**Agenda**

Workshop on the Effect of Specimen Geometry and Degree of Plasticity before Fracture on $T_o$

*May 23, 2007 – Norfolk, VA*

*Sponsored by Committee E08*

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<tr>
<th>Time</th>
<th>Title / Activity</th>
<th>Speaker</th>
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<tbody>
<tr>
<td>0800-0815</td>
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<td>EricksonKirk</td>
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<td>0900-0945</td>
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<td>Hall</td>
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<tr>
<td>0945-1000</td>
<td>COFFEE BREAK</td>
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<tr>
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<tr>
<td>1130-1230</td>
<td>Discussion and Actions</td>
<td>EricksonKirk</td>
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<thead>
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<th>FIRST NAME</th>
<th>LAST NAME</th>
<th>COMPANY NAME</th>
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</thead>
<tbody>
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<tr>
<td>William</td>
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<tr>
<td>Robert</td>
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<tr>
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<td>Wallin</td>
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Workshop on the Effect of Specimen Geometry and Degree of Plasticity before Fracture on $T_o$

Mark EricksonKirk
Component Integrity Branch
Materials Engineering Directorate
Division of Fuels, Engineering, and Radiological Research
Office of Nuclear Regulatory Research
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Norfolk Virginia
ASTM E08 Spring Committee Week
23rd May 2007
Specimens satisfying the requirements of ASTM E1921-02 can produce $T_o$ values that differ significantly from one another.

Specimen size/geometry/constraint effects are particularly important when fatigue-precracked Charpy V-notch specimens are tested.

- $T_o$ from precracked Charpy specimens can be up to 20°C lower than $T_o$ values determined by testing larger specimens.
Workshop Objective

- A forum for presentation and discussion of empirical and theoretical investigations concerning the effect of specimen geometry, size, and loading on $T_0$.

- Inform ASTM Task Group E08.08.03 in its deliberations regarding potential modification of ASTM Standard Test Method E1921-02 to provide quantitative guidance concerning the effect of specimen geometry, size, and loading on $T_0$. 
# Workshop Agenda

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</table>
Simplified Constraint Corrections for Standard Specimen Geometries

J. P. Petti
Sandia National Laboratories
Albuquerque, New Mexico

R. H. Dodds Jr.
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

May 23, 2007
Objectives & Background

- Computational work (Petti and Dodds – Nov. 2004) shows significant differences in constraint loss between SE(B) and C(T) specimens.
  - Used the Weibull stress micromechanical model to compute these constraint differences.
- Develop method which adjusts SE(B) toughness values to equivalent C(T) toughness values.
- Simplify for future use in ASTM E1921.

Proposed SE(B) Constraint Correction for E1921

• Correction Method:
  - Apply plane-strain conversion to measured $J_{SE(B)}$ values, $K_{SE(B)} = (J_{SE(B)} E / 1 - \nu^2)^{1/2}$
  - Convert experimental $J_{SE(B)}$ values to $M_{SE(B)} = b_{SE(B)} \sigma_0 / J_{SE(B)}$
  - Correct $K_{SE(B)}$ to $K_{C(T)}$ using the bilinear approximation
  - Corrected $K_{C(T)}$ values are at same thickness $(xB)$ as original xT SE(B) specimens

• Continue with E1921 procedure (including $M=30$ censoring and $B^{1/4}$ thickness adjustment).
Comparison of C(T) and SE(B)

Convert:

\[ K_{SE(B)} \rightarrow K_{C(T)} \]

Using:

\[ P_f(\sigma_{SE(B)}^w) = P_f(\sigma_{C(T)}^w) \]

\[
K_{C(T)} = \frac{1}{g(M)} \left[ K_{\min} + K_{SE(B)} \left( \frac{g(M)}{g(M_{C(T)})} \right)^{1/4} - K_{\min} \right] \left( \frac{B_{SE(B)}}{B_{C(T)}} \right)^{1/4}
\]

When \( g = 1 \), equation reduces back to E1921 thickness scaling


Comparison of C(T) and SE(B)

\[ K_{C(T)} = \frac{1}{g(M_{C(T)})^{1/4}} \left[ K_{\min} + \left[ K_{SE(B)} g(M_{SE(B)})^{1/4} - K_{\min} \right] \left( \frac{B_{SE(B)}}{B_{C(T)}} \right)^{1/4} \right] \]

when \( B_{SE(B)} = B_{C(T)} \)

\[ K_{C(T)} = \frac{g(M_{SE(B)})^{1/4}}{g(M_{C(T)})} \]

\[ K_{SE(B)} = \frac{K_{SE(B)}}{K_{C(T)}} \]
Constraint Function, $g(M)$

$$\sigma^m_w = \tilde{C} B K_J^4 g(M)$$

All size C(T)s follow the same curve (plotted vs. M)
**K_{SE(B)}/K_{C(T)}: \( E/\sigma_0 = 500, \ n = 10 \)**

