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Joint ICTP/IAEA Workshop on Irradiation-induced Embrittlement of Pressure Vessel Steels

23 - 27 November 2009

Irradiation Embrittlement Issues in WWER RPVs

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IRRADIATION EMBRITTLEMENT ISSUES IN WWER RPVs

Milan Brumovský

Joint ICTP/IAEA Workshop on Effects of Mechanical Properties and Mechanisms Governing the Irradiation-induced Embrittlement of Pressure Vessel Steels

23 - 27 November 2009

CONTENT

- INTRODUCTION
- OBJECTIVES FOR VVER RPVs
- VVER-440
- VVER-1000
- CONCLUSIONS

INTRODUCTION

- IRRADIATION EMBRITTLEMENT IS THE MOST PRONOUNCED AGEING MECHANISM PRACTICALLY IN ALL RPVs INCLUDING WWER
- IRRADIATION EMBRITTLEMENT MECHANISM IS PRACTICALLY THE DETERMINING DAMAGE MECHANISM FOR RPV SAFETY, INTEGRITY AND LIFETIME
- IRRADIATION EMBRITTLEMENT PLAYS AN IMPORTANT ROLE FOR VVER RPVs BECAUSE OF THEIR VERY LARGE NEUTRON FLUENCES

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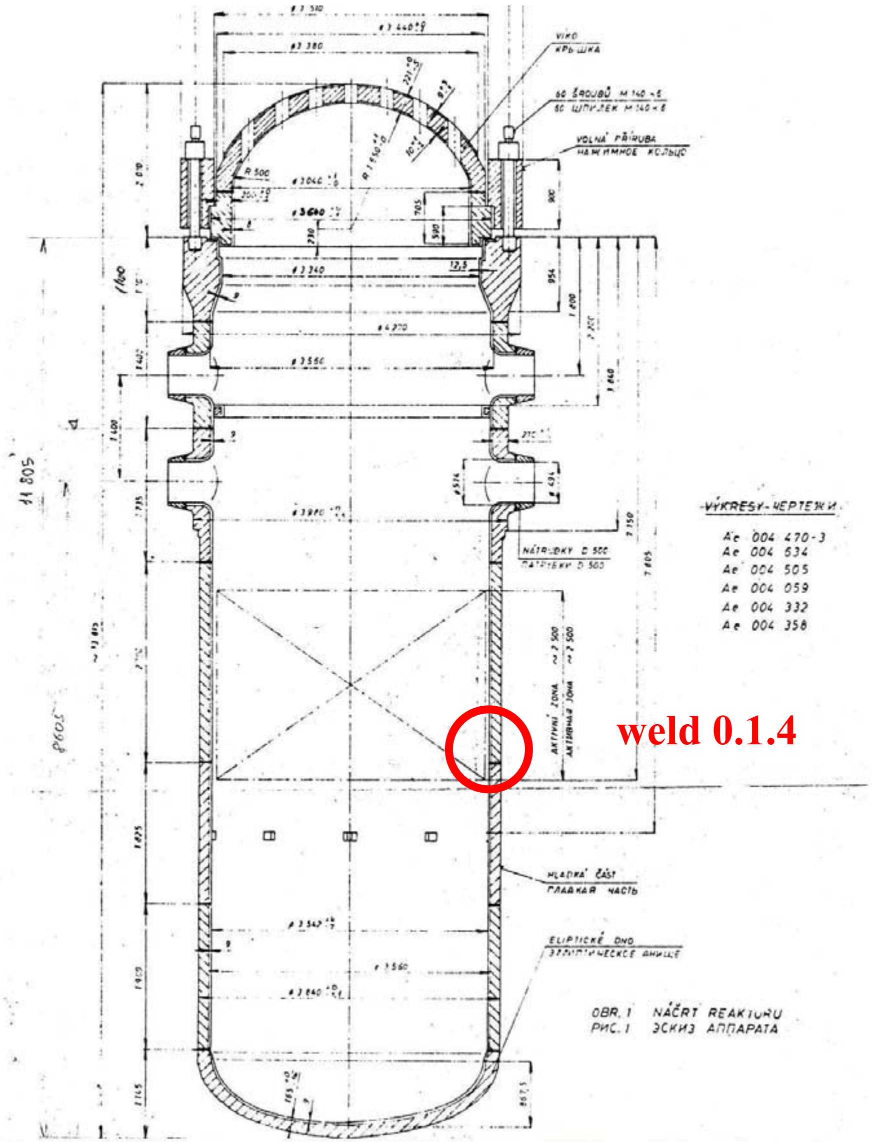
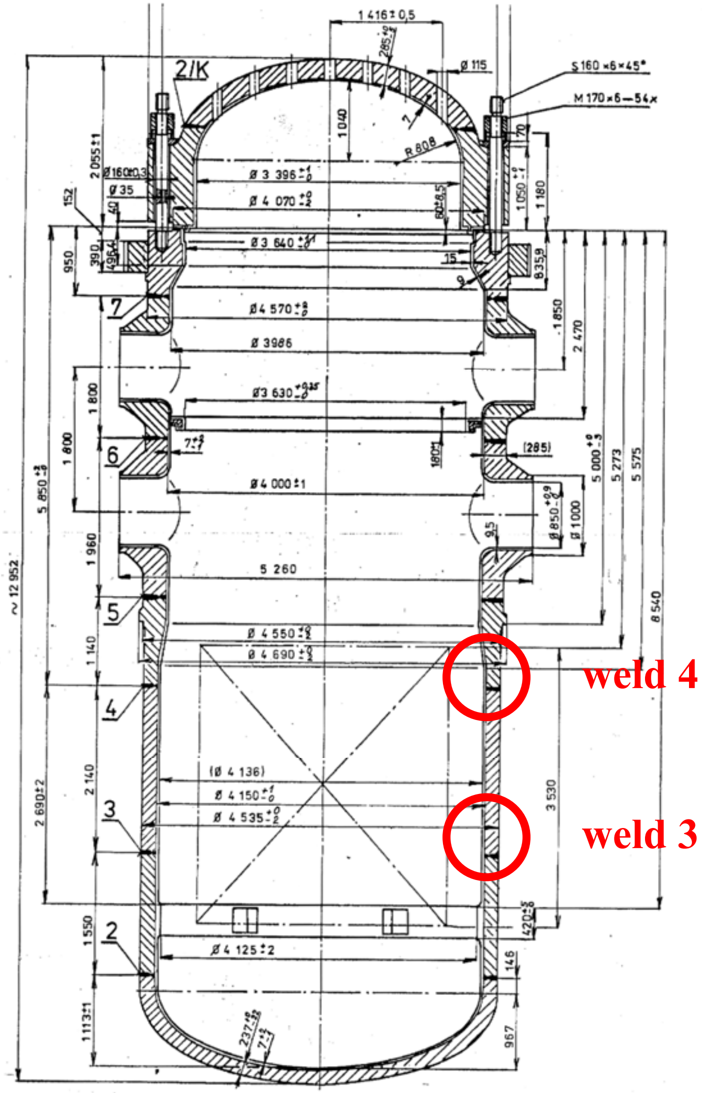


RPV VVER 440



RPV VVER 1000

F (En ≥ 0.5 MeV)

INTRODUCTION

IN PRINCIPLE, ALL SURVEILLANCE SPECIMEN PROGRAMMES SHOULD, WITH MAXIMUM POSSIBLE RELIABILITY, TO MONITOR CHANGES IN RPV MATERIALS PROPERTIES IN DEPENDENCE OF OPERATION TIME.

DIFFERENT TYPES OF REACTORS USED DIFFERENT DESIGNS AND SCHEMES OF SURVEILLANCE SPECIMEN PROGRAMMES BUT ALL MUST FULFIL THE REQUIREMENTS.

RESULTS FROM SURVEILLANCE PROGRAMMES ARE ANALYSED AND SUMMARIZED INTO SO-CALLED „IRRADIATION EMBRITTLEMENT TREND CURVES" THAT ARE USED FOR RPV INTEGRITY EVALUATION AS WELL AS LIFETIME PREDICTION

OBJECTIVES FOR VVER

- Embrittlement trend curves are important for:
  - WWER-440/V-230 RPVs without surveillance specimen programmes
  - WWER-440/V-213 RPVs for potential life extension
  - WWER-1000/V-320 RPVs with Standard surveillance programmes for comparison/ validation of results and life approval/ determination

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	Generation 1	Generation 2	
	VVER - 440/230	VVER - 440/213	VVER - 1000

Elements influenced on Radiation Embrittlement

	VVER - 440/230	VVER - 440/213	VVER - 1000
Cu	Up to 0,22%	Up to 0,22%	< 0,08%
P	Up to 0,048%	Up to 0,027%	< 0,012%
Ni	< 0,3%	< 0,3%	1,2 - 1,9%
V	0,1 - 0,35%	0,1 - 0,35%	

15Kh2MFA, 15Kh2MFAA, Sv 10KhMFT
15Kh2NMFA, 15Kh2NMFAA, Sv 10Kh2N2MFA

LIST OF ABBREVIATIONS USED IN WWER MATERIALS-1

Chemical elements:

Russian	Latin	
Б	B	- niobium
Ф	F	- vanadium
Г	G	- manganese
Х	Kh	- chromium
М	M	- molybdenum
Н	N	- nickel
Св	Sv	- welding wire
Т	T	- titanium
Э	E	- electrode

15Kh2MFA, 15Kh2MFAA, Sv 10KhMFT
15Kh2NMFA, 15Kh2NMFAA, Sv 10Kh2N2MFA

LIST OF ABBREVIATIONS USED IN WWER MATERIALS-2

- **Beginning of the designation:**

0	-	les than 0.1 mass %
08	-	mean value 0.08 %
15	-	mean value 0.15 %

Centre of the designation:

Kh2	-	mean value 2 %
M	-	lower than 1 %

End of the designation:

A	- high quality
AA	- very high quality/purity

WWER-440 RPVs

- V-230 types are reactors without any surveillance programme
- RPVs have limited possibility for sampling during operation, before and after annealing and re-embrittlement
- These RPVs possess only limited information on real chemical composition of weld metals (P, Cu) and initial transition temperature (T_{k0})

WWER-440 RPVs

- Normative predictive formula from „Standards for strength calculation of components and piping in NPPs" – PNAEG 7-002-86 gives the following predictive formulae:

$$\mathbf{\Delta T_F = A_F \, (F \, . \, 10^{-22})^{1/3}}$$

Tirr = 270 °C

WHERE ΔT_F = TRANSITION TEMPERATURE SHIFT, °C
A_F = RADIATION EMBRITTLEMENT COEFFICIENT, °C
F = NEUTRON FLUENCES WITH E_n>0.5 MeV, m^{-2}

VALUE OF A_F IS DEFINED AS:

A_F = 18 °C for BM 15Kh2MFA
= 12 °C for BM 15Kh2MFAA
= 800(P+0.07 Cu) °C for WM 15Kh2MFA
= 15 °C for WM 15Kh2MFAA

WWER-440 RPVs

- These formulae were based only on results from irradiation in experimental testing reactors where lead factor was by several orders **(>20 - 100)** higher than required by standards, i.e. between 1 and 3 (5) and it was supposed that they represent an upper boundary of all experimental results

- Thus, it was recommended to open an IAEA Co-ordinated research programme to correct such formulae on the basis of results from surveillance specimens, only

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WWER-440 RPVs

IAEA CRP-6 "Evaluation of Radiation Damage of WWER 440/V-213 Reactor Pressure Vessels using Database on RPV Materials"

was opened to evaluate all possible data from VVER-440/V-213 type units and to propose a reliable predictive formula for irradiation embrittlement based on surveillance data

- Data were collected from all operated V-213 type RPVs – Russia, Ukraine, Finland, Hungary, Slovakia, Czech Republic
- Together from 15 units

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IAEA CRP-6

- Problems in creation of the database:

