OPEN REPORT
SCK•CEN-BLG-1020

SCK•CEN Participation to the IAEA CRP-8 – Area Topic #2: "Application of the Master Curve for Dynamic Testing" Activity 2005

Convention TRACTEBEL/SCK•CEN 2005
Task 1.1.3

E. Lucon

November, 2005

SCK•CEN
Boeretang 200
2400 Mol
Belgium

SCK•CEN Participation to the IAEA CRP-8 – Area Topic #2: "Application of the Master Curve for Dynamic Testing"
Activity 2005

Convention TRACTEBEL/SCK•CEN 2005
Task 1.1.3

E. Lucon

November, 2005
Status: Unclassified
ISSN 1379-2407

SCK•CEN
Boeretang 200
2400 Mol
Belgium

Name	Institute	Number
E. Lucon	SCK•CEN, RMO	1
J.-L. Puzzolante	SCK•CEN, RMO	1
J. Schuurmans	SCK•CEN, RMO	1
M. Scibetta	SCK•CEN, RMO	1
E. van Walle	SCK•CEN, RMO	1
	Secretariaat RMO	3
R. Gérard	Tractebel Engineering	3

© SCK•CEN
Belgian Nuclear Research Centre
Boeretang 200
2400 Mol
Belgium

Phone +32 14 33 21 11
Fax +32 14 31 50 21

http://www.sckcen.be

Contact:
Knowledge Centre
library@sckcen.be

RESTRICTED

All property rights and copyright are reserved. Any communication or reproduction of this document, and any communication or use of its content without explicit authorization is prohibited. Any infringement to this rule is illegal and entitles to claim damages from the infringer, without prejudice to any other right in case of granting a patent or registration in the field of intellectual property.
SCK•CEN, Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucléaire
Stichting van Openbaar Nut – Fondation d'Utilité Publique - Foundation of Public Utility
Registered Office: Avenue Herrmann Debroux 40 – B-1160 Brussel
Operational Office Boeretang 200, 2400 Mol, Belgium

Table of contents

Abstract

The latest IAEA Co-ordinated Research Project (CRP-8) focuses on the application of the Master Curve approach to monitor fracture toughness of reactor pressure vessels in nuclear power power plants. Three main work areas have been identified: (a) constraint and geometry effects on Master Curve T_o values; (b) loading rate effects up to impact conditions; (c) potential changes of Master Curve shape for highly embrittled materials.

After the kick-off meeting in Vienna in October 2004, the first Research Coordination Meeting was held in May 2005, hosted by AEKI Budapest. The present document focuses on the participation and contribution of SCK•CEN to Topic Area #2 (*Loading rate effects on Master Curve – Impact Loading*), for which E. Lucon acts as co-task leader.

A Round-Robin exercise is planned for early 2006, consisting in 10 tests per participant on precracked Charpy-V specimen of JRQ, tested dynamically using an instrumented pendulum; the results will be analysed using the Master Curve procedure (ASTM E1921-05) and compared to data obtained at other loading rates (quasi-static and/or dynamic). Guidelines and detailed specifications have been produced and circulated after the meeting in Budapest.

SCK•CEN has also produced data reporting sheets in EXCEL97 form, which will be used for reporting all fracture toughness test results (at quasi-static, dynamic or impact loading rates) performed in the framework of the CRP-8.

Keywords

IAEA, CRP-8, Master Curve, RPV integrity, loading rate effects, Round-Robin exercise, JRQ, data reporting sheets.

1. Introduction

On 20-22 October 2004, a kick-off meeting was held in Vienna for a new co-ordinated research project (CRP-8) of the International Atomic Energy Authority (IAEA) with the title "*Master Curve Approach to Monitor Fracture Toughness of Reactor Pressure Vessels in Nuclear Power Plants*".

The new CRP is a follow-up of previous successful projects aimed at resolving technical issues associated with the application of the Master Curve (MC) methodology to RPV integrity assessment [1-6].

The overall objectives of CRP-8 are the following:

(a) better quantification of fracture toughness issues relevant to testing surveillance specimens for application to RPV integrity assessment;
(b) development of approaches for addressing MC technical issues in the integrity evaluation of operating RPV's.

More specifically, the following primary issues identified in CRP-5 [6] will be addressed in this activity:

- constraint/geometry effects;
- evaluation and use of MC data generated under dynamic loading conditions, including development of standardized test methods for measuring dynamic toughness from small specimens;
- role of MC shape in evaluation of highly embrittled steels;

This report specifically addresses the participation and contribution of SCK•CEN in the Topic Area relevant to the second issue mentioned above (*Application of the Master Curve for Dynamic Testing*). Task leader in this area is Hans-Werner Viehrig (Forschungszentrum Rossendorf, FZR – Germany), assisted by E. Lucon as co-task leader.

2. Topic Area #2: Application of the Master Curve for Dynamic Testing (effect of loading rate)

Three loading rate regimes are addressed in this task:

- *quasi-static loading rate*, corresponding to the range presently allowed by the ASTM E1921-05 standard (*dK/dt* during the initial elastic portion between 0.1 and 2 MPa√m/s);
- *dynamic loading rate*, above the limit allowed by ASTM E1921-05 but below impact loading rate;
- *impact loading rate*, including precracked Charpy testing.

A Round-Robin exercise will be carried out within this task, consisting in instrumented impact tests on precracked Charpy specimens of the IAEA JRQ material, to be analysed according to the Master Curve methodology. This constitutes the mandatory portion, to be executed by all participating institutions.

For the non-mandatory portion, each participant is encouraged to provide data on national steels to address any combination of the following topics:

- ➢ comparison between unloading compliance and monotonic loading in the quasi-static regime;
- ➢ criteria for use of side-grooving;
- ➢ estimation of K_{Ia} (crack arrest toughness) from instrumented tests on notched and precracked Charpy specimens;

- effects of irradiation and/or yield stress changes on the relationship between static and dynamic fracture toughness.

3. Status of the activities at the end of 2005

The first Research Coordination Meeting (RCM) for CRP-8 was held between 11 and 13 May at AEKI in Budapest (Hungary). The official minutes of the meeting were taken by S. Rosinski (EPRI – USA) and are reproduced in Annex 1.

Within Topic Area #2, I delivered two presentations concerning the most recent draft of the ESIS TC5 procedure for instrumented precracked Charpy V-notch impact testing (slides in Annex 2) and summarising SCK•CEN experience and expertise in this type of tests (slides in Annex 3).

The activities to be carried out by the participants within this Topic Area, with specific emphasis on the Round-Robin exercise, were discussed at length, both during the general session and in a more restricted meeting.

The detailed specifications for the Round-Robin exercise are reported below.

Machining of the specimens (over 200) will be executed by JRC Petten and side-grooving will be performed by NRI Rez; side-grooving will be done by AEKI Budapest. Shipment of the samples should take place at the beginning of 2006.

3.1 Specifications for the Round-Robin Exercise (RRE)

3.1.1 Test conditions

- Loading rate: 1 to 1.5 m/s
- Test temperature range (provisonal): -40 to 0 °C [to be specified after FZR tests – Jan 2006]
- Number of specimens: 10/participant
- Specimen geometry: SE(B), Charpy-type, Charpy V-notch + sharpened notch (for crack initiation) = total depth 2.5 mm; specimens will be 20% side-grooved
- Minimum response frequency of the acquisition system: 100 kHz
- Minimum sampling rate: 2 µs

NOTE: If a lab cannot fulfil all the prescribed requirements, the deviations from the guidelines shall be clearly indicated in the test report and the consequences of such deviations will be assessed in the overall analysis of the RRE results.

3.1.2 Test procedure and measurements

- *(Only for JRC-IE)* Precracking conditions: initiation of fatigue crack K_{max} = 25 MPa√m; finish sharpening K_{max} = 18.5 MPa√m.
- *(Only for AEKI)* Side-grooving: according to E1921, §7.7.
- Perform pre-test dimensional measurements: B, B_N, W (precision: 0.01 mm)
- Dynamic yield strength properties for the calculation of the validity limit K_{lim} will be provided by FZR together with the definitive test temperature range; validity of the test results will be assessed in accordance to ASTM E1921 (K_{lim}, Δa).

- Test the first 2 specimens at the lowest temperature (-40 °C) and the remaining ones at temperatures chosen as a function of the provisional results (with nominal a_o); if a valid T_o has already been obtained with 8/9 tests, test the last two/one specimen at the highest indicated temperature (0 °C).
- Status of machine/thermocouple calibration and temperature control/conditioning times/transfer time: requirements of ASTM E23 should be followed
- Set acquisition time to a value such that all test data are captured, until force signal goes back to the baseline.
- Perform post-test crack size measurements: a_o, a_f (9-point average method, precision 0.01 mm)

3.1.3 Test analysis

In principle, no correction should be performed on the force values; "raw" force values should be used. The labs can perform additional calculations using correction procedures (such as the so-called "dynamic calibration"), but these should be clearly identified.
Identify cleavage point on the force/displacement trace (t_f, F_c, d_c)
Evaluate the absorbed energy up to the cleavage point (W_c) and until test termination (W_t); in case cleavage occurs after less than 3 oscillations ($t_f < 3\tau$), this circumstance has to be reported.
Calculate the J-integral at cleavage using:

$$J_c = J_{el} + J_{pl} = \frac{K_c^{\,2}(1-\nu^2)}{E} + \frac{1.9 \cdot W_{c(pl)}}{B_N\left(W - a_0\right)}$$

with:

$$E(MPa) = 207000 - (T - 20) \cdot 87$$

$$K_c = \left[\frac{F_c \cdot S}{\sqrt{B \cdot B_N} \cdot \sqrt[3]{W^2}}\right] \cdot f\left(a/W\right)$$

$$f(a_0/W) = \frac{3 \cdot \sqrt{\dfrac{a_0}{W}} \cdot \left[1.99 - \left(\dfrac{a_0}{W}\right) \cdot \left(1 - \dfrac{a_0}{W}\right) \cdot \left(2.15 - 3.93 \cdot \left(\dfrac{a_0}{W}\right) + 2.7 \cdot \left(\dfrac{a_0}{W}\right)^2\right)\right]}{2 \cdot \left(1 + \dfrac{2a_0}{W}\right) \cdot \sqrt{\left(1 - \dfrac{2a_0}{W}\right)^3}}$$

S = span of the anvils (for DIN ISO pendulum, accounting for anvil radius = 42 mm)
$W_{c(pl)}$ = plastic part of the absorbed energy up to the onset of cleavage, given by:

$$\mathrm{W}_{\mathrm{c(pl)}} = W_c - W_{c(el)} = W_c - \frac{\mathrm{C_M} \cdot \mathrm{F_c}^2}{2}$$

C_M = machine compliance = 10^{-5} mm/N (average value, based on compliance measurements for several machines; labs can use their own measured value if available).

Convert J_c into K_{Jc} using:

$$K_{Jc} = \sqrt{\frac{E \cdot J_c}{1-\nu^2}}$$

Use the calculated K_{Jc} values to evaluate the reference temperature T_o in accordance with ASTM E1921-03.

3.1.4 Reporting of results

- Fill in the appropriate report sheet (general section + individual specimen data + reference temperature calculations)
- Provide additionally:
  - digital pictures of the fracture surface taken at a suitable magnification, including the scale indication;
  - all raw test data (time, force and any additional parameters) in ASCII format.

A paper containing background information on the topic, prepared by H.-W. Viehrig and reviewed by myself before the meeting in Budapest, in enclosed in Annex 4.

3.2 Data reporting sheets

Data reporting sheets, to be used not only by Topic Area #2 participants but also by anyone who will perform fracture toughness tests in the framework of CRP-8, were prepared by SCK•CEN in the form of EXCEL97 files.

Three files were prepared, one for each loading rate interval: *Quasi-static toughness tests* (within E1921 allowed range - Annex 5), *Dynamic toughness tests* (above E1921 allowed range but below impact loading rates – Annex 6) and *Impact toughness tests* (instrumented impact tests on precracked Charpy specimens – Annex 7).

The main features of the reporting sheets are the following:

- the data sheets are password-protected, except for the cells where the user has to input data (identified by green dotted borders);
- some items have to be chosen from preexisting or drop-down lists, rather than freely entered (e.g. machine type, measured displacement, specimen geometry etc);
- in the individual test results sheets (15 for quasi-static, 10 for dynamic and impact tests), the following calculations are performed automatically based on the input data:
  - initial and final crack size
  - validity check of initial crack size
  - total J-integral at cleavage ($J_{elastic} + J_{plastic}$)
  - K at cleavage (K_{Jc})
  - maximum specimen capacity (K_{limit})
  - validity of test result ($K_{Jc} < K_{limit}$)
  - loading rate (dK/dt)

- for quasi-static or dynamic tests, force/crosshead displacement and force/CMOD or LLD diagrams are available; in case of impact tests, the diagrams included are force/time and force/displacement;
- in all cases, the last sheet relates to Master Curve calculations in accordance with ASTM E1921-05; on the basis of previously evaluated individual test results, automatic calculations include:
    - number of tests (performed and valid);
    - determination of the reference temperature T_o (obtained via a Visual Basic macro by clicking on a button) and relevant validity checks;
    - average loading rate for the specimens tested;
    - plot of normalized (1TCT) fracture toughness vs temperature, with Master Curve and relevant confidence bounds (5-95%); censored data are indicated by closed symbols;
- in all sheets, space is available for user's remarks.

The data reporting sheets have been circulated amongst all CRP-8 participants and officially approved after minor corrections and adjustments.

References

[1] "*Co-Ordinated Research Programme on Irradiation Embrittlement of Pressure Vessel Steels*," IAEA-176, Vienna, 1975.

[2] IAEA Technical Report Series No. 265, "*Analysis of the Behaviour of Advanced Pressure Vessel Steels under Neutron Irradiation*," Vienna, 1986.

[3] IAEA TECDOC-1230, *Reference Manual on the IAEA JRQ Correlation Monitor Steel for Irradiation Damage Studies*, July 2001.

[4] "*Assuring Structural Integrity of Reactor Pressure Vessels*", Final Report of IAEA Coordinated Research Project, in final preparation.

[5] IAEA TECDOC-1435, "*Application of Surveillance Programme Results to Reactor Pressure Vessel Integrity Assessment*", April 2005.

[6] IAEA Technical Report Series No. 429, "*Guidelines for Application of the Master Curve Approach to Reactor Pressure Vessel Integrity in Nuclear Power Plants*", Vienna, 2005.

ANNEX 1

Minutes of the first CRM (Budapest, May 2005)

taken by Stan Rosinski

IAEA Co-Ordinated Research Project (CRP) on Master Curve Approach to Monitor Fracture Toughness of RPVs in NPPs

11-13 May 2005
Budapest, Hungary

The first Research Coordination Meeting (RCM) for CRP-8 was held 11-13 May 2005 at AEKI in Budapest, Hungary. CRP-8 is a follow-on to previous successful CRPs on resolving technical issues associated with application of the Master Curve (MC) approach to RPV integrity assessment. Overall objectives of CRP-8 include: 1) better quantification of fracture toughness issues relative to testing surveillance specimens for application to RPV integrity assessment, and 2) development of approaches for addressing MC technical issues in integrity evaluation of operating RPVs. The meeting agenda and participant list are included in the package of electronic files distributed to all participants.

Ferenc Gillemot, Hungary, provided welcoming remarks as the local meeting host. Mr. Ki-Sig Kang, IAEA, opened the meeting and introductions were made. Mr. Kang discussed background information regarding the previous IAEA CRPs that have been completed on the MC approach. A new CRP on Pressurized Thermal Shock is being developed (CRP-9). The final TRS report documenting the MC application guidelines from the previous CRP (CRP-5) has been published and is now available (TRS-429). The summary report of the CRP-5 test results has also been published and is now available as TECDOC-1435, *Application of Surveillance Programme Results to Reactor Pressure Vessel Integrity Assessment*. Both documents were included with the electronic files distributed to all participants. Mr. Kang summarized the scope of CRP-8, the proposed agenda for this RCM, and the anticipated product to be developed. The 2nd RCM for this CRP is tentatively scheduled for October 2006. The 3rd RCM is scheduled for February 2008.

William Server, United States, provided opening remarks as the Chief Scientific Investigator for this CRP. Mr. Server discussed a presentation on this CRP made during the April 2005 meeting of the International Group on Radiation Damage Mechanisms (IGRDM). Mr. Server reviewed the history of CRPs in this topic area and discussed the topic areas to be investigated. These include: 1) constraint/geometry effects; 2) the role of MC shape in evaluation of, for example, highly embrittled RPV steels; and 3) the evaluation and use of MC data generated under dynamic loading conditions including development of standardized test methods for measuring dynamic fracture toughness on small specimens.

Presentations were made by the designated leaders for each of the three topic areas to be investigated in this CRP. The agenda was altered to allow for late arrival of the co-leader of topic area #1. An outline of each topic area is provided at the end of these minutes.

Hans-Werner Viehrig, Germany, and Enrico Lucon, Belgium, discussed topic area #2 on Loading Rate Effects. Three specific loading rate ranges have been defined: 1) quasi-static in the range of allowable rates within ASTM E1921-05; 2) dynamic loading at intermediate rates between the ASTM allowed loading rates and impact loading; and 3) impact loading using precracked Charpy (PCVN) specimens. Mr. Lucon indicated that ASTM is presently considering preparation of an appendix to E1921 that would provide guidance on testing at loading rates above the range presently allowed in the standard. The preparation of a separate technical document summarizing the results of the proposed instrumented impact testing round robin exercise was discussed. This will be readdressed following completion of the round robin exercise. The results generated through this topic area will be an important contribution for future standardization activities (ISO and ASTM) regarding loading rate testing of MC samples. A draft of the proposed ESIS TC5 procedure on dynamic testing was discussed and included in the electronic files distributed to all participants.

Open issues in this topic area to be addressed include: 1) number of specimens required and pre-cracking (whether performed centrally or by each participant); 2) test conditions and evaluation procedure, and 3) data to be delivered (evaluated/recorded data). A target minimum of 3 participants should perform quasi-static and dynamic loading. All participants should perform impact testing.

Tapio Planman, Finland, discussed topic area #3 on Master Curve Shape. Data suggest that, in general, the MC shape does not change for data within 50°C of T_o. However, limited data exist outside this range that failed via cleavage and *do* deviate from the standard MC shape. Similarly, maraging steels do not conform to MC behavior because they do not fail via a weakest link mechanism. Limiting testing to within a range of 50°C of T_o may falsely suggest that the MC does work for these materials.

Action: Mr. Server agreed to draft a letter to the chairman of the ongoing PERFECT project and propose IAEA participation in the user's group established under PERFECT regarding data sharing under this topic area.