Material FEM: \( E/\sigma_0 = 500, \ n = 10 \)

ENG: \( S_{ys} = 443 \text{MPa}, \ S_{ult}/S_{ys} = 1.25 \)

K_{SE(B)} and K_{C(T)} have equal thickness and NOT necessarily equivalent ligaments, so the W=2B SE(B) specimen and C(T) specimen have twice the ligament length of the W=B SE(B) when at the same thickness.
Bilinear Constraint Correction

\[
\frac{K_{SE(B)}}{K_{C(T)}} = \begin{cases} 
    \text{bias} & \text{if } M_{SE(B)} > M_{CL} \\
    \text{bias} + \text{slope} & \text{if } M_{SE(B)} < M_{CL}
\end{cases}
\]

\[
B_{SE(B)} = B_{C(T)}
\]
In practice, $m$ usually unknown

$8 < m < 20$ are reasonable bounds

How to fit bilinear approximation?
Bilinear Fit Criterion

- Fit Criterion
  - $m$ unknown, but reasonably bounded.
  - Desire a conservative estimate for $T_0$ from the corrected data.
  - The upper curves corresponding to smaller $m$ values produce more conservative estimates.
  - Engineering decisions required.
$K_{SE(B)}/K_{C(T)}: \frac{E}{\sigma_0} = 500, \ n = 10$

Material FEM: $\frac{E}{\sigma_0} = 500, \ n = 10$
ENG: $S_{ys} = 443\text{MPa}, \ S_{ult}/S_{ys} = 1.25$

$W=B$ SE(B)
$W=2B$ SE(B)

Example of a lower fit

$K_{SE(B)}/K_{C(T)} = 1.1 + 0.00053(175-M_{SE(B)})$
$W=2B$ SE(B)
$K_{SE(B)}/K_{C(T)} = 1.1 + 0.0022(175-M_{SE(B)})$
$W=B$ SE(B)
\[ \frac{K_{SE(B)}}{K_{C(T)}} : \frac{E}{\sigma_0} = 800, \, n = 5 \]

Material FEM: \( \frac{E}{\sigma_0} = 800, \, n = 5 \)

ENG: \( S_{ys} = 317 \text{MPa}, \, \frac{S_{ult}}{S_{ys}} = 1.84 \)

\[ \frac{K_{SE(B)}}{K_{C(T)}} = 1.06 + 0.00053(250 - M_{SE(B)}) \]
$K_{SE(B)}/K_{C(T)}: E/\sigma_0 = 300, n = 20$

Material FEM: $E/\sigma_0 = 300, n = 20$
ENG: $S_{ys} = 703\text{MPa, } S_{ult}/S_{ys} = 1.07$

$K_{SE(B)} / K_{C(T)} = 1.1 + 0.0016(150 - M_{SE(B)})$

$K_{SE(B)} / K_{C(T)} = 1.1 + 0.0042(125 - M_{SE(B)})$
• Bilinear fit for SE(B) $\rightarrow$ C(T) constraint correction. Generic flow properties ($n=5,10,20$).

• $K_{SE(B)}/K_{C(T)}$ ratios from 3D analyses show small dependence on $m$-value (Weibull modulus).

• Determining the *most appropriate* bilinear (or other) fit requires additional discussion/analysis.

• Effect of constraint correction: $T_0$ from corrected SE(B) experimental data may be substantially higher than from uncorrected data – but more consistent with $T_0$ computed from C(T)s
$K_{W=B}/K_{W=2B}: \text{Computational}$

Material FEM: $E/\sigma_0 = 500, n = 10 \text{ and } E/\sigma_0 = 800, n = 5$

- Hardening has a strong effect
- Weibull modulus, $m$, negligible effect
- At $M_{W=B} = 25$, 30-35% difference in $K_J$ for lower hardening

Both have the same $B$!
Linde 80 Weld $T_0$
Specimen Geometry Bias

J. Brian Hall
AREVA NP
Lynchburg, Virginia

E08 Workshop on Specimen Geometry Bias
May 23, 2007  Norfolk
Background

> **Automatic Submerged Arc welds with**
  - Mn-Mo-Ni filler wire (copper coated)
  - Linde 80 flux

