Materials Sampling from Components within the Nuclear Industry and the Extraction of Useful Materials Information

P.R. Roberts[1], J.B. Borradaile[2] and R.J. Mitchell[2]

[1] Rolls-Royce Submarines,
[2] Rolls-Royce Nuclear Materials and Chemistry Support,
PO Box 2000, Raynesway, Derby, UK, DE21 7XX

Rolls-Royce

Rolls-Royce Presence in Nuclear Sector

Defence Nuclear

Submarines

- **Design, manufacture & procurement of NSSS for all UK nuclear submarines**
  - >50 years PWR experience
  - ~100 reactor cores delivered
  - 27 reactor plants delivered
  - 2 nuclear licensed sites
  - 3 factories
  - Largest single UK employer of design and technical authority skills
- **Full lifecycle NSSS capability**

Civil Nuclear

Derby / Warrington - UK

- **Sizewell B component and vessel manufacture and support**
- **Current design support to reactor vendors**
- **Current licensing support**
- **High Temp Gas Reactor Turbine (Gen IV)**
- **Global Support to operational fleet**

Grenoble - France

- **Safety Instrumentation & Control (I&C) for civil nuclear plants**
  - System in operations in >100 plants worldwide
  - 35 years experience in safety critical I&C
  - References in 15 countries in Europe, U.S. and Asia

Statement of Requirements for Nuclear Plant

- Safety
- Cost
- Power
- Space
- Noise
- Weight
- Operation (simplicity)
- Availability, Reliability and Maintenance (ARM)
- Shock
- Core Lifetimes

Nuclear Regulatory Requirements in the UK

- **Meet ASME**

and

- **Satisfy Additional Measures including**
  - **Tighter Controls on Material Specifications**
  - **Testing of Actual Forgings and Weld Materials**
  - **Validation of Inspection Procedures**
  - **Defect Tolerance Studies**

Elements of a Safety Case

- **Safety Cases are based on Claim, Argument and Evidence**

- **Identification of hazards**
- **Provision of Safety Measures to control the hazards**
- **Justification of the adequacy of those safety measures**
- **Demonstration to oneself and to the regulator that risks are acceptable and ALARP**
- **Appropriate management arrangements in place to control safety through life**

For PLEX
- need to understand degradation mechanisms

- Irradiation Embrittlement
- Thermal Ageing Embrittlement
- Environmentally Assisted Cracking
- Fatigue
- Stress Relaxation / Irradiation Creep
- Aqueous Corrosion
- Wear

Management of Degradation Effects

- Degradation effects include loss of material, reduction of fracture toughness or cracking
- Management will depend on capability to detect, evaluate and potentially correct conditions of components
- Components ranked for susceptibility to ageing degradation mechanisms
- Components are assessed to define a safe and cost-effective ageing management strategy
- Scoop sampling may be used to identify and characterise the degradation mechanisms and to confirm / inform mechanistically based correlation models

Reasons for small specimen testing

- To make effective use of limited volumes available from scoop samples
- To make effective use of limited volumes available in test reactors
- To make more effective use of surveillance specimens
- To simplify the testing of active materials

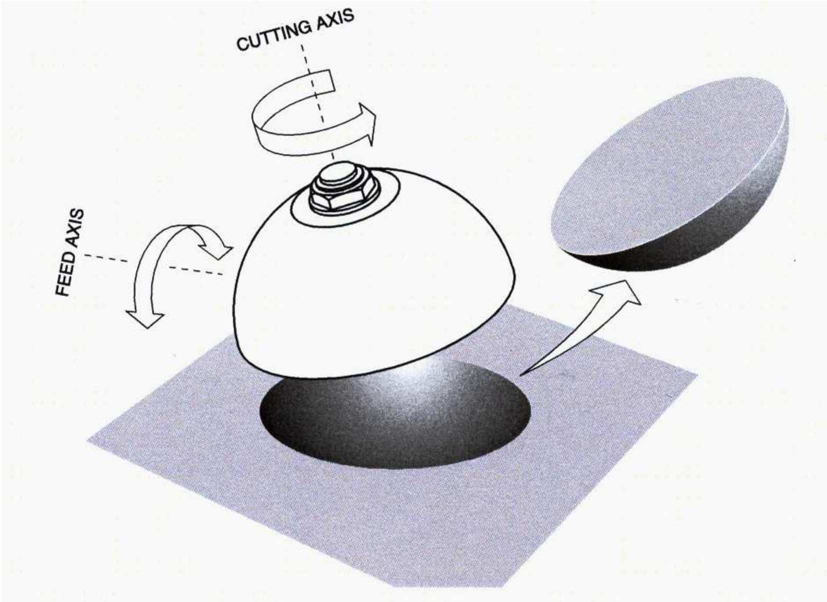
- A knowledge of the reliability of small specimen data with respect to full size specimen data is therefore very important