Randy Nanstad, United States, and Marc Scibetta, Belgium, discussed topic area #1 on Bias/Constraint/Geometry Effects. Mr. Nanstad presented data demonstrating a range of specimen bias values ranging from essentially no difference in T_o values between precracked CVN and larger specimens (e.g. 0.5T CT) to a difference of approximately 25°C. Mr. Nanstad also discussed the limits required to mitigate effects of specimen constraint. There may be a need to provide varying M_{lim} values depending on specimen type. Differences between numerical studies and experimental results need to be further reconciled regarding M_{lim}, T-stress, etc. Mr. Scibetta discussed past experience related to testing and modeling of constraint-related issues and the concept of T-stress application in this topic area. The bias between PCVN and C(T) specimens was discussed and the possible influence of several technical 'areas' on this bias, including: the equation for J determination; a difference in constraint level; side grooving; effect of ligament cross-section (W/B); inadequacy of size limit; testing temperature; and ligament size.

After discussion of the CRP-8 task areas individual participants presented their proposed testing programs. Presentations were made by the organizations/individuals shown below. The participation matrix was revised based on the presentations and is also provided below. Note: Countries indicated by italics were not present during this RCM and their specific contribution was not verified prior to completion of these minutes.

AEKI – Ferenc Gillemot
ATI Consulting – William Server (included in overall EPRI program)
BASI – not present
CIEMAT – Jesus Lapeña
CRIEPI – Naoki Miura
EC/JRC – Luigi Debarberis
EPRI – Stan Rosinski
FZR – Hans-Werner Viehrig
ININ – Rogelio Hernandez Callejas
JAERI – not present
KAERI – Bong-Sang Lee
NRI – Milan Brumovský

ORNL – Randy Nanstad
RRC KI – Information regarding their participation was obtained during the meeting
SCK-CEN – Marc Scibetta/Enrico Lucon
VTT – Tapio Planman

Organization	**Constraint**	**Load rate**	**MC shape**
AEKI/Hungary	**M/NM**	**M**	**T/D**
BASI/Bulgaria	***M***	***M***	
CIEMAT/Spain	**M/NM**	**M/NM**	**T/D**
CRIEPI/ Japan	**M/NM**	**M/NM**	**D**
European Commission/JRC	**M/NM**	**M**	
EPRI (ATI/ Westinghouse)/USA	**M**	**M/NM**	**D**
FZR/Germany	**M/NM**	**M/NM(Leader)**	**D**
ININ/Mexico	**M/NM**	**M/NM**	
JAERI/Japan		***M/NM***	***D***
KAERI/Korea	**M/NM**	**M/NM**	**D**
NRI/Czech Republic	**M/NM**	**M/NM**	**D**
ORNL/USA	**M/NM(Leader)**	**M**	**D**
RRC KI/Russia	**M/NM**		**D**
SCK-CEN/Belgium	**M/NM**	**M/NM**	**T/D**
VTT/Finland	**M/NM**	**NM**	**D (Leader)**

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

Following individual participant presentations the topic area task leaders developed the final testing matrix and reviewed with the participants.

Topic Area #1 – Bias/Constraint/Geometry Issues

Mr. Nanstad summarized the test matrix for topic area #1 on bias/constraint/geometry issues. The developed test matrices are shown below.

TABLE 1-1. Topic area 1: Overall view of participation

Lab./Country	**Mandatory**	**Non Mandatory**
AEKI/Hungary	X	X
BASI/Bulgaria	*X*	
CIEMAT/Spain	X	X
CRIEPI/ Japan	X	X
EC/ JRC	X	X
EPRI, ATI/USA	X	
FZR/Germany	X	X
ININ/Mexico	X	X
JAERI/ Japan	X	X
KAERI/Korea	X	X
NRI Rez/ Czech	X	X
ORNL/USA	X	X
RRC-KI/Russia	X	X
SCK-CEN/Belgium	X	X
VTT/Finland	X	X

TABLE 1-2. Topic area 1: Overall view of participation for the mandatory and non-mandatory portions *(Non-mandatory testing in bold italics)*

Lab./Country	**SE(B) W/B=1**	**SE(B) W/B=2**	**C(T)**	**SE(T)/Other**
AEKI/Hungary	PCVN ***a/W=0.1*** & a/W=0.5	0.4T		
BASI/Bulgaria				
CIEMAT/Spain	PCVN & ***0.5T***		0.5T, ***0.4T***	
CRIEPI/ Japan		0.4T	0.4T, ***1T, 2T, 4T***	
EC/ JRC	PCVN, ***a/W=0.1*** & a/W=0.5	0.4T, ***0.8T*** a/W=0.5	1T	
EPRI, ATI/USA		0.4T a/W = 0.3, 0.65, 0.75		
FZR/Germany	0.5T	0.5T	0.5T, ***1T***	
ININ/Mexico	PCVN		0.4T, ***1T***	
JAERI/ Japan				
KAERI/Korea	PCVN	0.4T	0.4T	
NRI Rez/ Czech	PCVN	0.4T	0.4T, ***1T***	
ORNL/USA	PCVN, ***1T***	0.4T, ***1T***	0.4T a/W=0.5 ***a/W=0.8*** ***1T*** ***a/W = 0.5***	
RRC-KI/Russia	PCVN		0.5T	
SCK-CEN/Belgium	PCVN ***a/W = 0.1*** a/W= 0.5		0.5T	***Not SE(T) W=50 biaxial loading of embedded elliptical flaw***
VTT/Finland	Size??? ***a/W=0.1*** *a/W*= 0.5	Size???		

TABLE 1-3. Topic area 1: Material used for the mandatory portion

Lab./Country	Material
AEKI/Hungary	JRQ and National Material
BASI/Bulgaria	
CIEMAT/Spain	JRQ and Aged JRQ
CRIEPI/ Japan	National Steels: SFVQ1A (~A508-3), SQV2A (~A533-B-1)
EC/ JRC	JRQ ???
EPRI, ATI/USA	National Material (HSST Plate 13B, A533-B-1)
FZR/Germany	JRQ and National Material (VVER-440)
ININ/Mexico	JRQ
JAERI/ Japan	
KAERI/Korea	JRQ and National Material (A508-3 heat treated)
NRI Rez/ Czech	JRQ and National Material
ORNL/USA	National Material (HSST Plate 13B, A533-B-1)
RRC-KI/Russia	JRQ
SCK-CEN/Belgium	A508-2 (from actual vessel)
VTT/Finland	???

The following guidance was provided by Mr. Scibetta regarding testing under topic area #1:

General recommendations for testing to be performed under the mandatory portion:

- Testing according to ASTM E1921-05 (except SE(T) that would need detail information on equation and methodology used)
- Testing temperature chosen to produce valid data and not too far from T_o. For example, PCVN could be tested at T_o-20°C. Multiple temperature method is allowed.
- Number of specimens to be tested should be large enough to obtain a valid T_o. A minimum number of 8 specimens is recommended.
- Same value of B is recommended for the different geometries.

Expected output for the mandatory portion:

- Increase the available data base
- Evaluate the T_o bias between C(T), SE(B), and SE(T) to further support previous findings
- To better define the average bias value in terms of T_o.

Expected output for the non-mandatory portion:

- Increase the available data base
- Evaluate the T_o in low constraint situation
- Evaluate and qualify the different analytical method

Mr. Lucon discussed development of the EURO toughness curve. During development of the EURO toughness curve the following issues were identified: influence of specimen type, influence of specimen size, and specimen bias. This information will be useful in defining the final testing conditions for this CRP.

It was suggested that those organizations performing analytical (finite element calculations) work as part of the non-mandatory portion also participate in an inter-comparison exercise to benchmark the various analytical methods on a defined example problem. Mr. Scibetta discussed the sample problem to be analyzed by participants in this exercise (included in electronic files distributed to participants). The organizations participating in this finite element benchmark will be contacted by Mr. Scibetta. The inter-comparison will be performed by the organizations below.

TABLE 1-4. Topic area 1: Analytical work for the non mandatory portion

Lab./Country	FE calculation	Other (FE Example)
AEKI/Hungary	X	Yes
BASI/Bulgaria		
CIEMAT/Spain		
CRIEPI/ Japan	X	X
EC/ JRC	X	Maybe
EPRI, ATI/USA		
FZR/Germany	X	Maybe
ININ/Mexico	X	Yes
JAERI/ Japan		
KAERI/Korea	X	Yes
NRI Rez/ Czech		
ORNL/USA	X	Yes
RRC-KI/Russia		
SCK-CEN/Belgium	X	Yes
VTT/Finland	X	No

TABLE 1-5. Topic area 1: FE work for the non mandatory portion

Lab./Country	T-stress	Q-factor	Area ratio	Beremin	Other
AEKI/Hungary				SE(B) a/W=0.1 & 0.5 Elliptical crack	
BASI/Bulgaria					
CIEMAT/Spain					
CRIEPI/ Japan					
EC/ JRC					
EPRI, ATI/USA					
FZR/Germany					
ININ/Mexico					
JAERI/ Japan					
KAERI/Korea			0.4 T SE(B) and CT a/W=0.5	0.4 T SE(B) and CT a/W=0.5	
NRI Rez/ Czech					
ORNL/USA	X	?	X	X	η_p
RRC-KI/Russia					
SCK-CEN/Belgium	Elliptical crack	SE(B) a/W=0.1 Elliptical crack	SE(B) a/W=0.1 Elliptical crack	SE(B) a/W=0.1 Elliptical crack	
VTT/Finland					

A summary of activities to be performed under topic area #1 is provided below.

- 8 Institutes will test JRQ Steel
- 11 Participants will test SE(B) of W/B=1

  - 9 with PCVN
  - 2 with 0.5T
  - 1 with 1T
  - 3 with multiple a/W
- 9 Participants will test SE(B) of W/B=2
  - 7 with 0.4T
  - 1 with 0.5T
  - 1 with 1T
  - 2 with multiple a/W
- 10 Participants will test C(T)
  - 6 with 0.4T
  - 4 with 0.5T
  - 6 with 1T
  - 1 with 2T
  - 1 with 4T
  - 1 with multiple a/W (for 0.4T)
- No Participants will test SE(T)
- 1 Participant will test biaxial specimens
- 9 Participants will perform finite element analyses

FUTURE ACTIVITIES

- Prepare specifications for testing
  - E1921-05 is basis for testing
  - Displacement measurement and validation
  - Loading rate in accordance with new ASTM E1921 ballot
  - Test temperature recommendations
  - Side grooves for PCVN

  Need to know the contact at each participating organization for finite element analysis
  - Other ???
- Prepare form for reporting test parameters and results
- Provide guidance for measuring crack-mouth opening displacement, and determining J/K_{Jc} for shallow crack tests, including guidance regarding specimen preparation for producing an a/W = 0.1.

ADDITIONAL INFORMATION DESIRED

- Results for irradiated specimens that would allow for direct comparison with the same specimen geometry and size tested in the unirradiated condition.
- Additional testing of specimens with low constraint for comparison with the same specimen geometry and size tested with relatively high constraint. For example, deeply cracked bend specimens with, e.g., a/W of 0.5, can be compared with shallow cracked specimens with, e.g., a/W of 0.1.
- Currently no participants have committed to test SE(T) specimens; thus, testing of such specimen type would be helpful to constraint evaluations for this topic area. Specimens could be rectangular or cylindrical. Detailed information on the appropriate equations and methodology for the precracked cylindrical bar can be obtained from Marc Scibetta (mscibett@sckcen.be).

- More detailed information regarding the type of analyses the participants will perform (see Table 1-5). Send information to the co-task leaders (mscibett@sckcen.be and nanstadrk@ornl.gov).

Topic Area #2 – Loading Rate

Mr. Lucon discussed the proposed ESIS TC5 procedure on instrumented PCVN impact testing. A summary of main procedure elements is provided below:

- Initial crack size: $0.3 \leq a/W \leq 0.55$. Side grooving is allowed (not required, nor recommended).
- Testing machine: A pendulum machine with variable speed is recommended. The striker must conform to ISO 148-2 (tup radius: 2 mm).
- Impact velocity: quasi-static up to ~5m/s; for a Charpy pendulum, it can be reduced to ~ 1 m/s.
- Crack size measurements: 5-point average method; average area method
- Crack-tip loading rate: fracture toughness properties must be reported with corresponding loading rate

Guidance is also provided in ESIS TC5 on selection of the particular test method to use for instrumented PCVN testing. The applicability of this proposed standard to a dynamic (impact) test was discussed. Comparison results will be presented at the next meeting. Fracture toughness values from this test method are said to be transferable to larger structures if specified conditions are met.

It was discussed to what extent this proposed standard could (should) be followed for the PCVN round robin exercise.

Mr. Lucon also discussed status of instrumented PCVN testing previously performed at SCK-CEN. The presentation was made in two parts: cleavage fracture and ductile fracture. The procedure developed by SCK-CEN for analyzing PCVN data under their program was proposed for consideration in the instrumented PCVN round robin to be performed under this topic area.

Mr. Viehrig further discussed instrumented fracture toughness impact testing and presented work conducted at FZR which provided insights for consideration during the instrumented PCVN round robin to be conducted under this topic area. Mr. Viehrig suggested the following test conditions for the dynamic fracture toughness round robin exercise:

- Specimens: Charpy SE(B), 20% side-grooved, a/W=0.5 (0.45 – 0.55)
- Specimen compliance: $3.79\ 10^{5}$ mm/N
- Impact velocity: 1.5 m/s
- Temperature range: -40°C to 0°C (tentative; to be finalized following first set of tests)
- Number of specimens: 10

Extensive discussion was held regarding fatigue pre-cracking and side-grooving of the specimens to be tested under the round robin. It is desirable to have a single organization perform the pre-cracking. With over 200 specimens to pre-crack, however, this would be a significant effort for any single organization. NRI indicated they could perform the pre-cracking. No decision was made regarding who would be able to perform the side-grooving. A target date of December 2005 was established for completion of sample machining and pre-cracking. All samples should be machined in TL orientation from the center ½ thickness of the plate (avoid inner ¼ T and outer ¼ T) to limit material through-thickness inhomogeneity. The recommended procedures in the ESIS draft standard should be followed for pre-cracking and side-grooving.

JRC will perform the original sample machining and send the specimens to NRI for pre-cracking. It is not clear who will perform the side-grooving. JRC will investigate the feasibility of performing the side-grooving.

The test procedure and results reporting format will be distributed following the meeting.

Mr. Viehrig discussed the E1921 ballot recently approved (E1921-05) regarding loading rates. A loading rate of 1 MPa√m/s was recommended for quasi-static loading. A rate of 10^5 MPa√m/s was discussed for impact loading. Loading rates between the two limits above could be used to investigate dynamic fracture toughness.

Mr. Scibetta discussed the evaluation of inhomogenous data with relation to topic area #2. A website has been created, www.sckcen.be/mastercurve that provides an *online* capability to evaluate up to 10 input values (more data can be analyzed with a license). The tool provides analysis capability for standard master curve evaluation; bi-modal analysis; and randomly inhomogeneous data analysis.

The final testing matrix for participation in topic area #2 is provided below.

TABLE 2-1. TOPIC AREA #2 TEST MATRIX.

Country/Laboratory	**Code**	**Impact**		**Dynamic**	**Quasi-static**	**Charpy-V Correlation**
		RRE	**specific**			
Bulgaria	BUL					
Belgium - SCK•CEN	BEL	X		X - T	X – D(5Q12)	X
Czech Republic - NRI	CZR	X				
European Commission JRC-IE	EUC	X		X - T		
Finland - VTT	FIN					
Germany- FZR	FZR	X	X		X – T(RRE)	X
Hungary - AEKI	HUN	X				
Japan - CRIEPI	JAP	X	X		X	X
Korea - KAERI	KOR	X	X	X - D		
Mexico - ININ	MEX	X				X
Russia - KUR	RUS	?				
Spain -CIEMAT	ESP	X		X - D	X-T(RRE)	X
United States – EPRI/ATI	USE	X		X – T X - D		
United States - ORNL	USO	X	X	X - D		X

TABLE 2-2. TOPIC AREA #2 TEST MATRIX – NON-MANDATORY

Who?	**What?**	**How?**	
		Testing	**Data**
BASI/Bulgaria	?	?	?
CIEMAT/Spain	- Estimation of toughness from Charpy data (CIEMAT procedure) - Effect of loading rate on T_o (JRQ)	- New instrumented Cv tests on JRQ block 8 - JRQ block 8 quasi-static rate (10 Cv)	- JRQ existing Charpy data - Data at different dynamic rates (previous CRP's)
CRIEPI/ Japan	- Estimation of toughness from Charpy data (CRIEPI procedure)	- New instrumented Cv tests on JRQ block 8	

Who?	What?	How?	
		Testing	**Data**
	- Effect of loading rate on T_o (other materials)		- Data on national steels + literature
European Commission/JRC	TBD	TBD	TBD
EPRI (ATI/ Westinghouse)/USA	- Effect of loading rate on T_o (JRQ)	- 10 PCCv tests on 2 materials (5JRQ and 13B) at two dynamic loading rates	
FZR/Germany	- Effect of loading rate on T_o - Effect of unloading compliance vs monotonic - Effect of side-grooving - Relationship between T_{41J} and T_o (static/dynamic) - Crack arrest properties (T_{4kN} vs NDT_o)	- 10 PCCv tests from RRE material at quasi-static rate - Min 10 PCCv (mon. loading) on 6JRQ12 - PCCv tests from 8JRQ25 - (Optional) *PCCv tests on highly irradiated JRQ and JFL*	- Data from JRQ and VVER-440 (GR8) + other RPV steels
ININ/Mexico	- Effect of loading rate on T_o	- Block 8JRQ34: PCCv+0.4TCT+Cv tests at different static rates	
JAERI/Japan	*?*	*?*	*?*
KAERI/Korea	- Impact PCCv tests on a different material - Effect of side-grooving	- 10-15 PCCv tests on Korean forging (following RRE condition)	- Dynamic PCCv data from 5JRQ (CRP-4) at 1200 mm/min - effect of side-grooving on 5JRQ
NRI/Czech Republic	- Crack arrest properties (T_{4kN} vs NDT_o) - T_o shift from static to impact		- *Existing data? (to be confirmed)* - *VVER materials*
ORNL/USA	- Crack arrest properties (T_{4kN} vs NDT_o)	- Instrumented CVN data to evaluate K_{Ia} on JRQ	

Who?	What?	How?	
		Testing	**Data**
	- Crack arrest properties (K_{Ia} Charpy vs E1221)		- Data on 72W, 73W etc (5 materials,some irr)
RRC KI/Russia	***NOTHING?***	***NOTHING?***	***NOTHING?***
SCK-CEN/Belgium	- Effect of strain rate on T_o (JRQ) - Definition of test procedure - Crack arrest properties - T_o shift from static to impact for various materials - Strain rate effect on irradiation-induced ΔT_o - Relationship between T_{41J} and T_o (static/dynamic)	- Dynamic rates (1000-5000 mm/min): 10 tests on PCCv specimens	- Quasi-static rates (0.1 mm/min): data from 5Q12 block - Input from SCK•CEN internal procedure and ESIS TC5 Draft - SCK•CEN experience on correlation between T_{4kN} and NDT - Data on 11 material conditions (7 unirr + 4 irr) - Data on several materials (RPV+RAFM) - SCK•CEN database (mainly RPV)
VTT/Finland	- Effect of strain rate on T_o (3 steels – low,medium,high YS)	- 8 specimens per condition; 2 static rates (lower/upper limit E1921)	

Topic Area #3 – Master Curve Shape

Mr. Planman reviewed the specific activities to be performed under topic area #3. The final testing matrix is shown in Table 3-1.