> **Linde 80 weld characteristics**
  - low upper shelf toughness
  - relatively high $IRT_{NDT}$
  - $IRT_{NDT}$ are controlled by $TT_{50}$

> **Room Temperature Yield**
  - $\sim 67$ ksi (460 Mpa) for unirradiated materials
  - $\sim 87$ksi (600 Mpa) for irradiated materials
Archive Linde 80 welds were tested per ASTM E1921

- Three heats were tested with PCVN & CT specimens
- Some testing conducted at different laboratories
- Specimen geometries
  - Precracked Charpy and 0.5TCT are compared
Variations in $T_0$

> **Loading rate adjustment per draft E1921**

\[
T_0 = \frac{T_{01} \cdot \Gamma}{\Gamma - \ln(\dot{K}_I)}
\]

or for the loading rate induced temperature shift:

\[
\Delta T_0 = \frac{T_{01} \cdot \ln(\dot{K}_I)}{\Gamma - \ln(\dot{K}_I)}
\]

where:

\[
\Gamma = 9.9 \cdot \exp\left(\frac{T_{01}}{190}\right)^{1.66} + \left(\frac{\sigma_{YS}}{722}\right)^{1.09}
\]

and where:
- $T_{01}$ refers to the quasi-static loading rate of $dK/dt = \dot{K}_I = 1$ MPa√m/s,
- $T_0$ and $T_{01}$ are in degrees Kelvin and $\sigma_{YS}$ is adjusted to temperature $T_0$ as described above and is converted to MPa.
Irradiated Data

5%/median/95% Master Curve

- WF-25 PCVN; To=66°C
- WF-25 0.5TCT; To=95°C
- SA-1526 PCVN; To=22°C
- SA-1526 0.5TCT; To=47°C
- WF-193 PCVN; To=-2°C
- WF-193 various CTs; To=15°C
Data Set Specific Comparison

<table>
<thead>
<tr>
<th>Linde 80 Heat</th>
<th>PCVN Bias with respective to</th>
<th>Unirradiated Bias (C)</th>
<th>Irradiated Bias (C)</th>
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<tbody>
<tr>
<td>299L44</td>
<td>0.5TCT</td>
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<tr>
<td>299L44</td>
<td>0.39CT &amp; 0.5CT</td>
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<td>0.39CT &amp; 0.5CT</td>
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<td>0.5TCT</td>
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<td>0.5TCT</td>
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<td>406L44</td>
<td>0.39CT, 0.5CT &amp; 0.94CT</td>
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<tr>
<td>821T44</td>
<td>0.5TCT</td>
<td>23</td>
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<tr>
<td><strong>Average</strong></td>
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<tr>
<td><strong>St. Deviation</strong></td>
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- Data was tested at different labs with different loading rates
- Adjusted per draft E1921 loading rate relationship
- Irradiated bias appears to be larger, however sample size is limited
In conclusion:

- The unirradiated Linde 80 precracked CVN data has a bias of about 13C relative to CT specimens.
- Irradiated Linde 80 precracked CVN data has a larger bias of about 23C relative to CT specimens.
IAEA COORDINATED RESEARCH PROJECT ON MASTER CURVE APPROACH TO MONITOR FRACTURE TOUGHNESS OF RPV STEELS: EFFECTS OF BIAS, CONSTRAINT, AND GEOMETRY

R. K. Nanstad¹, M. Scibetta², W. L. Server³

¹ORNL, ²SCK•CEN, ³ATI Consulting

ASTM Workshop on the Effect of Specimen Geometry and Degree of Plasticity before Fracture on To Norfolk VA, 23/5/2007
How does the IAEA Cooperative Research Project Work?

• IAEA officially invited all governments of member states to participate
• IAEA coordinates the research program
• In kind contributions are made by each member state to the project
• National funding to be found by each participant
What is the Objective of IAEA Coordinated Research Project 8 (CRP-8)?

