EFFECTS OF ADDITIONAL UNCERTAINTIES AND HANDLING AND MITIGATION OF UNCERTAINTIES

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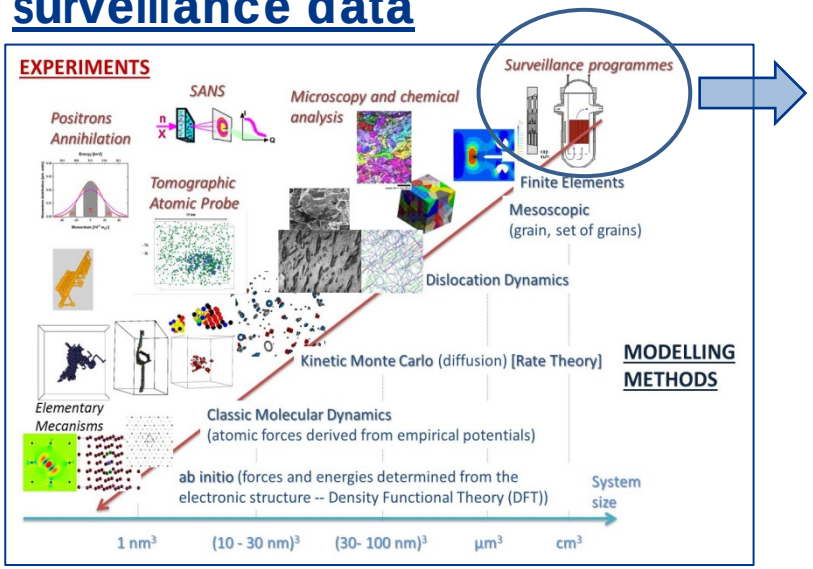
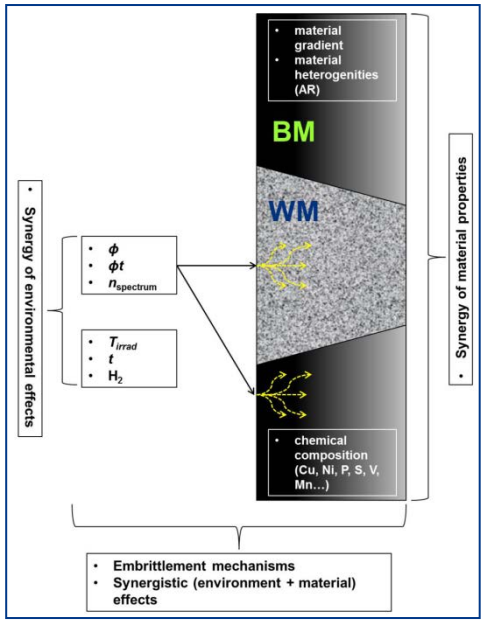
Contents

Introduction

- SOTERIA WP 3 “Evaluating uncertainties in fracture toughness measurement on irradiated RPV steels and mitigation approaches”
  - Objective: To improve the prediction of radiation induced ageing phenomena in **RPV steels** from an end-user perspective by improvement of the applicability of the use of
    - modelling tools and ETCs
    - **surveillance data**

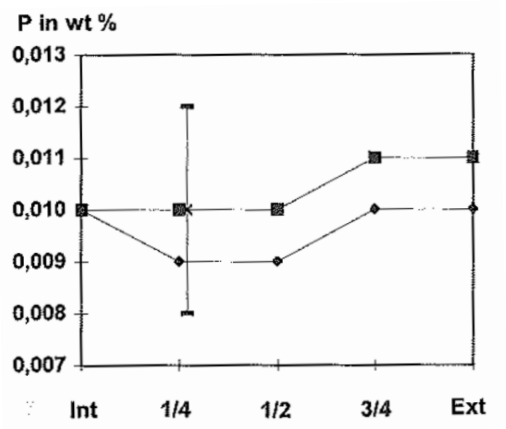




Introduction

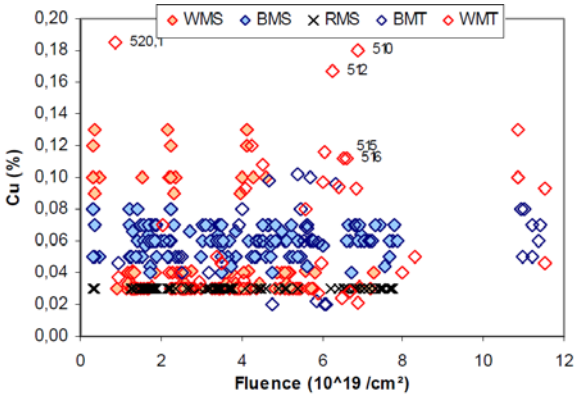
- Referring to surveillance data the uncertainties in determination of RPV fracture toughness under irradiation have to be known in terms of a reliable safety assessment
  - Examples of scatter from publications:

Chemical composition



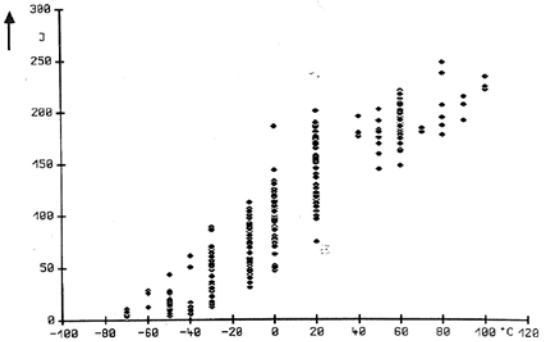
Brillaud et al, "Vessel Investigation Program of "CHOOZ A" PWR Reactor after shutdown," ASTM STP 1405, 2001

MTR (T) vs. surveillance (S) data



Todeschini et al, "Revision of the irradiation embrittlement correlation used for the EDF RPV fleet," Fontevraud 9, Avignon, 2010