Possible size effects

- Sample may contain insufficient grains or colony sizes to represent bulk material
- Deformation mechanisms may be influenced by grain size or colony size
- Deformation models depend on numbers of small defects
- Constraint has a major influence although side grooving may help
- For toughness specimens, the size and ligament are important

Material Scoop Sampling

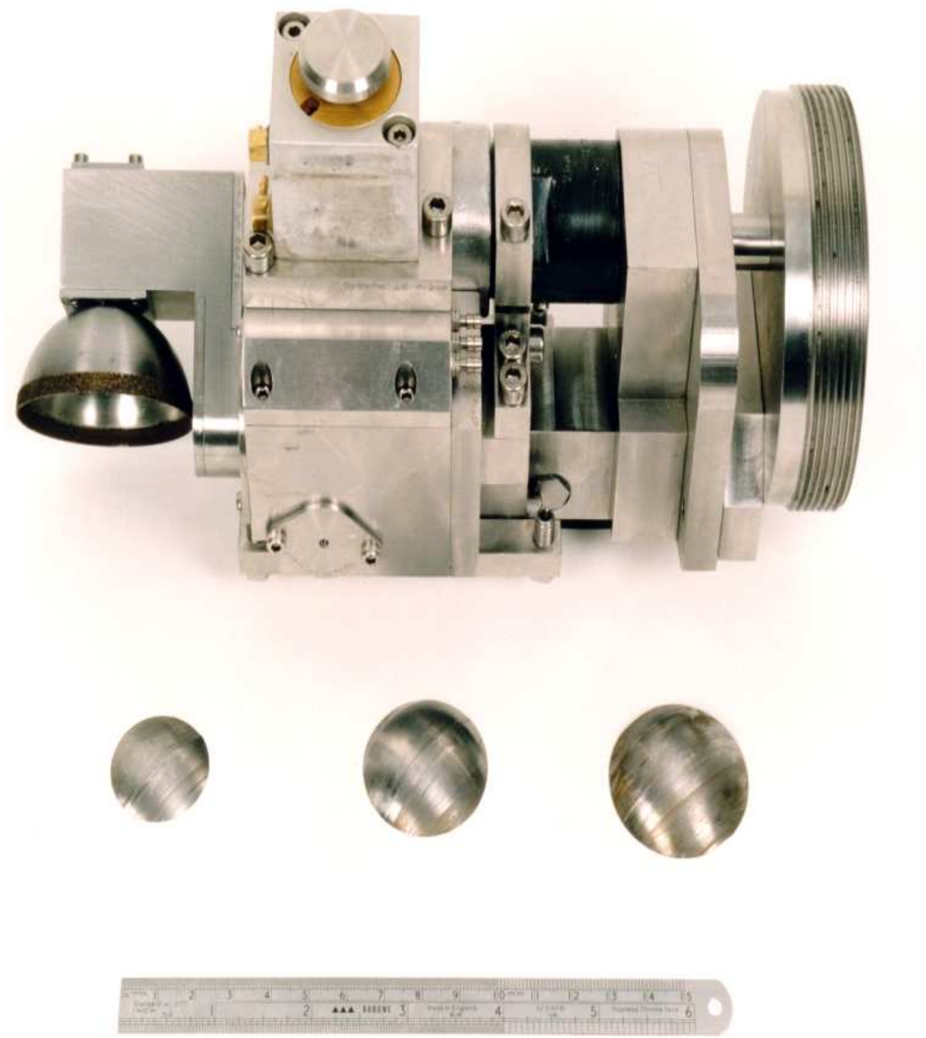
Scoop sampling – a means of removing a small amount of material from an in-service component for metallurgical analysis



