Present Status of the FRACTESUS Project: Round Robin on Unirradiated Materials

INCEFA-SCALE Mid-term Seminar: ENVIRONMENTALLY ASSISTED FATIGUE WORKSHOP

Santander, September 19-20, 2023

G. Bonny, I. Uytdenhouwen, E. Altstadt, P. Arffman, **S. Cicero**, F. Obermeier, T. Petit, H. Swan, R. Chaouadi, E. Gaganidze, B. Hargitai, M. Kolluri, R. Kopriva, P. Rozsahegyi, M. Serrano, P. Spätig, H. Wilcox, M. Yamamoto, M. Sánchez

OUTLINE

1. INTRODUCTION
   - 1.2 OBJECTIVES
   - 1.3 PARTNERS INVOLVED
   - 1.4 WHERE WE ARE
   - 1.5 WHAT WE WANT TO ACHIEVE
   - 1.6 PROJECT STRUCTURE
2. MATERIALS AND METHODS
   - 2.1 MATERIAL SELECTION
   - 2.2 SPECIMEN DESIGNS
   - 2.3 BENCHMARK ON FT DATA EVALUATION
3. RESULTS AND DISCUSSION
   - 3.1 ROUND ROBIN RESULTS ON UNIRRADIATED MATERIALS
4. CONCLUSIONS

INTRODUCTION

OBJECTIVES

Goals

Validate usage of small-scale FT specimen testing for the safety assessment of RPV