TABLE 3-1. TOPIC AREA #3 TESTING MATRIX.

Lab	**Data**	**Testing**	**Other activity**[1]	**Test/Data**[2]
AEKI/Hungary	JRQ and other	irradiated JRQ etc. up to 10^{20} n/cm^2	(US)	T, D
CIEMAT/Spain		JRQ aged		T, LR
CRIEPI/Japan	Aged			D
FZR/Germany (Task 2 Leader)	High fluence ($20x10^{19}$) JRQ & JFL, irradiated VVER 440 BM (Greifswald, F=$2.5x10^{19}$ n/cm^2)		Fractography, GBF cases, data from irradiation experiments (GBF)	D
KAERI/Korea	Martensitic steels			D
NRI Rez/CZ	Irradiated JRQ and VVER 440 materials (high fluence)		Different F and T_{irr} (270, 290^{o}C), data from VVER-440 database	D
ORNL/USA (Task 1 Leader)	HSST (72W, 73W), KS01 W, irradiated and aged steels (IGF)		Data on thermally embrittled steels, FT-CVN correlation data, fractography, GBF cases	D
RRC KI/Russia	PCVN of WWER-440 highly embrittled, unirradiated and irradiated			D
SCK-CEN/ Belgium	JRQ data, A533B	JRQ (E 1921)	Heat treatments for various GBF levels (GBF)	T/D
VTT/Finland (Task 3 Leader)	From SAFIR, ORNL, PTSE-1 etc. programmes	(Thermally aged)	Data analyses (GBF)	D
EPRI;ATI/USA	Western steels, Linde 80 weld		Data collection and evaluation	D
JAERI/Japan	Japanese inhomogeneous data (?)			D
BASI/Bulgaria				-
JRC/EC				-
ININ/Mexico				-

[1] Main activity: Grain Boundary Fracture (GBF)/Upper Shelf (US) toughness

[2] Mandatory Portion: Data collection and/or analyses

Schedule

It was suggested that a timeline be established for those organizations that are actually performing testing in order to allow sufficient time for testing, data collection, analysis, etc. It is desired that any new ‘promised’ data be provided as early as possible (target May 2006). The topic area leaders are encouraged to contact organizations providing data to express the importance of meeting the May 2006 deadline. Additionally, the task leaders will outline the minimum information that should be included with provided data sets to ensure appropriate analysis as part of this CRP. Mr. Viehrig will develop a data submittal format by December 2005 that is applicable for all three topic areas.

The following schedule (and responsible participant) was established for major activities under this CRP.

Activity	**Topic Area 1**	**Topic Area 2**	**Topic Area 3**
JRQ specimen prep (round robin exercise; RRE)	--	12/2005 (Debarberis)	--
Analytical FE exercise	6/2006 (Scibetta)	--	--
Test Procedures Data Requirements	Constraint; 10/2005 (Nanstad)	Impact Procedures; 10/2005 Temperatures: 2/2006 (Viehrig/Lucon)	--
Web-Based Data Collection	Data System; 12/2005 (Viehrig) Data Collection; 5/2006 (All)		
Testing	?	RRE; 5/2006	?
Next meeting (RCM)	10/2006		

Technical Meetings

1. 2nd RCM: 11-13 October 2006 (Tentatively at FZR-Rossendorf in Dresden)
2. CT Meeting; Spring 2007 (Vienna – limited to small group including topic area leaders)
3. 3rd RCM: February 2008 (Vienna)
    a. 3rd CT: February 2008 (Vienna)
    b. Finalization of technical document
    c. Prepare for next CRP

Electronic copies of all presentations, these minutes, and select meeting photographs were provided to all meeting participants.

The meeting adjourned at 12:30 on 13 May.

These minutes were prepared by Stan Rosinski, United States.

OUTLINE OF TOPIC AREAS FOR CRP-8

TOPIC AREA #1

Bias/ Constraint/Geometry Effects

Randy Nanstad, Task Leader
Marc Scibetta, Co-Task Leader

Scope

- Focus on specimen loading geometries to assess bias between specimen types

Mandatory Portion

- Materials to be selected by participants
- Each participant must select at least two of the following geometries for testing and/or assessment:
    - Single edge bend specimen [SE(B)] with specimen width to thickness equal to 1 [W/B=1]
    - SE(B) with W/B=2
    - Compact tension specimen [C(T)] with W/B=2
    - Single edge tension specimen [SE(T)] with W/B defined by participant
- It is recommended that the same value of B is used for the two specimen types selected
- New material testing is not required; previously obtained data can be supplied provided appropriate CRP-requested information is available.

Non-mandatory Portion

- Additional testing on more or different specimen geometries is encouraged
- Study of the effects of shallow crack and deep crack specimens also is encouraged
- Testing on a broad range of ferritic materials and conditions would be of benefit in assessing this topic area, such as:
    - RPV and other component materials
    - Range of yield strengths
    - Irradiated RPV steels
    - Thermally aged NPP component materials
- Study of the relationship of specimen constraint to loading conditions in components with assumed or real flaws also is encouraged and would be of great value

TOPIC AREA #2
Loading Rate Effects

Hans-Werner Viehrig, Task Leader
Enrico Lucon, Co-Task Leader

Scope

- Three specific loading rate ranges have been defined for this study:
  - Quasi-static in the range of allowable loading rates within ASTM E 1921-03
  - Dynamic loading (intermediate rate between quasi-static and impact)
  - Impact – using instrumented precracked Charpy (IPCVN) testing
- Test procedures for performing IPCVN testing and data analysis need development

Mandatory Portion

- Participate in round robin exercise to validate IPCVN testing and analysis procedures for impact loading using supplied specimens of JRQ material (minimum of 10 tests)

Non-mandatory Portion

- Test additional materials
- Compare results from unloading compliance and monotonic loading in the quasi-static range
- Evaluate the need for side grooves for small Charpy-type specimens
- Establish relationship between instrumented Charpy V-notch (CVN) test results and measured fracture toughness and T_0
- Evaluate methods for estimating K_{Ia} from IPCVN and instrumented CVN results
- Evaluate the effect of irradiation and/or yield strength changes on relationship of static and dynamic fracture toughness

TOPIC AREA #3
Master Curve Shape

Tapio Planman, Task Leader
Kunio Onizawa, Co-Task Leader

Scope

- Assess limits of applicability for Master Curve
    - Application at upper range of transition region in the standard Master Curve form
    - Effects of heterogeneity (material and environment conditions)
    - Fracture mode change (i.e., upper shelf ductile or intergranular fracture, IGF)

Mandatory Portion

- Participate in data collection and/or new testing to assess potential Master Curve shape changes in highly embrittled material (either irradiated, thermally aged or other condition that induces IGF)
    - Pedigree database relative to quality of old data
    - Select materials and conditions that can challenge the Master Curve shape limits

ANNEX 2

Presentation by E. Lucon (Budapest, 11 May 2005)

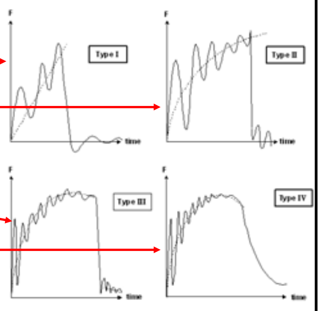
ESIS TC5 Procedure – Draft 19

Proposed Standard Methods for Instrumented Pre-Cracked Charpy Impact Testing of Steels (ESIS TC5 - Draft 19: April 2005)

presented by Enrico Lucon
SCK•CEN – Mol (Belgium)

Determination of fracture toughness properties

Material response/fracture behaviour	corresponding diagram type (see Fig.1)	R-curve	Characteristic Parameters (with relevant influencing parameters given in brackets)
essentially linear-elastic	I	-	K_{Id} ($\dot{K}_I$)
elastic plastic, unstable cleavage without significant stable crack extension (Δa<0.2mm)	II	-	J_{ucd} (B, $\dot{J}$)
elastic plastic, unstable cleavage after stable crack extension (1.6mm>Δa>0.2mm)	III	-	J_{ud} (B, Δa, $\dot{J}$)
elastic plastic, unstable cleavage after gross stable crack extension (Δa>1.6 mm)	IV	J_d-R-curve δ_d-R-curve	$J_{0.2Bd}$ ($\dot{J}$) $\delta_{0.2Bd}$ ($\dot{\delta}$)
elastic plastic; no unstable crack extension	IV	J_d-R-curve δ_d-R-curve	$J_{0.2Bd}$ ($\dot{J}$) $\delta_{0.2Bd}$ ($\dot{\delta}$)

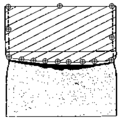


General features

- <u>Specimens</u>
  - Allowed range of initial crack size: 0.3 ≤ a/W ≤ 0.55 (for comparison with static toughness: 0.45 ≤ a/W ≤ 0.55)
  - Side-grooving is allowed (not required, nor recommended)
- <u>Testing machines</u>
  - Various machines allowed (recommended: pendulum with variable speed; allowed: drop-weight, servo-hydraulic, special pendulum types with moving anvils)
  - Striker must conform to ISO 148-2 (tup radius: 2 mm)

General features

- <u>Test procedures and measurements</u>
  - *Impact velocity*: any value allowed from quasi-static up to about 5 m/s; for a Charpy pendulum, it can be reduced to approx 1 m/s
  - *Time to fracture* (t_f): if $t_f < 5\tau$, crack initiation cannot be detected from F/d trace (independent measure is required)
  - *Crack size measurements*:
    - 5-point average method (limit of non-uniform crack growth: 10%)
    - Area average method



General features

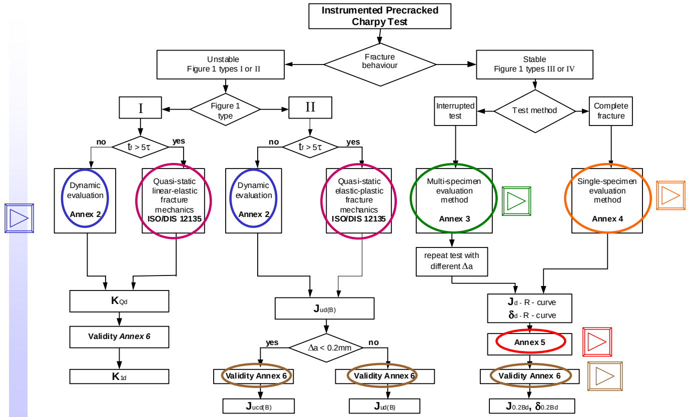
- Crack-tip loading rate
  - Fracture toughness properties must be reported with corresponding loading late in parenthesis

$$\dot{K}_I = \frac{\dot{F} \cdot S}{t_f \cdot \sqrt{B \cdot B_N} \cdot W^{3/2}} \cdot f\left(\frac{a_0}{W}\right)$$

$$\dot{J} = \frac{F_m \cdot v_0}{B_N \cdot (W - a_0)} \cdot \eta\left(\frac{a_0}{W}\right)$$

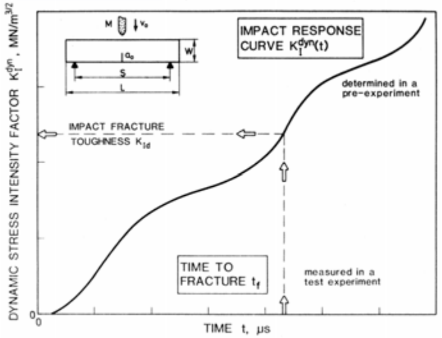
$$\dot{\delta} = \frac{0.4 \cdot (W - a_0) \cdot v_0}{S}$$

Flow-chart for selection of test method



Annex 2
Dynamic evaluation of fracture toughness

- Impact Response Curve (Kalthoff, Winkler & Böhme, DYMAT 1985)



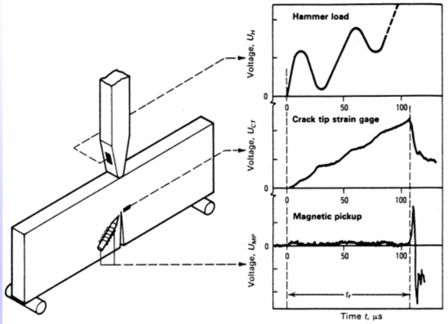
$$K_1^{dyn} = R v_0 t''$$

function of machine compliance

t" is tabulated as a function of t_f

Annex 2
Dynamic evaluation of fracture toughness

- Crack Tip Strain Gauge Method (McGillivray & Cannon, ASTM STP 1130, 1992)



Annex 3
Resistance curves by multi-specimen methods

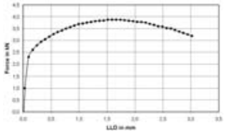
- Low-Blow Test
  - Impact velocity is changed to achieve variable *Δa*
  - Available energy sufficient for propagating the crack, but not to break the specimen fully
  - Small differences between initial velocities are neglected
- Stop Block Test
  - Striker movement is arrested before the specimen is fully broken
  - Striker arrest position is changed to achieve variable *Δa*
  - Not recommended for "*normal use with standard machines*" (damage to the load cell)
- Cleavage R-curve Method
  - Tests are performed in the transition region, varying the test temperature in order to achieve variable *Δa*
  - Small differences between test temperatures are neglected

---

Annex 4
Resistance curves by single-specimen methods

- Normalization method (ASTM E1820)
  - force normalization $$P_{N(i)} = \frac{P_{(i)}}{WB\left[\frac{W-a_{b(i)}}{W}\right]^{\eta_{pl}}}$$
  - plastic displacement normalization $$v'_{pl(i)} = \frac{v_{pl(i)}}{W} = \frac{\left(v_{(i)} - P_{(i)}C_{(i)}\right)}{W}$$
  - normalization function $$P_N = \frac{a + bv'_{pl} + cv'^{2}_{pl}}{d + v'_{pl}}$$

Annex 4
Resistance curves by single-specimen methods



- Normalization method (ASTM E1820)
  - applicability requirements:
    - ➡evenly distributed data points
    - ➡minimum 10 points available
    - ➡all fitted points within 1% of measured data
    - ➡maximum *Δa* =lesser of 4 mm or 15% of (W-a_o)
  - applicability confirmation:
    - ➡test additional specimen to deflection corresponding to *Δa* = 0.5 mm (using NM *J-R* curve)
    - ➡measured crack extension must be 0.5 ± 0.25 mm

IS ALL THIS REALLY RELEVANT TO A DYNAMIC (IMPACT) TEST???

Annex 4
Resistance curves by single-specimen methods

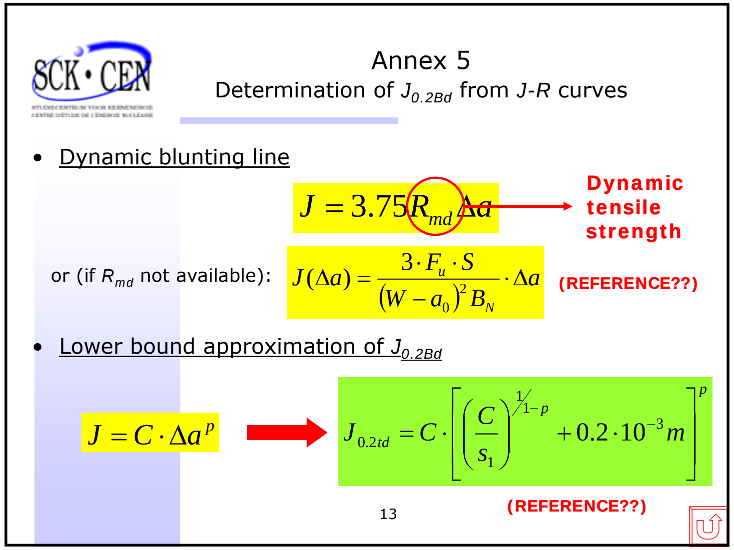
- Analytical 3-parameter approach (Schindler, ASTM STP 1380, 1999)

$$J(\Delta a) = \left(\frac{2}{p}\right)^{p} \cdot \frac{\eta_{pl}(a_0)}{B\,(W-a_0)^{1+p}} \cdot W_t{}^{p} \cdot W_{mp}{}^{1-p} \cdot \Delta a^{p} + \frac{K_I^2(F_{gy}, a_0 + \Delta a)}{E}(1-\nu^2)$$

$$p = \frac{3}{4} \cdot \left(1 + \frac{W_{mp}}{W_t}\right)^{-1}$$

Plastic part of energy at maximum force

$$K_I(F,a) = \frac{2.659 \cdot F_{gy} \cdot S}{\sqrt{BB_N} \cdot W^{3/2}} \cdot \left(\frac{a_0 + \Delta a}{W}\right)^{1/2} \cdot$$
$$\left(1.090 - 1.735\left(\frac{a_0+\Delta a}{W}\right) + 8.20\left(\frac{a_0+\Delta a}{W}\right)^2 - 14.18\left(\frac{a_0+\Delta a}{W}\right)^3 + 14.57\left(\frac{a_0+\Delta a}{W}\right)^4\right)$$



SCK • CEN

Annex 5
Determination of $J_{0.2Bd}$ from *J*-*R* curves

- Dynamic blunting line

$$J = 3.75 R_{md} \Delta a$$

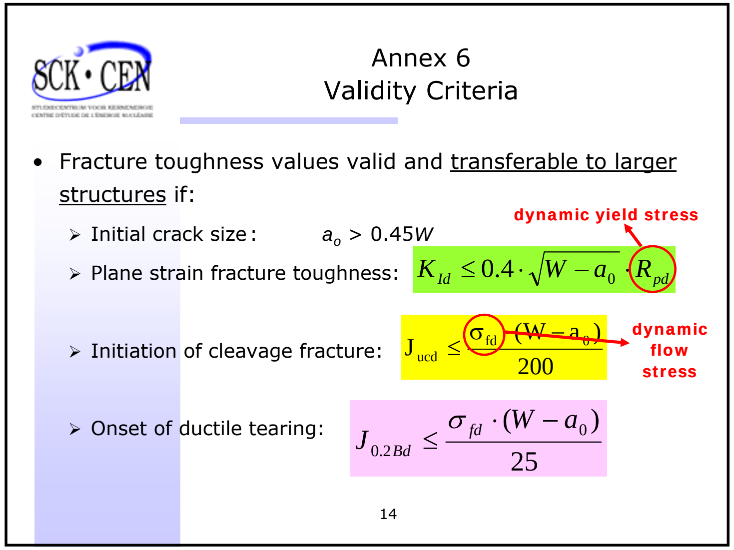
Dynamic tensile strength

or (if R_{md} not available): $$J(\Delta a) = \frac{3 \cdot F_u \cdot S}{(W - a_0)^2 B_N} \cdot \Delta a$$ **(REFERENCE??)**

- Lower bound approximation of $J_{0.2Bd}$

$$J = C \cdot \Delta a^p \quad \Rightarrow \quad J_{0.2td} = C \cdot \left[\left(\frac{C}{s_1} \right)^{1/1-p} + 0.2 \cdot 10^{-3} m \right]^p$$

(REFERENCE??)