• Master Curve Approach to Monitor the Fracture Toughness of RPVs in NPPs
  ➢ To evaluate the Limitations of the Master Curve Approach for RPV Integrity Assessment Using Small Surveillance Specimens

• Overall objective:
  ➢ To better quantity fracture toughness Master Curve issues relative to testing surveillance specimens and application to RPV (and other ferritic components) integrity assessment
Scope of CRP-8 is Split up in 3 Task Area

- **Constraint/geometry effects:**
  - Effect of constraint between different surveillance-type specimens and application to the RPV

- **Master Curve shape:**
  - Limitations for Master Curve approach (or its adjustment) to highly embrittled RPV steels

- **Testing procedures and application for dynamic fracture toughness:**
  - Use of the Master Curve approach for data generated under dynamic (impact) loading and its application to RPV integrity will be studied
  - Since no standardized test methods exist for measuring dynamic fracture toughness on small surveillance specimen impact tests, procedures will be written and a round robin program will be conducted
Participants in IAEA CRP8 are from Europe, Far East, and North America

<table>
<thead>
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<th>Organization</th>
<th>Constraint</th>
<th>Load rate</th>
<th>MC shape</th>
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<tbody>
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<td>AEKI/Hungary</td>
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<td>T/D</td>
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<td>T/D</td>
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<td>M/NM</td>
<td>D</td>
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<td>M/NM</td>
<td>D</td>
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<td>FZR/Germany</td>
<td>M/NM</td>
<td>M/NM(Leader)</td>
<td>D</td>
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<td>M/NM</td>
<td>M/NM</td>
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<td>JAERI/Japan</td>
<td>M/NM</td>
<td>M/NM</td>
<td>D</td>
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<td>D</td>
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<td>M/NM</td>
<td>M/NM</td>
<td>D</td>
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<td>ORNL/USA</td>
<td>M/NM(Leader)</td>
<td>M</td>
<td>D</td>
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<td>M/NM</td>
<td></td>
<td>D</td>
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<tr>
<td>SCK-CEN/Belgium</td>
<td>M/NM</td>
<td>M/NM</td>
<td>T/D</td>
</tr>
<tr>
<td>VTT/Finland</td>
<td>M/NM</td>
<td>NM</td>
<td>D (Leader)</td>
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M = participating in mandatory portion of task
NM = participating in non-mandatory portion of task
T = testing
D = data collection and/or providing data from outside test programs
*Italics* – No participation in May 2005 RCM; contributions not verified
Three IAEA Coordinated Research Projects Have Shown PCVN Bias from -12 to -22°C for JRQ Plate and -12 to -45°C for a Variety of Other RPV Steels

<table>
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<th>Specimen Type</th>
<th>Reference Temperature $T_0$ for JRQ Plate, °C</th>
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<tbody>
<tr>
<td></td>
<td>Third CRP</td>
</tr>
<tr>
<td>Compact</td>
<td>-53</td>
</tr>
<tr>
<td>Precracked Charpy SE(B)</td>
<td>-66</td>
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<tr>
<td>PCVN Bias</td>
<td>-13</td>
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- In CRP-5, four organizations reported 7 cases of $T_0$ comparisons with SE(B) (most PCVN) and CT specimens of different steels, with the SE(B) specimen giving the lower $T_0$ in every case. Differences ranged from 12 to 45°C, with an average value of 22°C.

- Other studies by Joyce & Tregoning for A533B plate, Wallin for 22NiMoCr37 forging, Rathbun & Odette for A533B plate, and Nanstad for Weld Metal report biases of -14, -15, -13, and -21°C, respectively.
The Materials Properties Council Conducted Cooperative Testing Program also Support the Existence of a Bias

- Nine laboratories from four countries participated in testing HSSI Weld 72W supplied by ORNL.
- Tests were conducted at \(-120^\circ C, -100^\circ C, \) and \(-75^\circ C\), with more than 250 PCVN specimens tested.
- PCVN: \(T_o = -75^\circ C\)
- 1TC(T): \(T_o = -54^\circ C\)
- PCVN BIAS = \(-21^\circ C\)
IAEA CRPs have observed a potential dependence of $T_0$ on test temperature for JRQ steel.

This effect could be a result of constraint (test temperature increase $\Rightarrow$ M decrease $\Rightarrow$ loss of constraint $\Rightarrow$ $T_0$ increase).

![Graph showing the effect of test temperature on $T_0$ for JRQ plate.](image)

The graph shows the relationship between test temperature and reference temperature for JRQ plate. The equation $T_0 = 0.22T - 52.2$ is given, where $T$ is the test temperature in °C. The graph also shows data from CRP 4/5, CRP 5/6, and all data combined, with a linear trend line labeled 'Linear (All Data).'

