Impact of Thermal Ageing on the LTO of VVER Piping and Components

Maksym Zarazovskii (IPP-Centre), Radim Kopriva (ÚJV Řež, a. s.), Ildiko Szenthe (EK-CER), Petra Gavelova (CVR Řež), Jari Lydman (VTT), Viktor GÁL (BZN), Marek Adamech (VUJE)

PWR Prague 2026 Conference
20-21 October 2026

DELISA LTO
DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

Funded by the European Union

Content



- Introduction to thermal ageing
- Thermal ageing monitoring for WWER components and piping
- Study the thermal ageing within the EU funded DELISA-LTO project
  - Experimental methodology
  - Result and Discussion
- Conclusions and lessons learned

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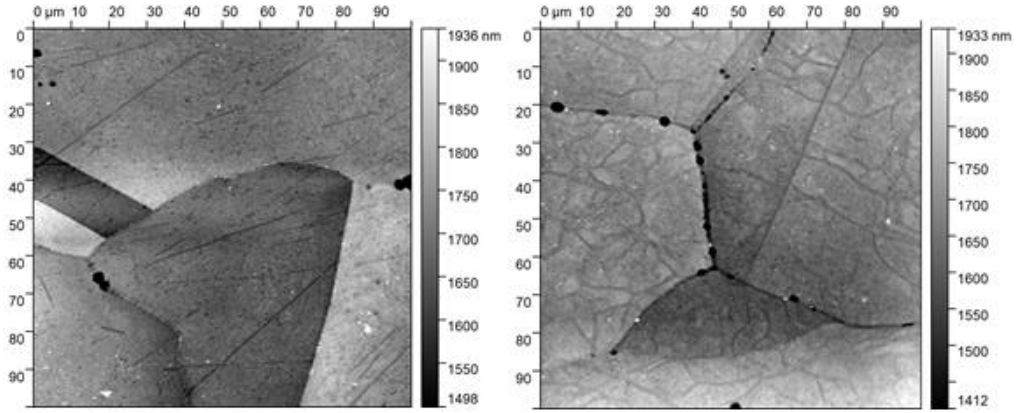
Intro. Thermal ageing

Mechanisms of thermal ageing (literature background)

In some materials a diffusion-controlled precipitation mechanism is active even at service temperatures. This process called thermal aging leads to a loss of ductility, deformability and toughness. The significant parameters responsible for these processes are:

main factors

– temperature;
– material state (microstructure, type of steel);
– time.



The conditions required for thermal aging include having an "unstable" material (with a quenched structure in particular) in which the atoms are able to rearrange themselves by diffusion. The rate of diffusion is higher for bainitic low-alloy steels or ferritic and martensitic (body-centered cubic) stainless steels than for austenitic steels or alloys (face-centered cubic structure).

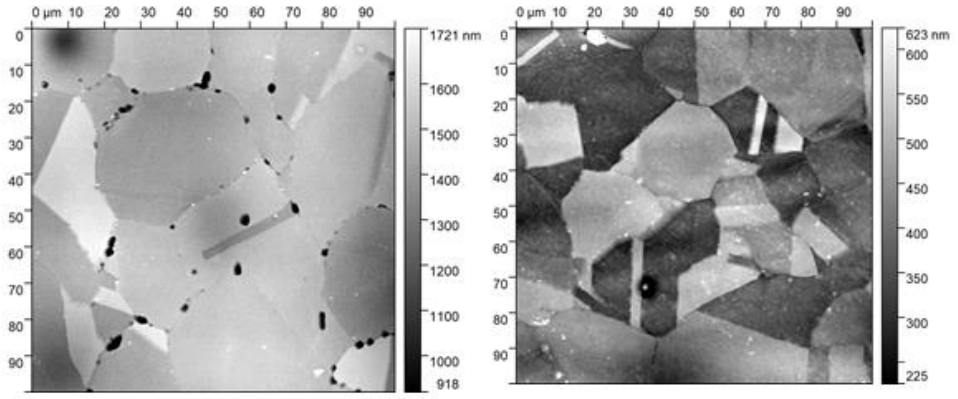
Intro. Thermal ageing

Mechanisms of thermal ageing (literature background)

The two main phenomena causing thermal aging are:

– intergranular segregation of phosphorus in martensitic and bainitic steels

– "unmixing" of chromium from its solid solution in the ferrite of duplex austenitic-ferritic stainless steels and in martensitic stainless steels



RPV materials and low alloy steels. Number of processes could lead to the embrittlement these steels subjected to long-term service at elevated temperatures. These processes include: formation of hardening phases, such as copper-rich precipitates; segregation of phosphorus to grain boundaries leading to a lower intergranular fracture stress; and segregation of impurities to dislocations leading to strain aging.

Thermal ageing of cast stainless can lead to precipitation of additional phases in the ferrite, e.g. formation of Cr-rich α–prime, phase by spinodal decomposition; nucleation and growth of α -prime; precipitation of a Ni- and Si-rich phase, and growth of existing carbides at the ferrite/austenitic phase boundaries.

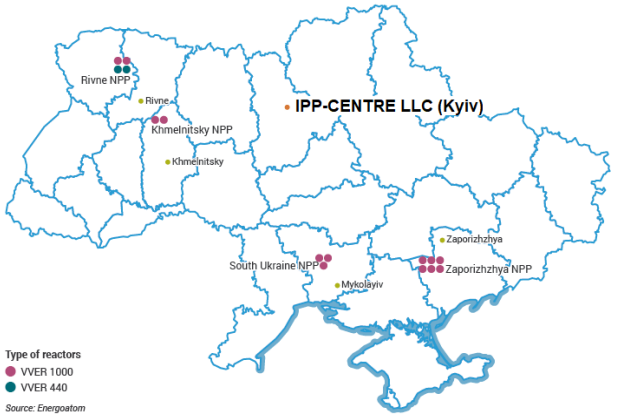
Service Lifetime of Ukrainian NPPs



Zaporizhua NPP



South-Ukrainian NPP





Rivne NPP



Khmelnytskiy NPP

NPP	Unit #	Electric Power,MW	Type	Operation started	End of design life	Extended till
KhNPP	1	1000	V-320	22.12.1987	13.12.2018	The service life has been extended till 31.12.2029 New works are underway
	2	1000	V-320	07.08.2004	07.09.2035	—
RNPP	1	440	V-213	22.12.1980	22.12.2010	The service life has been extended till 22.12.2030
	2	440	V-213	22.12.1981	22.12.2011	The service life has been extended till 22.12.2031
	3	1000	V-320	21.12.1986	11.12.2017	The service life has been extended till 11.12.2037
	4	1000	V-320	10.10.2004	07.06.2035	—
SUNPP	1	1000	V-302	31.12.1982	02.12.2013	The service life has been extended till 02.12.2033
	2	1000	V-338	09.01.1985	12.05.2015	The service life has been extended till 31.12.2025 New works are underway
	3	1000	V-320	20.09.1989	10.02.2020	The service life has been extended till 10.02.2050
ZNPP	1	1000	V-320	10.12.1984	23.12.2015	The service life has been extended till 23.12.2025 New works were planned until 2022…
	2	1000	V-320	22.07.1985	19.02.2016	The service life has been extended till 19.02.2026 New works were planned until 2022…
	3	1000	V-320	10.12.1986	05.03.2017	The service life has been extended till 05.03.2027
	4	1000	V-320	18.12.1987	04.04.2018	The service life has been extended till 04.04.2028
	5	1000	V-320	14.08.1989	27.05.2020	The service life has been extended till 27.05.2030
	6	1000	V-320	19.10.1995	21.10.2026	The works were planned in 2022…