→ MC(T) testing on wide group RPV steels, unirradiated & irradiated

→ Comparison between MC(T) and large specimens supported by FEM

→ Set-up guidelines for MC(T) testing & possibly propose changes to standards

Project Data

Project start date: 1 October 2020

Project duration: 4 years

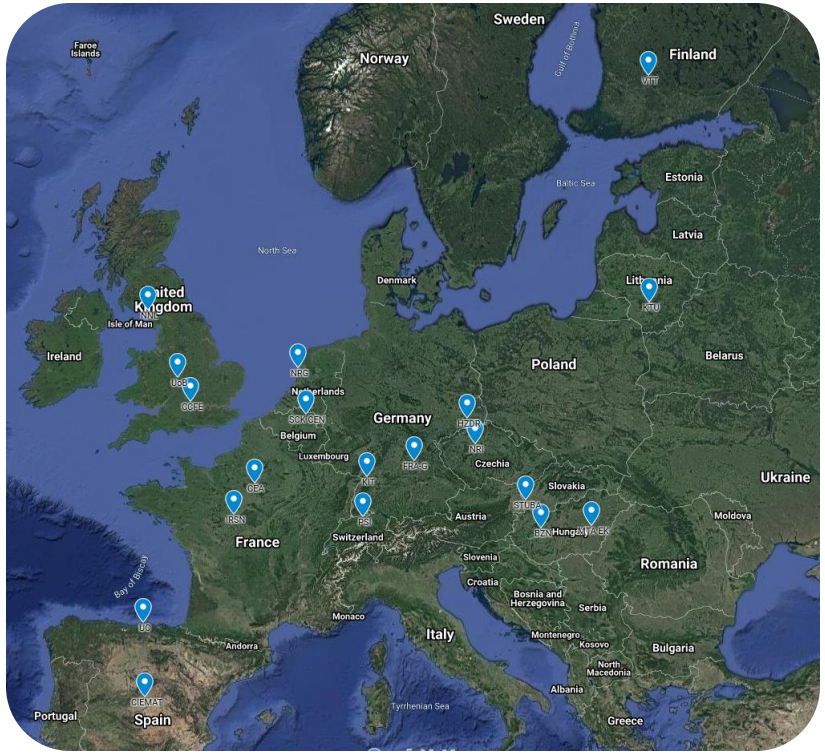
Total cost: € 4.7 M

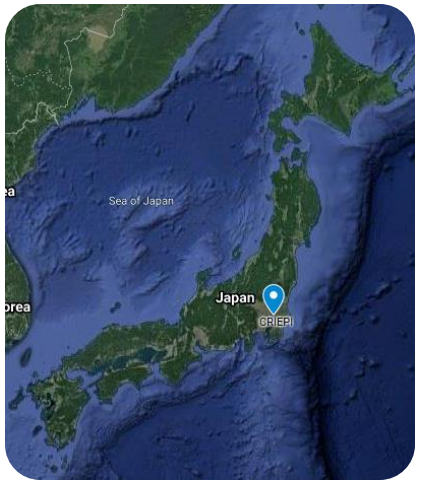
Total EC contribution: € 3.0 M

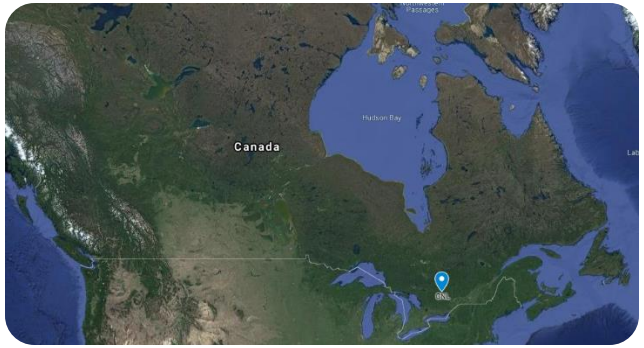
INTRODUCTION

PARTNERS INVOLVED

21 partners from 14 countries



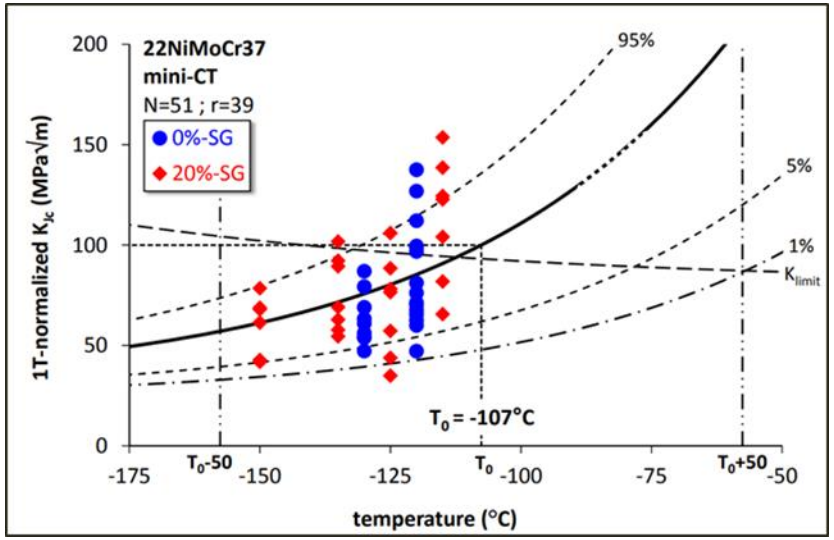




INTRODUCTION

WHERE WE ARE

- **ASTM E1921** standard determine T_0 using C(T) specimens of different size in specified conditions (temp., tensile properties…)
- Testing condition windows are more narrowed for smaller specimen (e.g smaller K_{limit} value)
- **ASTM E1820** standard: ductile fracture



First promising results on T_0 determination using MC(T) are reported for RPV steels, but many unknowns exist:

-applicability for various material states resulting from irradiation exposure

-test validity windows required by standards

-specimens geometry and fabrication accuracy

-…..

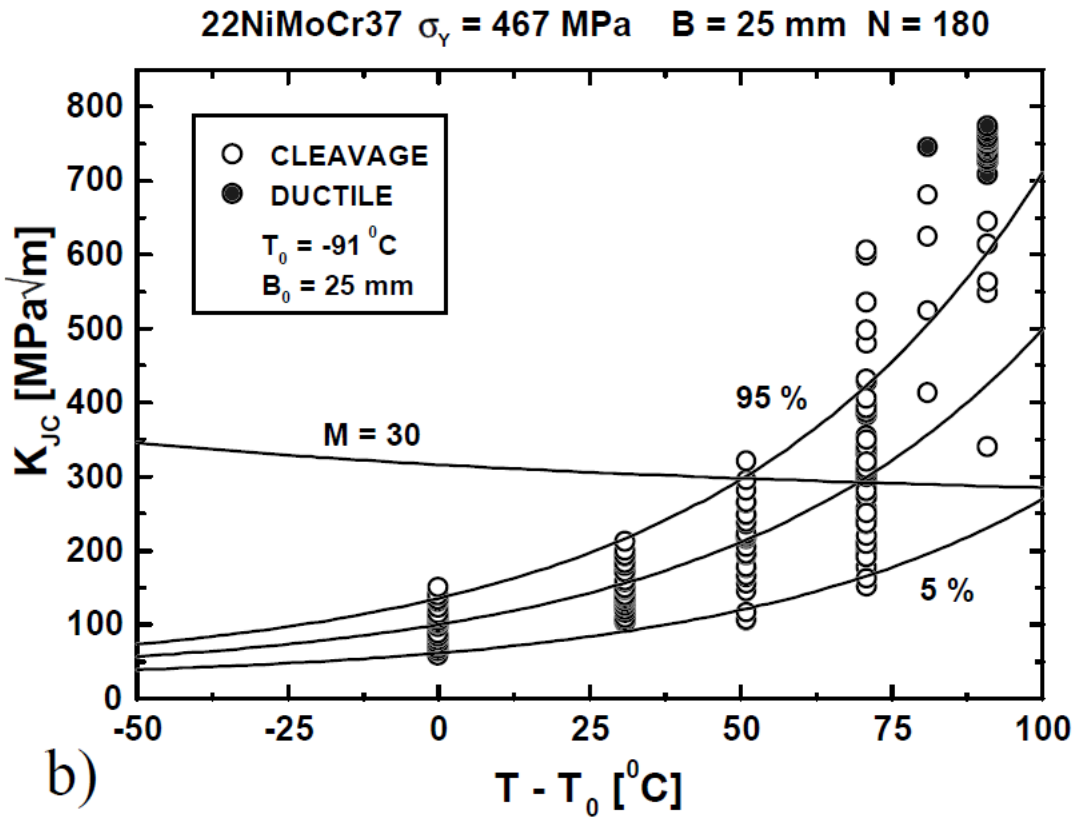
TRL5

- In the most of surveillance programs CVN specimens are used to estimate fracture toughness (no direct fracture toughness determination).
- Eight **MC(T)** may be cut from CVN and 20 from 0.5C(T) and used to determine FT directly

- **Need for MC(T) validation and demonstration of applicability in conditions relevant from the point of view of Nuclear Power Plants maintenance and design procedures**