Additional observations:

- $\Delta T = 50°C$
- $\Delta T_0 = 14°C$
As a Result of Such Observations, IAEA CRP-8 Task1 Focuses on the Issues of Constraint/Specimen Geometry as Related to the Observed Bias in $T_0$

- Questions regarding **measuring capacity limits** ($M$) for the MC method
- The potential use of **even smaller specimens** highlights the significance of this issue.
- There are many potential reasons for the observed differences in $T_0$. The primary focus is generally on different levels of **constraint** for the different specimen types.
- Differences in constraint are related to specimen **geometry, size** effects, and the relationship of crack length to specimen width.
The CRP Includes Mandatory and Optional Work

- Each topic area is divided into **mandatory** and **optional** parts
- Topic area 1: Loss of Constraint
  - Analytical techniques to evaluate loss of constraint
    - Area/ volume, Weibull stress, Q/T-factor
  - Experimental
    - One data set of $T_0$ for SE(B) and C(T) with equivalent thickness
    - Additional materials, shallow crack, elliptical crack, cruciform, SE(T)
Objectives of the Round Robin on Analytical Techniques

- Increase international acceptance of the analytical tool
- Validate the finite element tool

Part 1
- Execute a simple model to cross check results

Part 2
- Extend Part 1 to compare two useful specimen configurations
Although Optional, Ten Laboratories Have Participated in the Round Robin

- AEKI Hungary
- CIEMAT Spain
- CRIEPI Japan
- JAEA Japan
- JRC EC
- FZR Germany
- ININ Mexico
- KAERI Korea
- ORNL USA
- SCK•CEN Belgium
Specifications for the Round Robin Parts 1 and 2 Developed to Reach the Objectives

- 3D 8 node brick
- Elastic-plastic incremental theory of plasticity,
- Large strain displacement model,
- Crack is inserted in the model
- Simple power hardening law
- Simple boundary conditions
Part 1 is ¼ of a SE(B) Specimen
10x10x40 mm
Part 2 is $\frac{1}{4}$ of an SE(B) Specimen 10x10x40 deep and with a shallow crack
Status of the Round Robin

- Part 1 has been completed and results are presented here
- Part 2 has been completed by 40% of the participants
Various Finite Element Codes were Used

<table>
<thead>
<tr>
<th>Code</th>
<th>Nb. of users</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABAQUS</td>
<td>6</td>
</tr>
<tr>
<td>ANSYS</td>
<td>2</td>
</tr>
<tr>
<td>MSC.MARC</td>
<td>2</td>
</tr>
<tr>
<td>SYSTUS</td>
<td>1</td>
</tr>
</tbody>
</table>
Several Iterations were Needed before Error Free Results were Obtained

- No results are distributed before all participants have submitted their results
- Results are submitted to the coordinator
- Results are compared to the database and eventual recommendations may be made to check the model
- Maximum of 3 iterations was registered
- Average of 1.5 iterations/participant were needed
Results for Round Robin phase 1
The two laboratories that have higher forces were identified to be the only ones using ANSYS, 4 labs were within 0.3% while others were within 3%
Expected use of part 2 of the Round Robin

- Additional requirements
  - Calculation of the Weibull stress with $m=6$
  - Calculation of the plastic volume for which the maximum principal stress is above $1.7 \sigma_Y$

- Will allow calculation of $T_0$ shift between the two geometries
  - Same plastic volume $\Rightarrow$ same failure probability
  - Same Weibull stress $\Rightarrow$ same failure probability
  - Difference in J level for the same failure probability can be translated in $T_0$ shift
Acknowledgments for Finite Element Round Robin

- E. Altstadt\textsuperscript{1}, R. Bass\textsuperscript{2}, T. Fekete\textsuperscript{3}, F. Gilmot\textsuperscript{3}, R. Hernández Callejas\textsuperscript{4}, B.-S. Lee\textsuperscript{5}, N. Miura\textsuperscript{6}, K. Onizawa\textsuperscript{7}, E. Paffumi\textsuperscript{8}, J. Schuurmans\textsuperscript{9}, M. Serrano\textsuperscript{10}, H.W. Viehrig\textsuperscript{1}

- \textsuperscript{1}FZR, \textsuperscript{2}ORNL, \textsuperscript{3}AEKI, \textsuperscript{4}ININ, \textsuperscript{5}KAERI, \textsuperscript{6}CRIEPI, \textsuperscript{7}JAERI, \textsuperscript{8}JRC, \textsuperscript{9}SCK-CEN, \textsuperscript{10}CIEMAT

- K.-S. Kang IAEA coordinator
Selection of SE(B) and C(T) Geometries for Testing by Participants is Fairly Well Distributed - JRQ Steel Has Been Selected for Testing by Many Organizations