Scoop sampling illustration

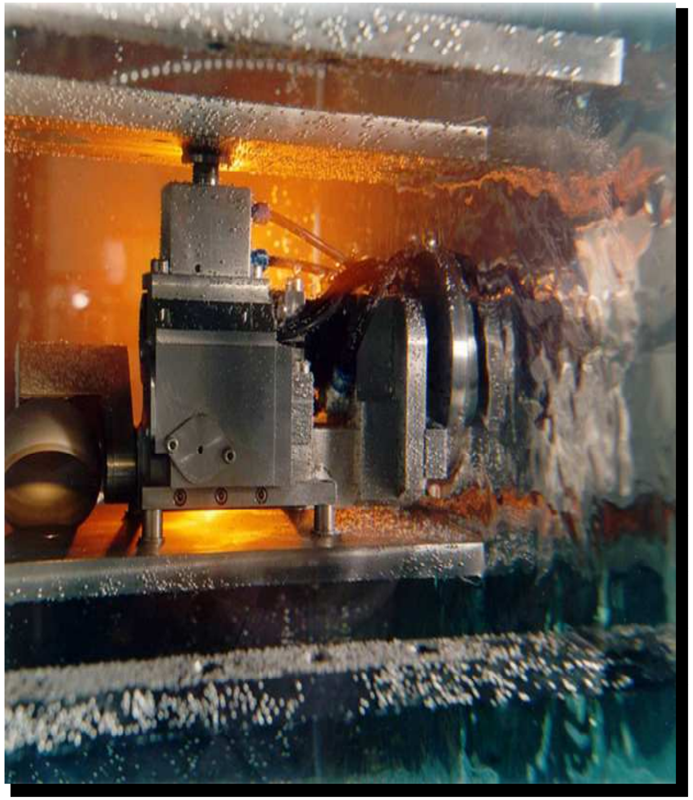
Rolls-Royce

Material Scoop Sampling



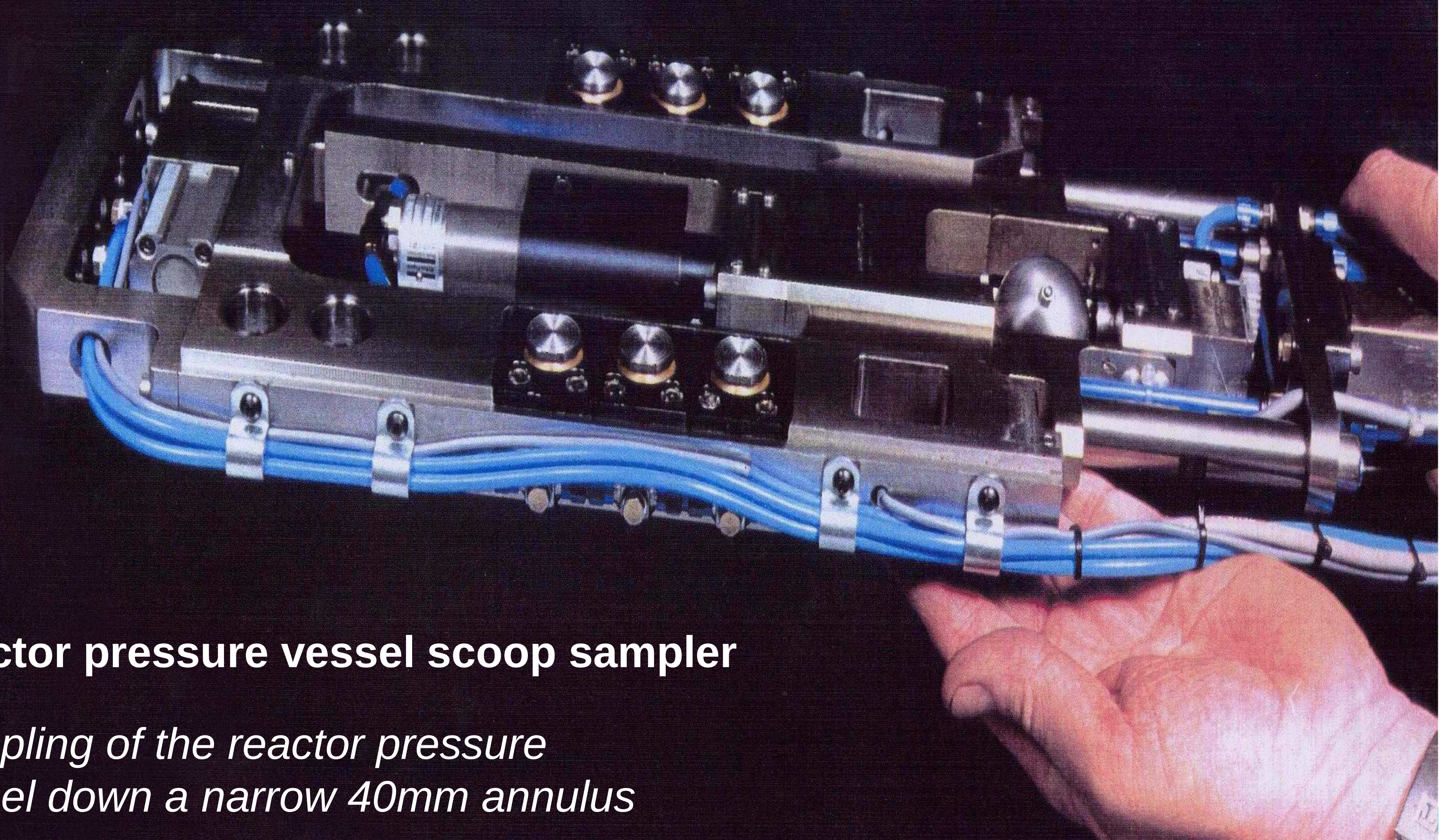
Material Scoop Sampling

- Pneumatic or electric drive
- Low stress raising dimple in the component
- Low Intensity Machines - Low stress & temperature induced during sampling



Underwater scoop sampling

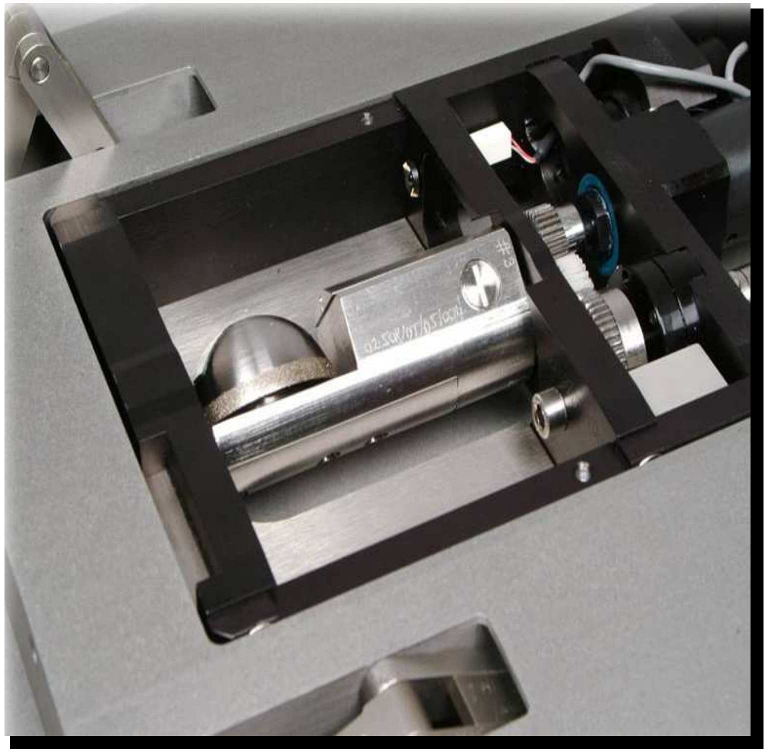