INTRODUCTION

WHERE WE ARE



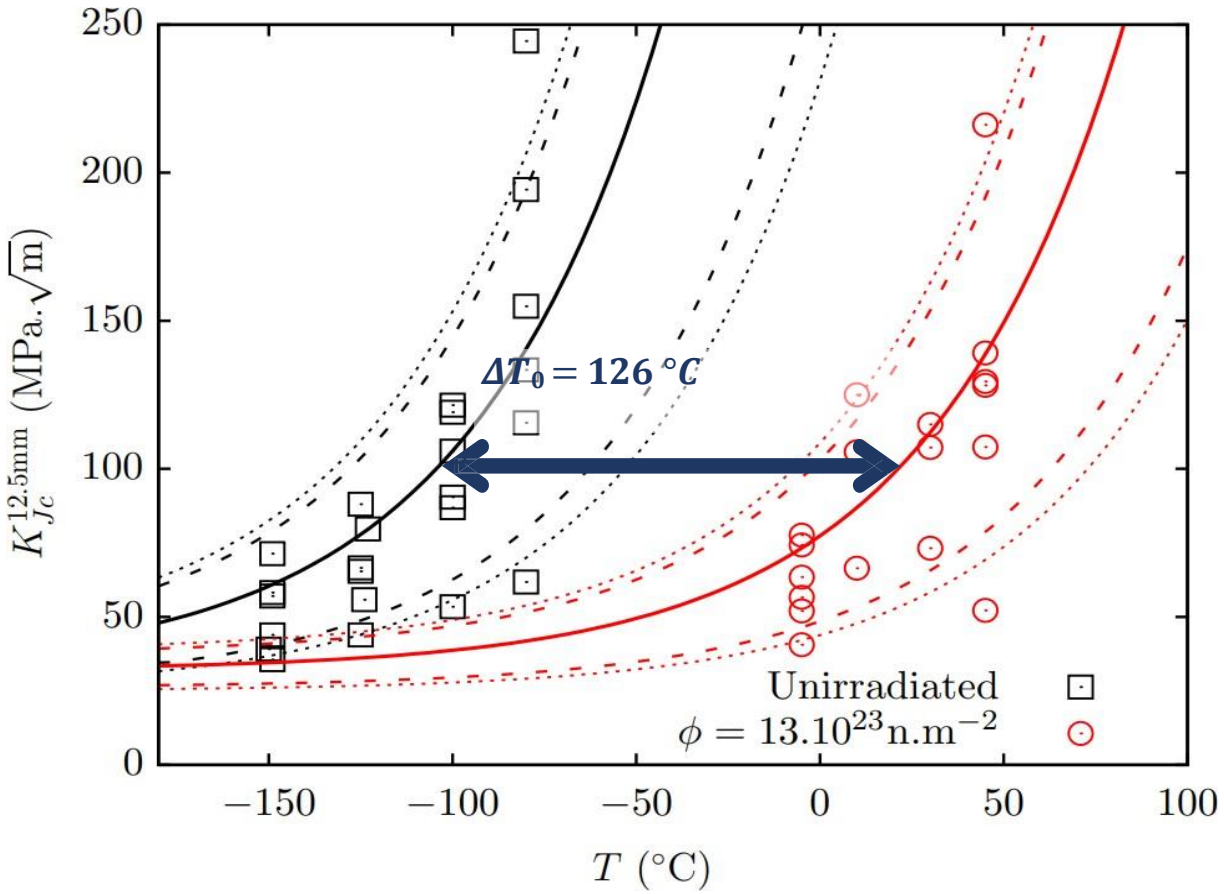
$$P_f = 1 - e^{-\frac{B}{B_0}\left(\frac{K_{JC}-K_{min}}{K_0-K_{min}}\right)^b}$$

$$K_{J_c,P_f} = 20 + \left(-\ln\left(1-P_f\right)\right)^{0.25}\left(11 + 77e^{0.019(T-T_0)}\right)$$

Wallin, K. *Master curve analysis of ductile to brittle transition region fracture toughness round robin data. The "EURO" fracture toughness curve*; VTT Publications 367, Julkaisija-Utgivare Publisher: Helsinki, Finland, 1998.

INTRODUCTION

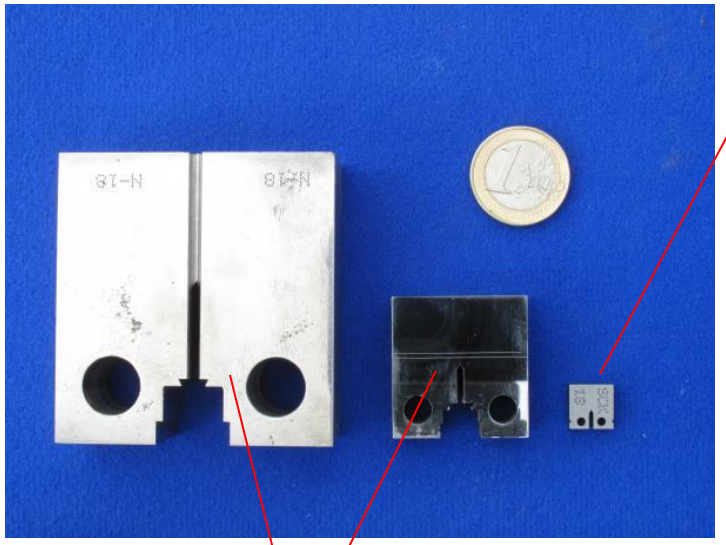
WHERE WE ARE



INTRODUCTION

WHAT WE WANT TO ACHIEVE

RPV materials with **various T_0**



- Database of results available
- Materials are available in sufficient amount

Selection of the best available materials

Mini FT testing

Comparison to large specimens (FEM supported)