<table>
<thead>
<tr>
<th></th>
<th>SE(B) W/B=1</th>
<th>SE(B) W/B=2</th>
<th>C(T)</th>
<th>SE(T)/Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>JRQ Steel</td>
<td>10</td>
<td>7</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Other Steels</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>All Steels</td>
<td>13</td>
<td>11</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>PCVN-JRQ</td>
<td>10</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCVN-Others</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCVN-All</td>
<td>13</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5T-JRQ</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5T-Others</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5T-All</td>
<td>2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1T</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2T-JRQ</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8T-JRQ</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple a/W-JRQ</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple a/W-Others</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple a/W-All</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overall, Compact Specimens from 0.4T to 4T Will Be Tested – For JRQ, 0.4T, 0.5T, and 1T Will Be Tested

<table>
<thead>
<tr>
<th>Compact Specimen Size</th>
<th>No. of Testing Organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4T-JRQ</td>
<td>4</td>
</tr>
<tr>
<td>0.4T-Others</td>
<td>2</td>
</tr>
<tr>
<td>0.4T-All</td>
<td>6</td>
</tr>
<tr>
<td>0.5T-JRQ</td>
<td>3</td>
</tr>
<tr>
<td>0.5T-Others</td>
<td>1</td>
</tr>
<tr>
<td>0.5T-All</td>
<td>4</td>
</tr>
<tr>
<td>1T-JRQ</td>
<td>4</td>
</tr>
<tr>
<td>1T-Others</td>
<td>2</td>
</tr>
<tr>
<td>1T-All</td>
<td>6</td>
</tr>
<tr>
<td>2T-Others</td>
<td>1</td>
</tr>
<tr>
<td>4T-Others</td>
<td>1</td>
</tr>
</tbody>
</table>
### Summary of experimental test matrix for IAEA reference steel JRQ

<table>
<thead>
<tr>
<th>Institute/Country</th>
<th>SE(B) W/B=1 (PCVN=.4T)</th>
<th>SE(B) W/B=1</th>
<th>SE(B) W/B=2</th>
<th>C(T)</th>
<th>SE(T)/Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIEMAT/Spain</td>
<td>0.4T</td>
<td>0.5T</td>
<td></td>
<td>0.4T, 0.5T</td>
<td></td>
</tr>
<tr>
<td>AEKI/Hungary</td>
<td>0.4T</td>
<td></td>
<td>0.4T</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a/W=0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a/W=0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JRC/EC</td>
<td>0.4T</td>
<td></td>
<td>0.4T</td>
<td>1.0T</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a/W=0.1</td>
<td></td>
<td>0.8T</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a/W=0.5</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>NRI Rez/Czech</td>
<td>0.4T</td>
<td></td>
<td>0.4T</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>a/W=0.1</td>
<td></td>
<td>0.5T</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a/W=0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRC-KI/Russia</td>
<td>0.4T</td>
<td></td>
<td></td>
<td>0.5T</td>
<td>4x10 SE(B)</td>
</tr>
<tr>
<td>ININ/Mexico</td>
<td>0.4T</td>
<td></td>
<td></td>
<td>0.4T</td>
<td>1.0T</td>
</tr>
<tr>
<td>KAERI/Korea</td>
<td>0.4T</td>
<td>0.2T</td>
<td>0.4T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FZR/Germany</td>
<td>0.5T</td>
<td>0.5T</td>
<td>0.5T</td>
<td>1.0T</td>
<td></td>
</tr>
</tbody>
</table>

- A similar matrix exists for testing of “national steels”
For Data Collection Phase, an Excel Spreadsheet was Developed with Data Fields Developed for Use by Each Task

- The following data fields comprise Level 0 of the matrix:
  - Material ID/block
  - Source
  - Specimen type [C(T), SE(B), etc.]
  - a/W
  - W (mm)
  - B (mm)
  - Bnet (mm)
  - Loading Rate (MPa-m1/2/s)
  - To (°C)
  - σTo (°C)
  - Σ ni (number of tests)
  - Partial unloading? (Y/N)
  - Test standard and deviations
  - Other comments
Some Initial Results Have Been Reported

- ORNL (on the NRC-sponsored Heavy-Section Steel Irradiation Program) completed testing on a large matrix of bend specimens with varying thicknesses and W/B ratios for a plate of A533-B-1
- The results are compared with those from 1T compact specimens
- The results show some difference between 1T compact and 1T bend specimens, and a significant bias for the small bend specimens such as the PCVN.
Tests of 17 1T Compact Specimens and 17 1TSE(B) Bx2B Specimens at -60°C Show Lower $T_0$ for 1TSE(B) Specimens by 8°C