SCK • CEN

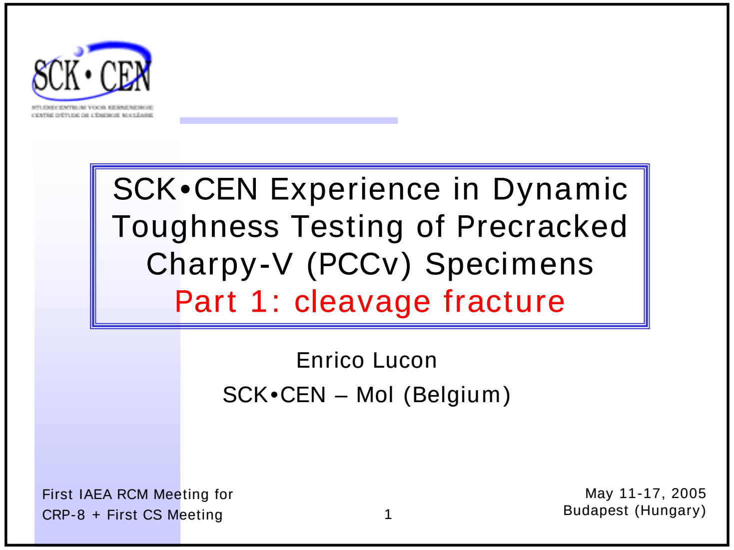
Annex 6
Validity Criteria

- Fracture toughness values valid and transferable to larger structures if:
  - Initial crack size: $a_o > 0.45W$
  - Plane strain fracture toughness: $K_{Id} \leq 0.4 \cdot \sqrt{W - a_0} \cdot R_{pd}$ **dynamic yield stress**
  - Initiation of cleavage fracture: $J_{ucd} \leq \frac{\sigma_{fd} \cdot (W - a_0)}{200}$ **dynamic flow stress**
  - Onset of ductile tearing: $J_{0.2Bd} \leq \frac{\sigma_{fd} \cdot (W - a_0)}{25}$

ANNEX 3

Presentation by E. Lucon (Budapest, 11 May 2005)

"SCK•CEN Experience in Dynamic Toughness Testing of Precracked Charpy-V (PCCv) Specimens"

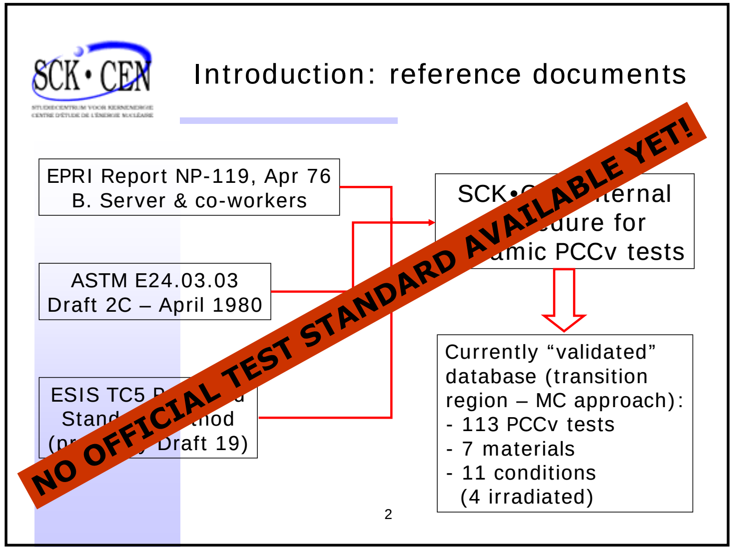


SCK•CEN Experience in Dynamic Toughness Testing of Precracked Charpy-V (PCCv) Specimens
Part 1: cleavage fracture

Enrico Lucon
SCK•CEN – Mol (Belgium)

First IAEA RCM Meeting for
CRP-8 + First CS Meeting

May 11-17, 2005
Budapest (Hungary)



Introduction: reference documents

EPRI Report NP-119, Apr 76
B. Server & co-workers

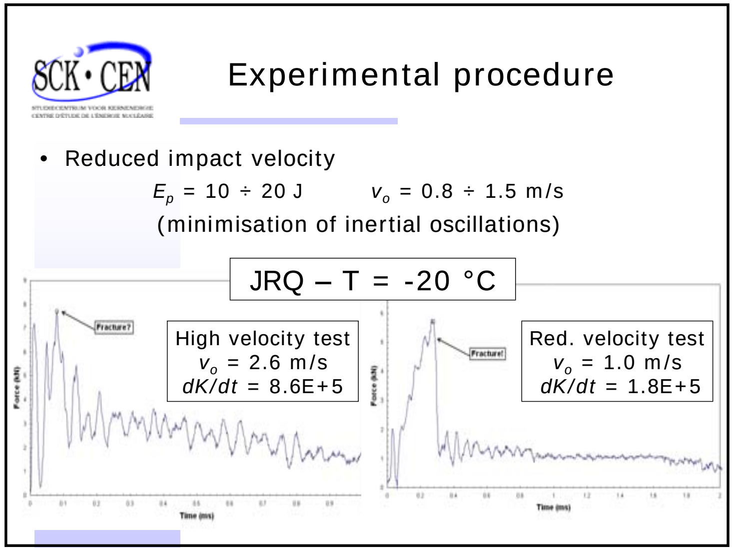
ASTM E24.03.03
Draft 2C – April 1980

ESIS TC5 P d
Stand thod
(pr Draft 19)

SCK• ternal
dure for
amic PCCv tests

Currently "validated" database (transition region – MC approach):
- 113 PCCv tests
- 7 materials
- 11 conditions
  (4 irradiated)

NO OFFICIAL TEST STANDARD AVAILABLE YET!



Experimental procedure

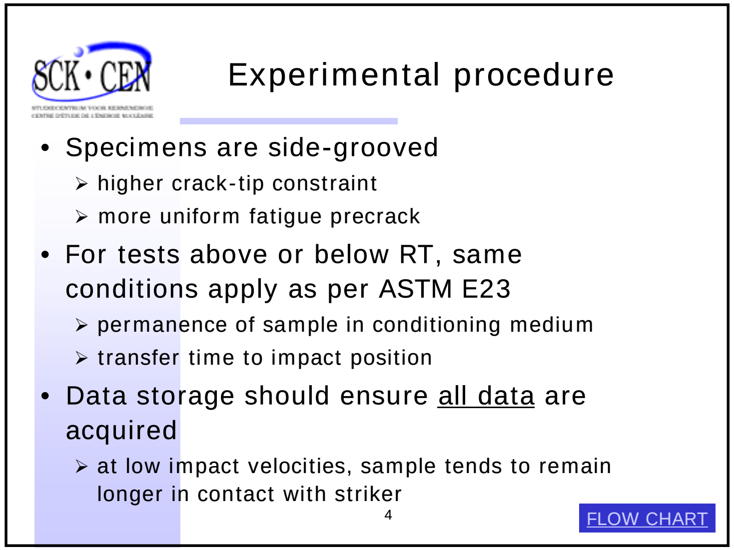
- Reduced impact velocity

E_p = 10 ÷ 20 J v_o = 0.8 ÷ 1.5 m/s
(minimisation of inertial oscillations)

JRQ – T = -20 °C

High velocity test
v_o = 2.6 m/s
dK/dt = 8.6E+5

Red. velocity test
v_o = 1.0 m/s
dK/dt = 1.8E+5



Experimental procedure

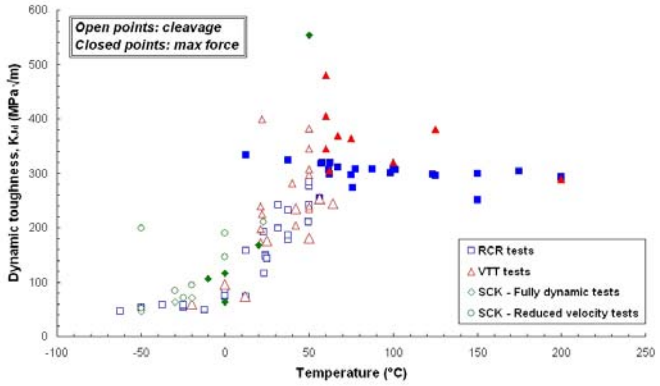
- Specimens are side-grooved
  - higher crack-tip constraint
  - more uniform fatigue precrack
- For tests above or below RT, same conditions apply as per ASTM E23
  - permanence of sample in conditioning medium
  - transfer time to impact position
- Data storage should ensure all data are acquired
  - at low impact velocities, sample tends to remain longer in contact with striker

FLOW CHART

Qualification tests on JRQ material

- First series: fully dynamic tests
  - Block ESIS
  - 8 tests, E_p = 65 J, v_o = 2.6 m/s, plain-sided specimens
- Second series: reduced velocity tests
  - Block ESIS
  - 10 tests, E_p = 6.7-17.4 J, v_o = 0.8-1.3 m/s, side-grooved specimens
- Third series: reduced velocity tests
  - Block 5Q12 (IAEA reference material – 1/4T layer)
  - 12 tests, E_p = 10-25 J, v_o = 1-1.6 m/s, side-grooved specimens
  - two different impact machines used

Comparison with IAEA CRP-IV database (Rossendorf & VTT, 1994)



Application of the Master Curve procedure

- The procedure as outlined in ASTM E1921-03 can be applied
- The only "delicate" point is the evaluation of the maximum K_{Jd} capacity of the specimen:

$$K_{Jd,\mathrm{limit}} = \sqrt{\frac{E(W-a_o)\sigma_{yd}}{30(1-\nu^2)}}$$

which yield strength value?

- **4 options are available** (presented here in order of increasing accuracy)

Assessment of dynamic yield properties

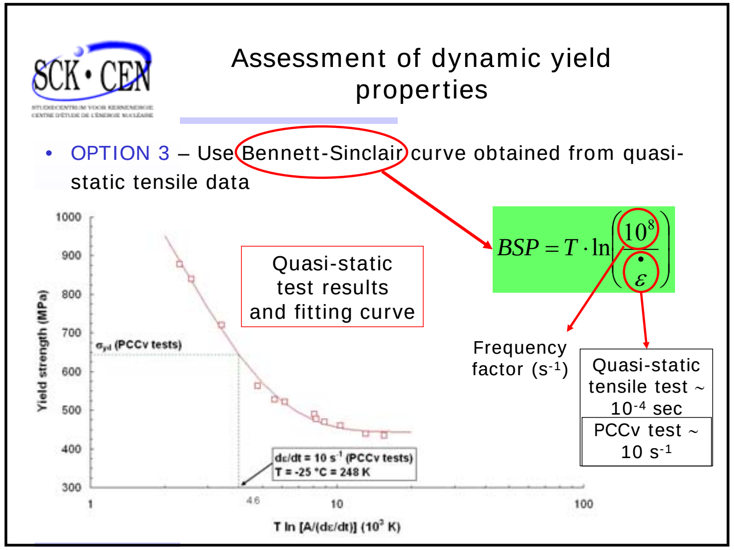
- OPTION 1 – Use quasi-static yield properties
  - $\sigma_{y,qs} < \sigma_{y,d} \rightarrow$ lower K_{Jd} limit ➨ **ANALYSIS CONSERVATIVE**
- OPTION 2 – Estimate $\sigma_{y,d}$ using F_{gy} from instrumented (precracked) Charpy tests:

1.866

$$\sigma_{y,d} = \frac{\beta \cdot S \cdot F_{gy}}{2C_F(W-a)^2 B}$$

constraint factor (different for ISO/ASTM, Cv/PCCv

(Server, 1978)



Assessment of dynamic yield properties

- OPTION 3 – Use Bennett-Sinclair curve obtained from quasi-static tensile data

$$BSP = T \cdot \ln\left(\frac{10^8}{\dot{\varepsilon}}\right)$$

Quasi-static test results and fitting curve

Frequency factor (s^{-1})

Quasi-static tensile test ~ 10^{-4} sec

PCCv test ~ 10 s^{-1}

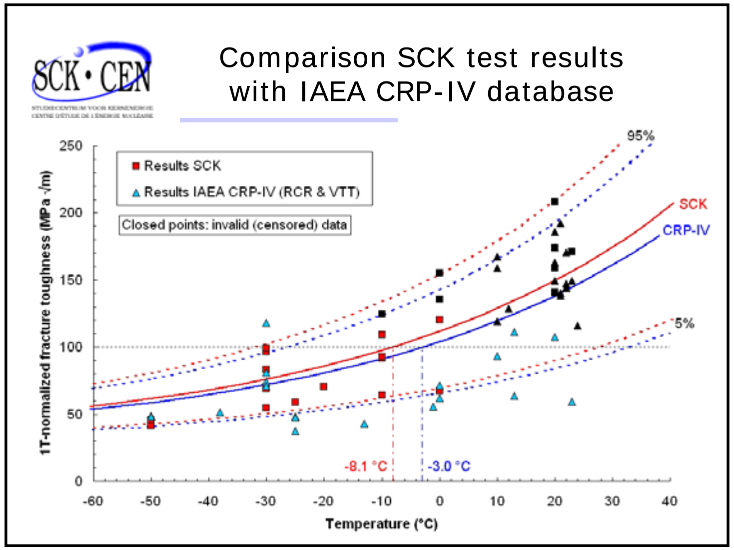
Assessment of dynamic yield properties

- OPTION 4 – Use dynamic tensile test results (approximate strain rate: 10 s^{-1})

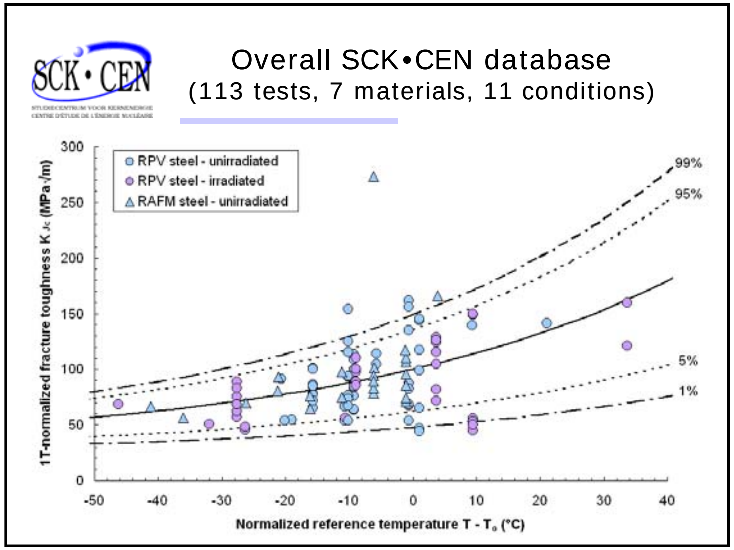
Influence of the option chosen

(IAEA CRP-IV database, JRQ, N = 36)

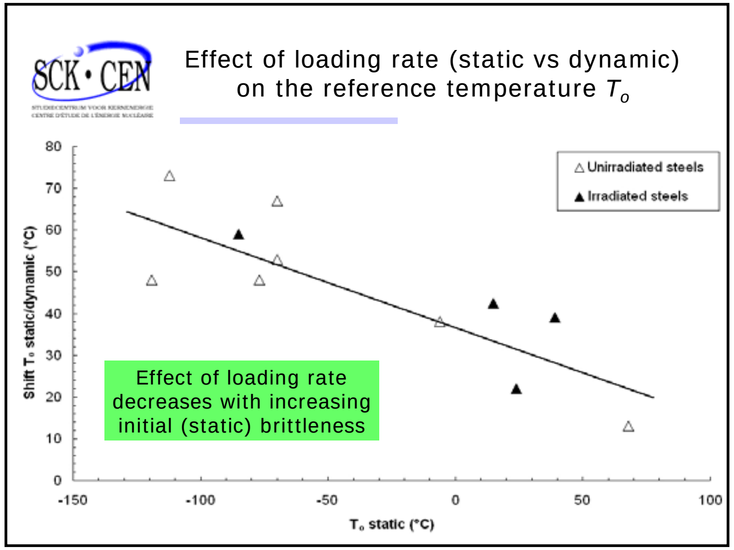
	T_o (°C)	r (#valid data)
Option 1	-0.8	16
Option 2	-2.8	17
Option 3	-3.0	21
Option 4	-2.9	19



Comparison SCK test results with IAEA CRP-IV database



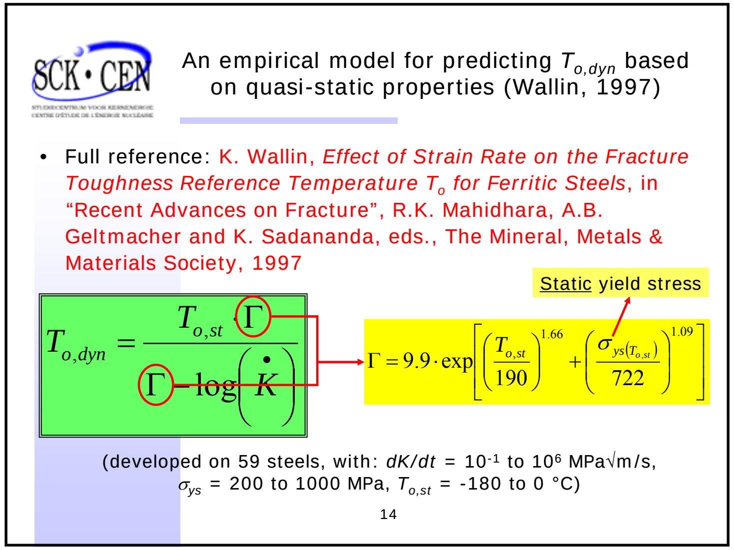
Overall SCK•CEN database
(113 tests, 7 materials, 11 conditions)



Effect of loading rate (static vs dynamic) on the reference temperature T_o

Effect of loading rate decreases with increasing initial (static) brittleness

---



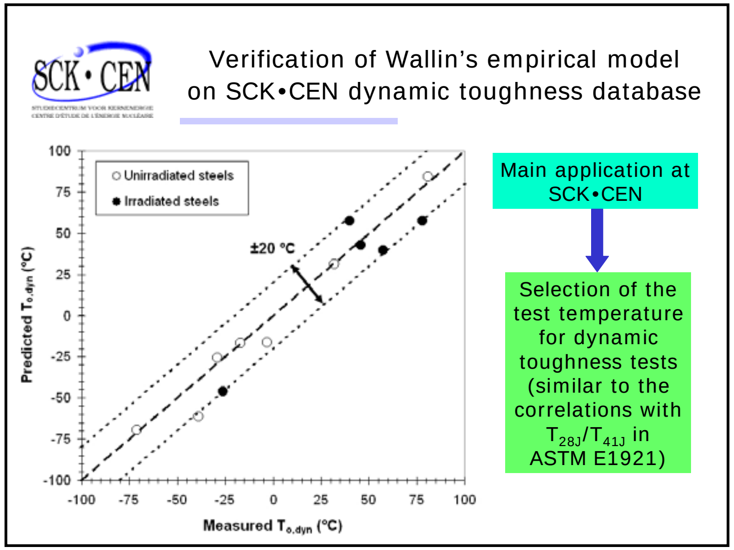
An empirical model for predicting $T_{o,dyn}$ based on quasi-static properties (Wallin, 1997)