Thermal ageing of the WWER RPV

Approaches for RPV thermal ageing

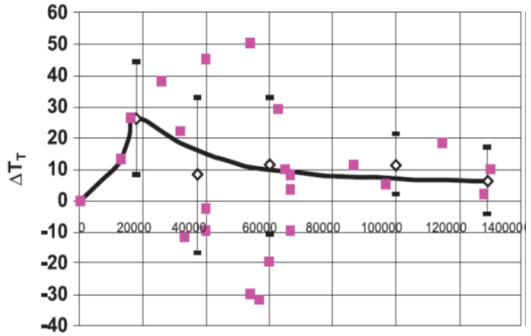
Thermal embrittlement

RPV zone	ΔT_T, ºC			
	SOU NAEK 087:2023	PNAE G-7-002-86	MRKR-CKhR-2004	VERLIFE
Base material	0	0	30	30 $t \geq 1\times10^5$ hours
Weld	0	0	0	–

Primary circuit material	ΔT_T, ºC
10GN2MFA	10
10GN2MFA (Weld)	10
38KhN3MFA	30*
10KhN1M	10
10KhN1M (Weld)	20
22K	30
22K (Weld)	20

30* - maximum value taken from PNAE G-7-002-86

TSNIINMASH data



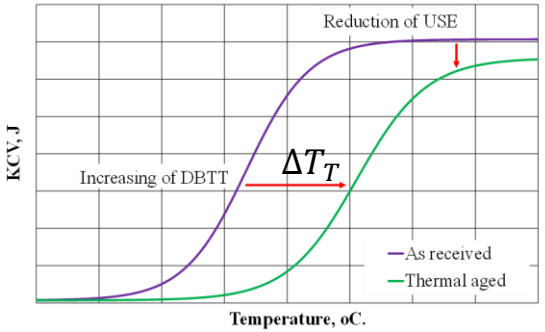
Time of ageing, hours

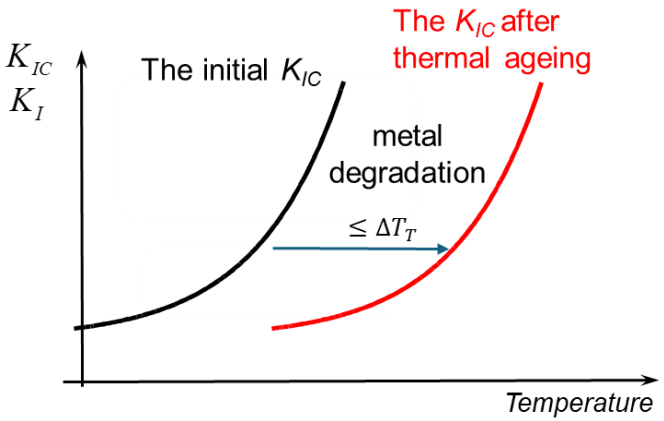
PNAE empiric formula for thermal embrittlement

$$\Delta T_T = \Delta T_T^{lim}\left[1 - e^{(-p\cdot t)}\right]$$

$$\Delta T_T = 49.982 - 46.366\left[1 - e^{-0.000185\cdot t}\right]$$

3.6°C for 60 years





Hardening in accordance with the PNAE, (change in Yield and Ultimate stress) is not considered for LTO

Thermal ageing monitoring

Hardness measurements followed by mechanical properties recalculation

SOU-N NAEK 133:2023

Material	Restriction	Mech. propert.	Equation
Ст3сп5, 10, 15, 20, 20К, 22К, 15Л, 20Л, 25Л, 15ГС, 16ГС *	HB>140	$R_{p0,2}$	3,4 HB -175
	HB<140	$R_{p0,2}$	2,15 HB
	no restrict.	R_m	$8,8\times10^{-4}HB^2 + 2,66HB + 103$
		A_5	$3,0\times10^4 / (2R_m + R_{p0,2})$
		Z	$1,9\times10^5 / (R_m + R_{p0,2} + 2000)$
16ГНМА, 16ГНМ, 10ХСНД, 12МХ, 12ХМ, 15ХМ, 20ХМ, 20ХМА, 10Х2М, 10ХН1М, 12Х1МФ, 15Х1М1Ф, 12Х2МФА, 18Х2МФА, 15Х3НМФА, 15Х3НМФА-А, 36Х2Н2МФА, 38ХН3МФА*	HB>200	R_m	3,4 HB - 90
		$R_{p0,2}$	3,6 HB - 240
	HB<200	R_m	2,5 HB + 90
		$R_{p0,2}$	2,4 HB
	no restrict.	A_5	$4,2\times10^4 / (2 R_m + R_{p0,2})$
		Z	$2,3\times10^5 / (R_m + R_{p0,2} + 2000)$
08Х18Н9, 09Х18Н9, 10Х18Н9, 12Х18Н9, 08Х18Н10, 12Х18Н9Т, 06Х18Н10Т, 08Х18Н10Т, 08Х18Н10Т-ВД, 08Х18Н10ТЛ, 12Х18Н10Т, 08Х18Н12Т, 12Х18Н12Т, 08Х16Н11М3, 10Х18Н9ТЛ, 08Х18Н12ТФ, 12Х18Н9ТЛ	no restrict.	R_m	1.9HB + 250
		$R_{p0,2}$	1,7 HB
		A_5	$7,5\times10^4 / (2R_m + R_{p0,2})$
		Z	$1,8\times10^5 / (R_m + R_{p0,2} + 2000)$
Austenitic welds	no restrict.	R_m	1, 9HB + 250
		$R_{p0,2}$	2,2 HB
		A_5	$6,8\times10^4 / (2 R_m + R_{p0,2})$
		Z	$1,8\times10^5 / (R_m + R_{p0,2} + 2000)$
15Х2МФА, 15Х2МФА-А, 15Х2НМФА-А, 15Х2НМФА	no restrict.	R_m	3,5 HB - 105
		$R_{p0,2}$	3,8 HB - 290
		A_5	$4,2\times10^4 / (2 R_m + R_{p0,2})$
		Z	$2,3\times10^5 / (R_m + R_{p0,2} + 2000)$
10ГН2МФА	no restrict.	R_m	2,2 HB + 180
		$R_{p0,2}$	2,45 HB
		A_5	$4,2\times10^4 / (2 R_m + R_{p0,2})$
		Z	$2,3\times10^5 / (R_m + R_{p0,2} + 2000)$

Mechanical property	Formula error, %	
	Base material	Welds
Ultimate stress, R_m	±10	±15
Yield stress, $R_{p0,2}$	±15	±20
Elongation, A_5	±20	±20
Reduction of Area, Z	±30	±30