For SE(B):
$T_0$ for BxB specimens are 8°C lower than that for Bx2B specimens.
Sixty-Five PCVN Specimens Tested at Three Temperatures Show $T_0$ of $-106^\circ C$, About $25^\circ C$ and $37^\circ C$ Lower Than 1TSE(B) and 1TC(T), Respectively, and with No Effect of Side-grooving

By Comparison, Previous tests of Plate 13A (LT Orientation) showed:

C(T): $T_0 = -83^\circ C$

PCVN: $T_0 = -111^\circ C$

Bias = $-28^\circ C$
IAEA CRP-8 on Master Curve Approach to Monitor Fracture Toughness of RPVs in NPPs Is in Progress

• The CRP includes three topic areas, one of which is designated Topic Area 1, which is focused on the issue of test specimen geometry effects, with emphasis on the PCVN bias.
• The topic area includes two activities, fracture toughness testing and finite element analysis.
• A finite element round robin analysis exercise was conducted and has been useful to qualify the finite element tool and to identify possible errors in the input file. This will be the basis for a more refined model to quantify loss of constraint.
• For the experimental activity of this topic area, participants selected the types and sizes of specimens and materials for testing. Many participants plan to test the IAEA reference steel designated JRQ, which provides the opportunity for a statistically sound comparison of specimen geometry effects on the reference fracture toughness parameter, T₀.
  • Additionally, a number of other steels, designated “national steels” will be tested, which offers the potential for evaluating the effects of different materials.
Seventeen Organizations are Participating in Topic Area 1 of CRP-8

- The authors acknowledge the participation of the following individuals and their contributions to Topic Area 1 of this IAEA Coordinated Research Project:
  - E. Altstadt (FZR)
  - R. Bass (ORNL)
  - M. Brumovsky M. (NRI)
  - T. Fekete (AEKI)
  - F. Gillemot (AEKI)
  - R. Hernández Callejas (ININ)
  - M. Korshunov (RRC-KI)
  - B.-S. Lee (KAERI)
  - N. Miura (CRIEPI)
  - T. Planman (VTT)
  - K. Onizawa (JAEA)
  - E. Paffumi (JRC)
  - J. Schuurmans (SCK-CEN)
  - M. Serrano (CIEMAT)
  - W. L. Server (ATI)
  - H.W. Viehrig (FZR)
  - S. Vodenicharov (BASI)
  - K.S. Kang (IAEA) is IAEA coordinator.
Finite element assessment of constraint of SE(B), SE(B) shallow crack and C(T) and its impact on the reference temperature

M. Scibetta, J. Schuurmans
SCK•CEN contributes to past and current analytical support for loss of constraint understanding

- Presented at the Miami November 2002 meeting
  - 1996 PhD thesis on CRB
  - 1999 PCCv FE simulation (BLG-860 rev 1)
  - 2000 C(T) FE simulation (BLG-861)
  - 2001 elastic field (plane strain or plane stress Young Modulus?) (LE IJF)
  - 2002 miniature C(T) FE simulation (BLG-923)

- Work performed since then
  - Weibull stress approach for
    - MC(T) B=4.15 mm,
    - 1T-C(T) B=25 mm
    - PCCv B=10 mm
    - PCCv a/W=0.1 B=10 mm
Approach of Anderson and Dodds based on volume of material stressed above a given value

\[ \sigma_1/\sigma_{YS} = 3 \]
Correction for specimen size and loss of constraint can be taken into account in a single equation

\[ K_{1T} = (K_c - 20) \left( \frac{B}{25.4} \right)^{1/4} + 20 \]

\[ K_{1TSSY} = (K_c - 20) \left( \frac{B}{25.4} \frac{A}{A_{SSY}} \right)^{1/4} + 20 \]
Loss of constraint correction depend on the fracture stress and is about 10 °C for PCCv
Loss of constraint correction depend on the fracture stress and is about 10 °C for mini-CT

\[ \frac{\sigma_1}{\sigma_{YS}} = 3.3 \]
\[ \frac{\sigma_1}{\sigma_{YS}} = 3 \]
\[ \frac{\sigma_1}{\sigma_{YS}} = 2.7 \]
Conclusions from previous work

- Crack round bar is a low constraint geometry
- T-stress is an interesting concept but have severe limitation
- C(T) versus SE(B) bias does not come from
  - J calculation ($\eta$-factor checked, $K_{el}$ checked)
  - For SE(B) J from LLD/CMOD equivalent
  - side grooving effect
  - W/B ratio with range of 1 to 2
Conclusions from previous work

