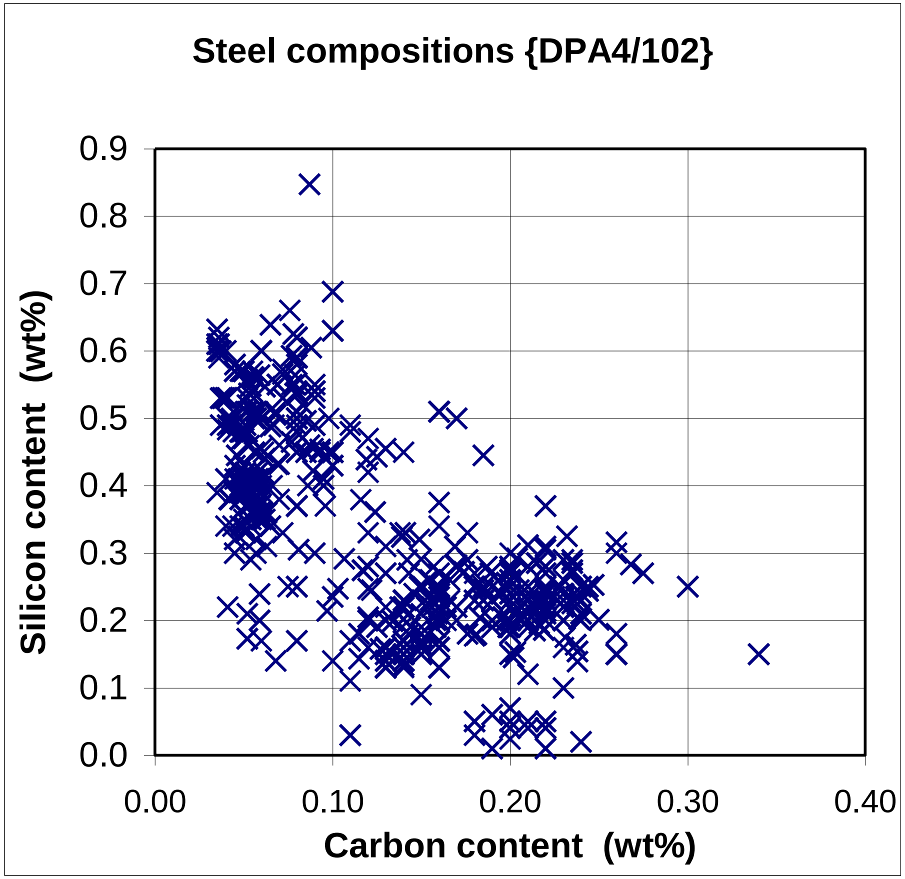
Insufficient knowledge	36%
Underestimation of influence	16%
Ignorance, carelessness, negligence	14%
Forgetfulness, error	13%
Relying upon others without sufficient control	9%
Objectively unknown situation	7%
Unprecise definition of responsibilities	1%
Choice of bad quality	1%
Other	3%



M. Matousek and Schneider, J., (1976) Untersuchungen Zur Struktur des Zicherheitproblems bei Bauwerken, Institut für Baustatik und Konstruktion der ETH Zürich, Bericht No. 59, ETH.