Special Purpose Machines – Material Scoop Sampling



Reactor pressure vessel scoop sampler

Sampling of the reactor pressure vessel down a narrow 40mm annulus

Special Purpose Machines – Material Scoop Sampling



Pressure vessel scoop sampler for a naval PWR

Tube scoop sampler

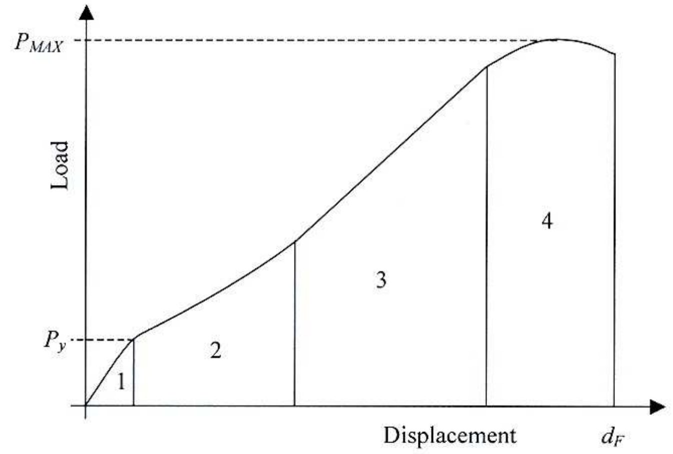
- **Highly restricted space sampling**
- **Typically takes 4mm samples within a 30mm wide annulus**