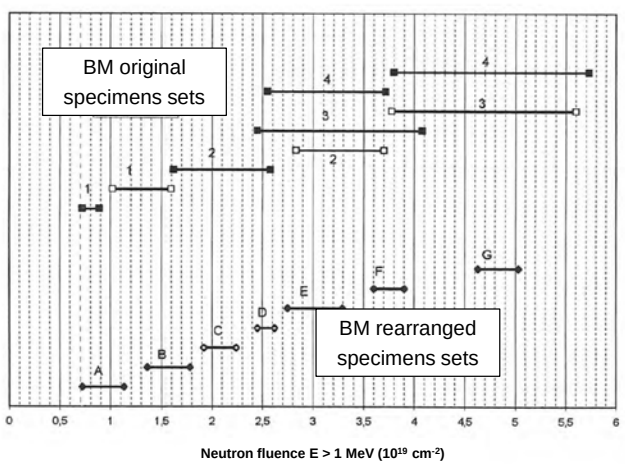
Measured Charpy energy

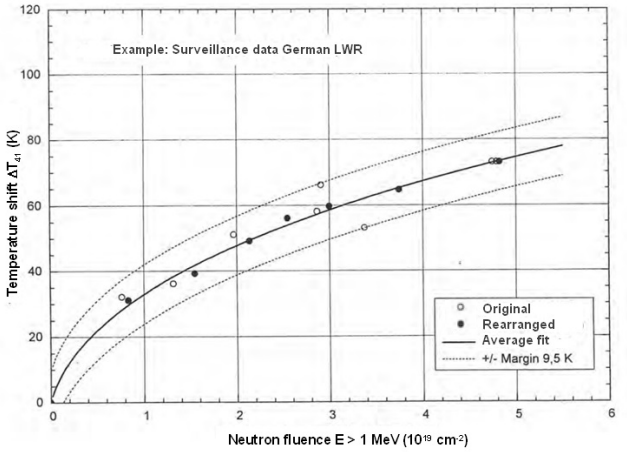


Erve, Leitz, "Irradiation behavior of RPV materials," Greifswald, 1989 - German RPV Shells, 20 MnMoNi5-5, ¼ T, T-L, 19 pre-products

Additional factors

- Some additional factors affecting radiation embrittlement in surveillance specimens exist due to the specifics of irradiation conditions, like:
  - Effect of initial heterogenities including segregations
  - Testing conditions and number of specimens in one test group
  - Thermal ageing
  - Neutron flux (i.e. lead factor) and neutron energy spectrum
  - Neutron fluence distribution within one test group



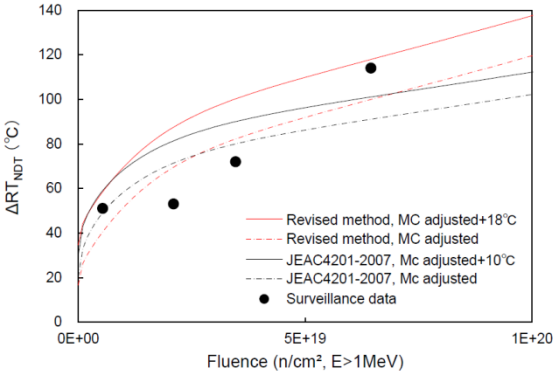


SOTERIA related work

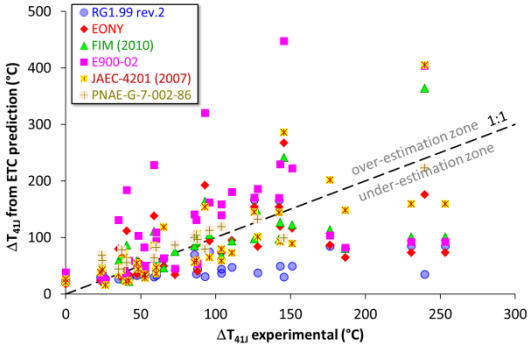
- Two specific tasks in SOTERIA (I)
  - T3.4: Effects of additional uncertainties in RPV surveillance data
    - Overview of the effects that can affect surveillance test data
      - initial conditions (location of specimens etc.)
      - irradiation conditions (uncertainties in neutron fluence, neutron spectrum, neutron flux, scatter between specimens etc.)
      - microstructural effects
    - Effect of testing conditions
      - testing procedure
      - standard vs. small size specimens
      - number of specimens
    - Effect of thermal ageing on radiation embrittlement
      - comparison of short and long term irradiations
      - effect of microstructure and chemical composition
    - Charpy notch impact vs. static fracture toughness (Master curve) testing
      - comparison of transition temperatures for different materials

SOTERIA related work

- Two specific tasks in SOTERIA (II)
  - T3.5: Applications and guidance for handling and mitigation of uncertainties
    - Guidance for analysis of scatter in RPV surveillance data considering sources of uncertainties
    - Identification of microstructural parameters relevant for predictive models
    - Evolution of nano-features with neutron fluence
    - Evaluation of impact of testing conditions on transition temperature uncertainty
    - Assessment and validation of Embrittlement Trend curves (ETC)



N. Soneda et al: High Fluence Surveillance Data Recalculation of RPV Embrittlement Correlation Method in Japan, PVP2013-98076, Proceedings of the ASME 2013 Pressure Vessels and Piping Conference PVP2013, July 14-18, 2013, Paris, France



E. Altstadt et al, "FP7 Project LONGLIFE: Overview of results and implications," NED 278 (2014) 753-757

SOTERIA related work

❑ Materials

- 19 RPV materials which are representative for European LWR are being examined by appropriate mechanical tests, chemical analyses and microstructural techniques.