+

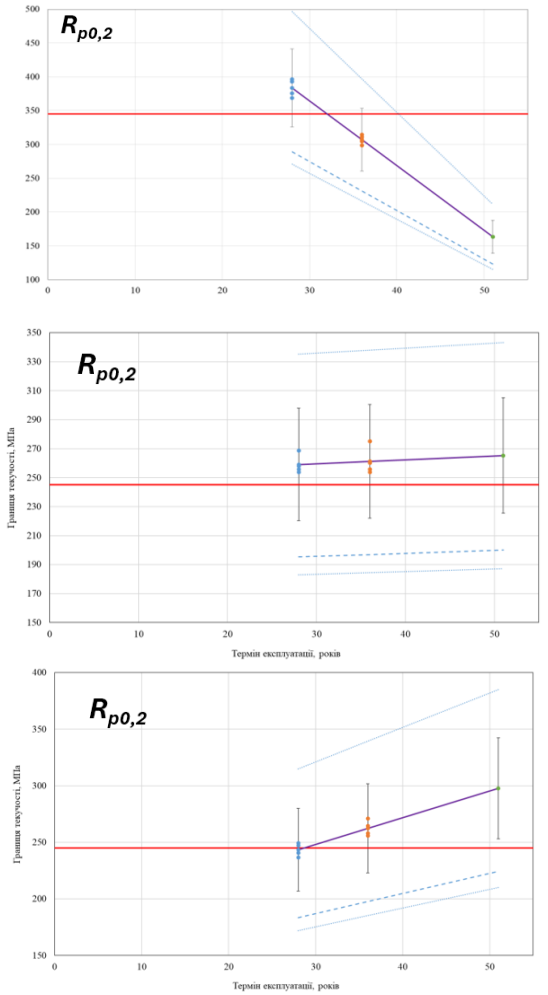
Hardness data scatter

+

Error of hardness measurement device

=

large uncertainty



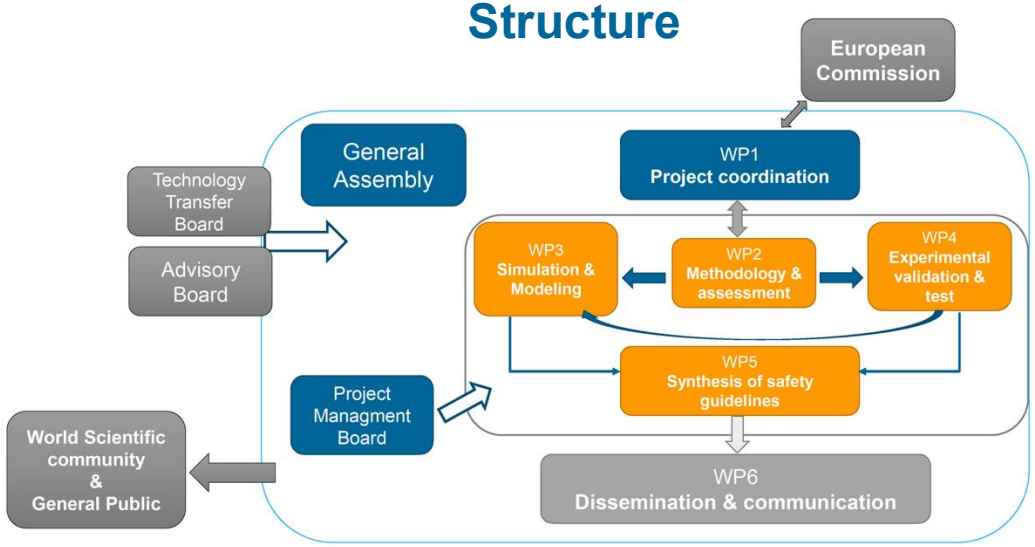
EU funded DELISA-LTO project main goals and structure

Providing “on-time” the effective tools and techniques for safe LTO with as non-destructive as possible way by combining the existing knowledge in three key areas: destructive testing, NDT and simulations.

Consortium



Structure



- To develop a tool for assessment of the LWR NPP's life-time prolongation
- To provide the set of recommendations for the future LTO related assessments based on the main project outputs
- To harmonize the national methodologies and techniques in order to obtain the generally acceptable set of recommendations for the assessment of the **thermal ageing** from the LTO point of view