- Full reference: K. Wallin, *Effect of Strain Rate on the Fracture Toughness Reference Temperature T_o for Ferritic Steels*, in “Recent Advances on Fracture”, R.K. Mahidhara, A.B. Geltmacher and K. Sadananda, eds., The Mineral, Metals & Materials Society, 1997

Static yield stress

$$T_{o,dyn} = \frac{T_{o,st} \cdot \Gamma}{\Gamma - \log\left(\dot{K}\right)} \rightarrow \Gamma = 9.9 \cdot \exp\left[\left(\frac{T_{o,st}}{190}\right)^{1.66} + \left(\frac{\sigma_{ys(T_{o,st})}}{722}\right)^{1.09}\right]$$

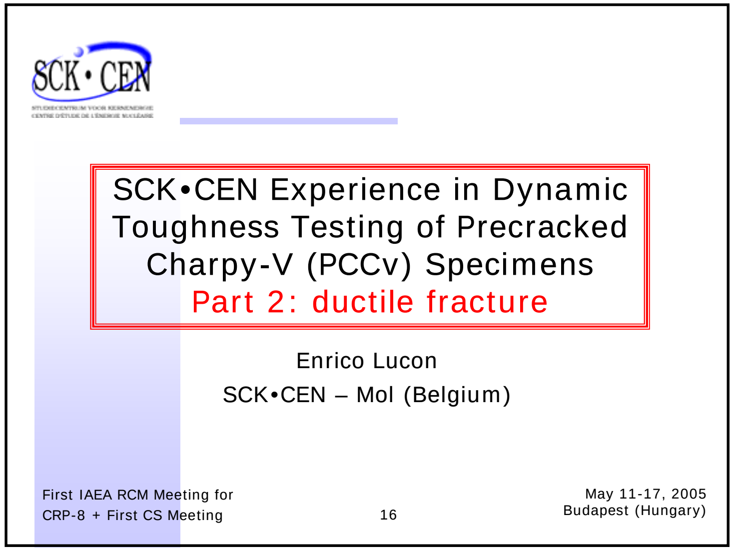
(developed on 59 steels, with: dK/dt = 10^{-1} to 10^{6} MPa√m/s, σ_{ys} = 200 to 1000 MPa, $T_{o,st}$ = -180 to 0 °C)



Verification of Wallin’s empirical model on SCK•CEN dynamic toughness database

Main application at SCK•CEN

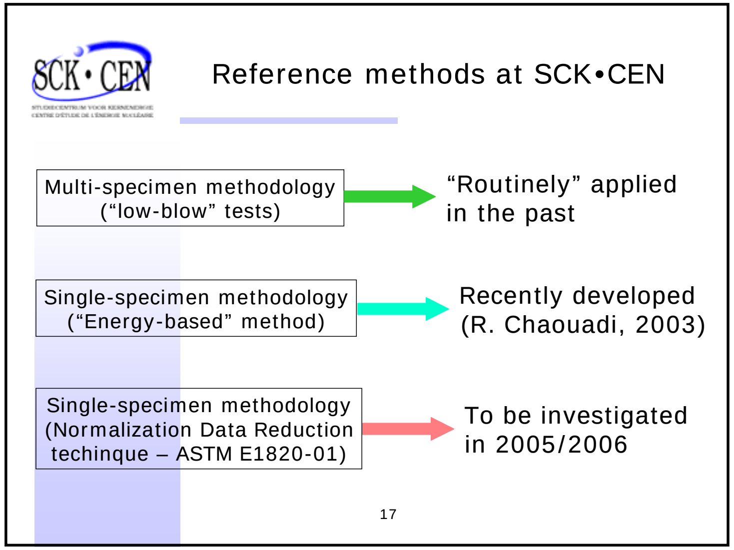
Selection of the test temperature for dynamic toughness tests (similar to the correlations with T_{28J}/T_{41J} in ASTM E1921)



SCK•CEN Experience in Dynamic Toughness Testing of Precracked Charpy-V (PCCv) Specimens
Part 2: ductile fracture

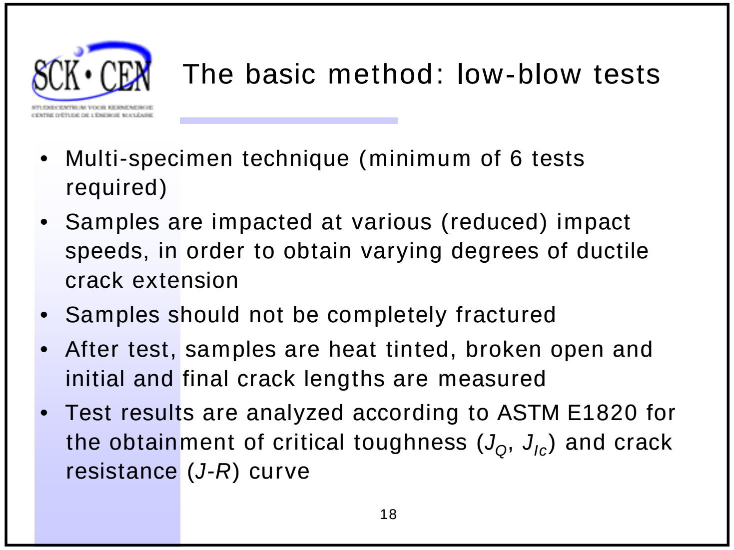
Enrico Lucon

SCK•CEN – Mol (Belgium)



Reference methods at SCK•CEN

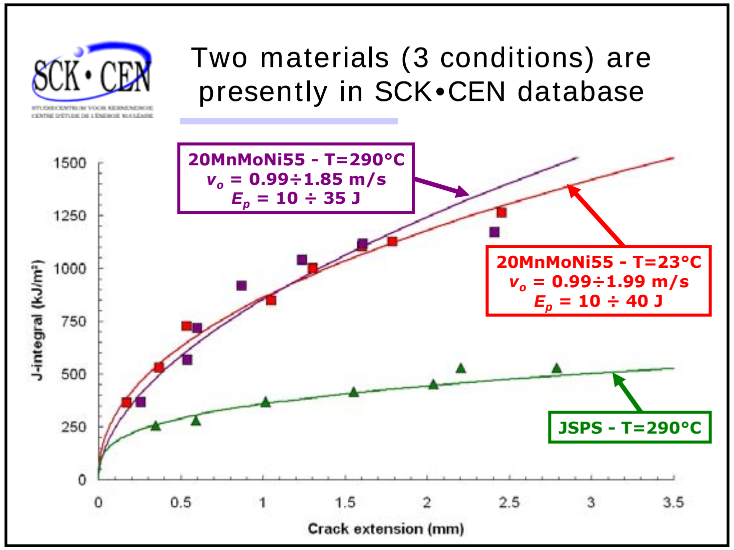
Multi-specimen methodology ("low-blow" tests)	"Routinely" applied in the past
Single-specimen methodology ("Energy-based" method)	Recently developed (R. Chaouadi, 2003)
Single-specimen methodology (Normalization Data Reduction techinque – ASTM E1820-01)	To be investigated in 2005/2006



The basic method: low-blow tests

- Multi-specimen technique (minimum of 6 tests required)
- Samples are impacted at various (reduced) impact speeds, in order to obtain varying degrees of ductile crack extension
- Samples should not be completely fractured
- After test, samples are heat tinted, broken open and initial and final crack lengths are measured
- Test results are analyzed according to ASTM E1820 for the obtainment of critical toughness (J_Q, J_{Ic}) and crack resistance (J-R) curve

---

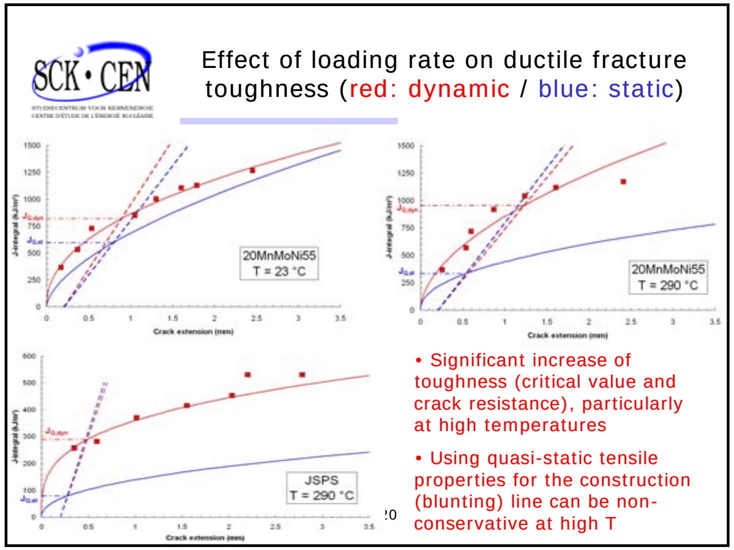


Two materials (3 conditions) are presently in SCK•CEN database

20MnMoNi55 - T=290°C
v_o = 0.99÷1.85 m/s
E_p = 10 ÷ 35 J

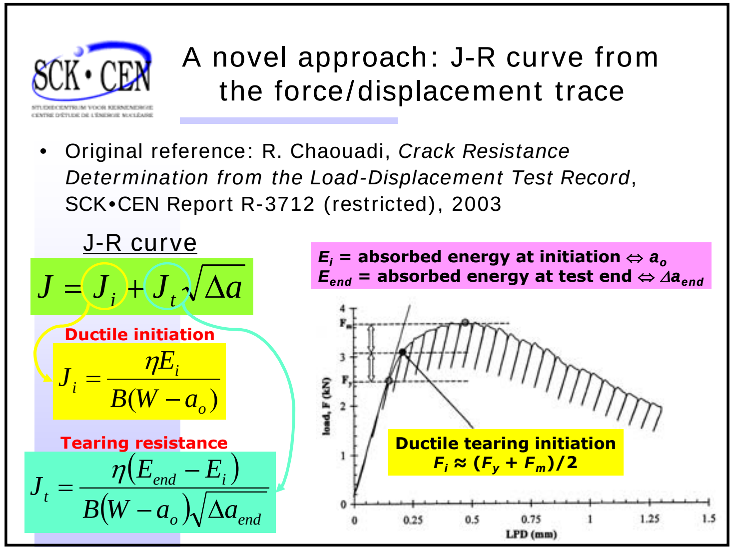
20MnMoNi55 - T=23°C
v_o = 0.99÷1.99 m/s
E_p = 10 ÷ 40 J

JSPS - T=290°C



Effect of loading rate on ductile fracture toughness (red: dynamic / blue: static)

- Significant increase of toughness (critical value and crack resistance), particularly at high temperatures
- Using quasi-static tensile properties for the construction (blunting) line can be non-conservative at high T



A novel approach: J-R curve from the force/displacement trace

- Original reference: R. Chaouadi, *Crack Resistance Determination from the Load-Displacement Test Record*, SCK•CEN Report R-3712 (restricted), 2003

J-R curve

$$J = J_i + J_t\sqrt{\Delta a}$$

Ductile initiation

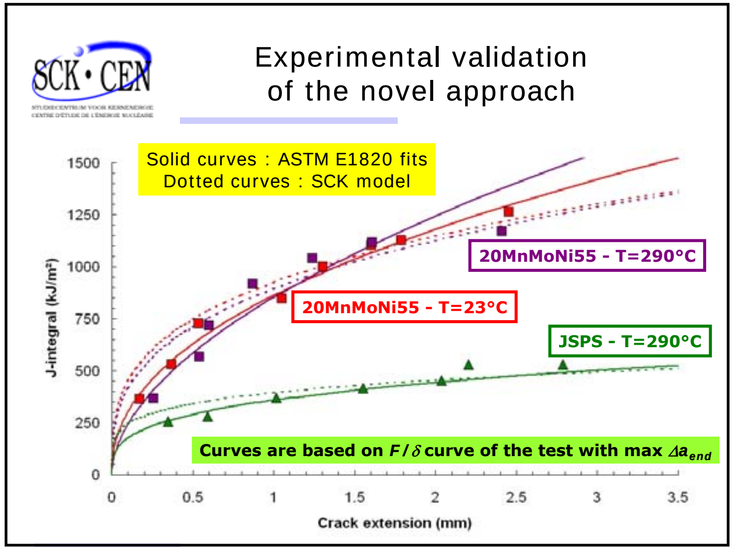
$$J_i = \frac{\eta E_i}{B(W - a_o)}$$

Tearing resistance

$$J_t = \frac{\eta\left(E_{end} - E_i\right)}{B\left(W - a_o\right)\sqrt{\Delta a_{end}}}$$

E_i = absorbed energy at initiation ⇔ a_o
E_{end} = absorbed energy at test end ⇔ Δa_{end}

Ductile tearing initiation
$F_i \approx (F_y + F_m)/2$



Experimental validation of the novel approach

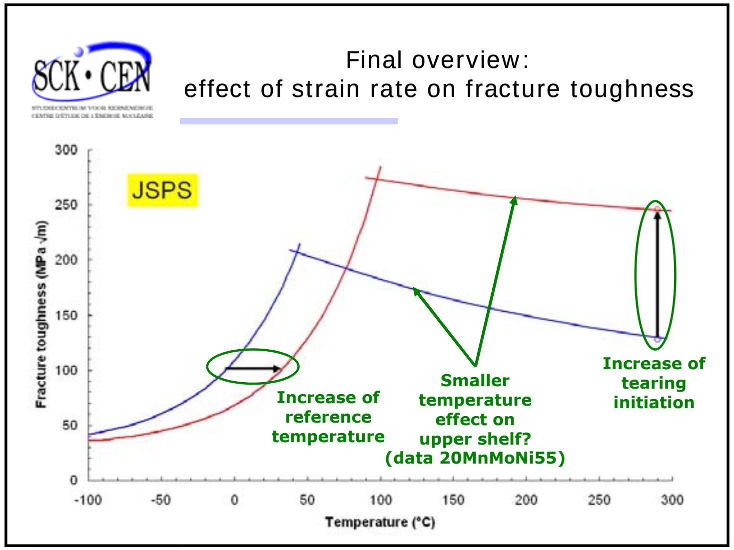
Solid curves : ASTM E1820 fits
Dotted curves : SCK model

20MnMoNi55 - T=290°C

20MnMoNi55 - T=23°C

JSPS - T=290°C

Curves are based on F/δ curve of the test with max Δa_{end}



Final overview: effect of strain rate on fracture toughness

JSPS

Increase of reference temperature

Smaller temperature effect on upper shelf? (data 20MnMoNi55)

Increase of tearing initiation

ANNEX 4

Paper by H.-W. Viehrig and E. Lucon

"USE OF INSTRUMENTED PRECRACKED CHARPY IMPACT TESTS FOR THE DETERMINATION OF FRACTURE TOUGHNESS VALUES"

USE OF INSTRUMENTED PRECRACKED CHARPY IMPACT TESTS FOR THE DETERMINATION OF FRACTURE TOUGHNESS VALUES

H.-W. Viehrig*, E. Lucon**

*Forschungszentrum Rossendorf e.V., Institute for Safety Research, P.O. Box 51019,
01314 Dresden, Germany
**SCK•CEN Mol, Reactor Materials Research Unit, Boeretang 200
2400 Mol, Belgium

INTRODUCTION

The most essential progress in the Charpy-V impact test methodology was the pendulum instrumentation by force and displacement gauges. This allows more information to be obtained from the simple, quick and very efficient test. Above all, the instrumentation made it possible to use the impact pendulum for dynamic fracture mechanics testing and, thus to apply it for structural integrity assessment. In the range of lower shelf and lower ductile-to-brittle transition (DBT) region, J-integral-based fracture toughness values, K_{Jc}, can be determined at the onset of cleavage crack initiation. The onset of cleavage fracture appears on the measured force versus time trace as a force drop. The execution of the tests and the calculation of dynamic fracture toughness data of pre-cracked Charpy specimens have not yet been defined by any official standard of international recognition. However, there are procedures and draft standards published by the Electric Power Research Institute (EPRI) in the report EPRI NP-119 (McCornell and Server, 1980; Ireland, 1980) and the Draft International Standard: ESIS TC5, European Structure Integrity Society: “Proposed Standard Methods for Instrumented Pre-cracked Charpy Impact Testing of Steels – Combined K_{Id}, J_{Id} and CTOD Tests Methods”, respectively. The state-of-the-art in the dynamic fracture toughness measurement using pre-cracked Charpy size specimens was summarised by Lucon (1999).
The Master Curve (MC) procedure is standardised in ASTM E 1921-03 “Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic steels in the Transition Range”. The standard is defined for quasi-static loading conditions. However, the extension of the MC method to dynamic tests is straightforward. This paper gives an overview about using the instrumented impact test to determine K_{Jc} values for the MC evaluation.