Material ID	Material	Remark
ANP-2	S3NiMo1/OP41TT	WM, outlier observed at 4.97 n/cm2
ANP-3	22NiMoCr3-7	BM, Kloeckner
ANP-4	22NiMoCr3-7	BM, reference material JSW
ANP-5	NiCrMo1/LW320, LW330	WM, test weld seam, high Cu
ANP-6	S3NiMo/OP41TT	WM, Uddcomb, high Ni
ANP-10	22NiMoCr3-7	BM
ANP-15	22NiMoCr3-7	BM, Kloeckner, 30 years thermally aged
CIE-01	SA-508 Cl.3	BM
EDF-4	16MnD5	BM
FZD-1b	A533B Class 1	JPC (Japanese A533B Class 1 material), low P
FZD-2	10Kh2MFT	WM (WWER-440/V-230) Greifswald unit 4, Ishora, K_{Jc} scatter T-S
FZD-3	15Kh2MFA	BM (WWER-440/V-230) Greifswald unit 4, Ishora, K_{Jc} scatter L-S
FZD-4	15Kh2MFAA	BM (WWER-440/V-213) Greifswald unit 8, Skoda, K_{Jc} scatter
JRQ	A 533-B	BM (IAEA reference steel)
JRQ UJV-2	Sv 12Kh2N2MAA or 15Kh2NMFA	WWER steel
UJV-2	15Kh2NMFA	WM (WWER-1000)
VFAB 1	S3NiMo/OP41TT	WM, Uddcomb, high Ni
VTT-1	10KhMFT	WM (WWER-440), high Cu
VTT-MW1	10KhMFT	WM (mock-up weld, WWER-440), high P content

Selected preliminary results

❑ Chemical composition measurements

- ANP-2, -4 (low Cu/Ni/P): OES for Cu, Ni, P, C, … of 5 samples each

unirradiated

ANP-2	C [%]	Mn [%]	P [%]	S [%]	Ni [%]	Cu [%]
average measured by OES	0,0607	1,052	0,0167	0,0054	1,020	0,034
s [%]	4,06	2,46	6,49	3,58	1,20	3,55
heat at manufacture	0,05	1,08	0,019	0,009	1,01	0,03
relative deviation [%]	21,4	-2,6	-12,2	-40,2	1,0	14,7
ANP-4	**C [%]**	**Mn [%]**	**P [%]**	**S [%]**	**Ni [%]**	**Cu [%]**
average measured by OES	0,182	0,925	0,0045	0,0045	0,886	0,063
s [%]	1,47	0,51	4,44	21,02	1,32	2,45
heat at manufacture	0,21	0,85	0,006	0,006	0,84	0,05
relative deviation [%]	-13,2	8,8	-25,0	-25,0	5,5	27,0

- VFAB-1 (high Ni): OES, ICP

irradiated

VFAB-1	Fluence (E> 1MeV) cm^{-2}	Sample ID	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu	V	Sn	Fe
AREVA 2015/OES	~3E18	R2	0,063	0,21	1,66	0,016	0,005	0,14	0,38	1,08	0,03	0,01	0,06	0,01	-	96,3
AREVA 2015/OES	~3E18	A7	0,09	0,21	1,52	0,012	0,006	0,14	0,41	1,08	0,02	0,01	0,08	0,01	-	96,3
AREVA 2015/OES	~3E18	G4	0,072	0,21	1,55	0,015	0,006	0,13	0,39	1,27	0,02	0,01	0,06	0,01	-	96,2
AREVA 2016/ICP	~3E18	R2	0,067	0,197	1,55	0,013	0,006	0,127	0,419	1,69	0,019	0,008	0,057	0,007	-	96,3
AREVA 2016/ICP	~3E18	A7	0,103	0,193	1,49	0,011	0,007	0,131	0,436	1,43	0,017	0,012	0,075	0,004	-	96,3
AREVA 2016/ICP	~3E18	G4	0,073	0,208	1,52	0,013	0,006	0,129	0,425	1,64	0,02	0,009	0,055	0,005	-	96,8
AREVA 2016/OES	0	R3	0,08	0,22	1,63	0,014	0,006	0,13	0,38	1,61	0,02	0,01	0,07	0,01	-	95,8
AREVA 2016/OES	0	A6	0,118	0,22	1,52	0,01	0,007	0,13	0,41	1,33	0,02	0,02	0,09	0,006	-	96,1
AREVA 2016/OES	0	G3	0,058	0,23	1,83	0,019	0,008	0,14	0,25	1,46	0,04	0,03	0,07	0,01	-	95,7

OES

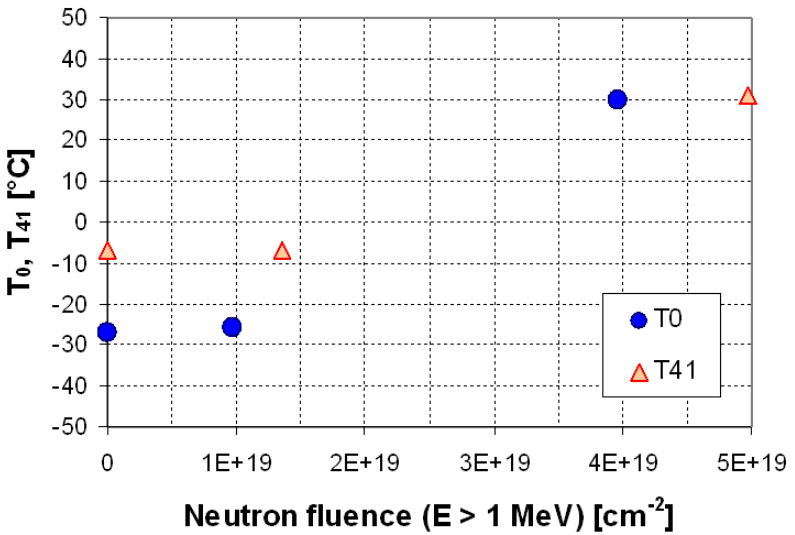
➡ Non-negligible deviations for Cu, Ni and P may affect ETC predictions

Selected preliminary results

❑ Removal position of specimens (I)

- ANP-2
  - Measured material properties confirmed by SANS and APT results
  - Reason of the unexpected irradiation behaviour?