Materials form WWER-1000 and WWER-440 NPPS



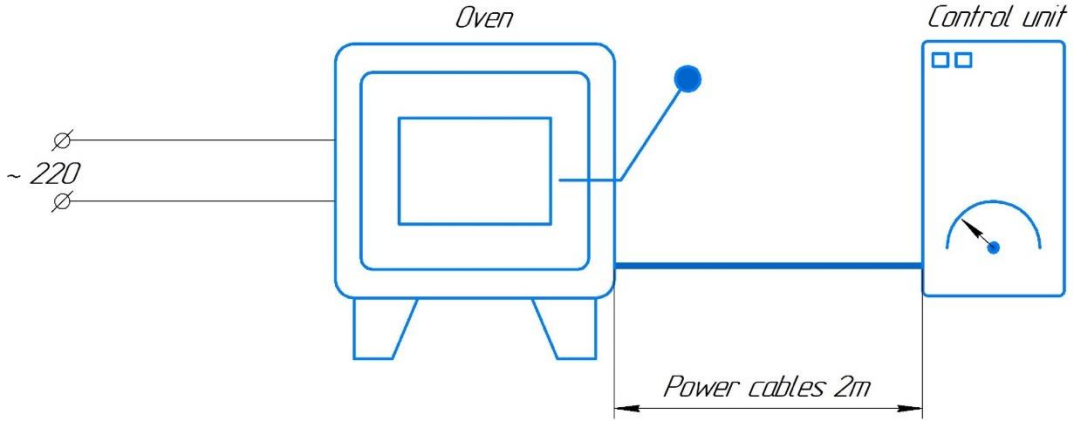
Material and experimental matrix

DELISA-LTO – WP2/WP4 Experimental matrix				Experimental Technique	A1 - Impact testing						A2 - Tensile Testing					A3 - Static Fracture Toughness										A4 - Hardness								A5 - SPT			A6 - Scanning Electron Microscopy					A7 - Optical Microscopy					A8 - TEM			A9 - Other methods								
				Available / Participating Laboratory	CVR		IPP		EK-CER	UJV	VTT	IPP	EK-CER	UJV	VTT	BZN	IPP		EK-CER	UJV		VTT		BZN		CVR	IPP	STUBA	EK-CER	UJV	VUJE	VTT	BZN		IPP	UJV	VUJE		CVR	STUBA	EK-CER	VUJE	VTT		CVR	STUBA	EK-CER	VUJE	VTT		CVR	STUBA	VTT		STUBA		VUJE		CVR			
Material No.		Material (description, *provider, operational temperature*)	Material Type	Material state / Specimen geometry	M	ST	M	ST	ST	M	M	ST	ST	ST	ST	ST	ST	M	ST	ST	M	ST	M	ST	M	ST	ST	M	ST	ST	ST	ST	ST	M	M	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1		**Main circulation piping - 08Ch18N12T** - NPP V1 – initial state *(VUJE)* - *Top* = 294 °C	BM	As received	■	■	-	-	■	■	■	■	-	■	■	■	■	■	-	■	■	-	■	■	■	■	■	■	■	-	■	■	■	■	-	■	■	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 2165 hours)	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	■	-	■	■	-	■	■	-	-	-	-	-	■	-	■	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	■	■	■
2		**Pressurizer surge line - 08Ch18N10T** - NPP EBO3 – initial state *(VUJE)* - Top = 276 °C	BM	As received	■	-	-	-	■	■	■	-	-	■	■	■	-	-	-	■	■		■	■	■	■	-	■	-	■	■	■	■	-	■	■	-	-	■	-	■	■	-	■	-	■	■	-	■	■	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 1085 hours)	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	■	■	-	■	■	■	■	■	-	-	-	-	-	■	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	■
3	3a	**Main circulation piping - 08Ch18N12T+WM** - NPP V1 – after 28 years in operation *(VUJE)* - Top = 294 °C	BM	As received	■	-	-	-	■	■	■	-	-	■	■	■	-	-	-	■	■	■	-	-	-	■	-	■	-	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 2474 hours)	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3b		WM	As received	-	■	-	-	■	■	■	■	-	■	■	■	■	■	-	■	■	■	-	-	-	■	■	■	-	■	■	■	■	■	■	■	-	■	■	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	■	■	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	■	-	-	-	-	-	■	-	-	-	-	■	■	-	-	■	-	-	-	-	■	■	-	-	-	-	-	■	-	■	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
	3c		HAZ	As received	-	■	-	-	■	■	■	N/A					-	-	-	■	■	-	-	-	-	■	■	■	-	■	■	■	■	-	■	■	-	■	■	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	■	■	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	■	-	-	-	-	-						-	-	-	-	-	-	-	-	-	■	■	-	-	-	-	-	-	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
4	4a	**Main circulation piping – triple T-junction - 08Ch18N12T+WM** - NPP V1 – after 28 years in operation *(VUJE)* - Top = 294 °C	BM	As received	-	-	-	■	-	-	-	-	■	-	-	■	-	-	■	-	-	-	-	-	-	-	-	■	■	■	■	-	-	-	-	■	■	-	-	■	■	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	-	-	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4b		WM	As received	-	-	-	■	-	-	-	-	■	-	-	■	-	-	■	-	-	-	-	-	-	-	-	■	■	■	■	-	■	-	-	■	■	-	-	■	■	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	-	-	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4c		HAZ	As received	-	-	-	-	-	-	-	N/A					-	-	-	-	-	-	-	-	-	-	■	-	-	■	-	■	-	-	-	■	-	-	■	-	■	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5		**Pressurizer surge line - 08Ch18N10T** - NPP V1 – after 28 years in operation *(VUJE)* - Top = 276 °C	BM	As received	■	■	-	-	-	-	-	■	-	■	■	■	■	■	-	■	■		■	-	-	-	■	■	-	■	■	■	■	-	■	■	■	■	■	■	-	■	-	■	■	-	■	■	-	■	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 1240 hours)	■	■	-	-	-	-	-	■	-	-	-	■	■	■	-	-	■	-	-	-	-	-	-	■	-	-	-	■	-	-	■	■	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	■
6		**WWER-1000 - Reactor flange fastening parts** after 30 years in operation *(IPP-C)* - Top = 240 - 305 °C	BM	As received	-	■	-	-	-	-	-	■	-	-	-	-	■	■	-	-	-	-	-	-	-	-	■	■	-	-	-	-	-	■	■	■	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	■	■	-
				Thermal Aged (450 °C / 252-3465 hours)	-	■	-	-	-	-	-	■	-	-	-	-	■	■	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	-
7		**WWER-1000 - Steam generator collector with HE tubes** - 08Ch18N10T - operated *(IPP-C)*	BM	As received	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	-	-	■	-	-	■	-	■	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	■	■	-
8		**WWER-1000 - Main circulation piping** - 10GN2MFA+SS cladding - NPP V1 – initial state *(IPP-C)* - Top = 290 °C	BM	As received	-	■	-	■	■	■	-	■	■	■	■	■	■	■	-	-	■	■	-	-	-	-	■	■	■	■	■	■	-	■	■	■	-	-	■	■	-	-	-	■	■	-	-	-	-	■	■	■	■	■	■	■	-
				Thermal Aged (450 °C / 3994 hours)	-	■	-	■	-	-	-	■	■	-	-	-	■	■	■	-	-	-	-	-	-	-	-	■	-	■	-	-	-	-	■	■	■	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	-
9	9a	**WWER-440 - Capsules** of the thermal specimens used in Paks NPP (2 pcs), 08Ch18N10T - 24 years in operation *(EK-CER)* - Top = 278 °C	BM	As received								-	■	-	-	-	N/A								-	-	■	-	-	-	-	-	-	-	■	■	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
				Thermal Aged (450 °C / 1510 hours)								-	■	-	-	-									-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9b	**WWER-440 - Capsules** of the thermal specimens used in Paks NPP (2 pcs), 08Ch18N10T - 32 years in operation *(EK-CER)* - Top = 278 °C	BM	As received								-	■	-	-	-	N/A								-	-	■	■	-	-	-	-	-	■	-	■	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
				Thermal Aged (450 °C / 1174 hours)								-	■	-	-	-									-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10		**WWER-440 - Main circulation pump** - Guide wheel - 10H18N9TL - 27 years in operation *(EK-CER)*	BM	As received	-	-	-	-	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	■	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	■	■	-	-	-	-	-	-	-	-	-	-

Artificial thermal ageing



№	Characteristics	Value
1	T_{max},°C	1100
2	Temperature stability, °C	±4
3	Power, kW	3.3
4	Temperature maintenance power, kW	0.5
5	Volume, l	20





Arrhenius approach

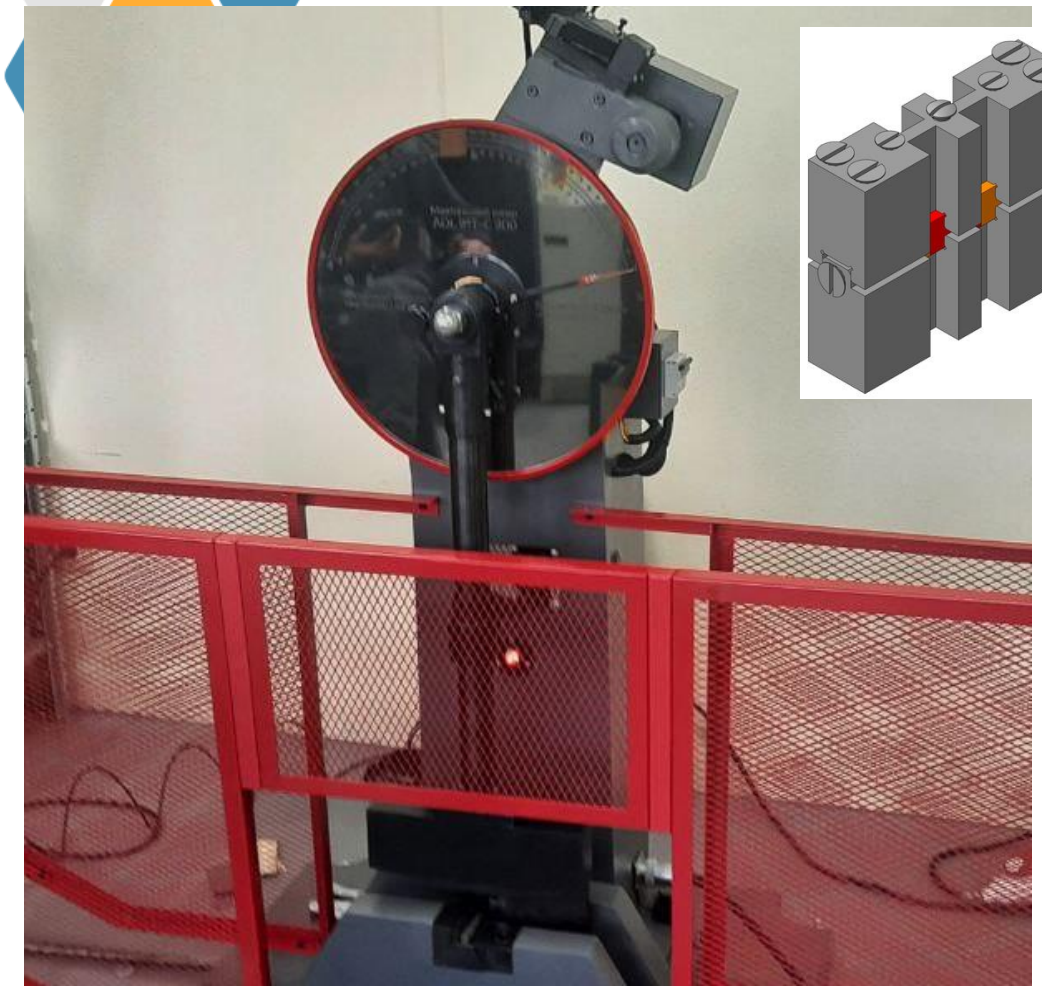
$$\frac{t_1}{t_2} = \exp\left[\frac{Q}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