FRACTURE TOUGHNESS AND MASTER CURVE CONCEPT

From the dynamic test record the absorbed impact energy is calculated from the area under the force-displacement curve up to the onset of cleavage fracture. The force is directly measured and the displacement is calculated, by double numerical integration of force/time data according to Eqs. (1) and (2).

$$V(t) = V_0 - \frac{1}{m}\int_{t_0}^{t} F(t)dt \qquad (1)$$

$$s(t) = \int_{t_0}^{t} V(t)dt \qquad (2)$$

m mass of the pendulum hammer

F	impact force measured at the striker of the pendulum hammer
V	actual velocity of the pendulum hammer
V_0	initial impact velocity of the pendulum hammer
s	displacement of the pendulum hammer and thus, the deflection of the specimen

The J integral at the onset of cleavage fracture, Eq. (3) is determined in ASTM E 1921-03 in analogy to the standards ISO/DIS 12135 “Metallic Materials – Unified Method of Test for the Determination of Quasistatic Fracture Toughness” and ASTM E1820 “Standard Test Method for Measurement of Fracture Toughness”.

$$J_c = J_{el} + J_{pl} = \frac{K_c^{\,2}(1-\nu^2)}{E} + \frac{2W_{c(pl)}}{B_N b_0} \qquad 3)$$

B_N	specimen net thickness between side grooves
b_0	specimen ligament
E	Young’s modulus
J_{el}	elastic part of the J-Integral
J_p	plastic part of the J-Integral
K_c	stress intensity at the onset of cleavage fracture
$W_{c(pl)}$	plastic part of the area under the force-deflection curve up to the onset of cleavage fracture
<	Poisson’s ratio

$$K_c = \left[\frac{F_c \cdot S}{\sqrt{B \cdot B_N} \cdot \sqrt[3]{W^2}}\right] \cdot f\left(a/W\right) \qquad (4)$$

where

F_c	force at the onset of cleavage failure
S	span value of the anvil (40 mm)
B	specimen thickness
W	specimen width
f(a/W)	specimen stress intensity function for SE(B) specimens
a_0	initial crack length

$$f(a_0/W) = \frac{3 \cdot \sqrt{\frac{a_0}{W}} \cdot \left[1.99 - \left(\frac{a_0}{W}\right) \cdot \left(1 - \frac{a_0}{W}\right) \cdot \left(2.15 - 3.93 \cdot \left(\frac{a_0}{W}\right) + 2.7 \cdot \left(\frac{a_0}{W}\right)^2\right)\right]}{2 \cdot \left(1 + \frac{2a_0}{W}\right) \cdot \sqrt{\left(1 - \frac{2a_0}{W}\right)^3}} \qquad (5)$$

The total absorbed impact energy W_{tot} is calculated from the area under the force-displacement curve up to the onset of cleavage fracture. This energy value contains some contributions not related to fracturing the specimen. The true specimen initiation energy, $W_{c(pl)}$, is determined according to Eq. (6).

$$\mathrm{W}_{c(pl)} = W_{tot} - \frac{\mathrm{C_M} \cdot \mathrm{F_c}^2}{2} \qquad (6)$$

C_M	machine compliance can be determined using different techniques (Ireland, 1974)

$$C_M = C - C_s \qquad (7)$$

C_S specimen compliance (FZR calculation by FEM for a Charpy size SE(B) specimen 20% side-grooved and a/W=0.5: 3.79 10^{-5} mm/N)

Acceptable force values F_c are obtained when the inertial oscillations have been sufficiently dampened after 3-times of the free oscillation (3 τ) (McCornell and Server, 1980; Ireland, 1980, Lucon, 1999) or 5-times of the free oscillation (5 τ) (ESIS TC5 draft).

J_c values are transformed into plan strain stress intensity factors K_{Jc} according to ASTM E 1921-03 using Eq. (8).

$$K_{Jc} = \sqrt{\frac{E \cdot J_c}{1-\nu^2}} \tag{8}$$

EXAMPLE OF DYNAMIC FRACTURE TOUGHNESS TESTING AND MASTER CURVE EVALUATION

Material and Specimens

The investigated material is the IAEA reference material JRQ (ASTM A533B Class 1 steel). Table 1 contains the chemical composition and the strength parameters. The 5JRQ22 block with a thickness of 225 mm was cut into 20 layers over the thickness using an electroerosive cutting machine. A specimen set consisted of up to 15 Charpy-V and pre-cracked and side grooved (20%) Charpy size single edge bend (SE(B)) specimens in TL orientation, respectively.

Table 1: Chemical composition (wt.%) and strength parameters of IAEA JRQ RPV steel

C	Si	Mn	Cr	Mo	Ni	P	Cu	S	Al
0.18	0.24	1.42	0.12	0.51	0.84	0.02	0.14	0.007	0.02

tensile yield strength:	477 ± 10 MPa
ultimate tensile strength:	630 ± 3 MPa

The microstructure of the plate varies through the thickness. At the surface there are both lower bainite and martensite. In the middle region heterogeneously composed upper bainite together with reticularly arranged martensite are visible. The reticularly arranged martensitic structure becomes more pronounced with the distance from the surface and could be explained by segregation.

Test Methods

The quasi-static fracture mechanical tests were performed according to the recommendations in the standard ASTM E 1921-97. The specimens were tested in a servohydraulic testing system MTS 810 - Test Star using the unloading compliance technique (Viehrig et al., 2002). Impact and dynamic toughness tests were carried out on an instrumented 300 J impact-pendulum. The test conditions are presented in Tab. 2.

Table 2: Test conditions

	Initial impact velocity V_0	Initial impact energy E_0
Charpy-V test	5,5 m/s	300 J
Dyn. fracture toughness test	2,8 m/s	78 J

Results and Discussion

The specimens were tested in the range from lower shelf cleavage fracture (Fig. 1 a), up to ductile crack initiation followed by cleavage rupture (Fig. 1 b) with an initial impact velocity of 2.8 m/s. Fig. 1a shows the time up to cleavage failure is lower than 3-times of the free specimen oscillation 3 τ (about 150 µs) and thus, the impact force and therefore the absorbed energy might be influenced by inertial oscillations.. In these cases the maximum force for true impact energy calculation according to Eqs. (4) and (6) was corrected to half the value of the oscillation before failure. Beyond about 300 µs the measured impact energy lead to K_{Jc} values above the validity criteria in ASTM E 1921. The temperature range to obtain valid K_{Jc} values was narrow at the applied impact velocity of 2.8 m/s.

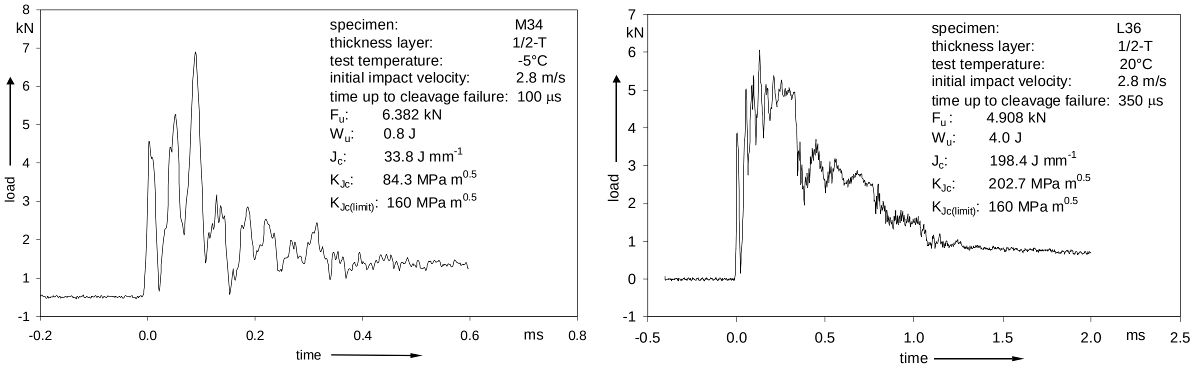


Figure 1 Impact test records of specimens tested in the linear elastic (a) and elastic plastic range (b)

Fig. 2 shows the dependence of Charpy-V TT (transition temperature) and reference temperatures for quasi-static, T_0^{st}, and dynamic, T_0^{dy}, loading from the sampling position along the thickness of the plate. Obviously, the trend curves have the same shape. The Charpy-V

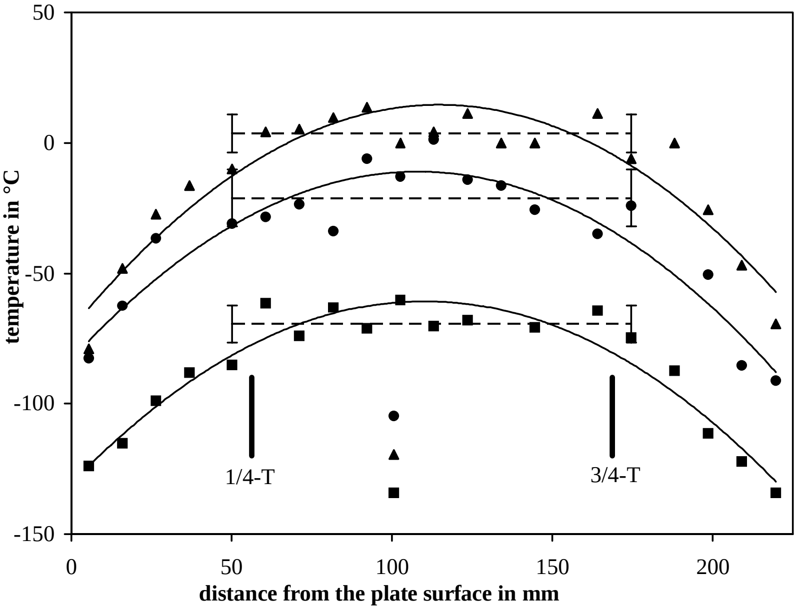


Figure 2 Charpy-V TT_{41J}, T_0^{dy} and T_0^{st} versus distance from the surface of the 5JRQ22 steel plate

transition and reference temperatures increase between surface and ¼, or respectively ¾, of the plate thickness and are almost constant in the middle section. The T_0^{dy} values are higher compared with the T_0^{st} values. For the middle section mean values of –70 °C for T_0^{st}, of –21°C for TT_{41J} and of +3°C for T_0^{dy} were determined. There is a difference between quasi-static and dynamic reference temperature of 73 °C. Dynamic tests conducted by Wallin (1995), Joyce (1998) and Tregoning and Joyce (2002) suggest that dynamic fracture toughness values confirm the MC course. When published results are compared with the results presented here the differences between T_0^{dy} and T_0^{st} are substantially smaller ranging from 30 K to 40 K. The reasons are possibly the lower loading rate applied in these papers and differences in the strain rate sensitivity of the investigated material.

All K_{Jc} values from ¼ to ¾ of the thickness were used together for the T_0 evaluation. Figs. 3 and 4 show the K_{Jc} values obtained by impact and quasi-static loading, respectively. The limits of validity according to ASTM E1921-03 for J-integral based toughness values, $K_{Jc(limit)}$, are marked for both loading conditions. Small differences in the evaluated T_0 presented in Figs. 2 to 4 are a result of the different evaluation procedures. It is obvious that the K_{Jc} values measured by impact and quasi-static loading follow the course of the MC. Some specimens were quasi-statically tested in the ductile region and so the R-Curves could be determined using the partial unloading technique. The physical crack initiation toughness K_i^{SZW} of these specimens was determined by measuring the stretch zone width (SZW). The mean value of the

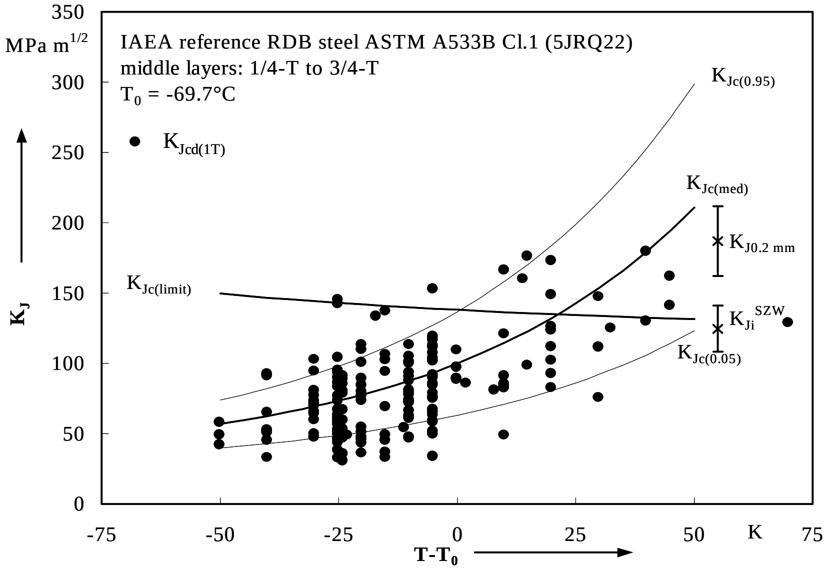


Figure 3 Quasi-static fracture toughness and MC

K_{Ji}^{SZW} values is depicted in Fig. 3. As shown the mean K_{Ji}^{SZW} is about 125 MPa√m and so within the range of the validity criteria of ASTM E1921-03. A number of impact loaded specimens in the DBTT region failed after an amount of ductile crack growth. The amount of ductile crack extension was measured on the fracture surface of these specimens. Using these values and the J-Integral at cleavage failure the “Cleavage R-Curve”, J-Δa, (Boehme et al., 2000) shown in Fig. 5 was determined. Physical crack initiation toughness J_{id}^{SZW} of these specimens was also determined by measuring the SZW and is marked in Fig. 5. The mean K_{Jid}^{SZW} is about 189 MPa√m. In Fig. 4 is also marked the dynamic crack initiation toughness, K_{Jid}^{AE}, determined by an analysis of emitted acoustic waves (Viehrig et al., 2000). The mean K_{Jid}^{AE} is 204 MPa√m and thus, 15 MPa $m^{0.5}$ higher than the SZW based initiation value. Both physical based initiation toughness values are higher than the $K_{Jc(limit)}$ values for the applied impact loading condition. Beyond the physical initiation toughness the K_{Jcd} values obtained from Charpy size specimens are influenced by the loss of the constraint (Joyce, 1998). The increase of the yield strength due to dynamic loading causes an about 30% higher K_J measuring capacity of the Charpy size specimen in comparison with the quasi-static loading. The dynamic yield strength was calculated with Eq. (9) adopted by Server (1978).

$$\sigma_{y(d)} = \frac{4 \cdot F_{GY} \cdot W}{C \cdot B_n \cdot (W - a_0)^2} \cdot \frac{S}{4} \tag{9}$$

a_0 initial crack length
C constraint factor depends on the specimen geometry and tup radius
F_{GY} force at General Yield
S span of the anvil (DIN Charpy-V pendulum S = 22 mm)

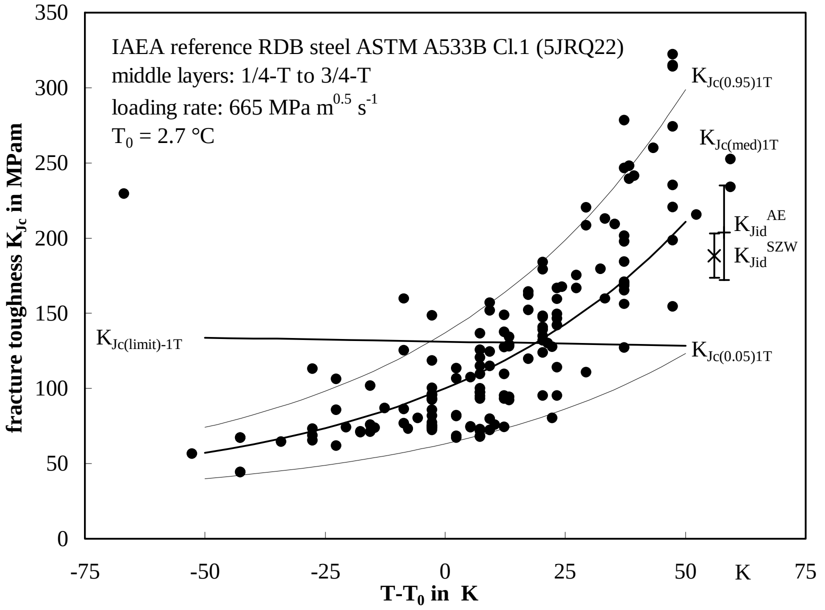


Figure 4 Dynamic fracture toughness and MC

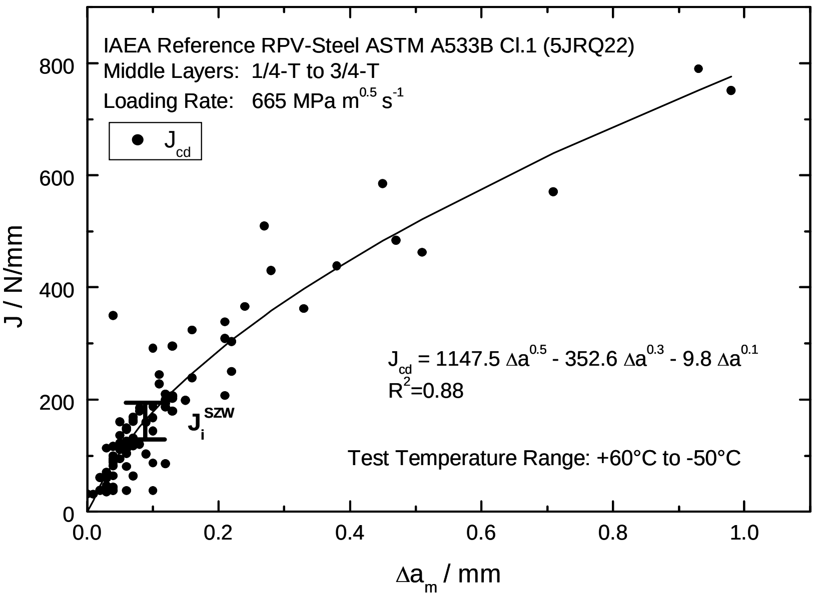


Figure 5 Dynamic Cleavage R-Curve

DRAFT TEST CONDITIONS FOR THE ROUND ROBIN EXERCISE

Figure 6 shows the force deflection trace of a Charpy size SE(B) specimen tested with an initial impact velocity of 1 m/s at -40°C. This test gave a force signal which can be assessed without uncertainties. The measured fracture toughness is about 53 MPa√m and lies in the range of the lower limit for the MC evaluation. An increase of the impact velocity up to 1.5 m/s is acceptable. The force deflection trace of a specimen tested at -20°C shown in Figure 7 can be assessed. The measured fracture toughness of 76 MPa√m is in the lower range of the target measuring range. A higher impact velocity results in a very small range for the measuring of valid fracture toughness values (Fig. 1).

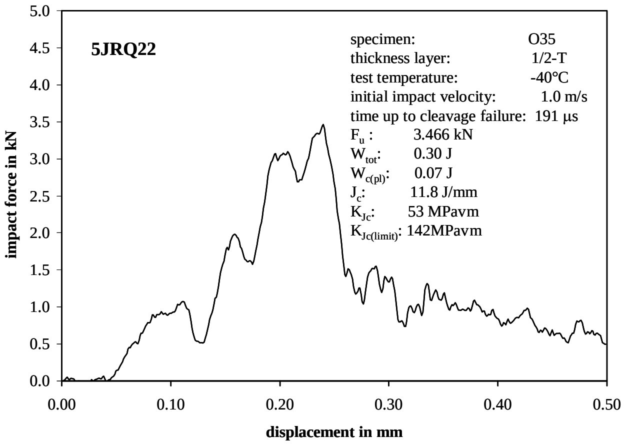


Figure 6 Impact test records of specimens tested at -40°C with an impact velocity of 1.0 m/s

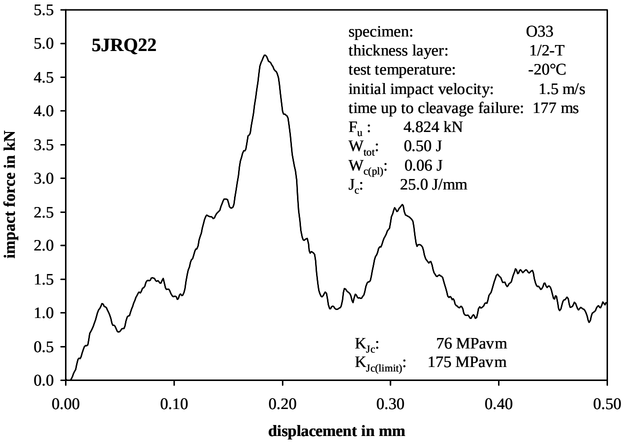


Figure 7 Impact test records of specimens tested at -20°C with an impact velocity of 1.5 m/s

The following test conditions are suggested for the dynamic fracture toughness round robin exercise:

specimens: Charpy size single edge notch bend (SE(B)) specimens, 20% side-grooved, a/W = 0.5
impact velocity: 1.5 m/s
temperature range: -40°C to 0°C
number of specimens: 10

SUMMARY AND CONCLUSION

Dynamic testing of specimens from various layers over the plate thickness of the 5JRQ22 block provides information about the applicability of the Master Curve (MC) method. The suitability of the MC to describe the material behaviour in the ductile-to-brittle transition region under dynamic loading conditions was proved. The K_{Jc} values determined under quasi-static and dynamic loading follow the course of the MC. The test temperature range assuring valid dynamic fracture toughness values, K_{Jcd}, is small at the applied test velocity of 2.8 m/s. The lower limit is determined by the 3 τ time and the upper limit is determined by the validity criteria of ASTM E 1921.An impact velocity of 1.5 m/s is suggested for the dynamic fracture toughness round robin exercise

REFERENCES

Boehme, W; Schindler, H.-J. (2000). Application of Single-Specimen Methods on Instrumented Charpy Tests: Results of DVM Round-Robin Exercises Pendulum Impact Testing: ACentury of Progress; STP 1380, T.A. Siewert and M. P. Manahan, Sr., Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 327-336.