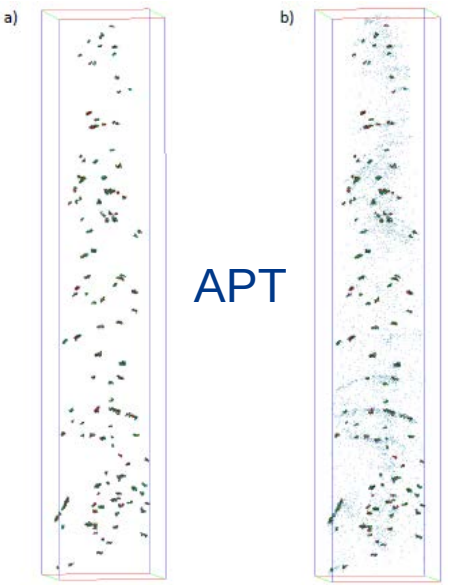
Material testing



only clusters

with P distribution

APT



Mn/Ni/Si/Cu enriched clusters in ANP-2 irradiated to 5x10^{19} n/cm^2

H. Hein et al, "Some recent research results and their implications for RPV irradiation surveillance under long term operation," IAEA Technical Meeting, 5-8 November 2013, Vienna, Austria

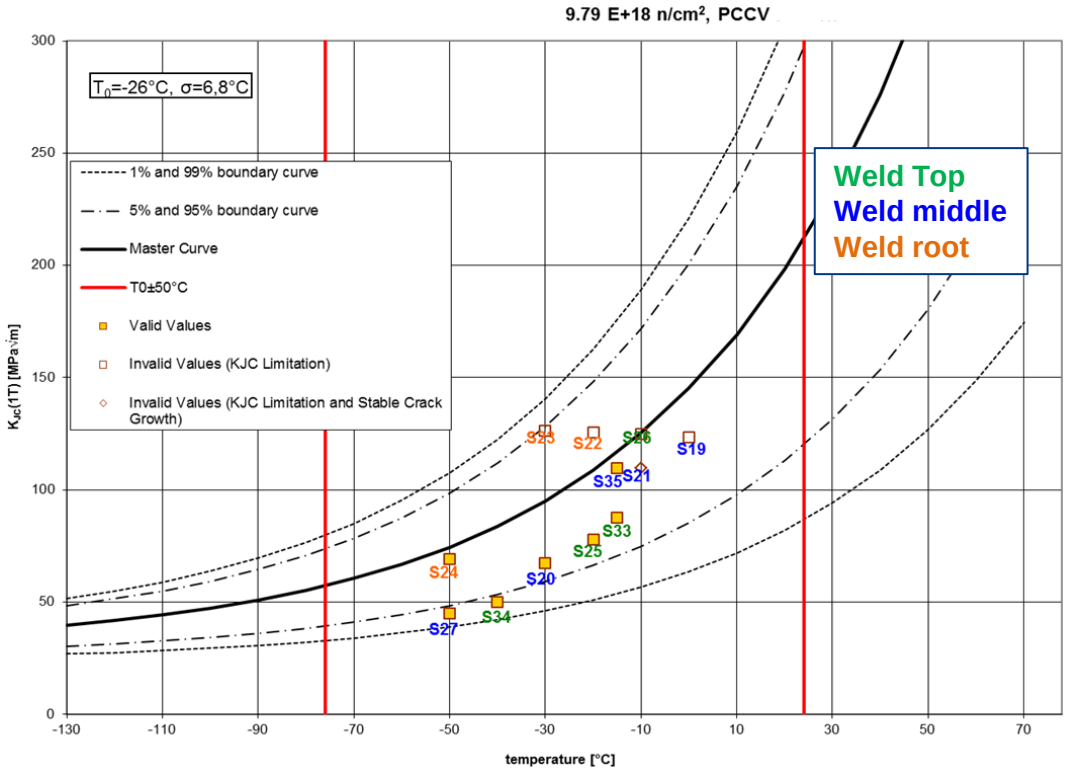
SANS

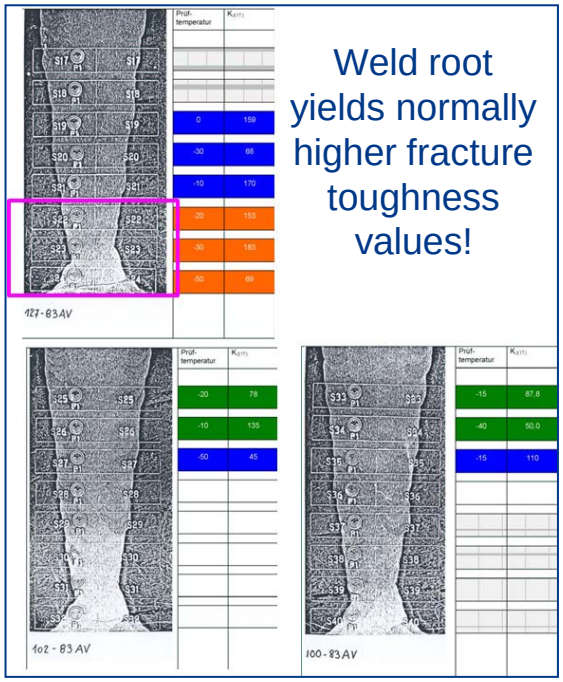
Fluence, Φ (10^{19} cm^{-2}) (E>1MeV)	Volume fraction, c (vol%)	Number density, N (10^{16} cm^{-3})	Radius, R_{mean} (nm)	Radius, R_{peak} (nm)	A-ratio
1.36	<0.005	2±2	-	-	~1
4.70	0.10±0.02	55±5	0.72	0.55	2.54±0.08

Selected preliminary results

❑ Removal position of specimens (II)

- ANP-2
  - Too low T_0 might be caused by use of specimens from weld root area
  - ≥10 K higher T_0 if specimens from weld root area are omitted