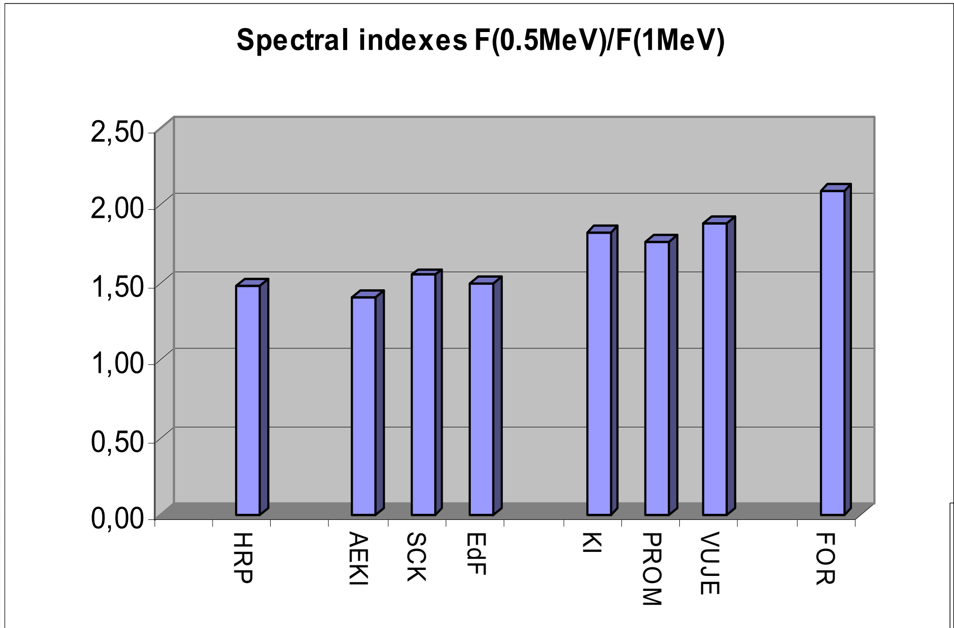
  - Correct irradiation temperature

  (only diamond type temperature monitors were used in Standard surveillance programmes, thus direct temperature measurements with the use of thermocouples was realised in Loviisa, Bohunice and Kola NPPs with positive results)

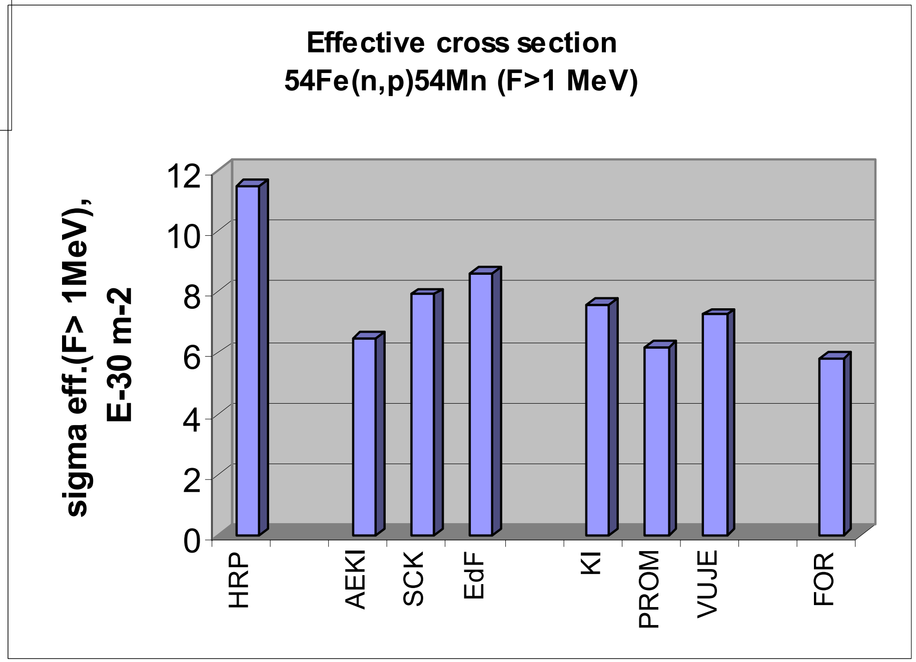
  - Correct/comparable determination of neutron fluence on specimens

  - Determination of transition temperature shifts

IAEA CRP-6



Comparison of effective cross sections show to some difference between individual units

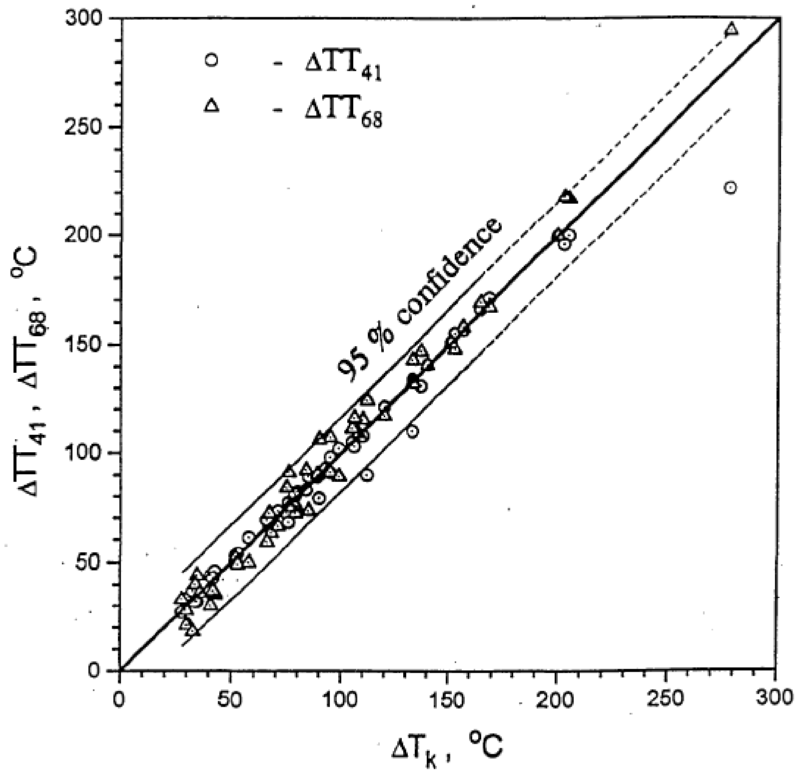


IAEA CRP-6

DETERMINATION OF TRANSITION TEMPERATURE SHIFTS

- DIFFERENT APPROACHES –
- PNAEG (DEPENDENCE ON YIELD STRENGTH) vs. ASTM (41 J = 50 J.cm-2)
  - USE OF ASTM APPROACH GIVES SMALLER SCATTER OF DATA
  - ASTM APPROACH APPLIED FOR IAEA PREDICTION FORMULAE
- DIFFERENT SIZES OF SPECIMENS, i.e.
  - STANDARD SIZE (10X10 mm) vs. SUBSIZE (5X5 or 3X4 mm)
    - SMALLER SHIFTS FOR SUBSIZE SPECIMENS

CORRELATION BETWEEN APPROACHES



Correlation between the values of radiation response measured in accordance with Russian Guide (ΔT_k) and those of ΔTT_{41} and ΔTT_{68}

A.Kryukov

The state of the art of WWER type RPV: radiation embrittlement and mitigation

SPECIALISTS MEETING ON IRRADIATION EFFECTS AND MITIGATION

Vladimir, Russia, 15-19 September, 1997

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CORRELATION WITH SMALL SPECIMENS

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IAEA RRE WWER-440 WM

❑ OPEN ISSUE

KOROLEV, NUCL.ENGN.DESIGN, 2000

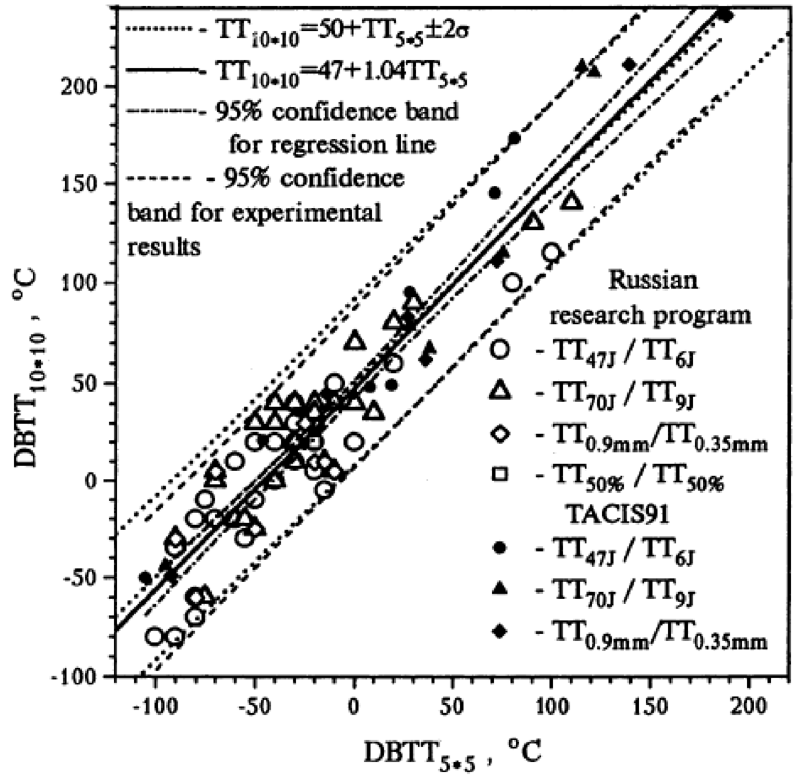


Fig.8.14. Correlation - T41J-T3x4

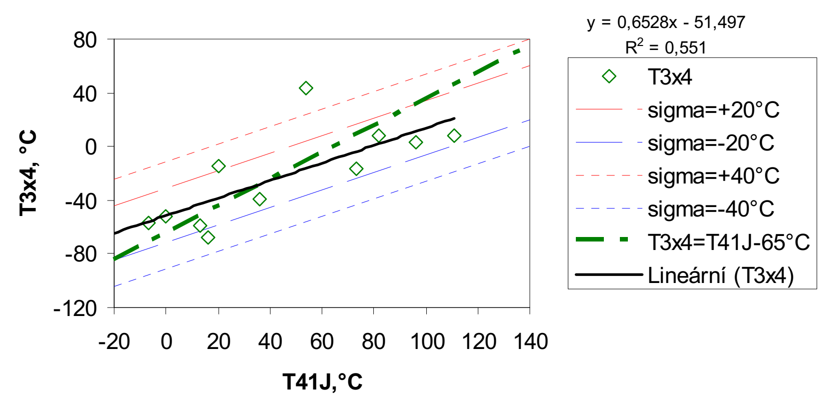
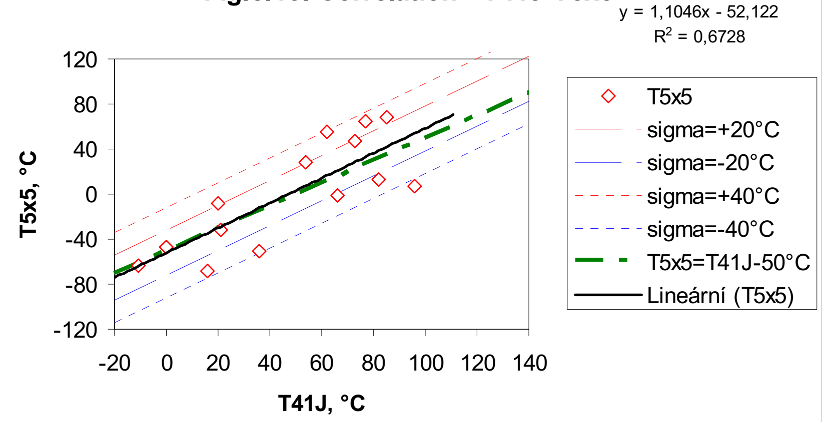


Fig.8.13. Correlation - T41J-T5x5



WWER-440
PREDICTION OF EMBRITTLEMENT

- IAEA CRP "Evaluation of Radiation Damage of WWER 440/V-213 Reactor Pressure Vessels using Database on RPV Materials"

Metal	Formula	SD
Weld metal*	$\Delta T = [884 * P + 51.3 * Cu] * \Phi^{0.29}$ $= 800 * (1.11 * P + 0.064 * Cu) * \Phi^{0.29}$	SD=22.6 °C
Base metal*	ΔT = 8.37* F0.43	SD = 21.7 °C

IAEA-TECDOC-1442

Guidelines for prediction of irradiation embrittlement of operating WWER-440 reactor pressure vessels