Fractesus scope

The same results

Guidelines and dissemination

TRL5 -> TRL7

Validation of MC(T) approach

Approval by the Authorities

Usage by NPP Operators

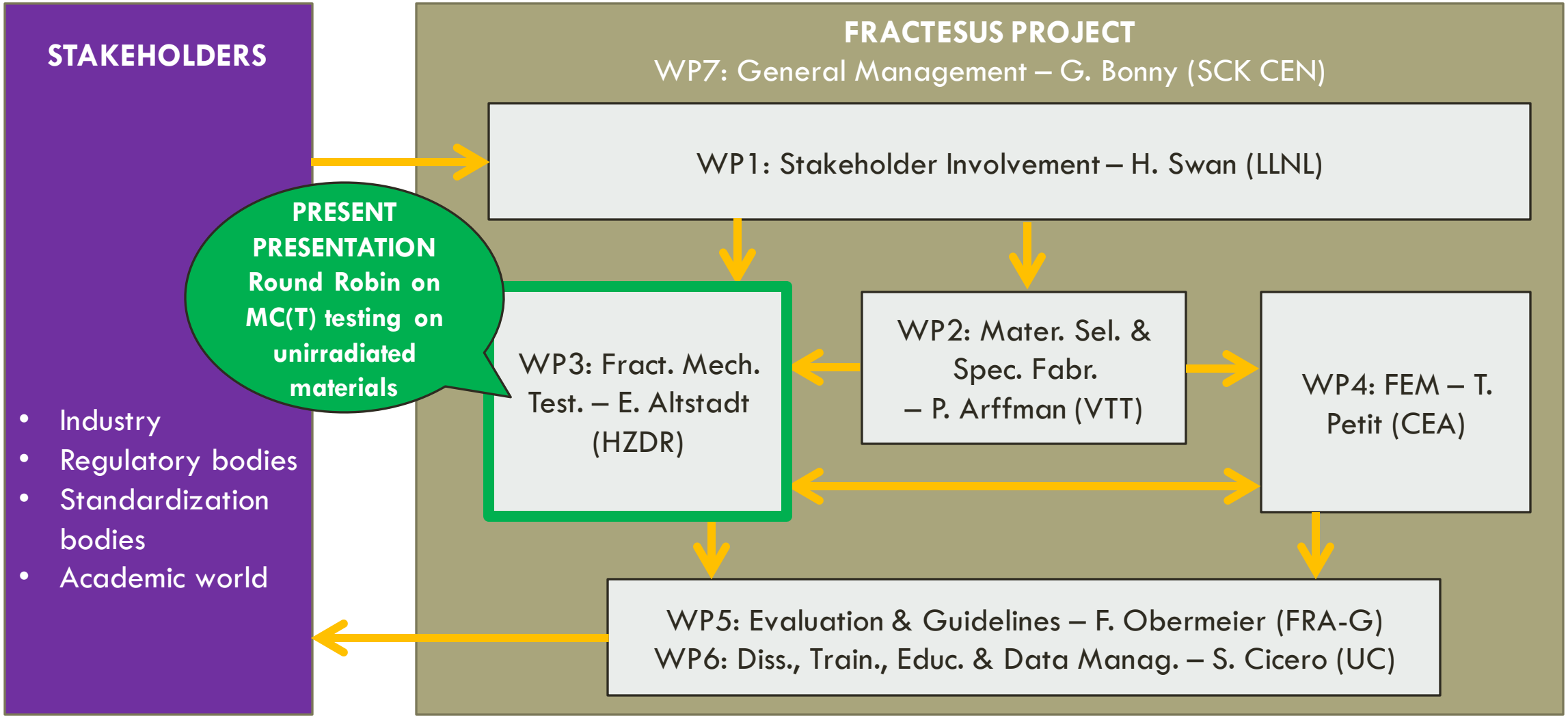
Correction method (including standards requirements change proposals if needed)

- Different results
- Discrepancy of results
- Validity problems

Investigate the reason/importance/trend… (FEM supported)

INTRODUCTION

PROJECT STRUCTURE



MATERIALS AND METHODS

MATERIAL SELECTION

RPV steels were selected following the principles to:

- use both base materials & welds
- cover a wide range of mechanical properties
- cover different chemical compositions
- be well characterized
- be available in sufficient quantity

MATERIALS AND METHODS

MATERIAL SELECTION

6 un-irradiated materials selected for the interlaboratory study

Material	Type	Origin
15Kh2MFAA	BM	VVER-440 RPV base material (Greifswald NPP, Unit 8)
A533B (JRQ)	BM	IAEA reference correlation material - "Optimizing Reactor Pressure Vessel Surveillance Programmes and their Analysis" (CRP-3)
73W	WM	Produced within 5th irradiation series in Heavy-Steel Technology Program conducted in 80's of 20th century
SA508 Cl.3	BM	Produced in 1995 to Equipos Nucleares ESNA for the fabrication of the replacement closure head of the RPV of the NPP Jose Cabrera (Zorita)
ANP-5	WM	Modified NiCrMo1 weld material, representative for RPV weldments in 1st Gen. pressurized water reactors (PWRs), eg. Obrigheim or Stade
A533B LUS (JSPS)	BM	Extensively tested within Japanese RR organized by Japan Society for the Promotion of Science (JSPS) in 1995 (increased P, S content)