Selected preliminary results

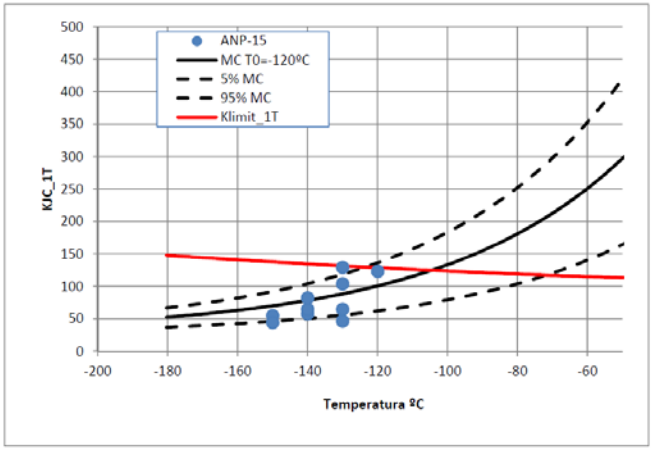
❑ Thermal aging

- Role of thermal aging in RPV irradiation surveillance programs
- ANP-15 (low Cu/Ni/P forged base material) ~30 years aged on PWR MCL at 290 °C
- T_0= -120 °C ⇨ no indication of thermal aging

ANP-15

MATERIAL	SPECIMEN	B	W	T0	KJCmed1T	s	n	r	FP
ANP-15	PCCV	10	10	-120.27	91.89	6.27	10	9	1.55

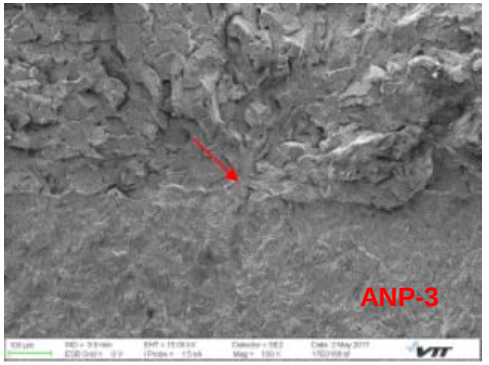
PROG	ID	T	KJC	KJC1T	d	Klimit
SOTERIA	Z4.19L	-120	150	123	1	152
SOTERIA	Z4.19R	-130	158	129	0	152
SOTERIA	Z4.21L	-150	64	55	1	152
SOTERIA	Z4.23L	-140	68	58	1	152
SOTERIA	Z4.21R	-150	51	44	1	152
SOTERIA	Z4.23R	-140	76	65	1	152
SOTERIA	Z4.31L	-130	126	104	1	152
SOTERIA	Z4.23L	-130	54	47	1	152
SOTERIA	Z4.33R	-130	76	65	1	152
SOTERIA	Z4.31R	-140	99	82	1	152

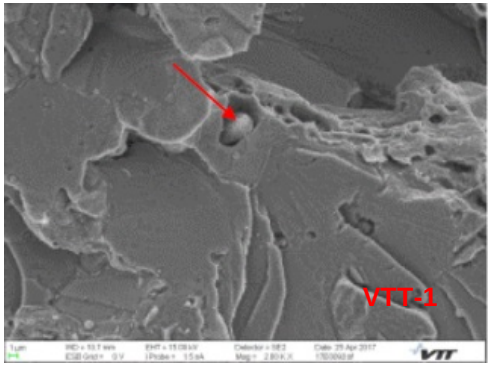


Selected preliminary results

- Material heterogeneities
  - Role of non-metallic inclusions
  - Role of specimen thickness if the specimen size is smaller than the distance between the heterogeneities (if any)

For ANP-3/-4 the primary initiation site is not characterized by a specific microstructural feature (precipitate or inclusion), whereas for VTT-1 the initiation sites of two specimens revealed a brittle Si and Mn rich particle.