Scoop Sample Characterisation

- Hardness measurements
- Metallographic examinations
  - Optical, SEM and EDS, Atom Probe, SANS and FEGSTEM
- Chemical analyses
  - Oxidative dissolution, Gas and Ion Chromatography, ICP and other advanced analytical techniques
- Mechanical property assessments
  - Small Punch (SP) tests
  - Automated Ball Indentation (ABI) and
  - Miniature Tensile, Creep tests and Toughness (both Compact Tension and Bend)

Small Punch Testing

- Tensile stress-strain behaviour constructed from load-deflection response, finite element modelling and uniaxial constitutive behaviour (1)
- Creep behaviour similarly constructed (2)
- Toughness - correlations observed between small punch transition temperatures, both T_{SP} (3) and T_{FM} (4) and Charpy T_{41J} transition temperatures
- T_{SP} shifted downward from standard Charpy transition temp by ~ 200 ℃
- Analytical method based on uniaxial constitutive behaviour proposed (4)
- SPT needs further exploration before relevance to transition toughness of pressure vessel steels is accepted



References

(1) Fleury, 1998

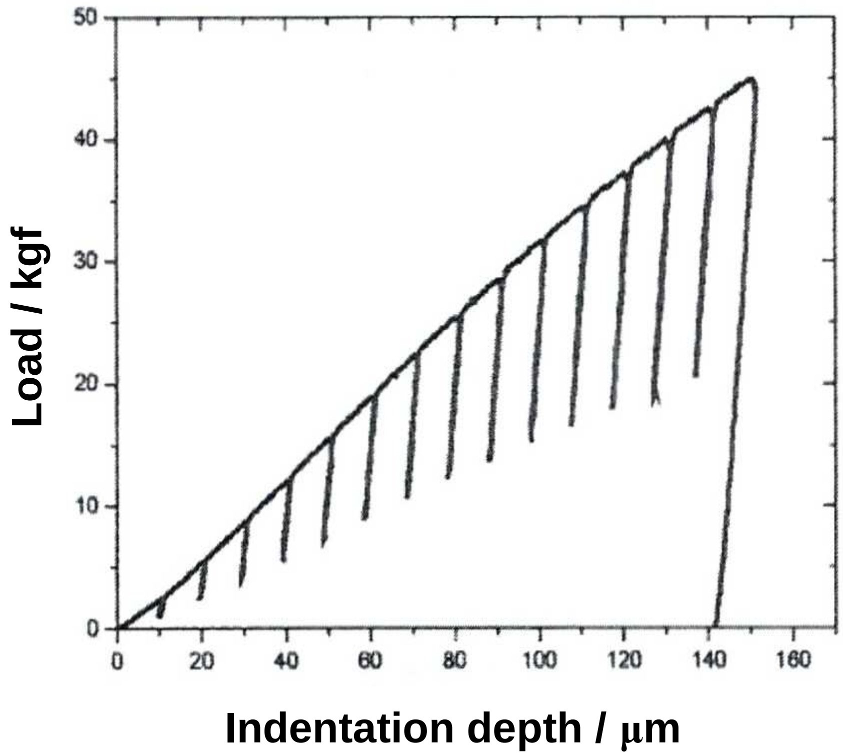
(2) Dymacek, 2008

(3) Baik, 1986

(4) Foulds, 1995

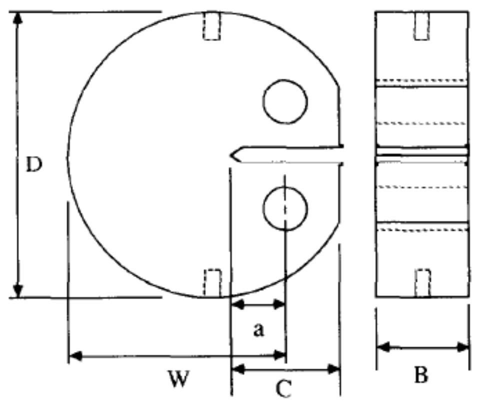
Automated Ball Indentation

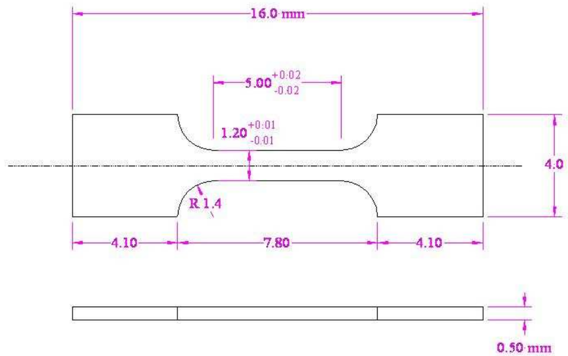
- **Load versus indentation depth curve used to derive stress–strain values by a combination of elastic and plastic analyses, and semi-empirical relationships**
- **Murty et al, 2004 have suggested that Fracture Toughness (K_{JC}) can be evaluated using ABI and the indentation energy to fracture model**
- **Less developed / accepted than SP testing**