Report prepared within the framework of the coordinated research project

IAEA
International Atomic Energy Agency

June 2005

WWER-440
PREDICTION OF EMBRITTLEMENT

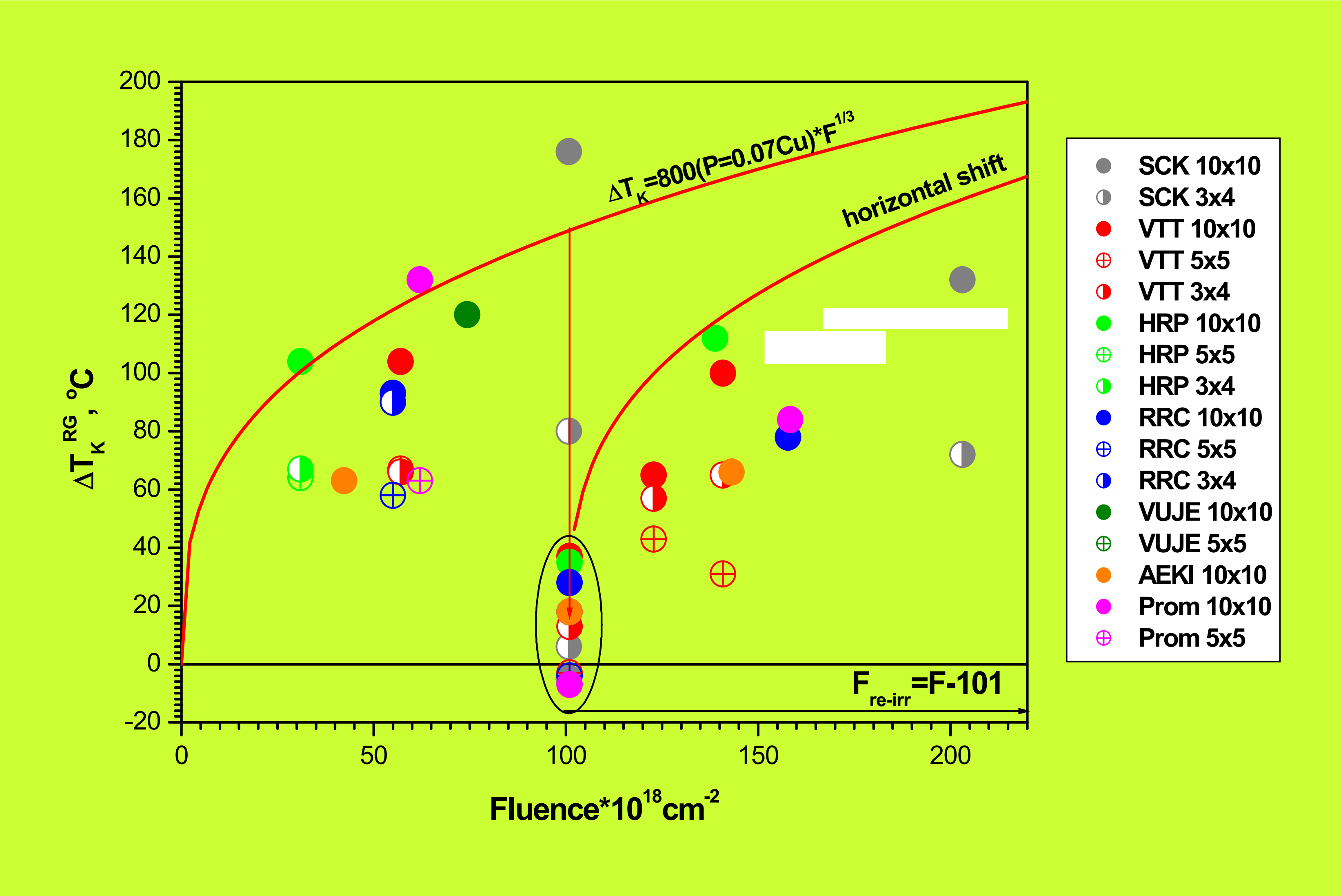
- **VALID FOR LEAD FACTORS:**
  - FULL CORE :
    - 12-13 (BM) AND 16-18 (WM)
  - REDUCED CORE :
    - 3-4 (BM) AND 5-6 (WM)
  - FLUX RATE STILL UNSOLVED,
    WITHIN SURVEILLANCE PROGRAMMES PROBABLY WITHOUT ANY PRONOUNCED EFFECT
  - FLUX RATE EFFECT COULD BE SOLVED BY SUPPLEMENTARY SURVEILLANCE PROGRAMMES IN POSITIONS WITH LOW LEAD FACTOR (CZECH REPUBLIC, SLOVAKIA)
  - RESULTS FROM SURVEILLANCE SPECIMEN PROGRAMMES CAN BE DIRECTLY USED (e.g. MASTER CURVE)

WWER-440/V-230
PREDICTION OF RE-EMBRITTLEMENT

- MOST OF WWER-440/V-230 RPVs WERE ANNEALED,
- MOST OF THEM ARE NOW SHUT DOWN OR JUST BEFORE SHUT DOWN
- OPERATED ANNEALED RPVs WILL BE ONLY OUTSIDE EU
- SPECIAL CASE : LOVIISA / V-213 BUT RPV OF V-230 TYPE AND QUALITY
- AND ALSO: ROVNO-1/ V-213 BUT RPV OF V-230 TYPE AND QUALITY

- RE-EMBRITTLEMENT WELL CONSERVATIVELY DESCRIBED BY „LATERAL SHIFT“ MODEL

IAEA RRE WWER-440 WM



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SAMPLES CUT OUT FROM OPERATED VVER RPVS

WWER-440/V-230 WITHOUT CLADDING

TAKING OUT SURFACE SAMPLES

- 1st stage - testing for chemical composition and initial properties and primary radiation embrittlement
- 2nd stage - testing for re-embrittlement rate
- 3rd stage - irradiation of annealed specimens in experimental reactor for re-embrittlement prediction

WWER-440/V-230 – DECOMMISSIONED REACTORS

CUT OUT TREPANS

NVAES-2, NORD 1, 2, 3, 4 ?

SAMPLES CUT OUT FROM OPERATED WWER RPVS

❑ OPEN ISSUES:

SAMPLES:

- ONLY SURFACE SAMPLES, NO INFORMATION ABOUT PROPERTIES THROUGH THICKNESS
- MOSTLY UNKNOWN INITIAL PROPERTIES
- CORRELATION BETWEEN STANDARD CHARPY AND SUBSIZE SPECIMENS – ABSOLUTE VALUES
- INFORMATION ABOUT CURRENT STATE, NO SHIFT
- FRACTURE TOUGHNESS TESTS – MASTER CURVE (?)

TREPANS FROM DECOMMISSIONED RPVs:

- MOSTLY UNKNOWN INITIAL PROPERTIES
- INFORMATION ABOUT CURRENT STATE, NO SHIFT
- FOUND SOME NONHOMOGENEITY IN CHEMICAL COMPOSITION (DISTRIBUTION OF Cu AND P)

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A.Kryukov

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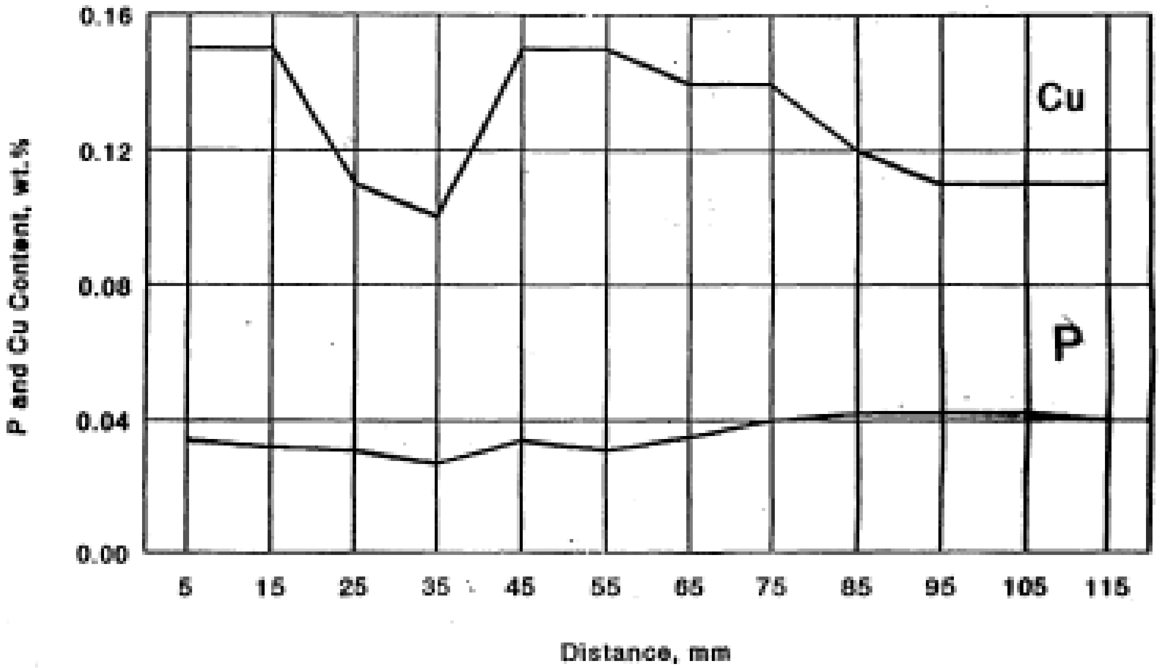

- The dependence of P and Cu variation though the wall thickness of RPV weld metal 4 NVNPP-2.

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RPV MATERIAL INVESTIGATIONS OF THE FORMER VVER-440 GREIFSWALD NPP

U. Rindelhardt, J. Konheiser, K. Noack,
H.-W. Viehrig, B. Gleisberg

Proceedings of ICONE15:
15th International Conference on Nuclear Engineering
April 22-26, 2007, Nagoya, Japan

Table 1: Chemical composition of the different samples (given in mg/g steel and for Nb in µg/g steel).

sample	1	2	3	4	5
P	0.44	0.102	0.095	0.111	0.28
V	1.3	2.74	2.6	2.65	1.1
Cr	14.8	26.9	25.1	25.4	14.7
Mn	11	4.27	3.99	4.03	9.0
Ni	2.5	1.88	1.78	1.81	2.3
Cu	4.0	2	1.84	1.92	3.1
Mo	3.9	6.52	6.01	6.08	4.2
Nb	7.7	2.6	1.1	1.3	1.5

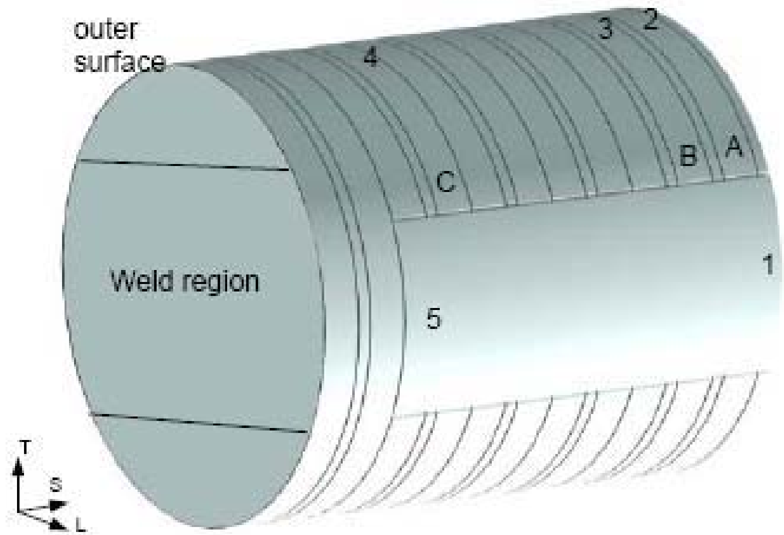

Fig. 2 : Trepan with cutting scheme and sample positions

SAMPLE	1 - IN	2	3	4	5 - OUT
P, mass %	0,044	0,0102	0,095	0,0111	0,028
Cu,mass %	0,40	0,20	0,184	0,192	0,31

WWER-1000

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	Generation 1	Generation 2	
	VVER - 440/230	VVER - 440/213	VVER - 1000