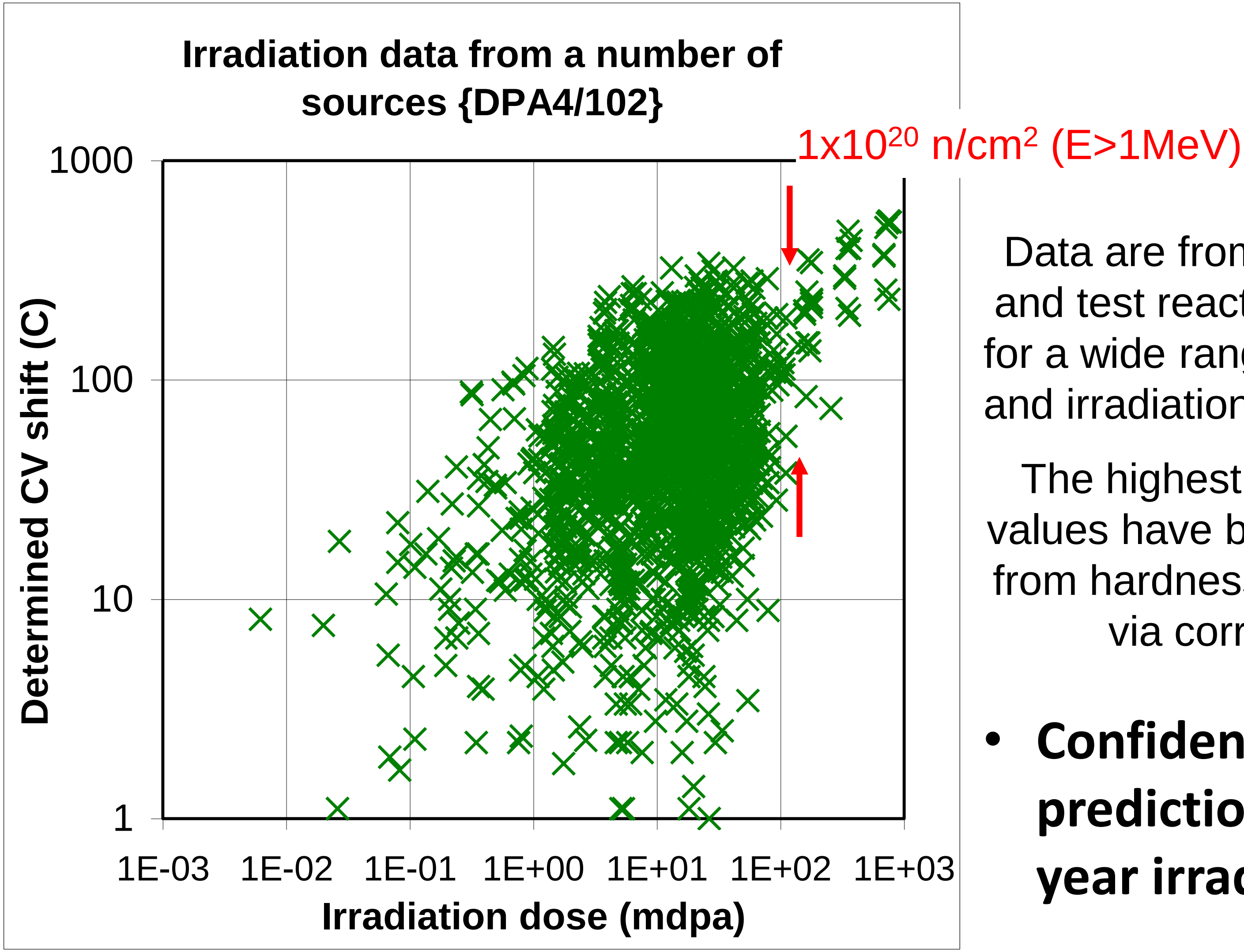
Issues for predictions for 80 year irradiations?