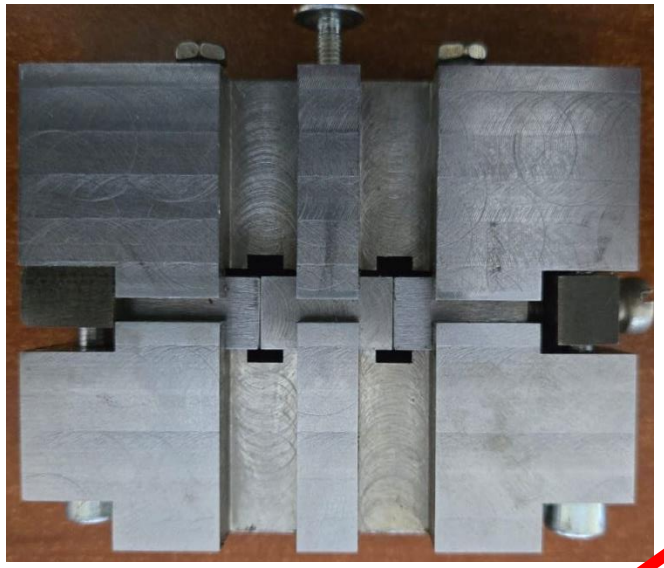
$$T_2 = 723\ \text{K}$$

$$t_2 = 252\ to\ 3944\ hours$$

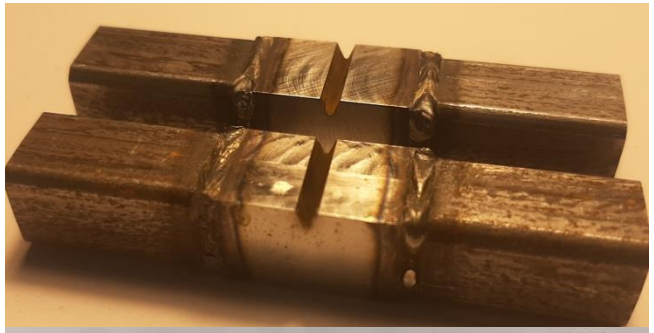
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Charpy V-notch Impact testing











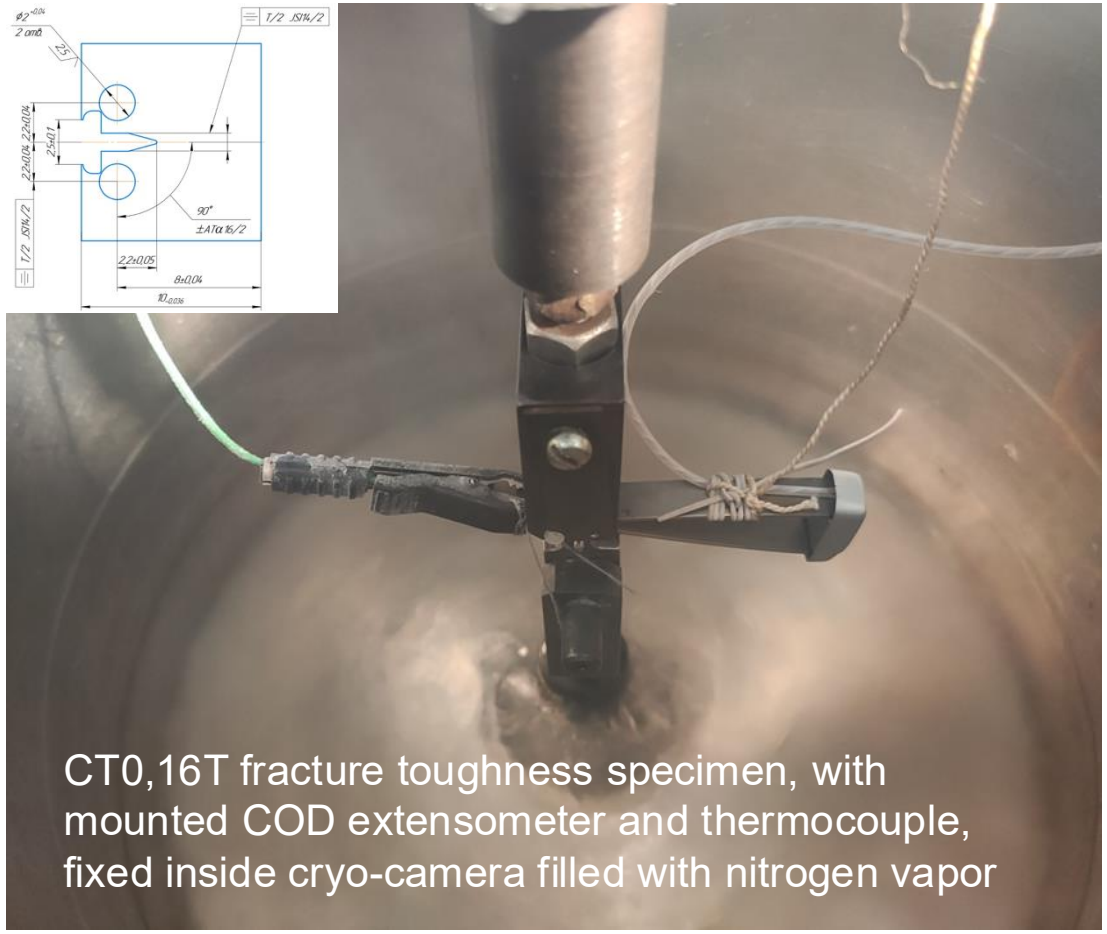




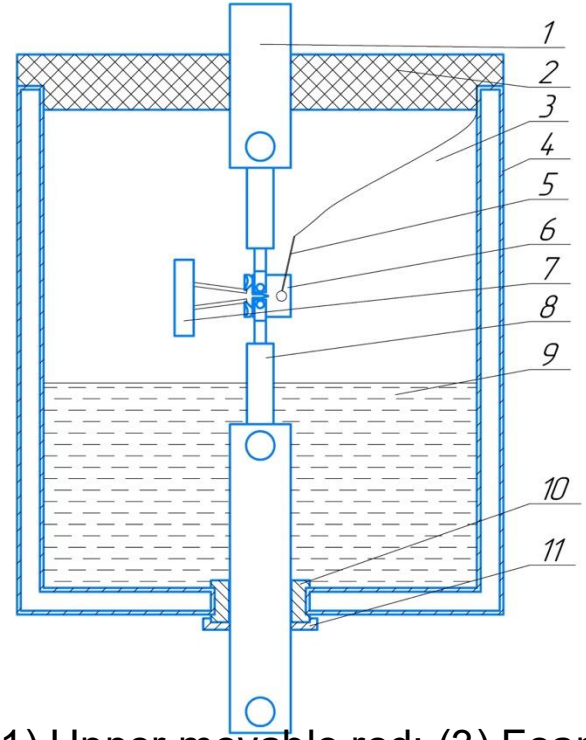
Static Fracture Toughness Testing

The technique for the tensile Fracture Toughness tests at cryogenic temperatures has been worked out.