Elements influenced on Radiation Embrittlement

	VVER - 440/230	VVER - 440/213	VVER - 1000
Cu	Up to 0,22%	Up to 0,22%	< 0,08%
P	Up to 0,048%	Up to 0,027%	< 0,012%
Ni	< 0,3%	< 0,3%	1,2 - 1,9%
V	0,1 - 0,35%	0,1 - 0,35%	

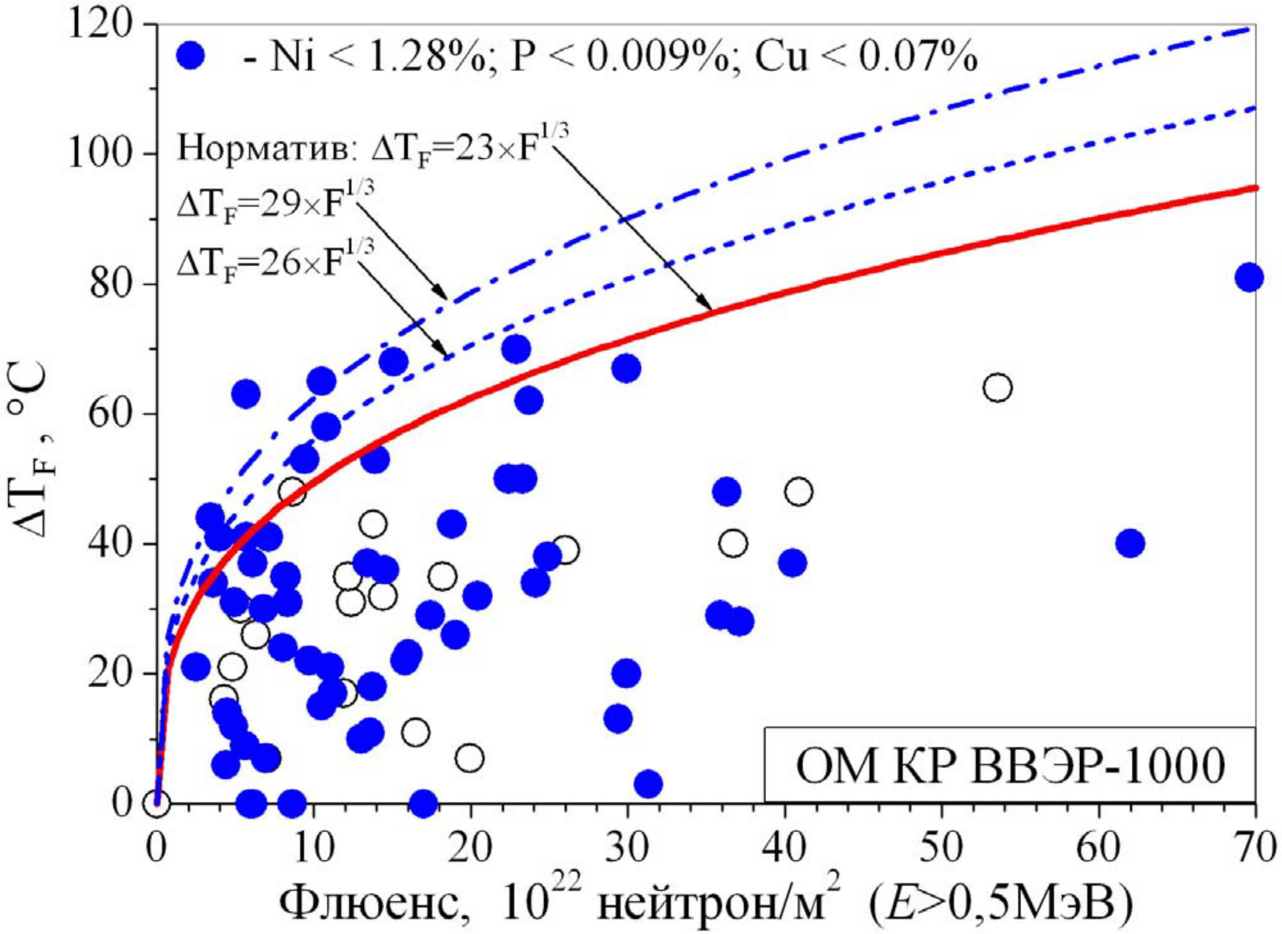
WWER-1000

- „Standards for strength calculation of components and piping in NPPs" – PNAEG 7-002-86

A_F = 23 C for steel 15Kh2NMFAA
(Tirradiation = 290°C)
= 20 C for weld metal Sv-12Kh2N2MAA with nickel content lower than 1.5 mass %
(Tirradiation = 290°C) ;

- weld metals with nickel content larger than 1.5 mass % must be evaluated separately (Qualification Program was performed with welds containing less than 1.5 mass % Ni, content of Ni was changed later during manufacturing)
- PROBLEM: THESE COEFFICIENTS WERE OBTAINED FROM IRRADIATION IN EXPERIMENTAL REACTORS, i.e. WITH HIGH LEAD FACTOR AND LOW NICKEL CONTENT (!)
- NO ENOUGH FULLY RELIABLE SURVEILLANCE DATA EXIST (ESPECIALLY FOR HIGH FLEUNCES) TILL NOW

NORMATIV TREND CURVE IS NOT CONSERVATIVE EVEN WITH LIMITED Ni < 1.3% IN WELD METALS



(STROMBAKH, 10th CONFERENCE PROMETEY, 2008)

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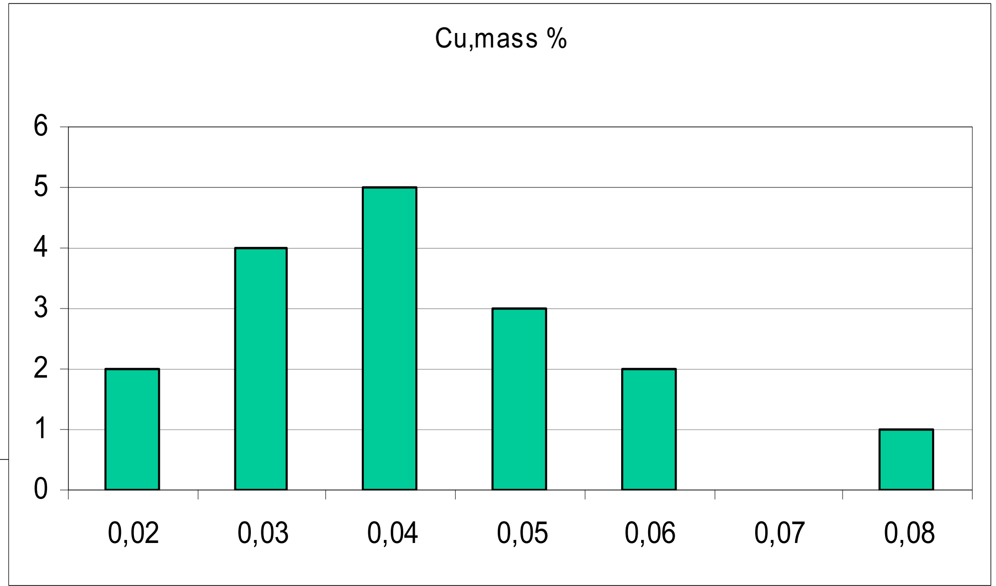
Database of surveillance results contains more than 200 points from 17 RPVs

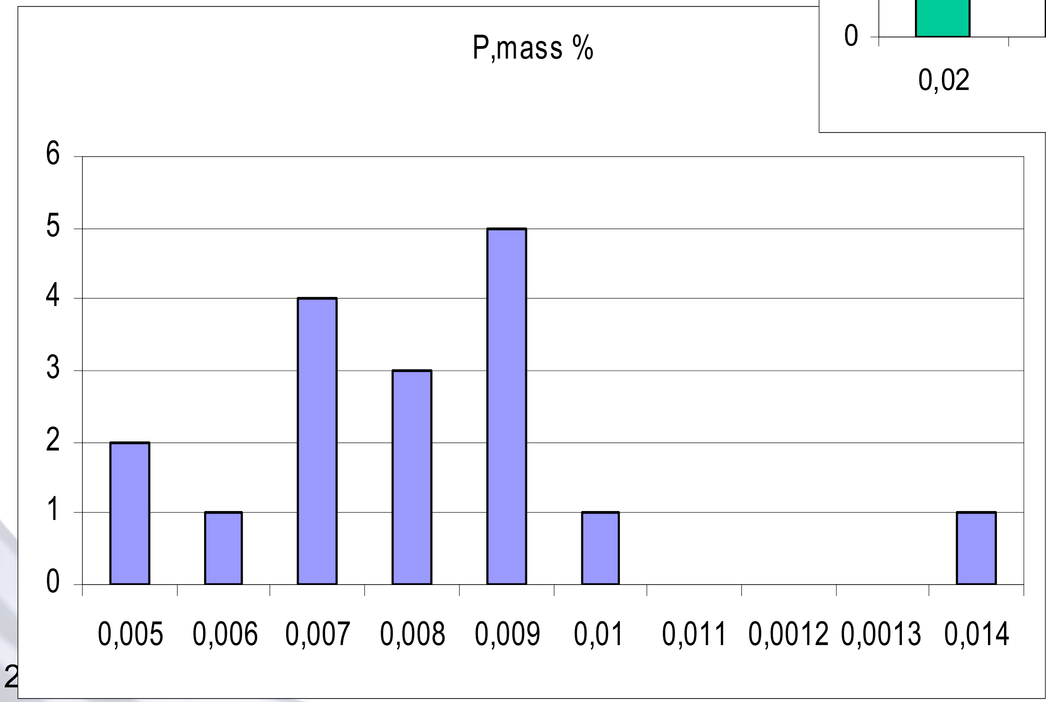
(STROMBAKH, 10th CONFERENCE PROMETEY, 2008)

Unit	Start	Weld № 4			Tested (withdrawn) sets					
		P, %	Cu, %	Ni, %	1	2	3	4	5	6
Бал.АЭС-1	85	0.009	0.03	1.88	+	+	+			
Бал.АЭС-2	87	0.009	0.05	1.59	+		+	+		
Бал.АЭС-3	87	0.007	0.05	1.57	+	+	+			
Бал.АЭС-4	93	0.007	0.04	1.61	+					
Кал.АЭС-1	84	0.010	0.04	1.76	+	+	+			
Кал.АЭС-2	85	0.008	0.02	1.59	+	+		+		
НВАЭС-5	80	0.014	0.04	1.21	+	+	+	(+)		
Зап.АЭС-1	84	0.005	0.03	1.10	+	(+)				
Зап.АЭС-2	85	0.009	0.04	1.12	+	+			+	
Зап.АЭС-3	86	0.008	0.03	1.55	+	+			+	
Зап.АЭС-4	87	0.009	0.06	1.70	+	+			+	
Зап.АЭС-5	89	0.009	0.08	1.60	+	+			+	
Ров.АЭС-3	86	0.008	0.03	1.64	+	+	+	+		
ХАЭС-1	88	0.006	0.02	1.88	+	+	+	+	+	
ЮУАЭС-1	82	0.007	0.04	1.70	+	+	+			
ЮУАЭС-2	85	0.007	0.05	1.74	+			+		
ЮУАЭС-3	89	0.005	0.06	1.72	+	+				