- Loss of constraint identified using the Anderson and Dodds approach and comparison to SSY
  - 10 °C bias between PCCv and 1T-C(T) tested at $K_{1T} \sim 80$ MPa$\sqrt{m}$
  - 10 °C bias between MC(T) and 1T-C(T) tested at $K_{1T} \sim 60$ MPa$\sqrt{m}$
  - No bias MC(T) and PCCv (also supported experimentally)
Current approach is based on Weibull stress (no need to compare to SSY)

- Same Weibull stress for 2 different geometries => same failure probability

\[
\sigma_w^m = \int_{V_p} \sigma_{1}^m \frac{dV}{V_0}
\]

- Alternatively the ratio \( g(M) \) between 2 different geometries can be used

\[
\sigma_w^m = g(M)BK^4 \quad M = \frac{b\sigma_{YS}}{J}
\]

\[
\sigma_w^m = g_X(M)K_{1T,X}^4 = g_Y(M)K_{1T,Y}^4
\]

\[
K_{1T,X} / K_{1T,Y} = g^{0.25}_Y(M) / g^{0.25}_X(M)
\]
1T-C(T) is taken as the reference geometry => g=1 for high M
Loss of constraint already start at $M=200$ for $E/s_{y}=500$, $n=10$
Sensitivity to loss of constraint decrease with higher m value

\[ g^{0.25}, g = \sigma_w m^4 / K^4 / B \]

\[ M = b_0 / J \]
As expected from dimensionless consideration, $1T-C(T)$ and $MC(T)$ are equivalent.
SE(B) is slightly less constraint than C(T)
Contrary to deep crack shallow crack sensitivity to loss of constraint increase with m
Loss of constraint in term of reduction of $g/K_1T$ can be translated in term of $T_0$ shift

$$\Delta T = -\frac{1}{0.019}\ln(g^{0.25})$$

Equation derived under the hypothesis that constraint loss apply only to the portion of $K$ above 30 MPa/$\sqrt{m}$
Comparison of the 4 geometries for the same measured K value result to compare for different M:

- **PCCv** \( K = 94 \text{ MPa} \sqrt{\text{m}} \) \( K_{1T} = 75 \text{ MPa} \sqrt{\text{m}} \) \( M = 84 \)
- **shal.** \( K = 94 \text{ MPa} \sqrt{\text{m}} \) \( K_{1T} = 75 \text{ MPa} \sqrt{\text{m}} \) \( M = 151 \)
- **MC(T)** \( K = 94 \text{ MPa} \sqrt{\text{m}} \) \( K_{1T} = 60 \text{ MPa} \sqrt{\text{m}} \) \( M = 109 \)
- **1T-C(T)** \( K = 94 \text{ MPa} \sqrt{\text{m}} \) \( K_{1T} = 94 \text{ MPa} \sqrt{\text{m}} \) \( M = 266 \)
Temperature shift plausible compare to experimentally observed value (m=10 used here)

- PCCv $\Delta T=25 \, ^\circ\text{C}$ $\Delta T=20 \, ^\circ\text{C}$
- shal. $\Delta T=54 \, ^\circ\text{C}$ $\Delta T=49 \, ^\circ\text{C}$
- MC(T) $\Delta T=25 \, ^\circ\text{C}$ $\Delta T=20 \, ^\circ\text{C}$
- 1T-C(T) $\Delta T=5 \, ^\circ\text{C}$ $\Delta T=0 \, ^\circ\text{C}$

Remark: numerical value not much affected by m except for the shallow crack => it is a nice geometry to calibrate the m value
Conclusions

- Weibull stress approach confirm conclusions of the Miami 2002 Workshop
  - 20 °C shift between 1T-C(T) and PCCv
  - No shift between MC(T) and PCCv
- 30°C shift between shallow and deep crack configuration
Slide Presented by Bob Dodds During Discussion
Qualitative Influence of Specimen Type, Absolute Size, $a/W$ Ratio, Temperature and Uniaxial vs. Biaxial Loading on Measured $T_0$

Test Temperature: $T - T_0$ - large C(T)s

R. Dodds, Jr., Nov. 6, 2006
Slides Presented by Kim Wallin
During Discussion
\[ K_{\text{CVN}} / K_{\text{SSYCT12.5}} = 1.1 \times \sqrt{1 + \exp(-M/30)} \]