Miniature Tensile, Toughness (Compact Tension and Bend) and Creep Tests

- Miniature tensiles evaluated as part of ASTM Cross Comparison Exercise (1) Results within 5%
- Miniature toughness investigated on F82H steel using DC(T) specimens. (2) Narrow temperature range where K_{JC} was valid but irradiated specimens showed valid results. (2)
- Miniature SE(B) (3)and CCB (4) specimens have been used to obtain transition toughness data.
- Significant work is required to verify and validate direct toughness measurement.

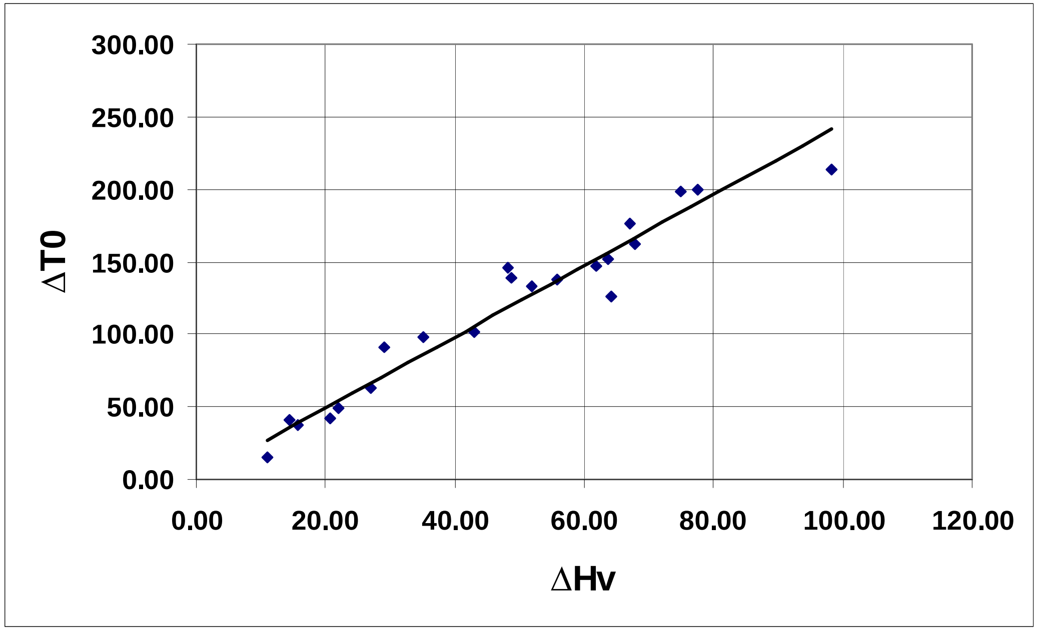




References: (1) Sharpe, 1998, (2) Sokolov, 2004, (3) Wallin, 2001 and (4) Birkett, 2002

Indirect measurements of toughness

- Charpy and Pellini drop weight still widely applied today.
- Good correlations between T_{SP} and T_{FM} and Charpy T_{41J} transition temperatures
- Similar good correlations established for change in hardness and change in T_0
- Although such correlations give comfort it is the direct measurement of toughness from small specimens that needs to make progress



Conclusions

- Ability to remove small volumes of material from difficult to access areas has increased in importance with the demand for plant life extensions.
- A range of novel material sampling machines have been developed for this purpose.
- Microstructural analytical techniques provide excellent quantitative and qualitative information on materials and their degradation mechanisms.
- Hardness testing can provide information of pertinence when a relationship between changes in hardness and changes in fracture properties has been established.

Challenges

- Directly measuring mechanical properties from small volumes of material.
- Regulatory bodies need to be engaged, at an early stage, to ensure acceptance of the techniques developed and the information they provide
- Specific areas to be addressed are (amongst others):
  - Development of the mechanical property evaluation techniques and appropriate governing international standards.
  - Demonstrable consistency / relationships between more conventional mechanical testing and the techniques developed.
  - Development of a competent and robust supplier network
- This can best be achieved through an industry wide collaborative effort.