CT0,16T fracture toughness specimen, with mounted COD extensometer and thermocouple, fixed inside cryo-camera filled with nitrogen vapor



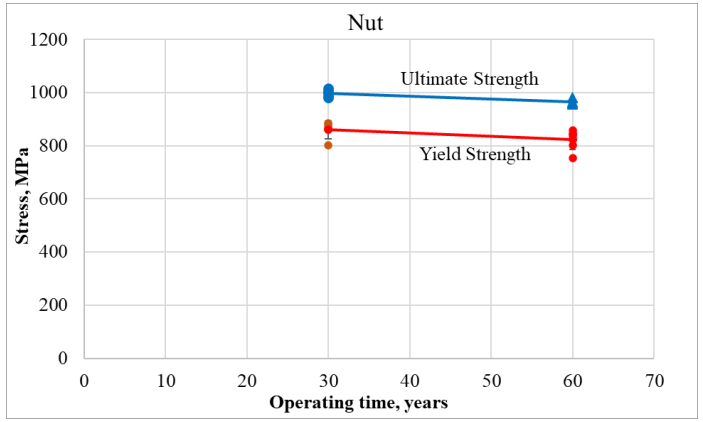
(1) Upper movable rod; (3) Foam cover; (4) Nitrogen vapor; (5) Metal body; (7) Thermocouple; (8) Specimen; (10) Extensometer; (11) Liquid nitrogen; (13) Lower fixed rod; (15) Sleeve; (17) Nut;

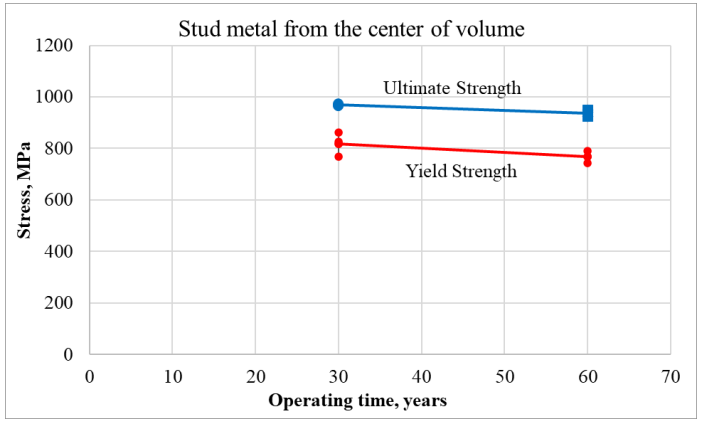
Experimental results to Tensile tests

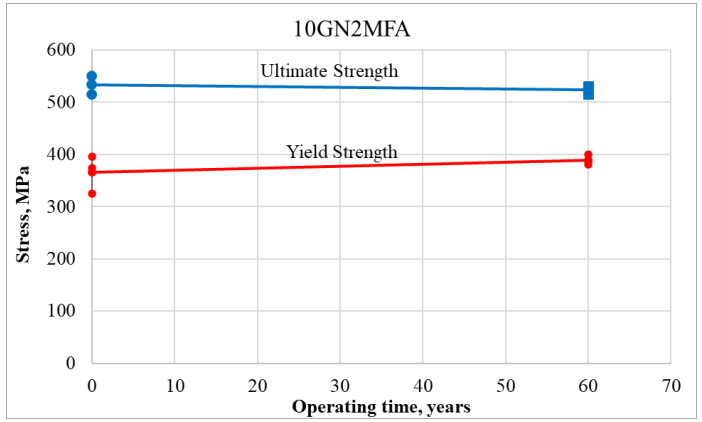
Mechanical properties of the investigated materials before and after artificial thermal ageing

Materials	Condition	Room temperature				Operating temperature			
		R_m, MPa	$R_{p0,2}$, MPa	A_5, %	Z, %	R_m, MPa	$R_{p0,2}$, MPa	A_5, %	Z, %
38KhN3MFA (1)*	As-received	1103±6	967±15	22±1	48±4	997±14	861±34	32±4	30±9
	Thermally aged	1078±9	967±11	20±2	46±4	965±9	824±39	28±6	27±7
38KhN3MFA (2)*	As-received	1098±10	965±11	24±1	35±2	982±5	838±48	34±3	32±2
	Thermally aged	1081±8	948±11	20±4	38±3	963±3	818±35	25±1	32±5
38KhN3MFA (3)*	As-received	1079±2	953±7	21±2	42±6	969±4	818±47	29±1	29±3
	Thermally aged	1066±8	935±13	24±1	44±1	938±12	767±24	26±3	35±5
10GN2MFA	As-received	591±3	429±12	37±2	73±2	533±18	365±36	46±12	72±1
	Thermally aged	585±16	410±27	36±1	71±3	524±8	389±10	48±3	66±2

(1) – Nut; (2) – stud metal near the thread turns; (3) – stud metal from the center of volume.

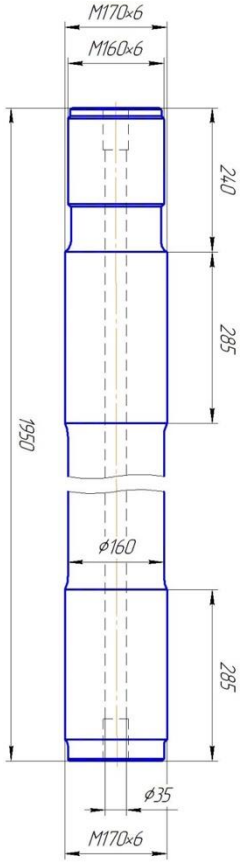




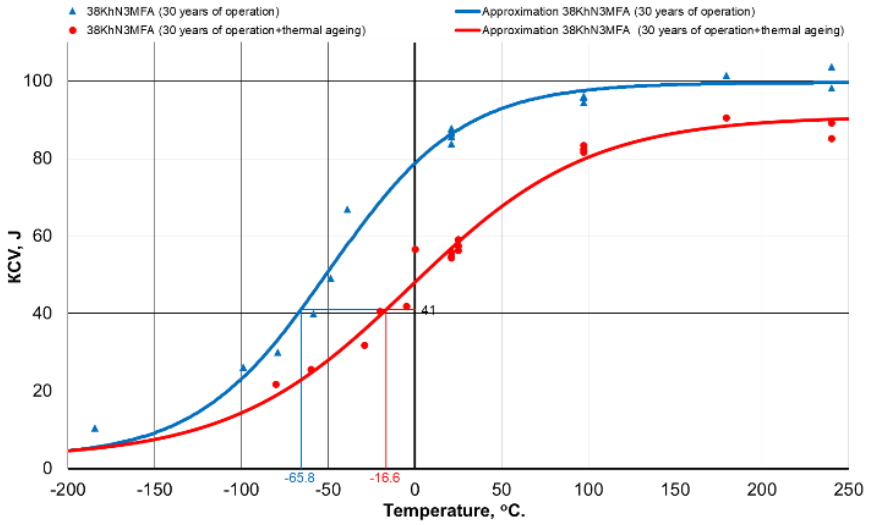


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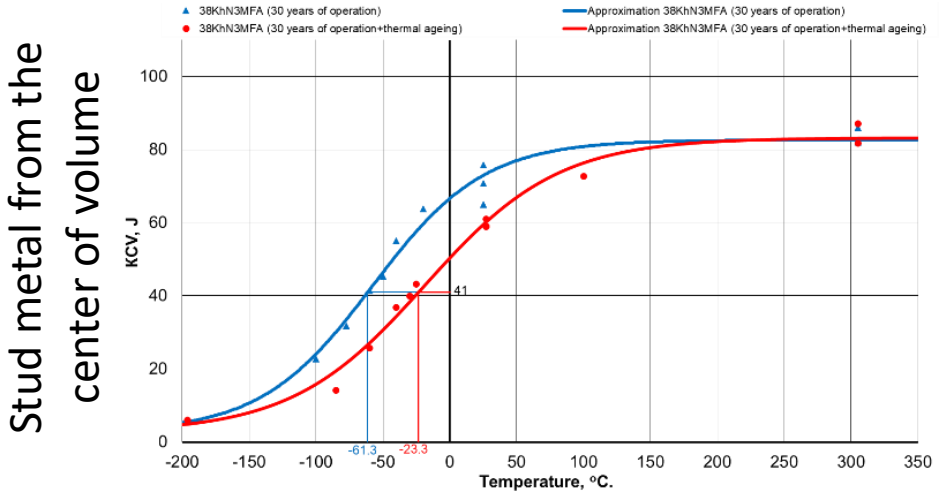
Experimental results to Charpy impact