MATERIALS AND METHODS

MATERIAL SELECTION

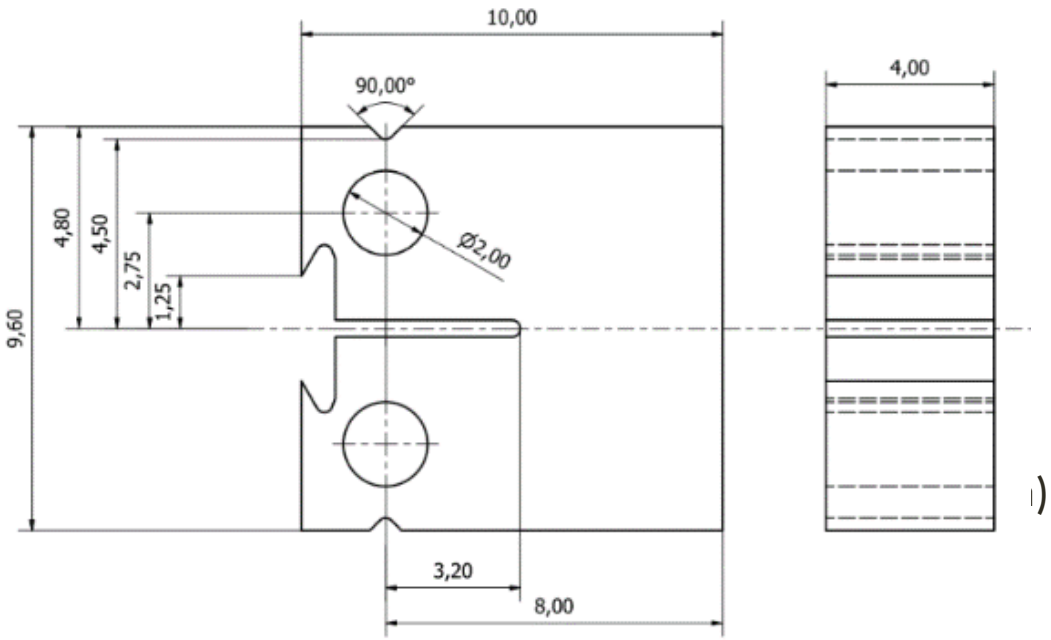
Material	Type	Provider	Orientation	σ_y at RT (MPa)	T_{41J} (°C)	T_0 (°C)	USE (J)
15Kh2MFAA	forging	HZDR	L-S	530	–54	-104	189
A533B LUS	plate	SCK CEN	T-L	455	+34	+12	72
A533B JRQ	plate	NRI	T-L	480	–25	-42	194
A508 Cl.3	forging	CIEMAT	R-C	470	–41	-62	230
ANP-5	weld	FRA-G	T-L	604	–12	-15	145
73W	weld	SCK CEN	T-L	495	–39	-59	135

Material	Content (wt.%)									
	C	Si	P	S	Cr	Mn	Ni	Cu	Mo	V
15Kh2MFAA	0.15	0.30	0.008	0.002	2.86	0.45	0.10	0.05	0.79	0.31
A533B LUS	0.24	0.41	0.028	0.023	0.08	1.52	0.43	0.19	0.49	n/a
A533B JRQ	0.18	0.25	0.019	0.004	0.12	1.38	0.82	0.14	0.49	0.003
A508 Cl.3	0.19	0.22	0.008	0.001	0.15	1.36	0.93	0.03	0.52	n/a
ANP-5	0.08	0.15	0.015	0.013	0.74	1.14	1.11	0.22	0.60	n/a
73W	0.10	0.45	0.005	0.005	0.25	1.56	0.60	0.31	0.58	n/a

MATERIALS AND METHODS

SPECIMEN DESIGN

Designs satisfy ASTM E1921-21



Partner	Spec. dim. $W_{tot} \times 2H \times B$ (mm)	offset X (mm)	COD (FFD or LLD)
SCK CEN	10 × 9.6 × 4	0	LLD
NRI	10 × 9.6 × 4	2	FFD
VTT	10 × 9.6 × 4	0	LLD
FRA-G	10 × 9.6 × 4	1.8	FFD
HZDR	10 × 9.6 × 4	2	FFD
KIT	11.5 × 9.6 × 4	3.5	FFD
BZN	10 × 9.6 × 4	2	FFD
EK-CER	10 × 9.6 × 4	0	LLD
NRG	10 × 9.6 × 4	0	LLD
CIEMAT	10 × 9.6 × 4	0	LLD
UC	10 × 9.6 × 4	2	FFD
PSI	11.25 × 10.8 × 4.5	0	LLD
CRIEPI	10 × 9.6 × 4	2	FFD

MATERIALS AND METHODS

BENCHMARK ON FT DATA EVALUATION

Aim

- inter-laboratory (10 participants) comparison of the evaluation of fracture toughness data
- **preparatory activity** for the round robins

Scope (2 actions)