LOW CONTENTS OF P AND Cu IN WELD METALS – LOW EFFECT ON EMBRITTLEMENT TREND CURVES

Relatively low Cu content in narrow band





Relatively low P content in narrow band

MOSTLY HIGH CONTENT OF Ni IN WELD METALS - STRONG EFFECT ON TREND CURVES

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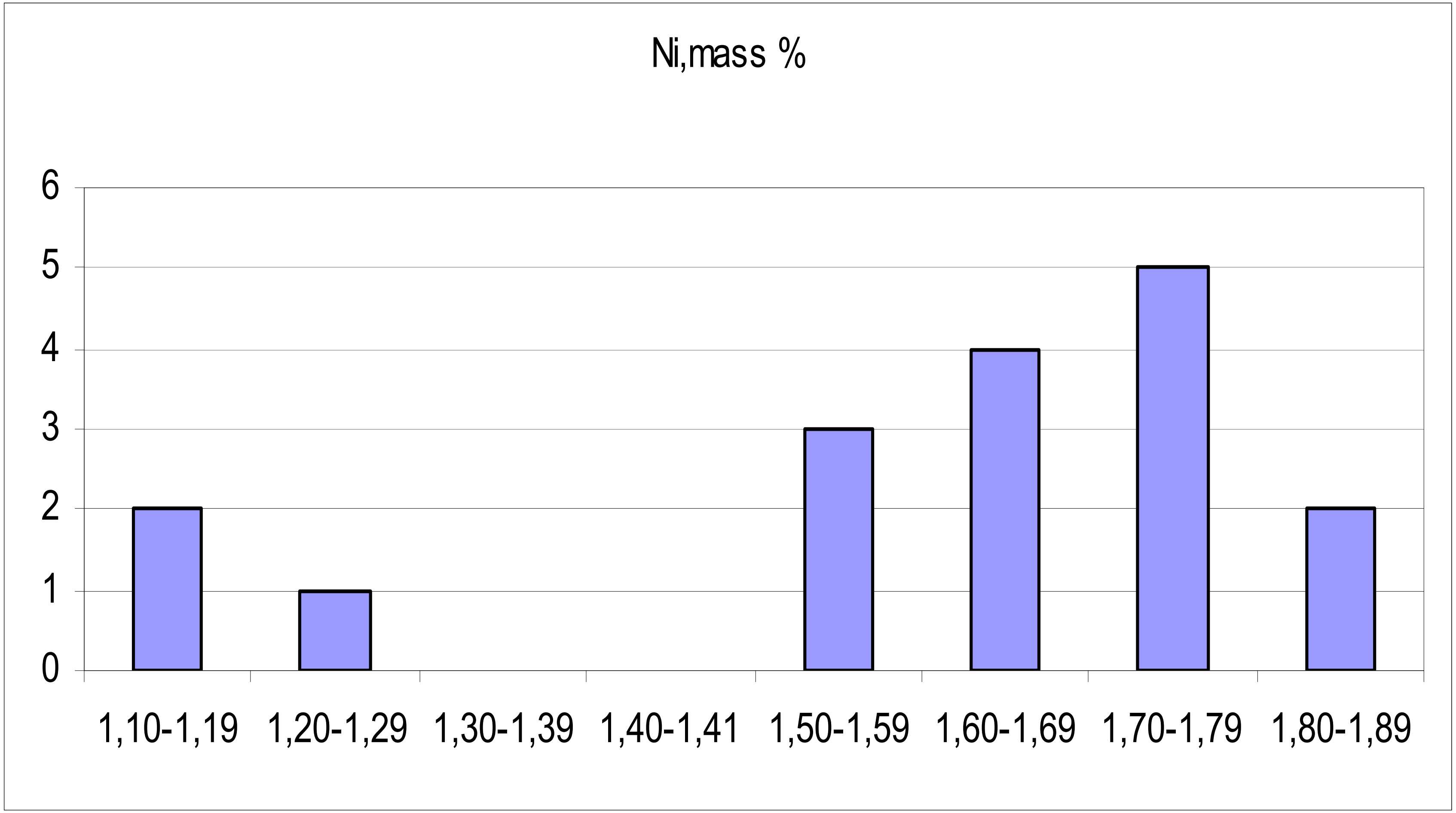
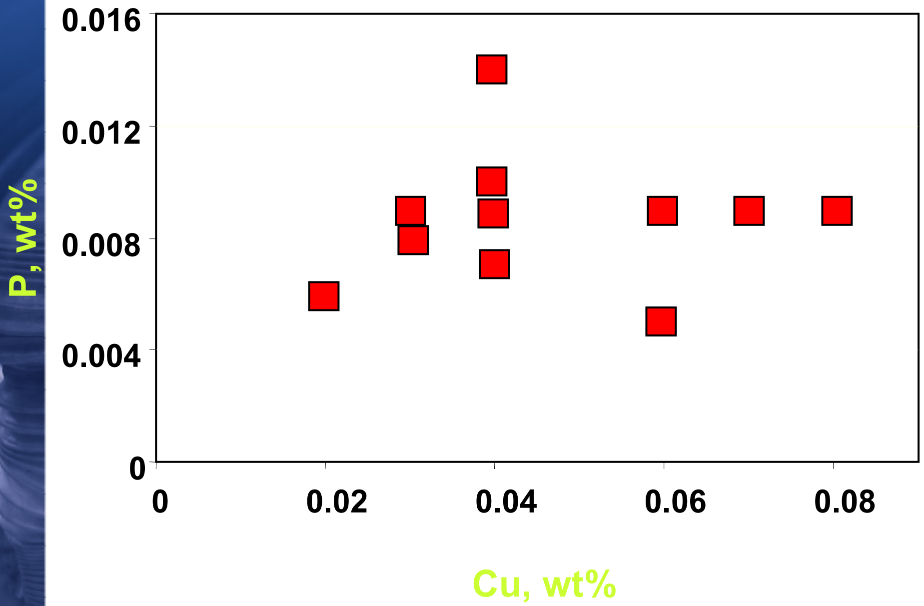
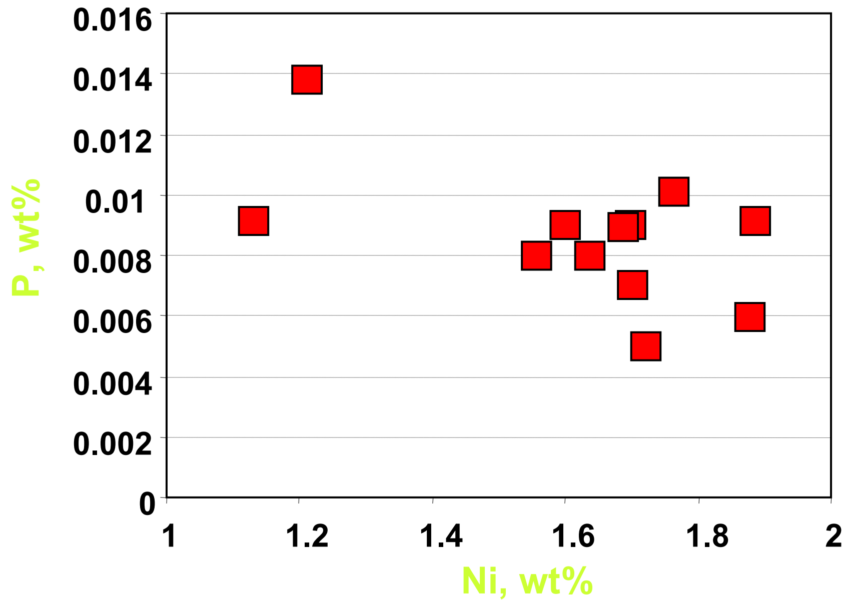
Two groups of Ni content



"Extended analysis of VVER-1000 surveillance data",
A.Kryukov, D.Erak, L.Debarberis, F.Sevini, B.Acosta,
International Journal of Pressure Vessel and Piping 79 (2002) 661-664, Elsevier Science Ltd



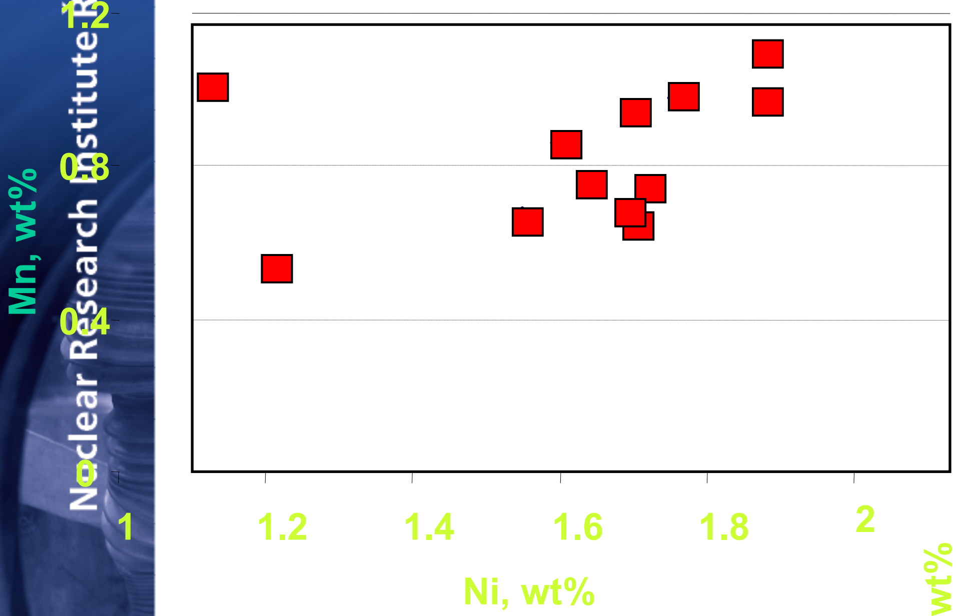


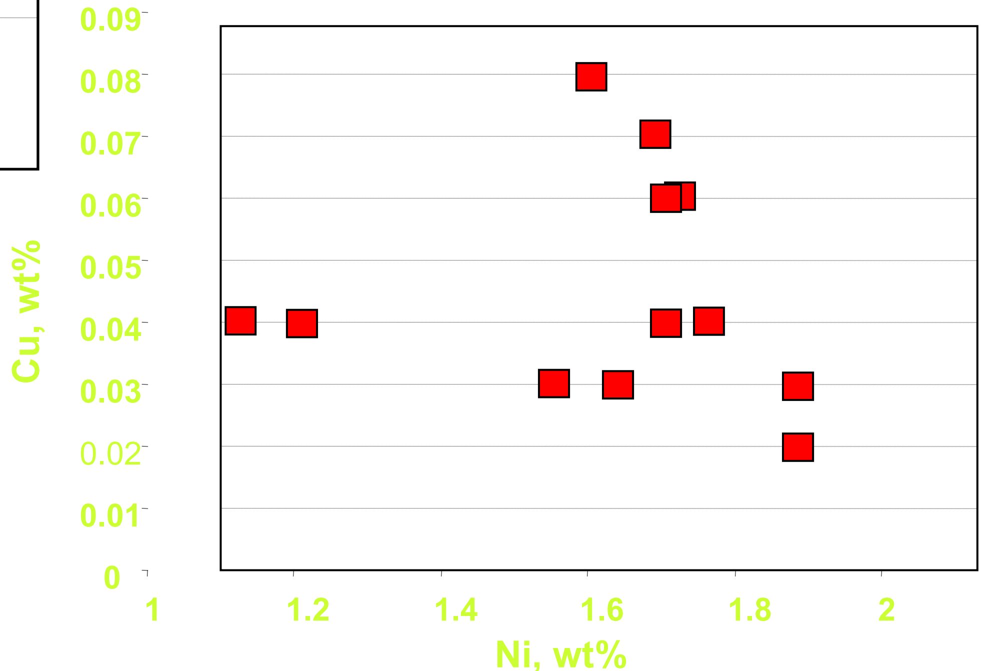
- Low P

- Some Cu variation (< 0.09 wt%)

- Ni from 1.2 to 1.9 wt%

Mn-Ni variation
Ni-Cu variation





Accelerated irradiation of VVER-1000 RPV weld materials

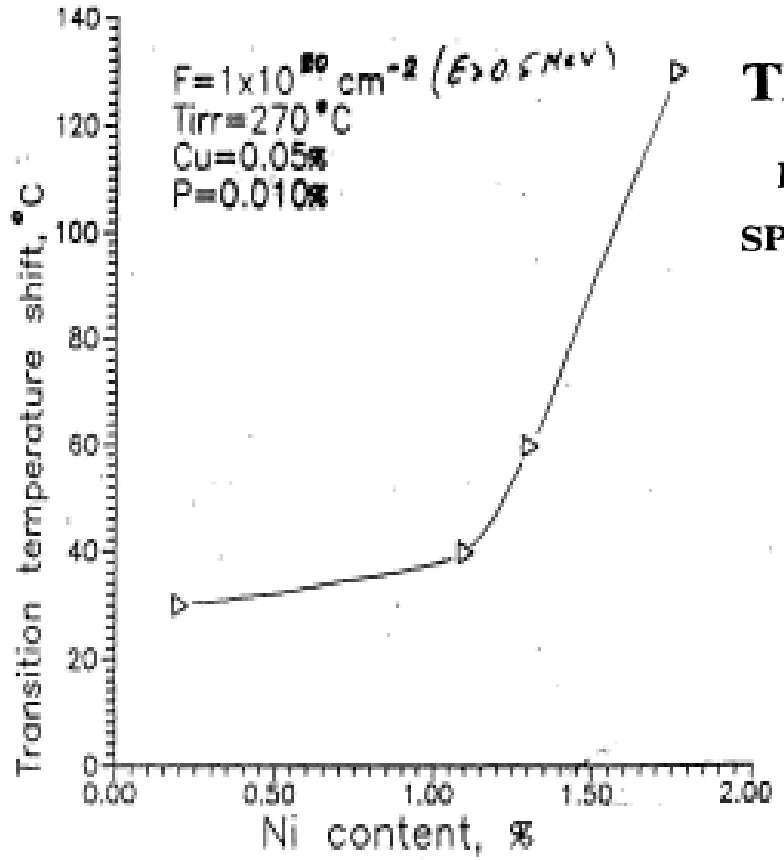


Fig.6 Transition temperature shift observed for melt with different levels of copper and phosphorus content