Ireland, D. R. (1974). Procedures and Problems Associated with Reliable Control of the instrumented Impact Test Instrumented Impact Testing, ASTM STP 563, ASTM, West Conshohocken, 1974, pp. 3-29

Ireland, D. R. (1980). A Review of the Proposed Standard Method of Test for Impact Testing Precracked Charpy Specimen of Metallic Materials. In Proceedings C.S.N.I. Specialists Meeting on Instrumented Precracked Charpy Testing. EPRI NP-2102-LD, Prepared by Electric Power Research Institute, Ed. by R. A. Wullaert, Palo Alto, USA, pp. 1-23 to 1-63.

Joyce, J. A. (1998). On the Untilization of High Rate Pre-Cracked Charpy Test Results and the Master Curve to Obtain Accurate Lower Bound Toughness Predictions in the Ductile-To-Brittle Transition. Small Specimen Test Techniques, ASTM STP 1329, W.R. Corwin, S.T. Rosinski and E. van Walle, Eds. American Society for Testing Materials, 1998, pp. 253-273.

Lucon, E. (1999). Dynamic Toughness Testing of Pre-Cracked Charpy V-Notch Specimens. Report BLG-808, SCK-CEN, April 1999, Mol, Belgium

McCornell, P., Server, W. L. (1980). EPRI Instrumented Impact Test Procedures. In Proceedings C.S.N.I. Specialists Meeting on Instrumented Precracked Charpy Testing. EPRI NP-2102-LD, Prepared by Electric Power Research Institute, Ed. by R. A. Wullaert, Palo Alto, USA, pp. 1-1 to 1-22.

Server, W. L. (1978). General Yielding of Charpy V-Notch and Precracked Charpy Specimens Journal of Engineering Materials and Technology, April 1978, Vol. 100, pp. 183- 188

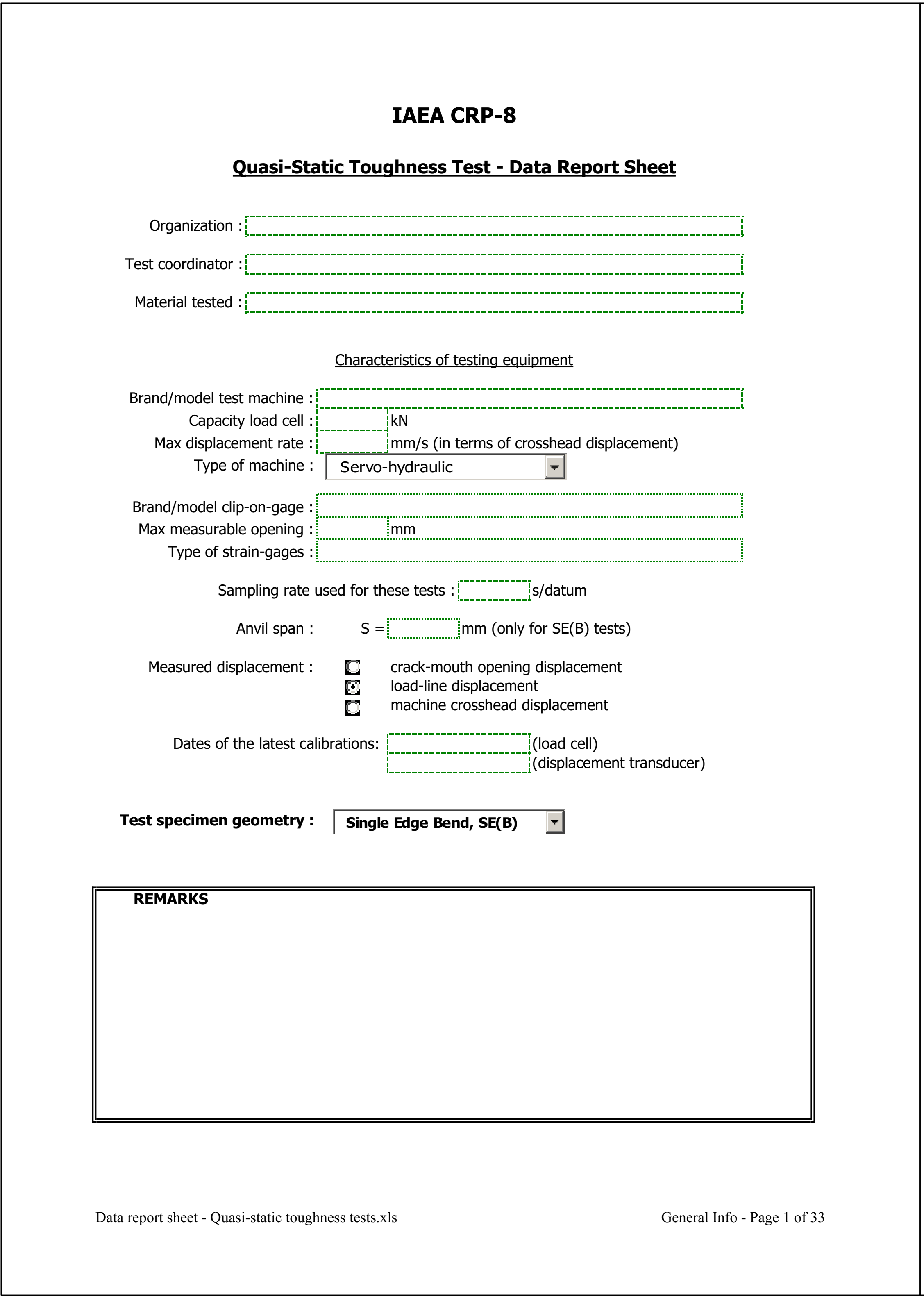
Tregoning, R. L., Joyce, J. A. (2002). Investigation of Censoring Limits for Cleavage Fracture Determination. Fourth Symposium on Small Specimen Test Techniques, to be published in ASTM STP 1405, M. A. Sokolov, J. D. Landes, and G. E. Lucas, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2002

Wallin, K. (1995). Summary of the IAEA/CRP3 Fracture Mechanical Results. Proceedings of a Specialists Meeting Organized by the International Atomic Energy Agency and held in Espoo., Finland 23-26 October 1999, IWG-LMNPP-95/5, Volume II, IAEA, Vienna, Austria.

ANNEX 5

Data reporting sheet

"Quasi-static Toughness Tests"



IAEA CRP-8

Quasi-Static Toughness Test - Data Report Sheet

Organization :

Test coordinator :

Material tested :

Characteristics of testing equipment

Brand/model test machine :
Capacity load cell : kN
Max displacement rate : mm/s (in terms of crosshead displacement)
Type of machine : Servo-hydraulic

Brand/model clip-on-gage :
Max measurable opening : mm
Type of strain-gages :

Sampling rate used for these tests : s/datum

Anvil span : S = mm (only for SE(B) tests)

Measured displacement :
○ crack-mouth opening displacement
● load-line displacement
○ machine crosshead displacement

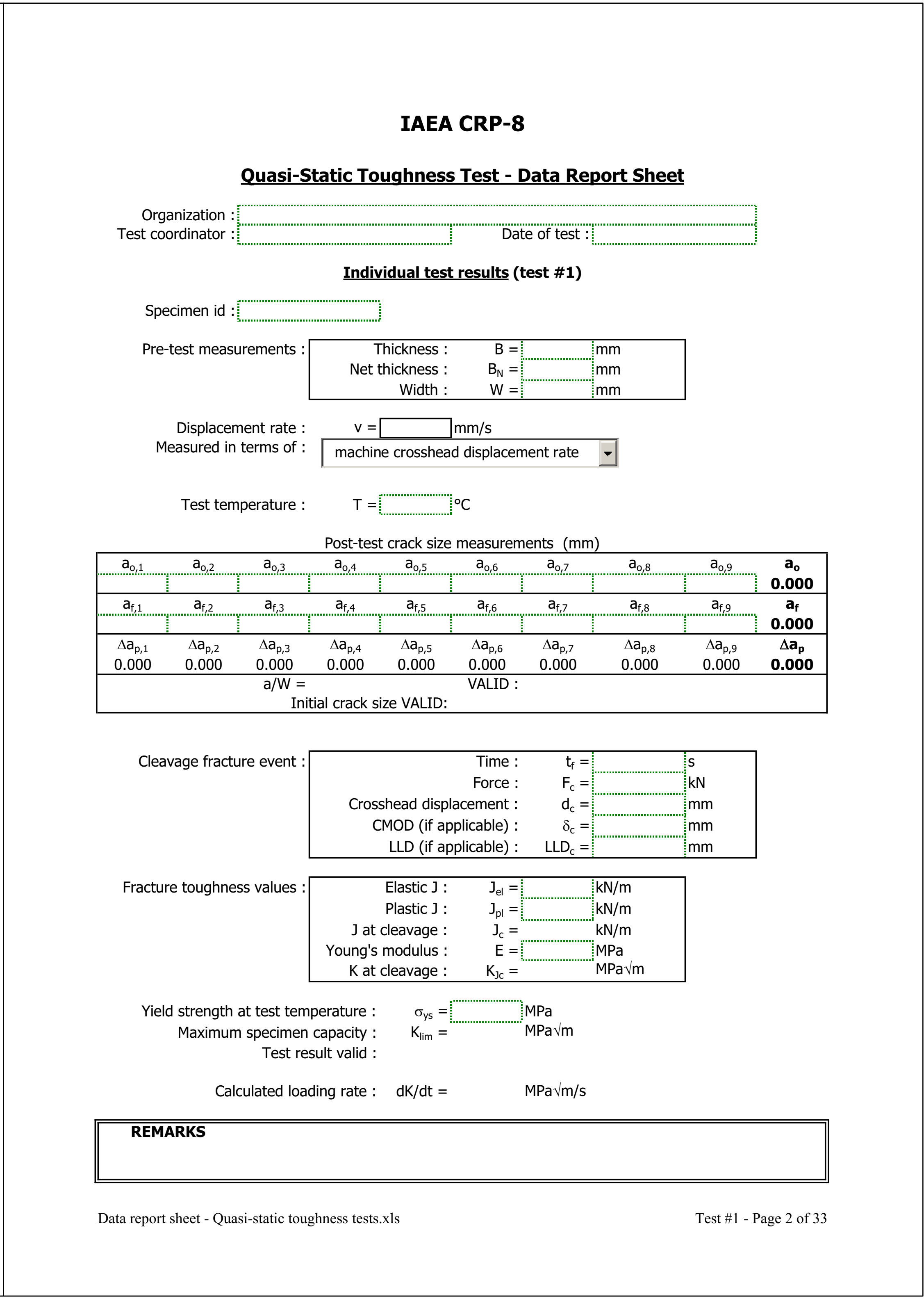
Dates of the latest calibrations: (load cell)
(displacement transducer)

Test specimen geometry : **Single Edge Bend, SE(B)**

REMARKS

Data report sheet - Quasi-static toughness tests.xls

General Info - Page 1 of 33



IAEA CRP-8

Quasi-Static Toughness Test - Data Report Sheet

Organization :
Test coordinator : Date of test :

Individual test results (test #1)

Specimen id :

Pre-test measurements :
Thickness : $B =$ mm
Net thickness : $B_N =$ mm
Width : $W =$ mm

Displacement rate : $v =$ mm/s
Measured in terms of : machine crosshead displacement rate

Test temperature : $T =$ °C

Post-test crack size measurements (mm)

$a_{o,1}$	$a_{o,2}$	$a_{o,3}$	$a_{o,4}$	$a_{o,5}$	$a_{o,6}$	$a_{o,7}$	$a_{o,8}$	$a_{o,9}$	$\mathbf{a_o}$
									0.000
$a_{f,1}$	$a_{f,2}$	$a_{f,3}$	$a_{f,4}$	$a_{f,5}$	$a_{f,6}$	$a_{f,7}$	$a_{f,8}$	$a_{f,9}$	$\mathbf{a_f}$
									0.000
$\Delta a_{p,1}$	$\Delta a_{p,2}$	$\Delta a_{p,3}$	$\Delta a_{p,4}$	$\Delta a_{p,5}$	$\Delta a_{p,6}$	$\Delta a_{p,7}$	$\Delta a_{p,8}$	$\Delta a_{p,9}$	$\mathbf{\Delta a_p}$
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
		a/W =			VALID :				
		Initial crack size VALID:							

Cleavage fracture event :
Time : $t_f =$ s
Force : $F_c =$ kN
Crosshead displacement : $d_c =$ mm
CMOD (if applicable) : $\delta_c =$ mm
LLD (if applicable) : $LLD_c =$ mm

Fracture toughness values :
Elastic J : $J_{el} =$ kN/m
Plastic J : $J_{pl} =$ kN/m
J at cleavage : $J_c =$ kN/m
Young's modulus : $E =$ MPa
K at cleavage : $K_{Jc} =$ MPa√m

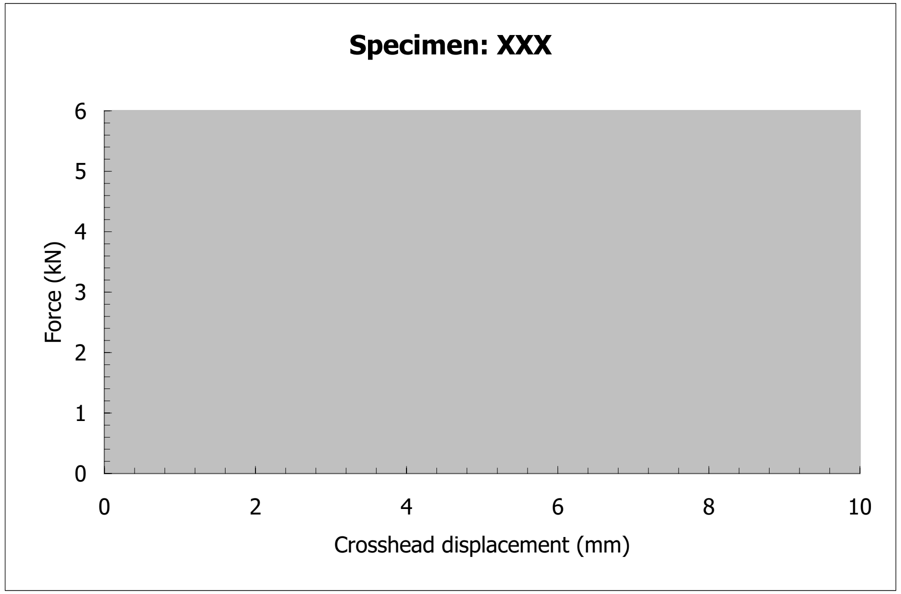
Yield strength at test temperature : $\sigma_{ys} =$ MPa
Maximum specimen capacity : $K_{lim} =$ MPa√m
Test result valid :

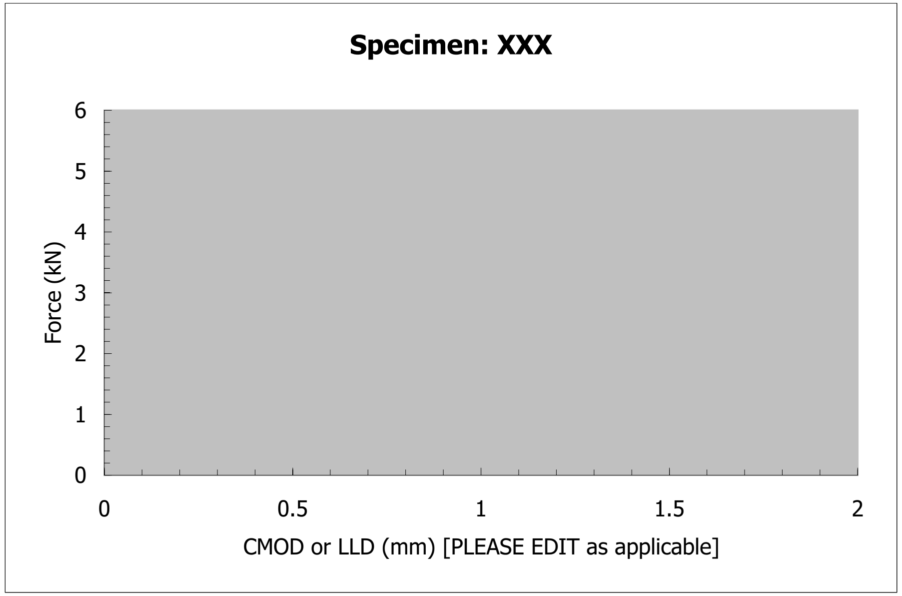
Calculated loading rate : dK/dt = MPa√m/s

REMARKS

Data report sheet - Quasi-static toughness tests.xls

Test #1 - Page 2 of 33





IAEA CRP-8 • Topic Area #2

Quasi-Static Toughness Tests - MASTER CURVE ANALYSIS

Organization :
Test coordinator : Date of analysis :