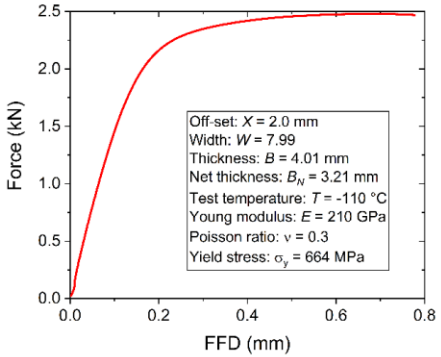
- **A1**: Calculation of K_{Jc} for a MC(T) sample from a given force-COD data set (COD measured at front face)
- **A2**: Calculation of T_0 from a given $K_{Jc}(T)$ data set according to ASTM E1921-21

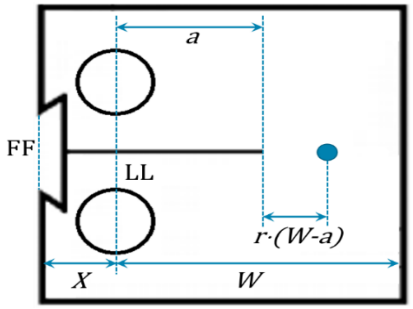
MATERIALS AND METHODS

BENCHMARK ON FT DATA EVALUATION

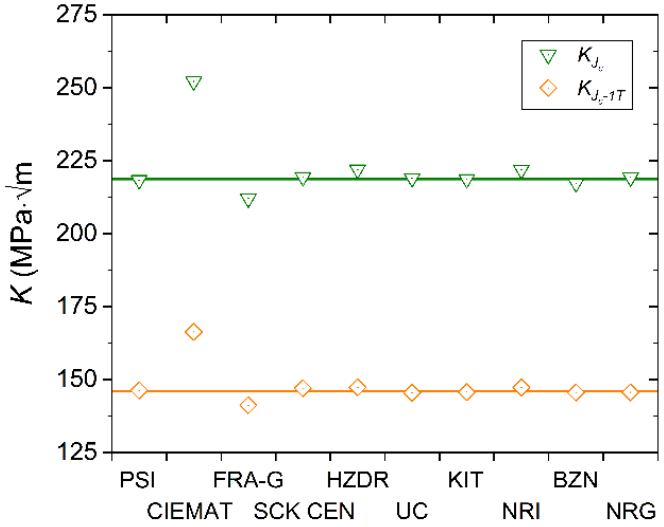
- **A1: Calculation of K_{Jc} for a MC(T)**

All partners analyzed the test following their standard procedures (consistent with ASTM E1921-21)





Lab	LLD/FFD
FRA-G	0.68
PSI	0.73
SCK CEN	0.73
UC	0.73
KIT	0.73
BZN	0.73
NRG	0.73
HZDR	0.75
NRI	0.75
CIEMAT	1.00



MATERIALS AND METHODS

BENCHMARK ON FT DATA EVALUATION

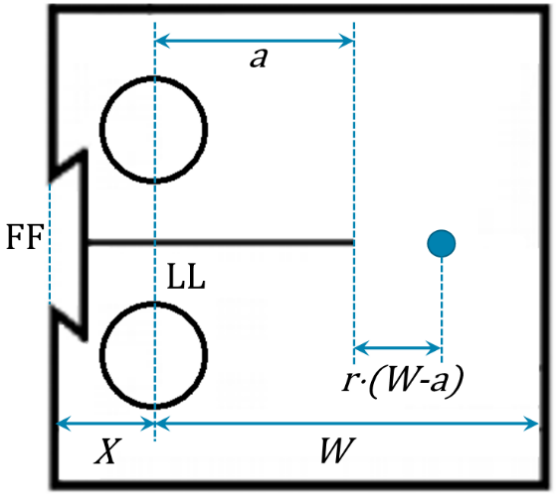
- **A1: Calculation of K_{Jc} for a MC(T)**

All partners analyzed the test following their standard procedures (consistent with ASTM E1921-21)

Lab	LLD/FFD
FRA-G	0.68
PSI	0.73
SCK CEN	0.73
UC	0.73
KIT	0.73
BZN	0.73
NRG	0.73
HZDR	0.75
NRI	0.75
CIEMAT	1.00

ASTM E1921-21 valid for $a/W \approx 0.5$ and $X/W = 0.25$

In the project: use $r = 0.352$ with actual a/W and X/W



$$\frac{LLD}{FFD} = \frac{a + r \cdot (W - a)}{a + r \cdot (W - a) + X} = \frac{a/W + r \cdot (1 - a/W)}{a/W + r \cdot (1 - a/W) + X/W}$$

J.D. Landes, Int. J. Fract 16 (1980) 183

MATERIALS AND METHODS

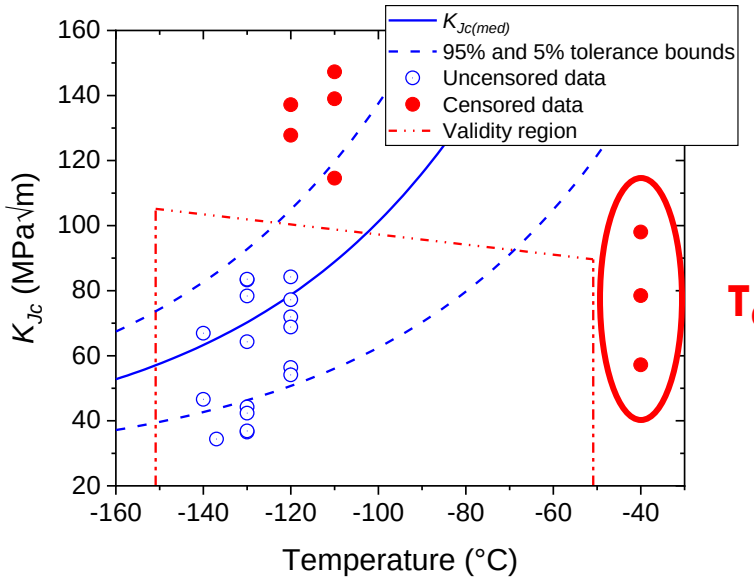
BENCHMARK ON FT DATA EVALUATION

- **A2: Calculation of $T0$ from a given $KJc(T)$ data set**

MC analysis using different software.