A.Kryukov

The state of the art of WWER type RPV: radiation embrittlement and mitigation

SPECIALISTS MEETING ON IRRADIATION EFFECTS AND MITIGATION

Vladimir, Russia, 15-19 September, 1997

EFFECT OF NICKEL ALONE

Accelerated irradiation of VVER-1000 RPV weld materials

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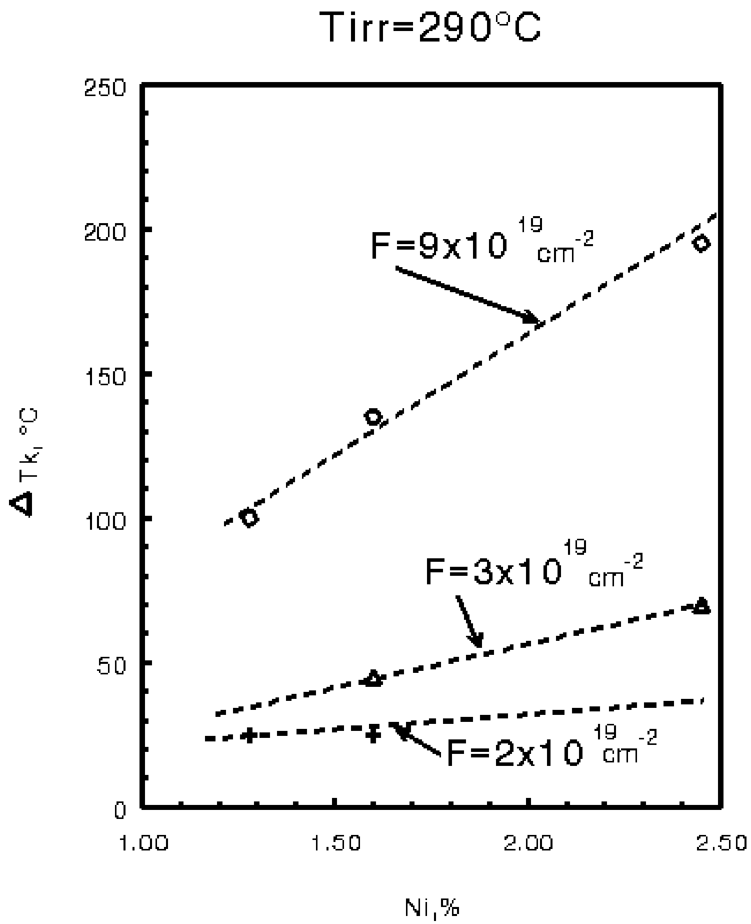
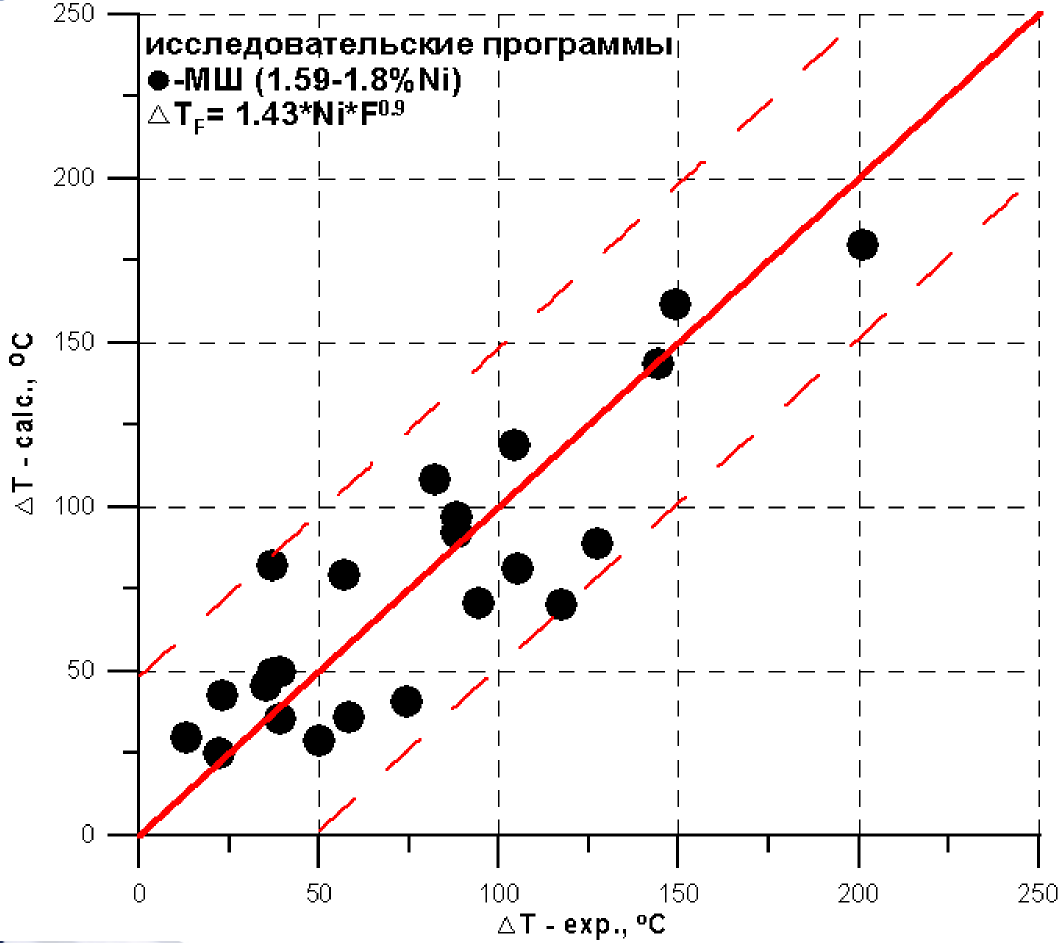


- Linear dependence on Ni content (Ni>1.3%)

Amaev A.D., Erak D.Yu., Kryukov A.M. "Radiation Embrittlement of WWER-1000 Pressure Vessel Materials." – Irradiation Embrittlement and Mitigation. Proceedings of the IAEA Specialists Meeting, Madrid, 1999