Summary of test results

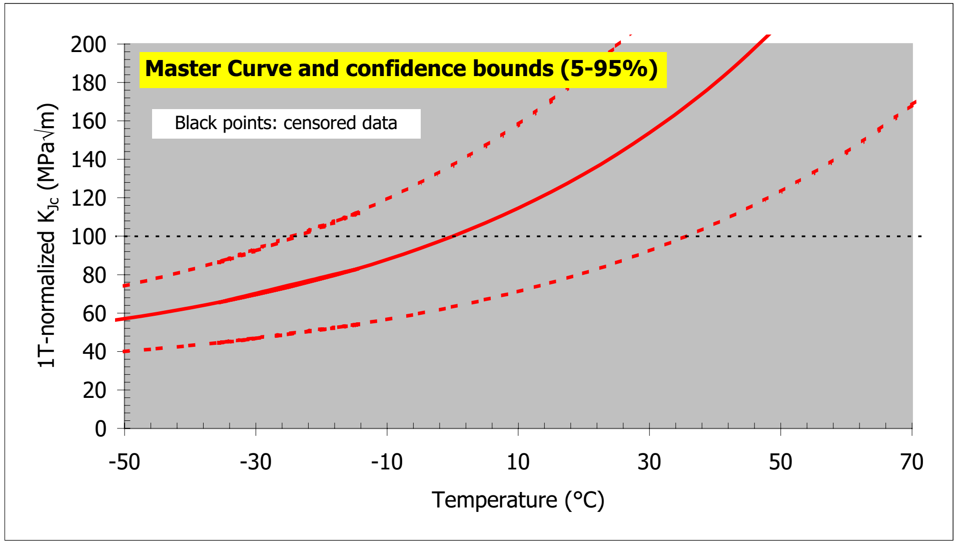
Spec. id	B (mm)	T (°C)	K_{Jc} (MPa√m)	K_{lim} (MPa√m)	Data valid	$K_{Jc,1T}$ (MPa√m)	δ_i	n_i

Number of tests
N = 0

\# valid tests
r = 0

Σ n_i = 0.000

Master Curve Reference Temperature : $T_{o,1}$ = °C **VALID : NO**
Independently calculated Reference Temperature : $T_{o,2}$ = °C VALID :
Average loading rate for the specimens tested : dK/dt = MPa√m/s



REMARKS

ANNEX 6

Data reporting sheet

"Dynamic Toughness Tests"

IAEA CRP-8 • Topic Area #2

Dynamic Toughness Test - Data Report Sheet

Organization :

Test coordinator :

Material tested :

Characteristics of testing equipment

Brand/model test machine :
Capacity load cell : kN
Max displacement rate : mm/s (in terms of crosshead displacement)
Type of machine : Servo-hydraulic

Brand/model clip-on-gage :
Max measurable opening : mm
Type of strain-gages :

Maximum achievable sampling rate : µs/datum
Sample rate used for these tests : µs/datum

Anvil span : S = mm (only for SE(B) tests)

Measured displacement :
- ○ crack-mouth opening displacement
- ● load-line displacement
- ○ machine crosshead displacement

Dates of the latest calibrations: (load cell)
(displacement transducer)

Test specimen geometry : **Single Edge Bend, SE(B)**

REMARKS

IAEA CRP-8 • Topic Area #2

Dynamic Toughness Test - Data Report Sheet

Organization :
Test coordinator : Date of test :

Individual test results (test #1)

Specimen id :

Pre-test measurements :
Thickness : B = mm
Net thickness : B_N = mm
Width : W = mm

Displacement rate : v = mm/s
Measured in terms of : machine crosshead displacement rate

Test temperature : T = °C

Post-test crack size measurements (mm)

$a_{o,1}$	$a_{o,2}$	$a_{o,3}$	$a_{o,4}$	$a_{o,5}$	$a_{o,6}$	$a_{o,7}$	$a_{o,8}$	$a_{o,9}$	**a_o**
									0.000
$a_{f,1}$	$a_{f,2}$	$a_{f,3}$	$a_{f,4}$	$a_{f,5}$	$a_{f,6}$	$a_{f,7}$	$a_{f,8}$	$a_{f,9}$	**a_f**
									0.000
$\Delta a_{p,1}$	$\Delta a_{p,2}$	$\Delta a_{p,3}$	$\Delta a_{p,4}$	$\Delta a_{p,5}$	$\Delta a_{p,6}$	$\Delta a_{p,7}$	$\Delta a_{p,8}$	$\Delta a_{p,9}$	**Δa_p**
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
		a/W =			VALID :				
		Initial crack size VALID:							

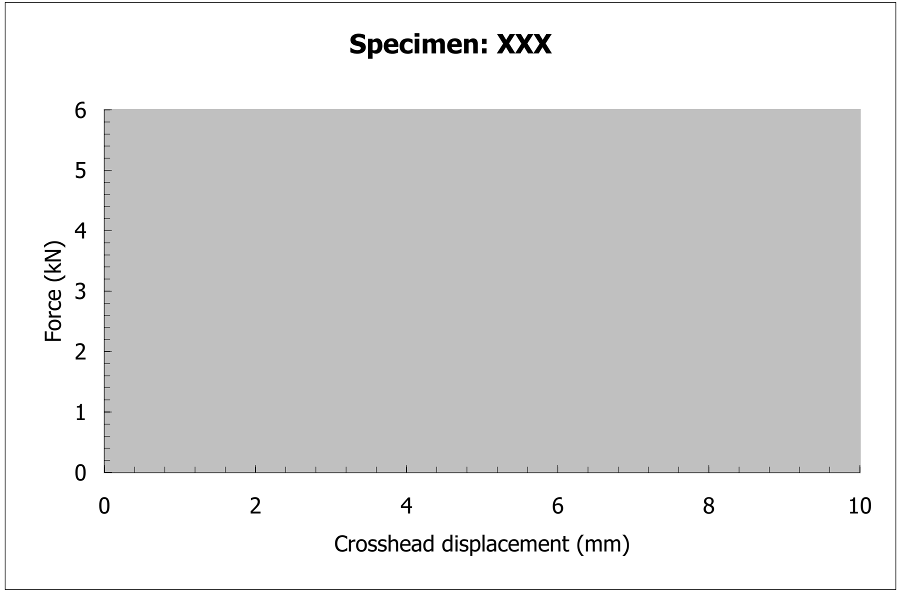
Cleavage fracture event :
Time : t_f = s
Force : F_c = kN
Crosshead displacement : d_c = mm
CMOD (if applicable) : δ_c = mm
LLD (if applicable) : LLD_c = mm

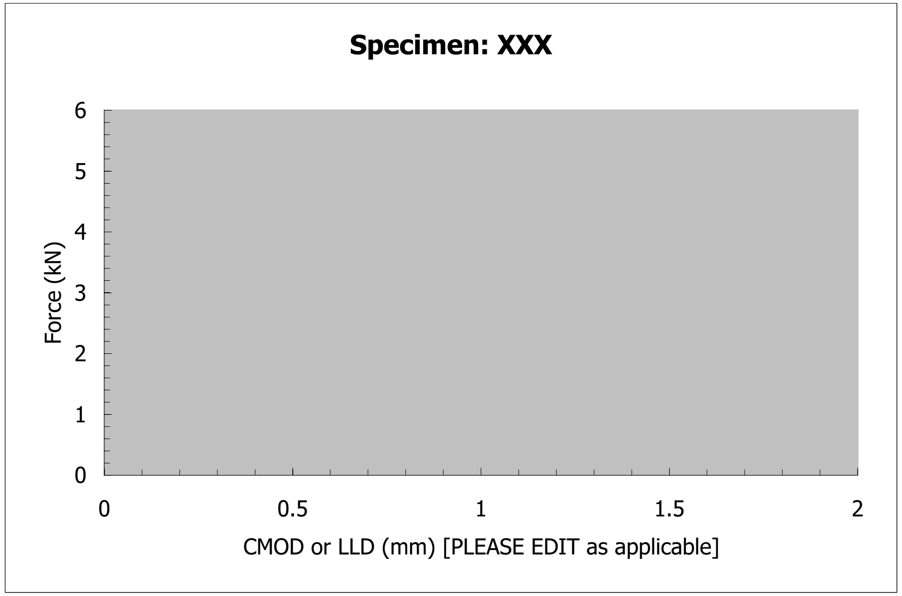
Fracture toughness values :
Elastic J : J_{el} = kN/m
Plastic J : J_{pl} = kN/m
J at cleavage : J_c = kN/m
Young's modulus : E = MPa
K at cleavage : K_{Jc} = MPa√m

Yield strength at test temperature : σ_{ys} = MPa
Maximum specimen capacity : K_{lim} = MPa√m
Test result valid :

Calculated loading rate : dK/dt = MPa√m/s

REMARKS





IAEA CRP-8 • Topic Area #2

Dynamic Toughness Tests - MASTER CURVE ANALYSIS

Organization :

Test coordinator : Date of analysis :

Summary of test results

Spec. id	B (mm)	T (°C)	K_{Jc} (MPa√m)	K_{lim} (MPa√m)	Data valid	$K_{Jc,1T}$ (MPa√m)	δ_i	n_i

Number of tests
N = 0

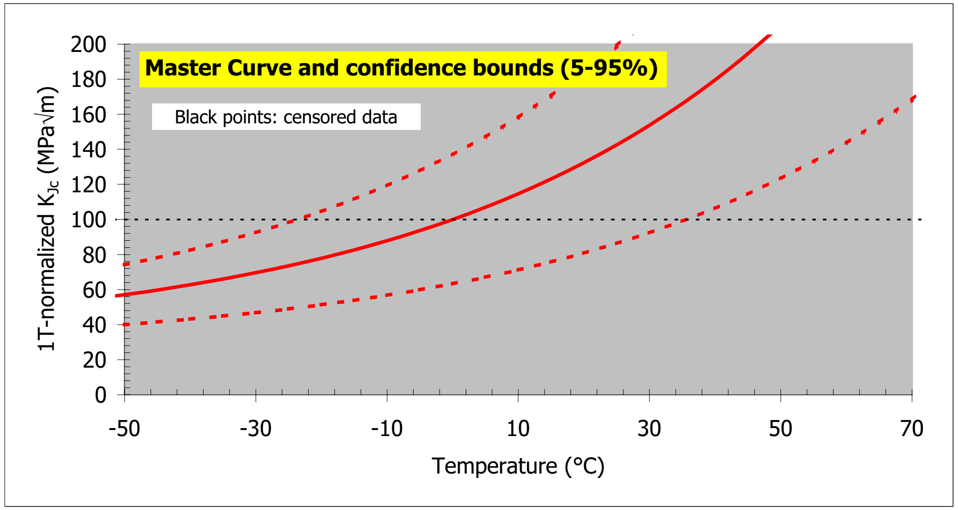
# valid tests
r = 0

$\Sigma n_i = 0.000$

Master Curve Reference Temperature : $T_{o,1}$ = °C **VALID : NO**

Independently calculated Reference Temperature : $T_{o,2}$ = °C VALID :

Average loading rate for the specimens tested : dK/dt = MPa√m/s



REMARKS

ANNEX 7

Data reporting sheet

"Impact Toughness Tests"

IAEA CRP-8 • Topic Area #2

Impact Toughness Test - Data Report Sheet

Organization :

Test coordinator :

Material tested :

Characteristics of testing equipment

Brand/model of pendulum :
Max potential energy : J
Max impact speed : m/s
Hammer type : C-type ▼

Hammer mass : m = kg
Pendulum length : l = m
Anvil span : S = mm

Radius of the striker : 8 mm (ASTM type) ▼

Frequency response of the measuring system : kHz

Displacement measurement :
● Indirect (from time/force measurements)
○ Direct measurement
(*please give details in the REMARKS section*)

Type of striker calibration : Static ▼

Upper limit of the calibration range: kN
Dates of the latest calibrations: (pendulum)
(temperature system)

Value of dial energy indicated after a free swing : J
(NB: starting from the position corresponding to the reduced impact velocity)

Machine compliance : C_M = mm/N
(NB: if measured autonomously by the lab, please give details in the REMARKS section)

REMARKS

IAEA CRP-8 • Topic Area #2

Impact Toughness Test - Data Report Sheet

Organization :
Test coordinator : Date of test :

Individual test results (test #1)

Specimen id :

Pre-test measurements :
Thickness : B = mm
Net thickness : B_N = mm
Width : W = mm

Initial potential energy : W_o = J
Blow angle : α = °
Impact velocity : v_o = m/s

Test temperature : T = °C

Post-test crack size measurements (mm)

$a_{o,1}$	$a_{o,2}$	$a_{o,3}$	$a_{o,4}$	$a_{o,5}$	$a_{o,6}$	$a_{o,7}$	$a_{o,8}$	$a_{o,9}$	$\mathbf{a_o}$
									0.000
$a_{f,1}$	$a_{f,2}$	$a_{f,3}$	$a_{f,4}$	$a_{f,5}$	$a_{f,6}$	$a_{f,7}$	$a_{f,8}$	$a_{f,9}$	$\mathbf{a_f}$
									0.000
$\Delta a_{p,1}$	$\Delta a_{p,2}$	$\Delta a_{p,3}$	$\Delta a_{p,4}$	$\Delta a_{p,5}$	$\Delta a_{p,6}$	$\Delta a_{p,7}$	$\Delta a_{p,8}$	$\Delta a_{p,9}$	$\mathbf{\Delta a_p}$
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
		a/W =			VALID :				
			Initial crack size VALID:						

Dial energy : KV = J (from the pendulum encoder/dial gage)
Total absorbed energy : W_t = J (from the force/displacement trace)

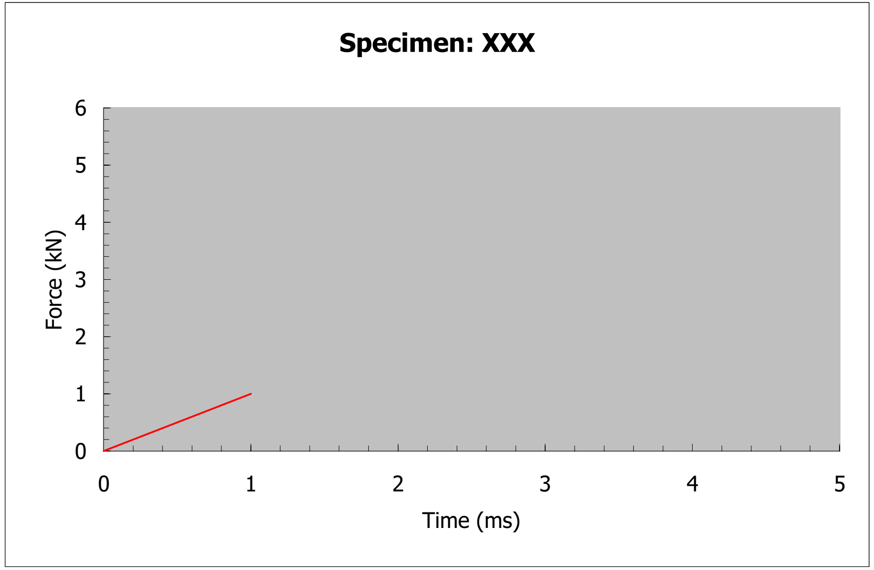
Cleavage fracture event :
Time : t_f = ms
Force : F_c = kN
Displacement : d_c = mm
Absorbed energy : W_c = J

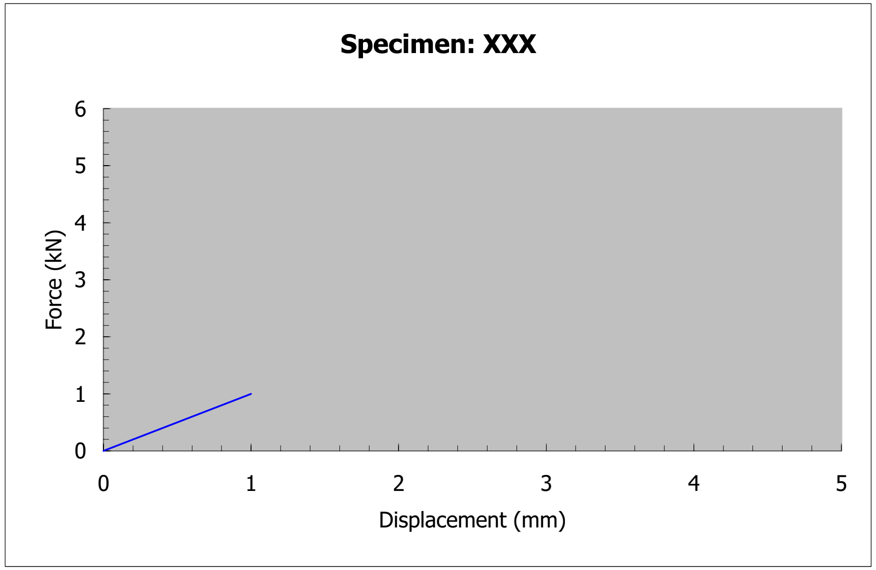
Fracture toughness values :
Elastic J : J_{el} = kN/m
Plastic J : J_{pl} = kN/m
J at cleavage : J_c = kN/m
Young's modulus : E = MPa
K at cleavage : K_{Jc} = MPa√m

Yield strength at test temperature : σ_{ys} = MPa
Maximum specimen capacity : K_{lim} = MPa√m
Test result valid :

Estimated loading rate : dK/dt = MPa√m/s

REMARKS





IAEA CRP-8 • Topic Area #2

Impact Toughness Test - MASTER CURVE ANALYSIS

Organization :

Test coordinator : Date of analysis :

Summary of test results

Spec. id	B (mm)	T (°C)	K_{Jc} (MPa√m)	K_{lim} (MPa√m)	Data valid	$K_{Jc,1T}$ (MPa√m)	δ_i	n_i

Number of tests
N = 0

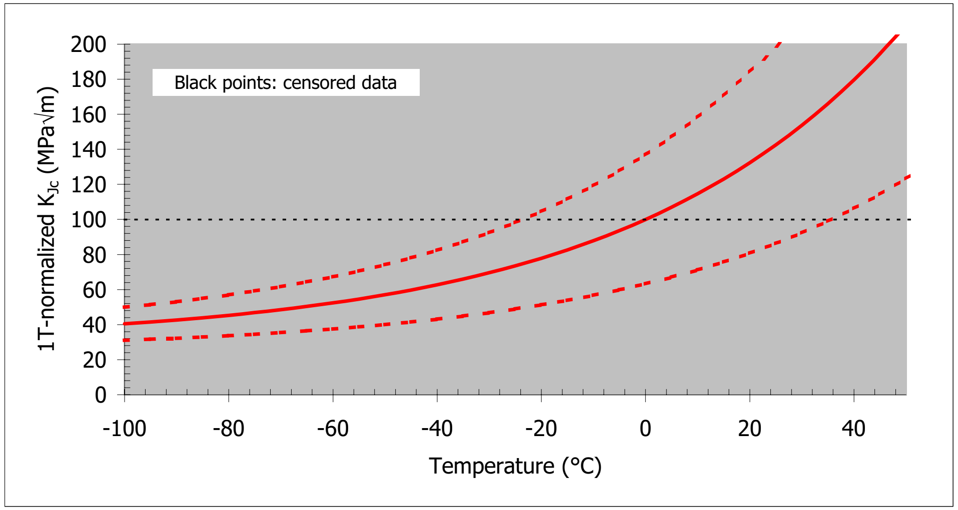
# valid tests
r = 0

Σn_i = 0.000

Master Curve Reference Temperature : $T_{o,1}$ = °C **VALID : NO**

Independently calculated Reference Temperature : $T_{o,2}$ = °C VALID :

Average loading rate for the specimens tested : dK/dt = MPa√m/s



REMARKS