50 °C temperature exclusion criterion proved essential

T0TEM software as reference is recommended



T_0 = -98 °C

Lab	T_0 (°C)	$\sum(r_i \cdot n_i)$	$T_{0\,srcn}$ (°C)
PSI	-100.9		
CIEMAT*	-100.9		
FRA-G	-100.9		-89.9
SCK CEN*	-100.9	2.375	-92.9
HZDR	-100.9	2.375	-92.9
UC	-100.9	2.375	-92.9
KIT	-101.2	2.380	
NRI	-100.9	2.375	
BZN	-100.9	2.375	-92.9
NRG	-101.1	2.375	

* T0TEM software

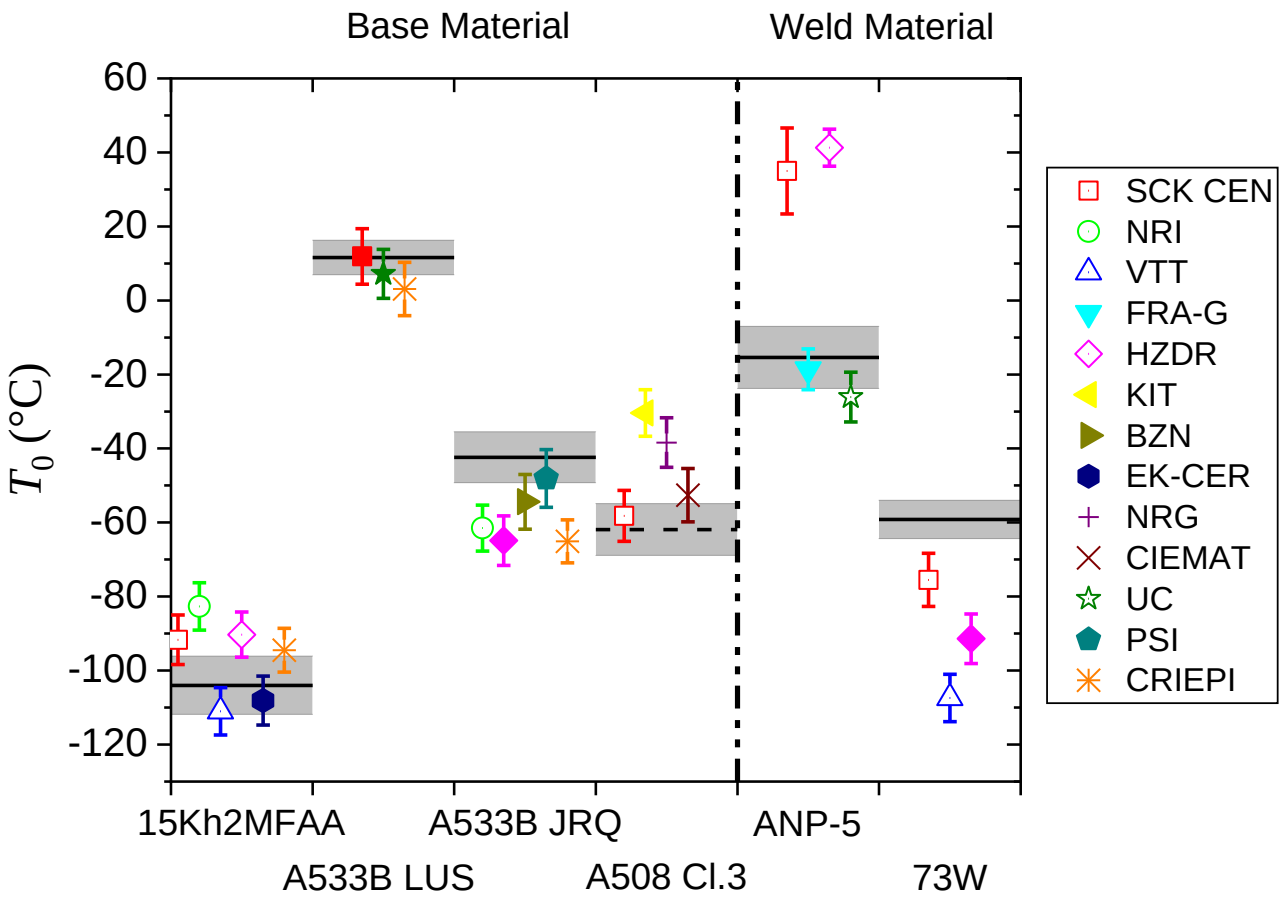
RESULTS AND DISCUSSION

ROUND ROBIN ON UNIRRADIATED MATERIALES

- Perform FT tests with MC(T) specimens (16 tests per material/partner)
  → Unirradiated: 6 round-robins (15Kh2MFAA, A533-JRQ, 73W, A508Cl3, ANP-5, A533B-LUS)
- Calculate K_{Jc} for each test
- Calculate T_0 from K_{Jc} data sets
  → Combination of data sets from different labs
- Evaluation of round robin exercises
  → Effect of test temperatures, censoring statistics
  → Effect of sample geometry
  → Scatter of data, inhomogeneity effects