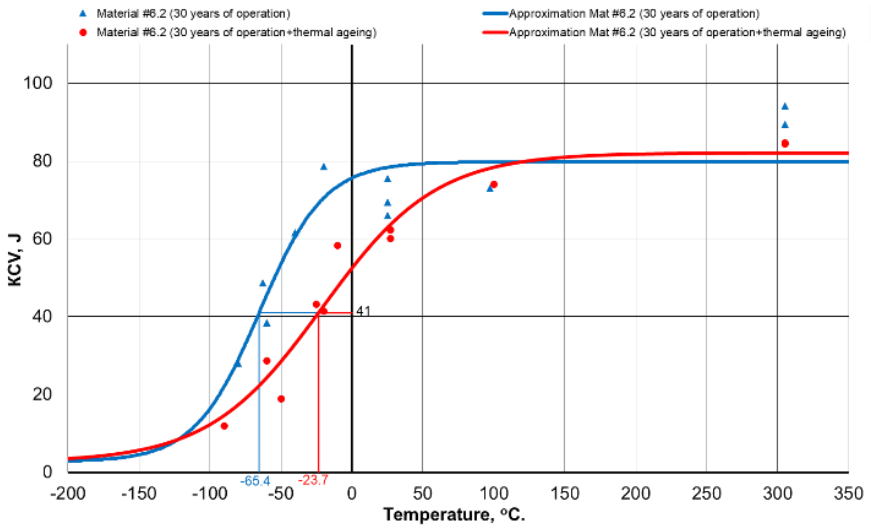
Nut



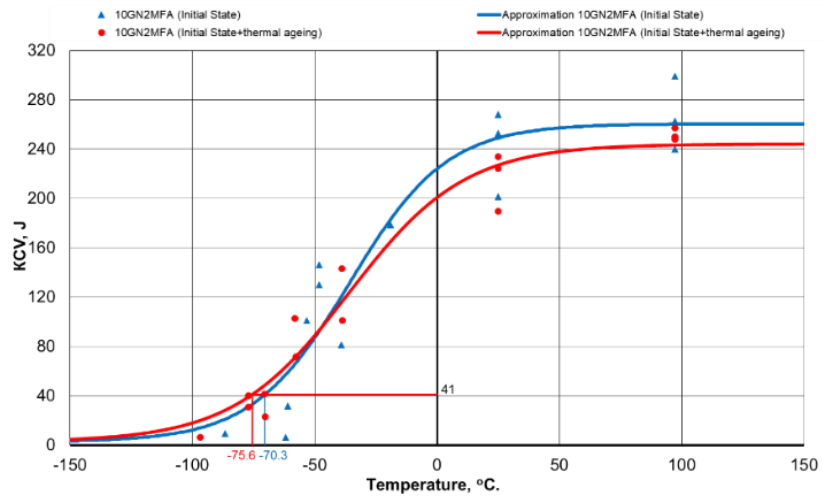
Stud metal from the center of volume



Stud metal near the thread turns



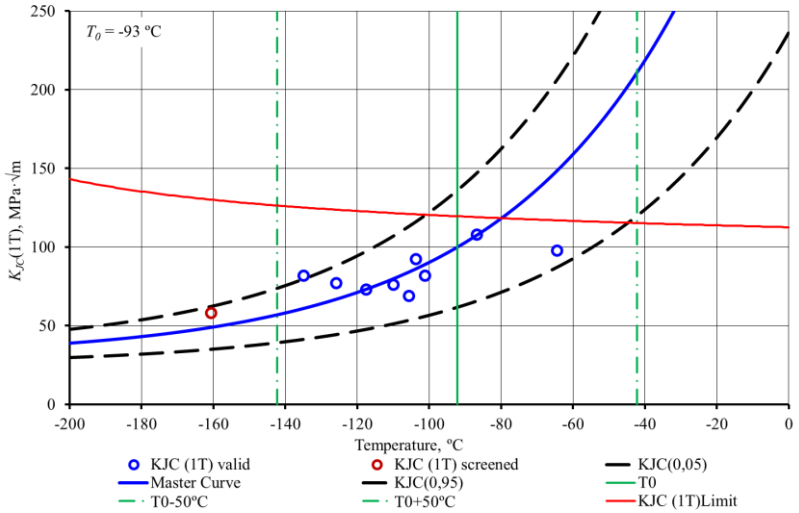
10GN2MFA steel



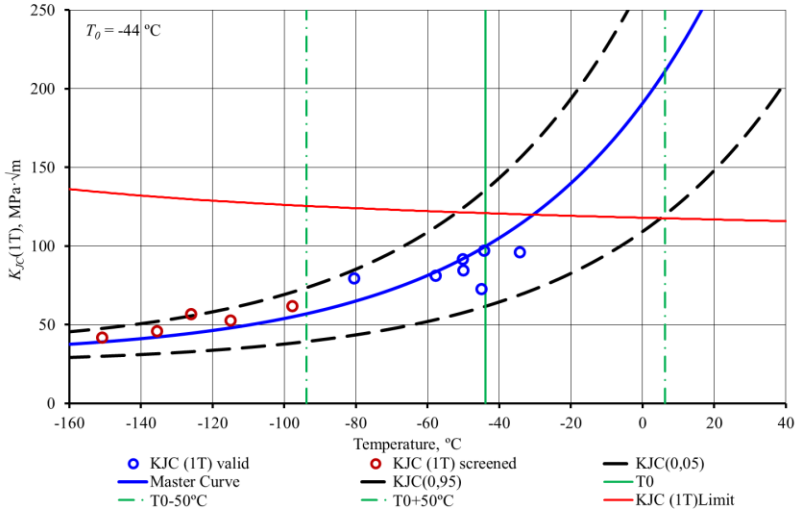
Static Fracture Toughness



Nut before thermal ageing

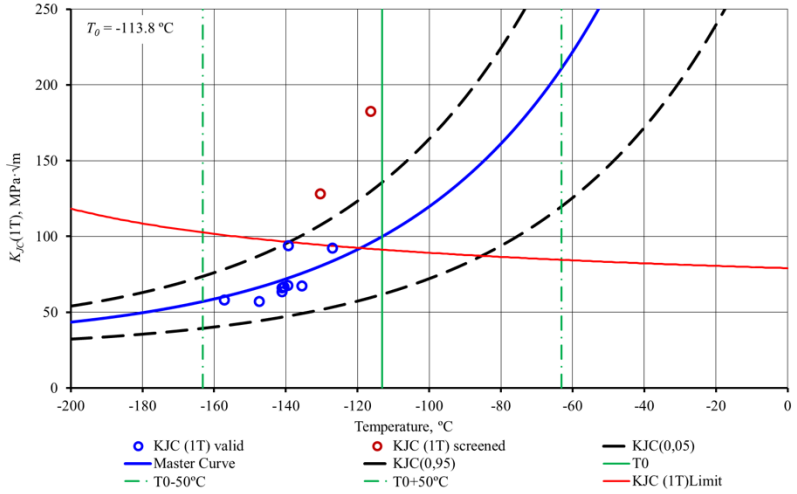


Nut after thermal ageing

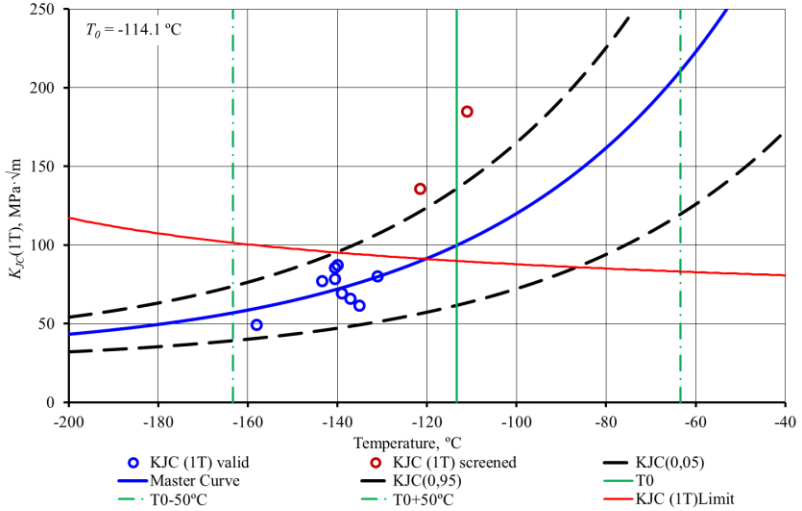




10GN2MFA – initial state

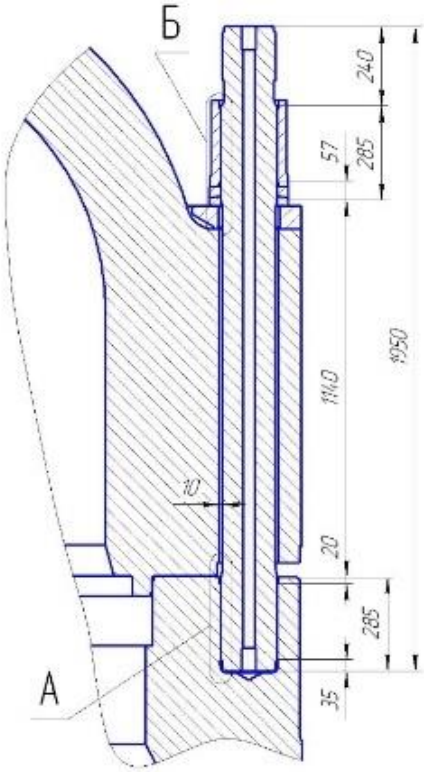


10GN2MFA steel after thermal ageing



Experimental results to Charpy impact

Summary of Charpy impact toughness results (T_k and USE) for all materials



Material	Condition	T_{41J}, °C	ΔT_{41J}, °C	T_K, °C	ΔT_K, °C	USE, J	ANL USE, Дж	НЗТ USE, Дж	Impact energy [J], 20 °C
38ХН3МФА (1)*	As-received	-65.8	49.2	-55.8	53.7	99.5	–	–	85.9
	Thermally aged	-16.6		-2.0		90.2	15.9	48.4	57.5
38ХН3МФА (2)*	As-received	-65.4	41.7	-58.0	46.9	79.8	–	–	70.3
	Thermally aged	-23.7		-11.1		82.0	14.7	62.4	61.5
38ХН3МФА (3)*	As-received	-61.3	38.0	-48.3	40.4	82.5	–	–	70.5
	Thermally aged	-23.3		-7.9		82.8	16.6	64.8	59.6
10ГН2МФА-IPP	As-received	-70.3	-5.3	-71.4	-5.6	260.5	–	–	257.5
	Thermally aged	-75.6		-77.0		244.1	96.5	0.6	216.0
10ГН2МФА- ЕК-СЕР	As-received	-82.5	22.3	-84.0	22.4	301.6	–	–	261.4
	Thermally aged	-60.2		-61.6		295.3	96.5	0.6	233.3

Footnote: (1) – Nut; (2) – stud metal near the thread turns; (3) – stud metal from the center of volume.

Conclusions regarding thermal ageing of DELISA materials (60 years)

Austenitic Materials

- Impact Energy: Thermal ageing causes a minor to moderate 1.16- to 1.26-fold drop in upper shelf energy for base material and welds. In general room temperature impact energy remains identical or close to operating temperature energy.
- Tensile Properties: Changes in UTS and YS are negligible for most grades (within experimental data scatter). Minor changes (2% to 14%) occur for some materials.
- Fracture Toughness: Base metals and welds maintain high structural stability with minimal thermal degradation through 60 equivalent years.

Ferritic Materials

- WWER-1000 stud and nut. Nut: Suffers severe thermal embrittlement. The transition temperature increases by nearly 50 °C, and the Master Curve reference temperature drops by 50°C, accompanied by a reduction in USE. Stud: WWER-1000 Stud: Displays a critical TT shift of 40 °C and a massive Master Curve reference temperature shift of 49 °C to 68 °C. This exceeds the 30 °C normative threshold of PNAE G-7-002-86, posing a challenge for LTO.