Research programs RRC KI (LF>20) & Prometey (LF>100) for high Ni welds



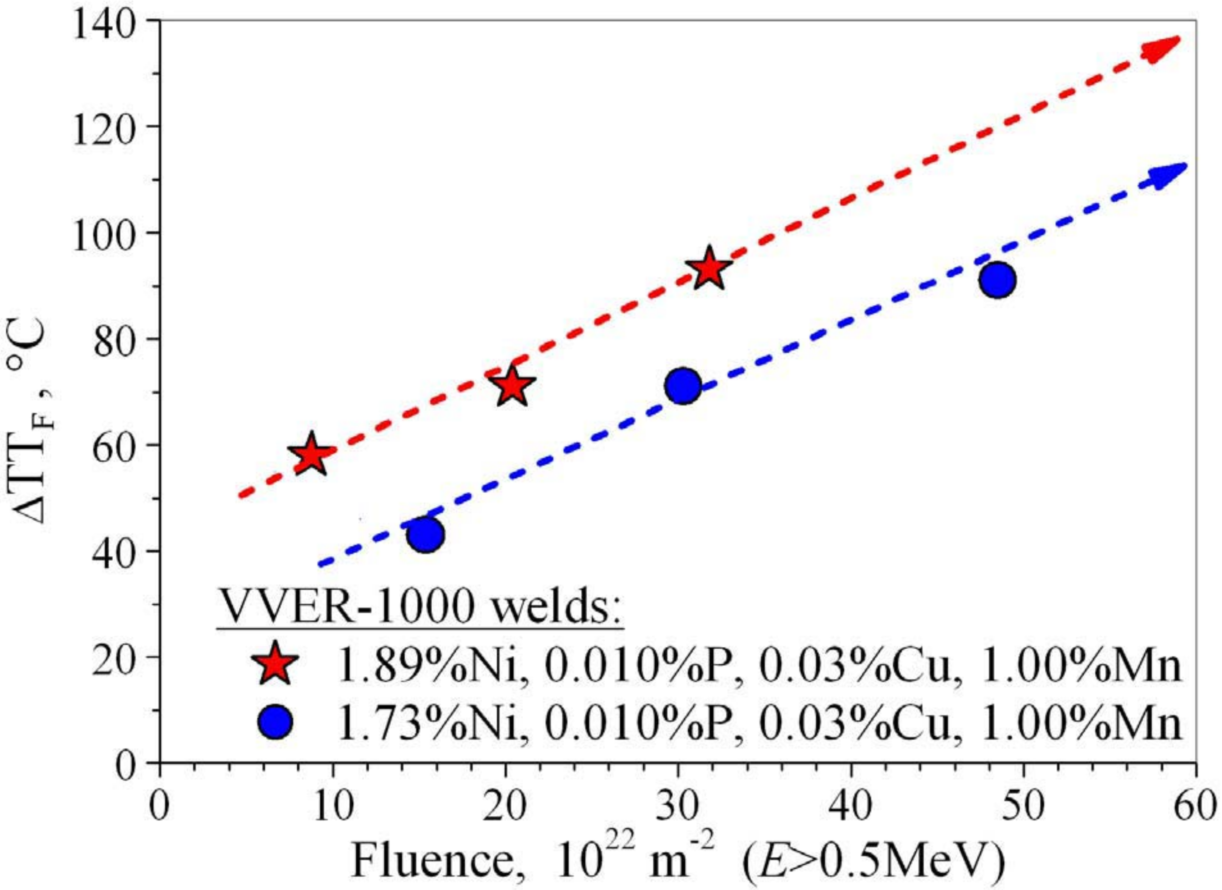
Welds with

1.59 – 1.8% Ni

In experimental programmes

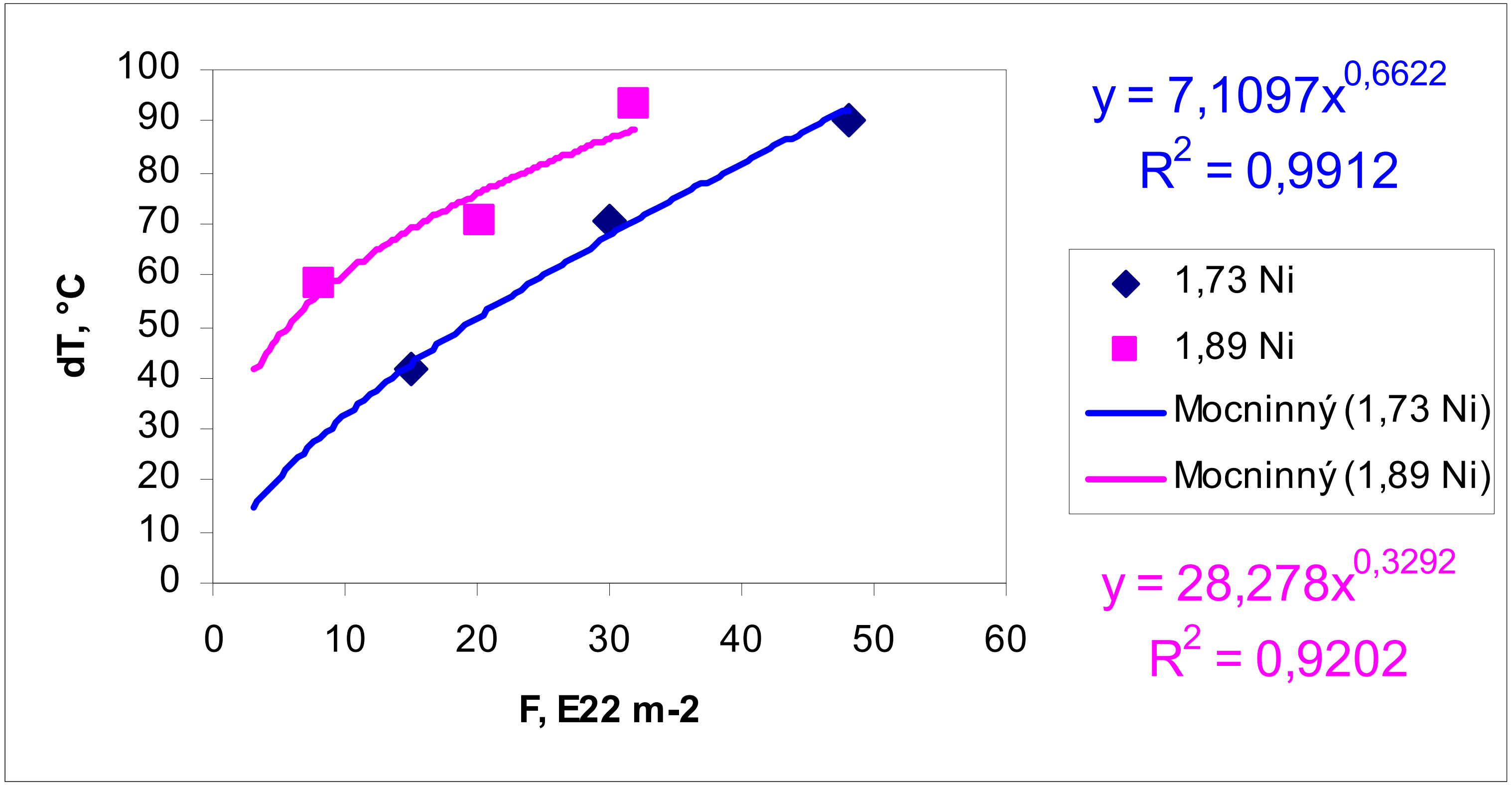
$$\Delta Tk = 1.43*Ni*F^{0,9}$$

Irradiation of weld metals with high nickel content at one irradiation time show close to linear trend dependence radiation embrittlement on neutron fluence



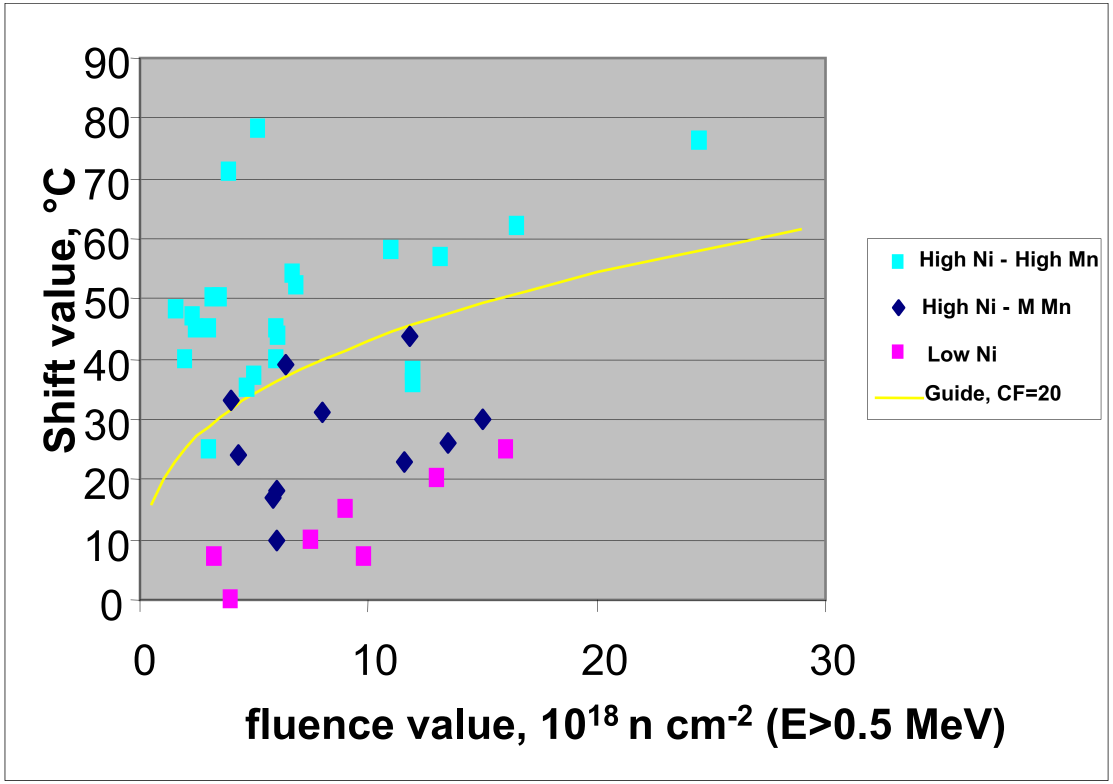
(ERAK, 10th CONFERENCE PROMETEY, 2008)

ALTERNATIVE SOLUTION
of previous results



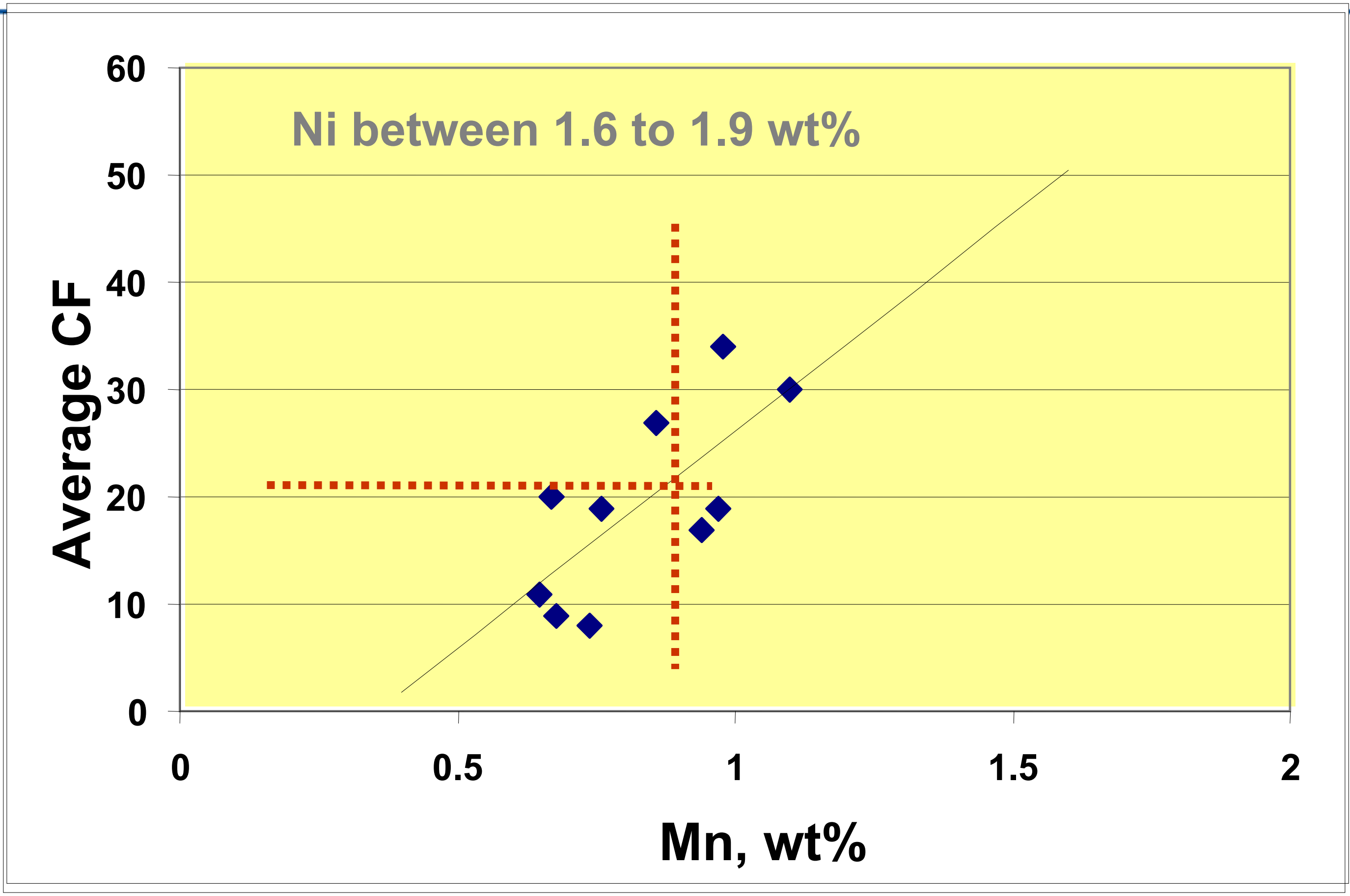
Embrittlement trend curves

- Synergistic effect of Ni - Mn



KRYUKOV, A., ERAK, D., DEBARBERIS, L., SEVINI, F., ACOSTA, B. - Extended Analysis of VVER-1000 Surveillance Data. Intern. Journal of Pressure Vessels and Piping, Vol. 79, Issues 8-10 (2002) 661-664 -

Synergistic effect of Ni - Mn



Critical content of Mn is close to 0.85 mass %

THERMAL AGEING

- **This steel is susceptible also to thermal ageing:**
  - WHILE IN PNAEG NO EFFECT OF THERMAL AGEING IS GIVEN (UP TO 100,000 h), i.e.

    $$\Delta T_T = 0\ °C$$

    IN REALITY IT IS NECESSARY TO TAKE THIS EFFECT INTO ACCOUNT

    (PROBLEM:

    – TEMPERATURE OF THERMAL SURVEILLANCE SPECIMENS IS HIGHER – by approx. 20 °C – THAN IRRADIATED SURVEILLANCE SPECIMENS !