The areas of dataspace investigated are incomplete, even in two dimensions

Variability of irradiation damage

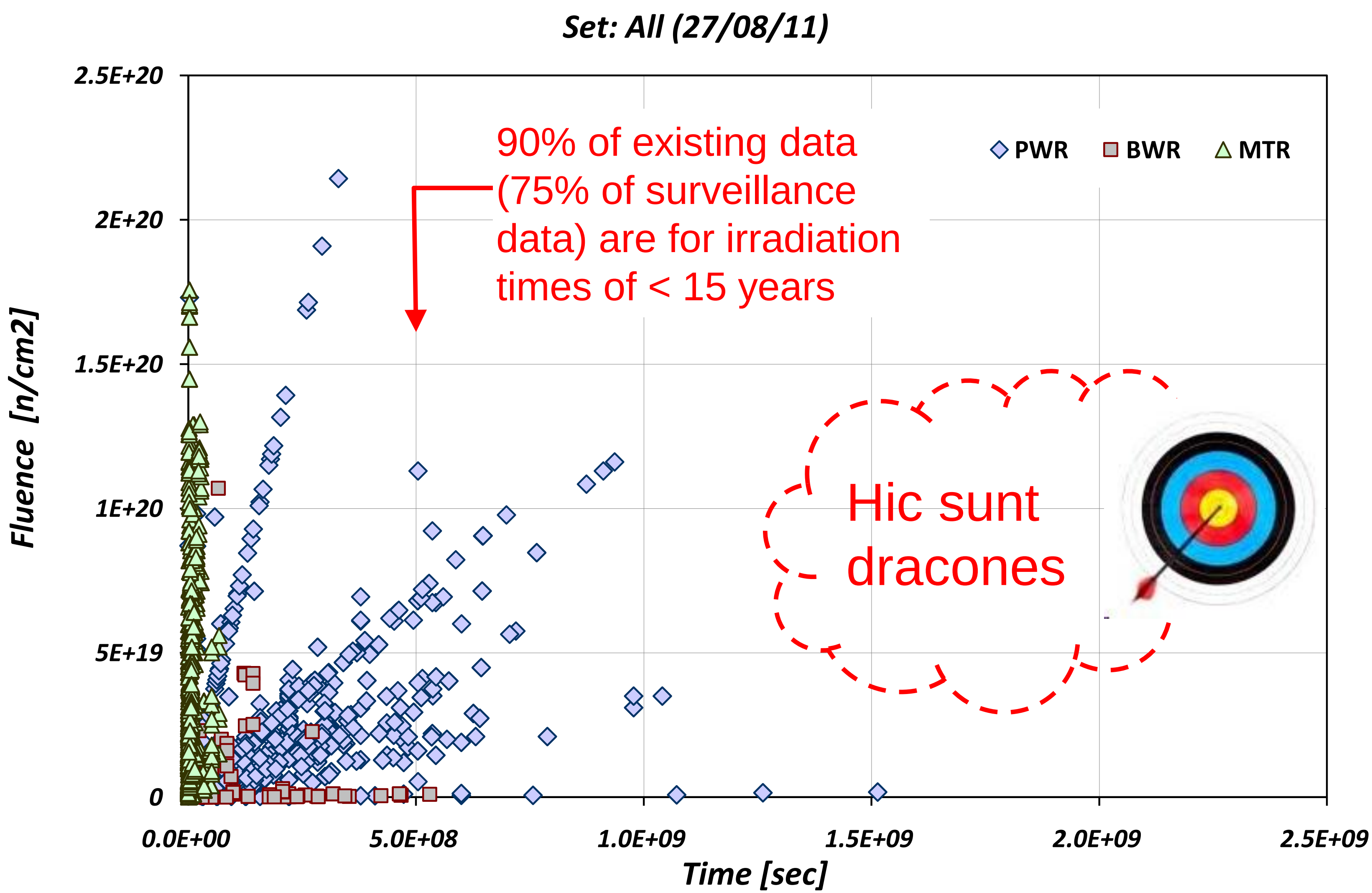


Data are from surveillance and test reactor irradiations for a wide range of materials and irradiation environments

The highest Charpy shift values have been estimated from hardness change data via correlations

- **Confidence in predictions for 80 year irradiations?**

Issues for predictions for 80 year irradiations?



Data plot thanks to Mark Kirk

What do we do? (1)

- **Develop mechanistic understanding**
  - **Knowledge not information**
  - **Reduces dependence on ‘time-served’ experts**
  - **Enables MS/MP models (eg PERFORM60)**
  - **Increases confidence in extrapolation**
- **Assume guilt until innocence is demonstrated**
  - **eg Late Blooming Phases – until it is demonstrated that there is no late embrittlement effect, we have to assess the risk of such an effect**
    - **Risk = (probability that it exists) x (consequences of ignoring it)**

What do we do? (2)

- Challenge codes, procedures and assumptions
  - (Aloha Airlines Flight 243 disaster)
- Actively investigate gaps
- Survey of ASTM Radiation Damage Symposium and IGRDM presentations

- >90% of papers on the 'popular' topics: copper, nickel, manganese, flux, transition region toughness, correlations, RPV annealing
- All undoubtedly important, but are we to some extent 'following the ball'?

Less-popular topics

- **Unimportant?**
  - **Effect of flux on low copper materials**
  - **Influence of reactor duty cycle**
  - **Superposition of hardening**
  - **Lüders strain**
  - **Effect of irradiation on fatigue crack growth**
  - **Heat affected zones**
  - **Stress effect on irradiation**
  - **Irradiation-enhanced tempering**
  - **Effect of irradiation on upper shelf toughness**

What do we do? (3)

- **Prepare for unexpected issues (D3/T2)**
  - **Additional surveillance samples**
  - **Archive materials and records**
  - **Develop tools**
  - **Maintain expertise**
    - o **Funding issues**
    - o **Use resource effectively**
    - o **Collaborate**

Many thanks for your attention