- Main Circulation Piping: Thermal ageing has a minor effect on WWER-1000 piping The TT shift is limited to 20 °C, the USE drop is only 5–15 J, and reference temperature changes are statistically negligible (<5.2 °C).
- Tensile Properties: Strength variations are minimal, though more noticeable in YS than UTS. Materials 6 and 10 show minor adjustments between 2% and 14% over 60 equivalent LTO years.

Impact on LTO

- Critical RPV Components: The severe thermal embrittlement of the WWER-1000 reactor stud and nut represents a high priority for long-term operation. The transition temperature shifts (40 °C to 50 °C) and Master Curve reference temperature shifts (up to 68 °C) directly violate the 30 °C normative threshold of PNAE G-7-002-86. This behavior requires updating regulatory guidelines and potentially implementing component replacement or localized monitoring strategies to ensure safe extension to 60 years and deep LTO especially.
- Primary Circuit Piping & Base Metals: The WWER-1000 main circulation piping and all evaluated austenitic base metals (08Kh18N12T and 08Kh18N10T) and welds show excellent structural stability. Degradation levels remain low or within experimental scatter through 60 equivalent years, meaning thermal ageing will not limit the life extension of these specific assets.

Lessons learnt for Thermal Ageing

1. Effects of thermal ageing became observed after 30 years of operation

2. Different models have certain limitations and are applicable for specific materials. In general, the selected models (ANL and Japanese) describe the 60-year LTO thermal ageing kinetics for Yield Stress and Ultimate Stress well enough for most materials.

3. ANL and Japanese models do not predict adequately Charpy impact energy and there are no models for TT and Master Curve T_0 predictions

4. Predictiveness of thermal ageing behavior at period 60+ requires clarification because thermal ageing process may speed up.

5. Further researches should be extended in part of:

   - Thermal ageing - predictiveness of thermal ageing behavior at period 60+

Thank you for attention!

DELISA LTO
DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

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