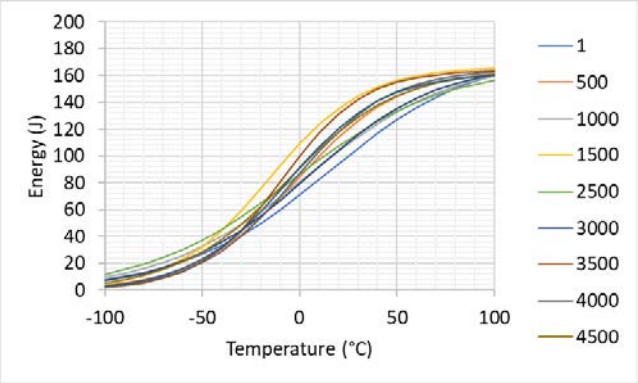


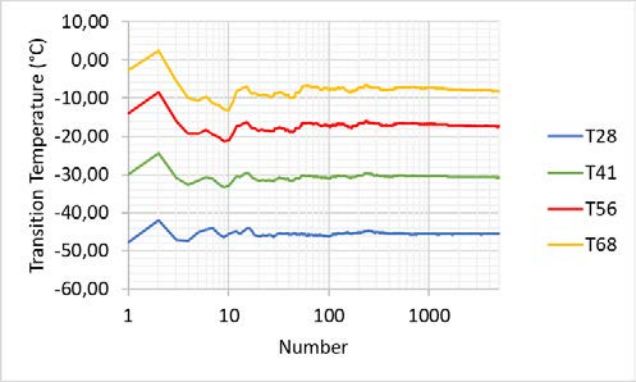
Selected preliminary results

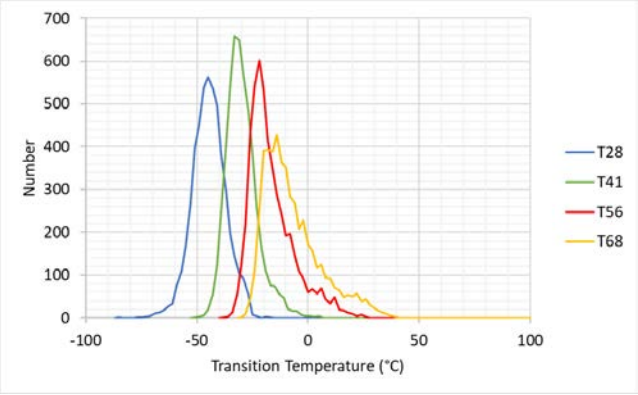
- Impact of the testing procedure on the uncertainty of the ductile to brittle transition temperatures (I)
  - Charpy data set for 16MND5 material
    - Focus on test matrix effects on uncertainty
    - Specimens machined from ¾ T to reduce micro/meso-segregation heterogeneities
    - MC simulation: 5000 random selections of test result sets according to conventional test matrices (Surveillance Program-like, RCC-M, …)
    - Tanh fitting: determination of parameters w/o constraint
    - Computation of T_{28}, T_{41}, T_{56} and T_{68} transition temperatures
    - Standard deviation sigma and other statistical characteristics
    - Uncertainties defined at +/- 2 sigma for the chosen test matrix

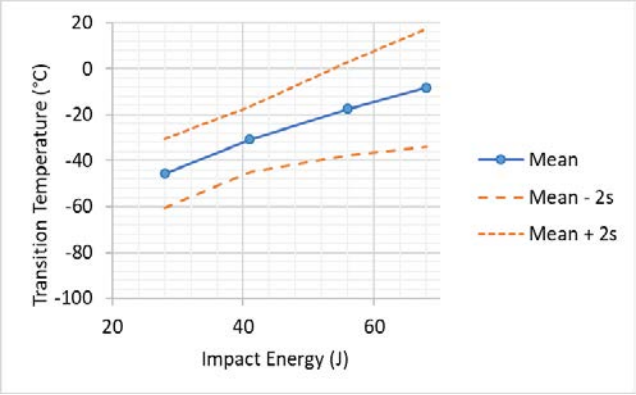
Selected preliminary results

- Impact of the testing procedure on the uncertainty of the ductile to brittle transition temperatures (II)
  - 12 tests for 16MND5 material
    - 3 tests each at -60 °C, -30 °C, -20 °C and 100 °C



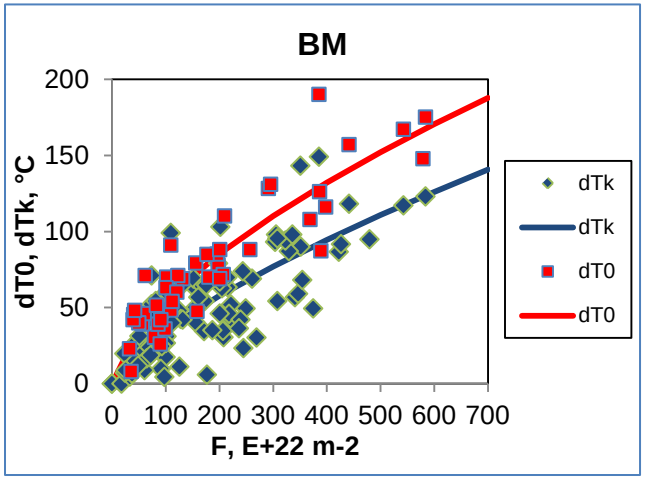




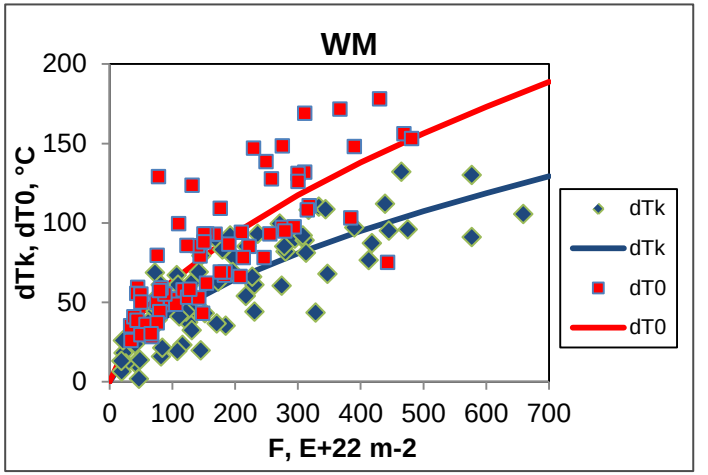


Selected preliminary results

- Scatter between fracture toughness and Charpy impact shifts
  - Sources :
    - Scatter due to heterogeneities within specimen group for one type of testing
    - Scatter due to heterogeneities between two groups of specimens
    - Scatter due to differences in irradiation of these two groups of specimens
    - Scatter due to uncertainties of test parameters

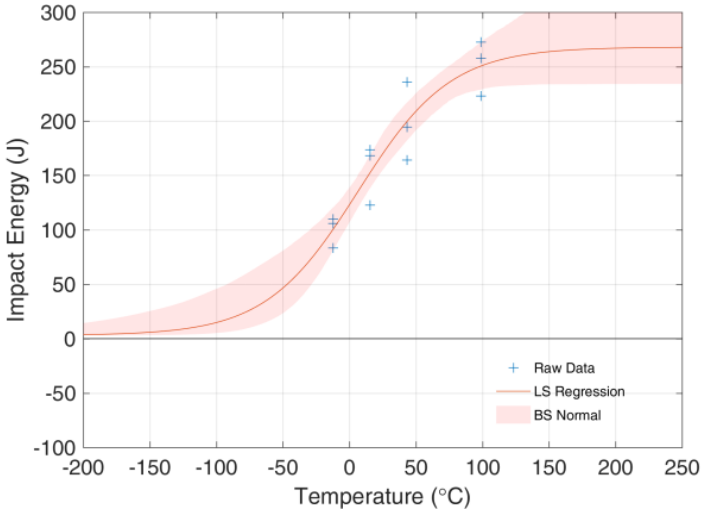


Steel
15Kh2MFAA
(WWER 440)