RESULTS AND DISCUSSION

ROUND ROBIN ON UNIRRADIATED MATERIALES



Excellent agreement

15Kh2MFAA; A533B LUS

Slight under/overestimation

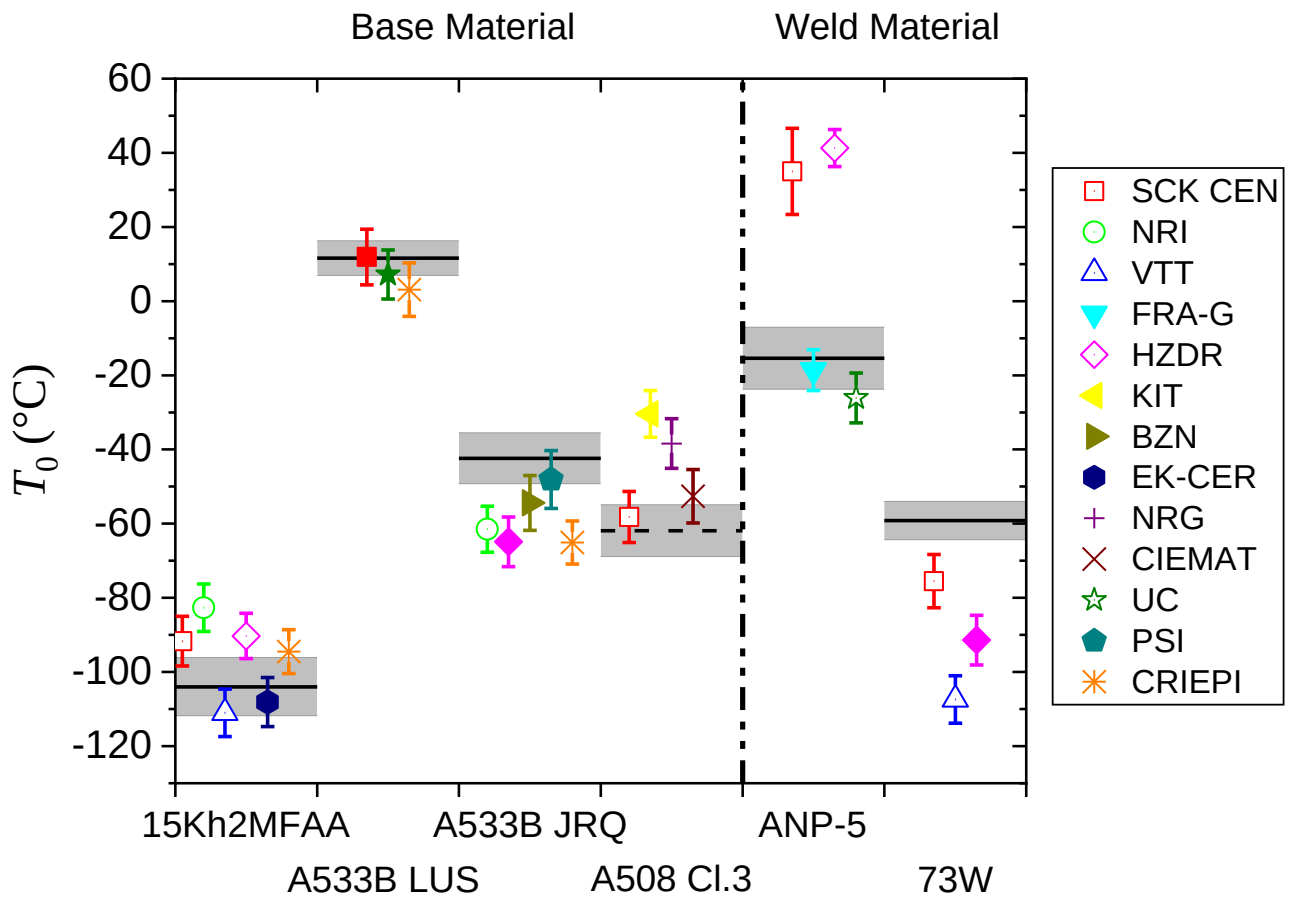
A533B JRQ; A508 Cl.3

Large under/overestimation

ANP-5; 73W

RESULTS AND DISCUSSION

ROUND ROBIN ON UNIRRADIATED MATERIALES



Homogeneity issue

MC(T) specimens often yield material's inhomogeneity compared to the results from larger specimens. The small sampling volume combined with the weakest link theory interpretation means that local differences in the material may result in a large variation from one tested MC(T) specimen to another.

CONCLUSIONS

- FT data for unirradiated Fractesus materials are available for further use within the project (27 test series on six materials)
- Different T_0 values from different sub-sets of several material

  → probably caused by macroscopic inhomogeneities
- The significance of inhomogeneity will be investigated further

THANK YOU VERY FOR YOUR ATTENTION!

Sergio Cicero
sergio.cicero@unican.es

ANY QUESTIONS?

This research has received funding from the Euratom research and training programme 2019-2020 under grant agreement N° 900014.