Selected preliminary results

- Uncertainty assessment of T_{41} from Charpy tests by Bootstrapping is a promising tool (work still ongoing)
  - Synergies from NUGENIA+ project AGE60+
    - Charpy testing in the upper and lower shelf rather than repeat in the transition region may reduce uncertianties
    - Bootstrapping during testing may optimize the choice of test temperatures



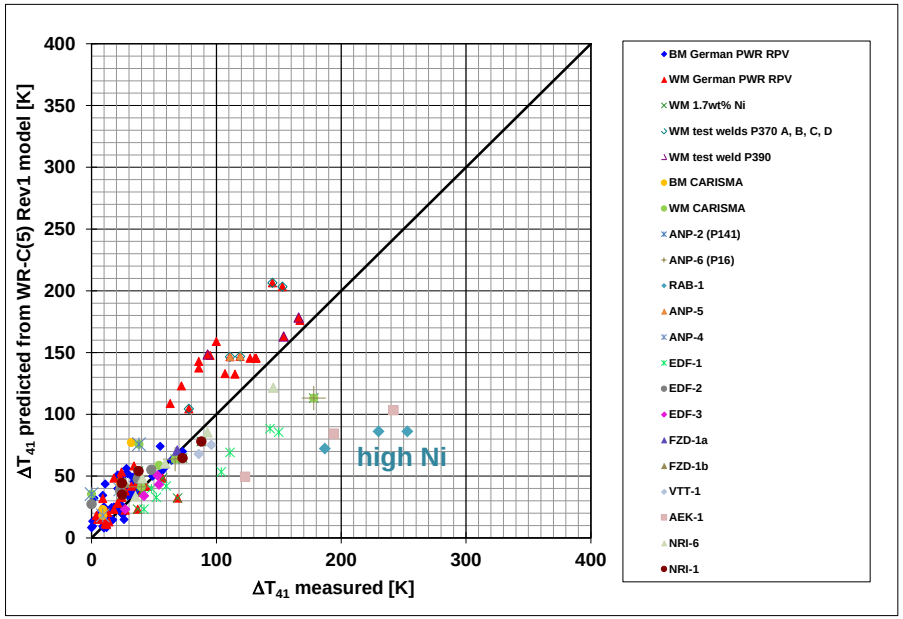
S. Ortner et al, "Applicability of ageing related data bases and methodologies for ensuring safe operation of LWR beyond 60 years," http://s538600174.onlinehome.fr/nugenia/wp-content/uploads/2016/11/22__AGE60+_V1.pdf

Selected preliminary results

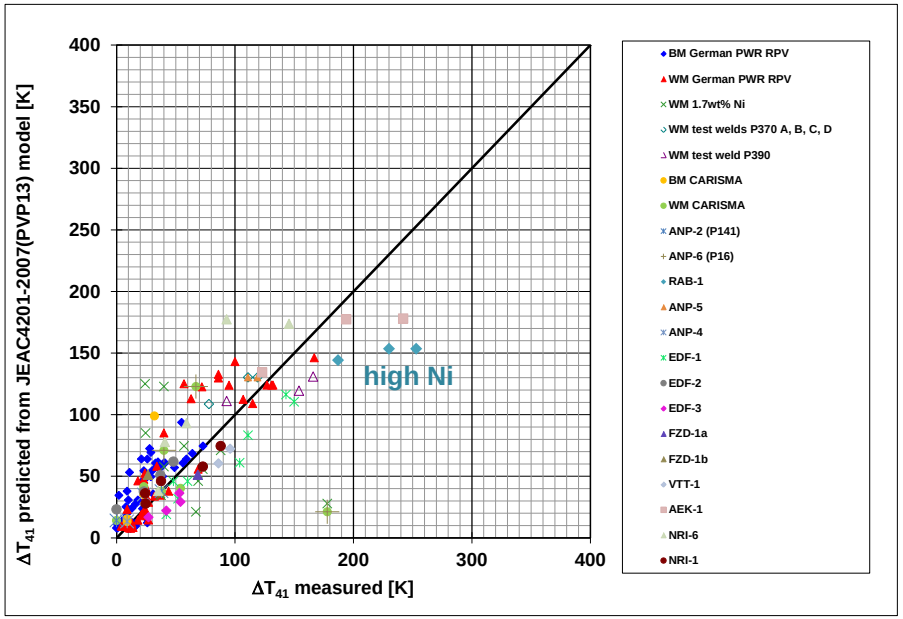
❑ Embrittlement Trend Curves (I)

- Several well-known ETC models are applied for irradiation embrittlement of selected SOTERIA materials
  - ASTM E900-02, FIM RSE-M, RG 1.99 Rev 2, 10CFR50.61a, WR(5), Erickson CVE (Fit 6), JEAC4201-2007

WR(5)



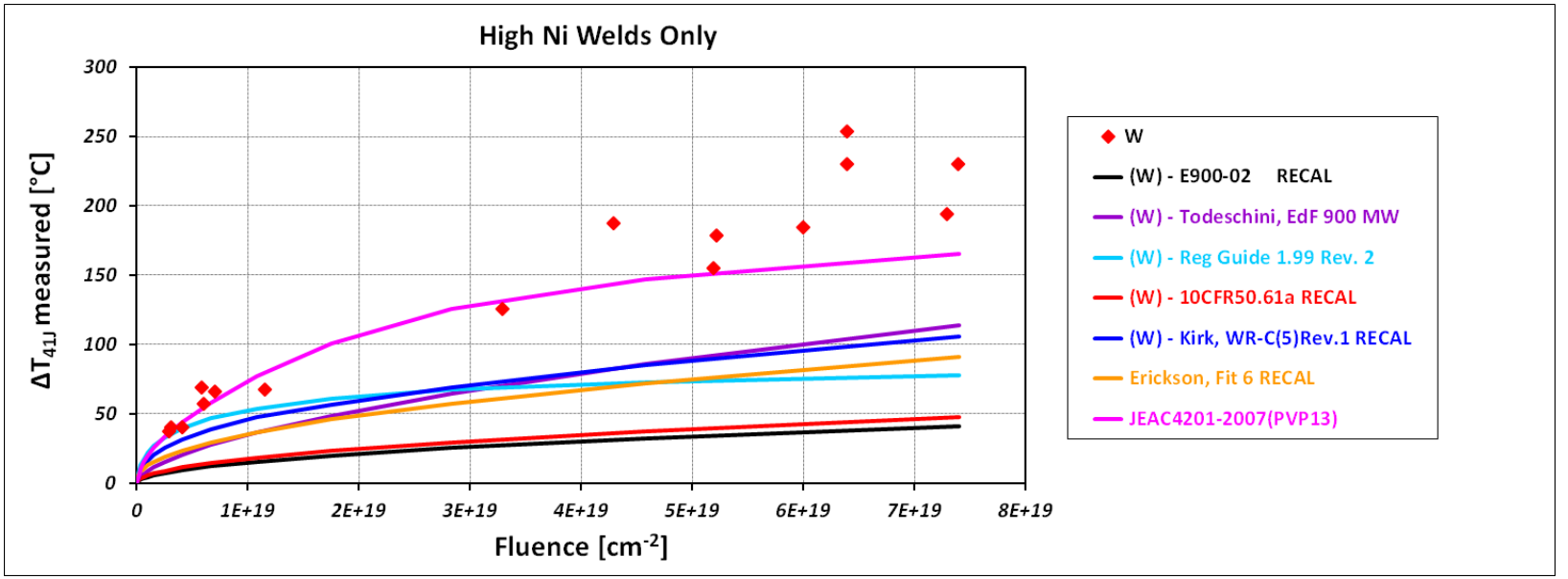
JEAC4201-2007



Selected preliminary results

❑ Embrittlement Trend Curves (II)

- ETC predictions need careful application rules depending on material conditions



Selected preliminary results

Identification of microstructural parameters relevant for predictive models (I)

- Basic needs of experimental data for the same material:
  - Tensile curve at different temperature (ideally one near T_0 and enough other temperatures to estimate change in properties with temperature) and irradiation dose (as tested).
  - Spatial & size distribution of carbides (assuming these are initiators)
  - Experimental toughness obtained at different temperatures and doses (for the identification of Beremin or MIBF parameters in function of the temperature)
  - Information on tests performed to determine toughness (i.e. specimen type, size, crack depth etc)

- Any unusual/extreme results:
  - Any unusual tensile behaviour / characteristics
  - Nature/size/location of the initiator
  - Any particles that didn't fail that maybe should / any particles that failed and didn't cause cleavage

- Some approaches include additional specific information:
  - Information on typical grain sizes (average/max/min)
  - Location of particles in proximity to the grain boundaries
  - Note that some models may consider variation in properties, so an idea of possible distribution of tensile properties, i.e. mean, max, min yield / UTS etc (for one temp / dose condition at a minimum)

Selected preliminary results

- Identification of microstructural parameters relevant for predictive models (II)
  - Analysis techniques Atom Probe Tomography (APT), Transmission Electron Microscopy (TEM), Electron Backscatter Diffraction (EBSD) and Small Angle Neutron Scattering (SANS):
    - chemical composition of the solid solution (which determines the friction stress) – APT
    - the average dislocation density (responsible for the forest hardening) – TEM
    - the grain size of the material (inducing the Hall-Petch effect) – TEM
    - grain size distributions and grain hierarchy – EBSD
    - distribution of carbides or inclusions (for mechanical behavior but also for fracture models) – APT, TEM
    - irradiation defects (in general) and evolution of nano-features with neutron fluence as a physical basis to ETCs – APT, TEM, SANS

Selected preliminary results

- Applications and guidance for handling and mitigation of uncertainties will cover following issues
  - Material properties
    - As-received micro and macrostructure and vessel manufacturing (heterogeneities)
    - Effects of inclusions
    - Chemical composition
    - Removal position
  - Environmental effects
    - Neutron flux and fluence
    - Neutron spectrum
    - Irradiation temperature
    - Thermal aging
  - Synergistic effects
    - Late irradiation effects
  - Surveillance programs
    - Representativeness of specimens, neutron flux and fluence, irradiation temperature, specimen types
  - Experimental method and analysis
    - Testing conditions
    - Evaluation of test results
    - Non-destructive characterization and techniques
    - Characterization of irradiation induced damage
  - Predictive models
    - Embrittlement trend curves (ETC) and predictive models
    - Multiscale modeling

Summary and Conclusions

- Studies are ongoing in SOTERIA WP3 on effects of additional uncertainties and handling and mitigation of uncertainties
- To improve the prediction of radiation induced ageing phenomena in RPV steels from an end-user perspective by improvement of the applicability of the use of modelling tools and ETCs, and surveillance data
- A number of important effects of uncertainties were identified
- Applications and guidance for handling and mitigation of uncertainties will be issued at the end of SOTERIA
- A summary of obtained results will be given on international symposium Fontevraud 9, 17-20 September 2018 in Avignon, France

The SOTERIA Consortium

SOTERIA

cea — DE LA RECHERCHE À L'INDUSTRIE

IRSN — INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

ÚJV

KTH VETENSKAP OCH KONST

ARTS ET MÉTIERS ParisTech

EDF

VATTENFALL

UPC — UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

grupo tecnatom

PAUL SCHERRER INSTITUT PSI

VTT

ARTTIC — INTERNATIONAL MANAGEMENT SERVICES

AREVA

Centrum výzkumu Řež s.r.o. Research Centre Rez

framatome

MANCHESTER 1824 The University of Manchester

wood.

PHIMECA — Solutions for robust engineering

HZDR — HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

SCK•CEN — STUDIECENTRUM VOOR KERNENERGIE CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

European Commission

GOBIERNO DE ESPAÑA — MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat — Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

cnrs

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This project received funding under the Euratom research and training programme 2014-2018 under grant agreement N° 661913.