    - TEMPERATURE OF IRRADIATED SURVEILLANCE SPECIMENS IS HIGHER - by approx. 10 °C –THAN RPV IN BELTLINE REGION

QUALIFICATION PROGRAMME of steel

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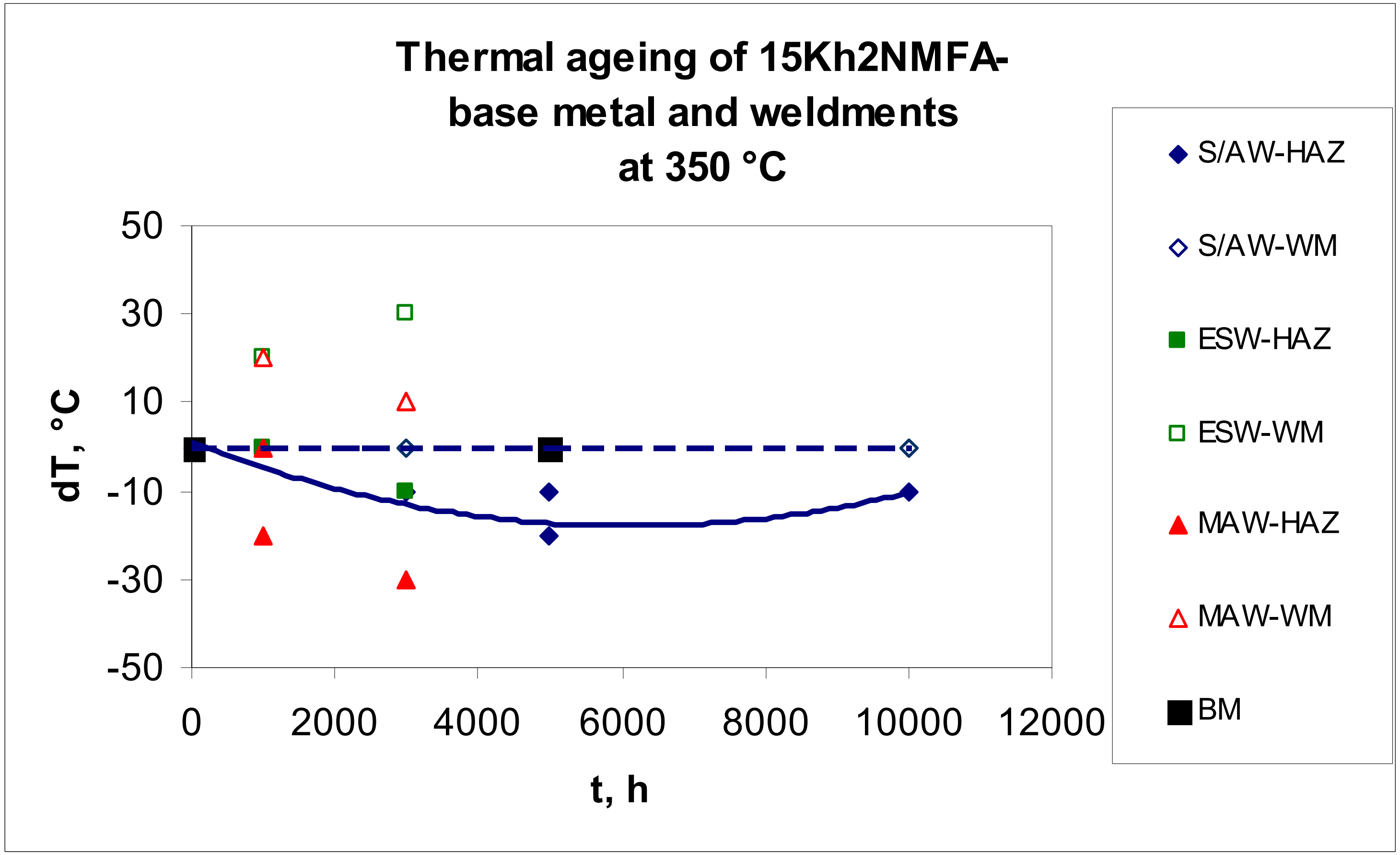
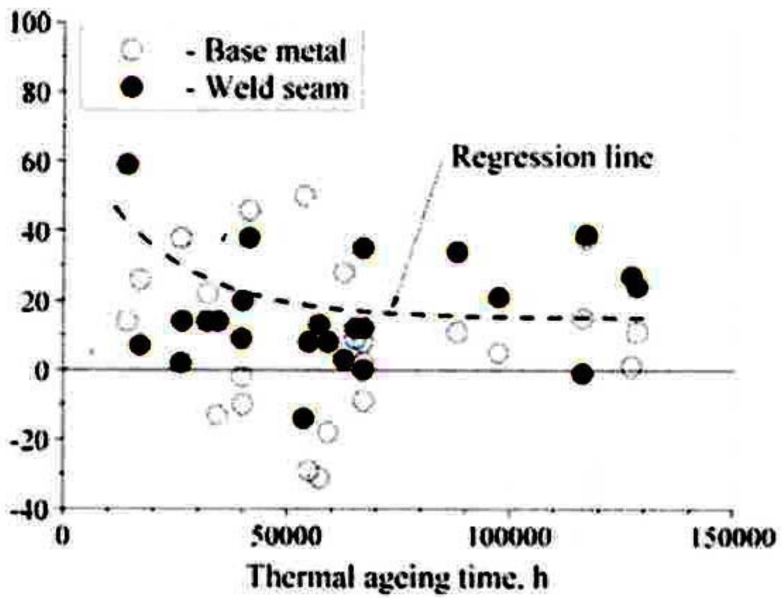
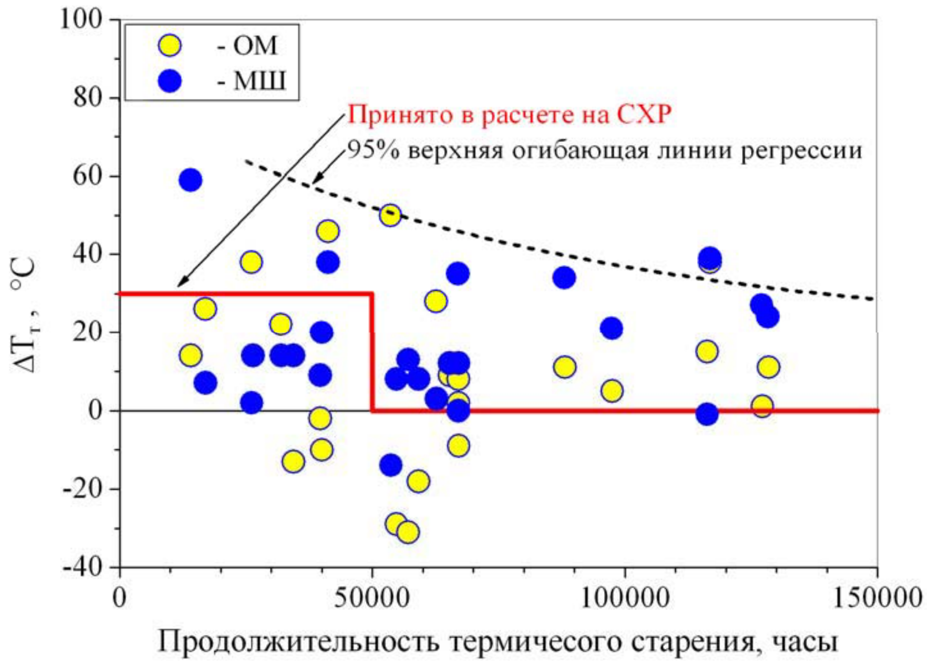


Relation of the type $\Delta Tk = A*f1(Ni,Mn,Si)*F^n$ obtained from testing surveillance specimens cannot be applied both to accelerated and surveillance specimen test results

Additional problem – thermal ageing effect in WWER-1000 RPV materials is much higher than given in the Standard and is close to ~40°C even for holding time 120-130,000 hours





Yu. Nikolaev "Radiation Embrittlement of Cr-Ni-Mo and Cr-Mo RPV steels", Journal of ASTM International, Vol4 #8, paper ID JAI 100695

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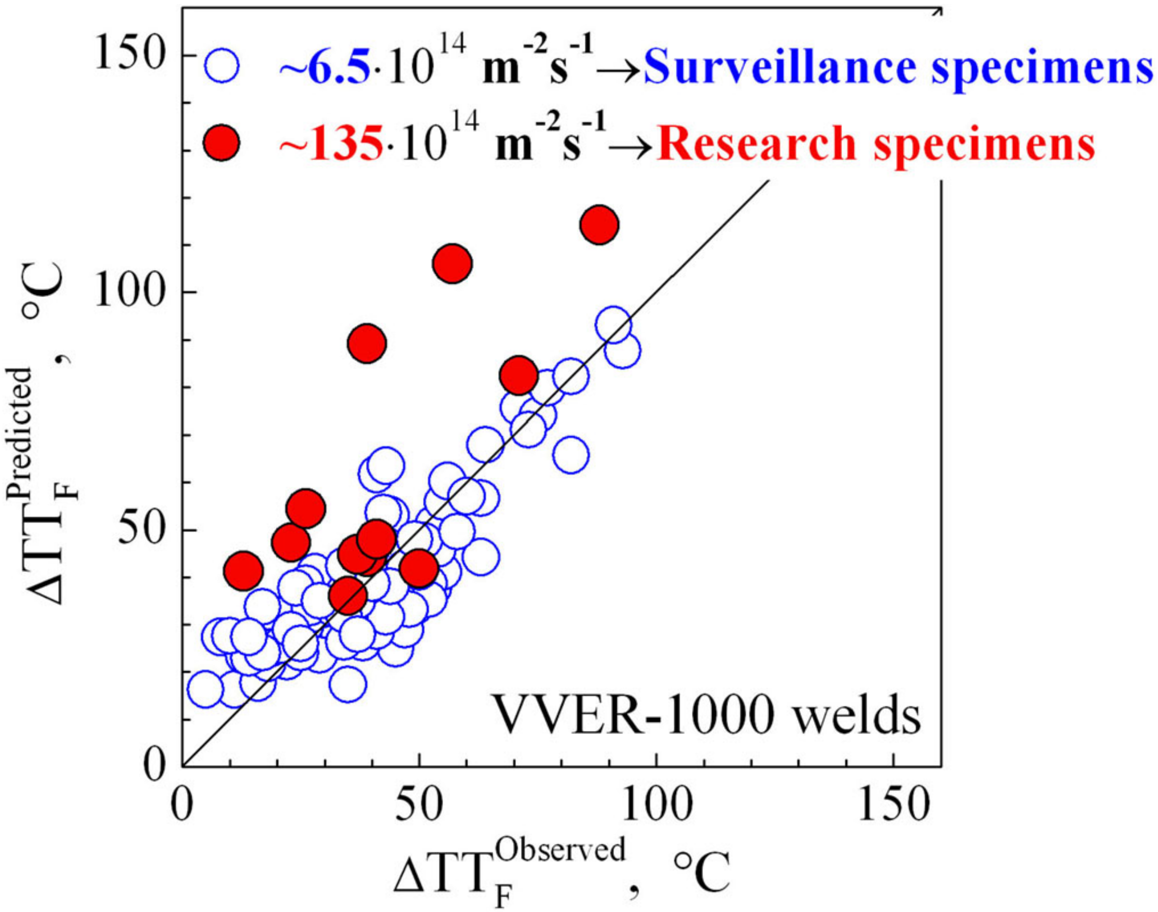
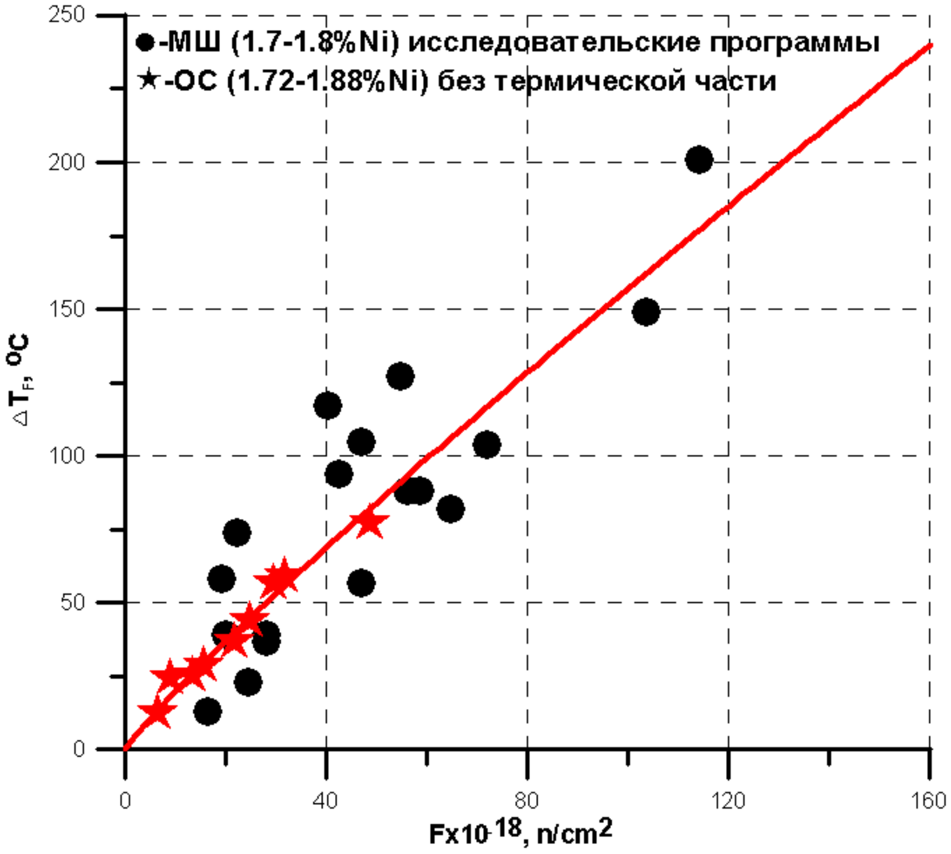
- Comparison of irradiation in surveillance position and in experimental test reactor shows to a potential effect of irradiation time – i.e. thermal ageing





$$\triangle T_F = 1.43 * Ni * F^{0.9}$$

Good agreement between research (•) and SS (★) results (without thermal part)

Welds with 1.7 – 1.8% Ni

⇨

PROBABLY NO FLUX RATE EFFECT, ONLY EFFECT OF THERMAL AGEING !

WWER-1000 – WELD METALS

Using of dependence as

(ERAK, 10th CONFERENCE PROMETEY, 2008)

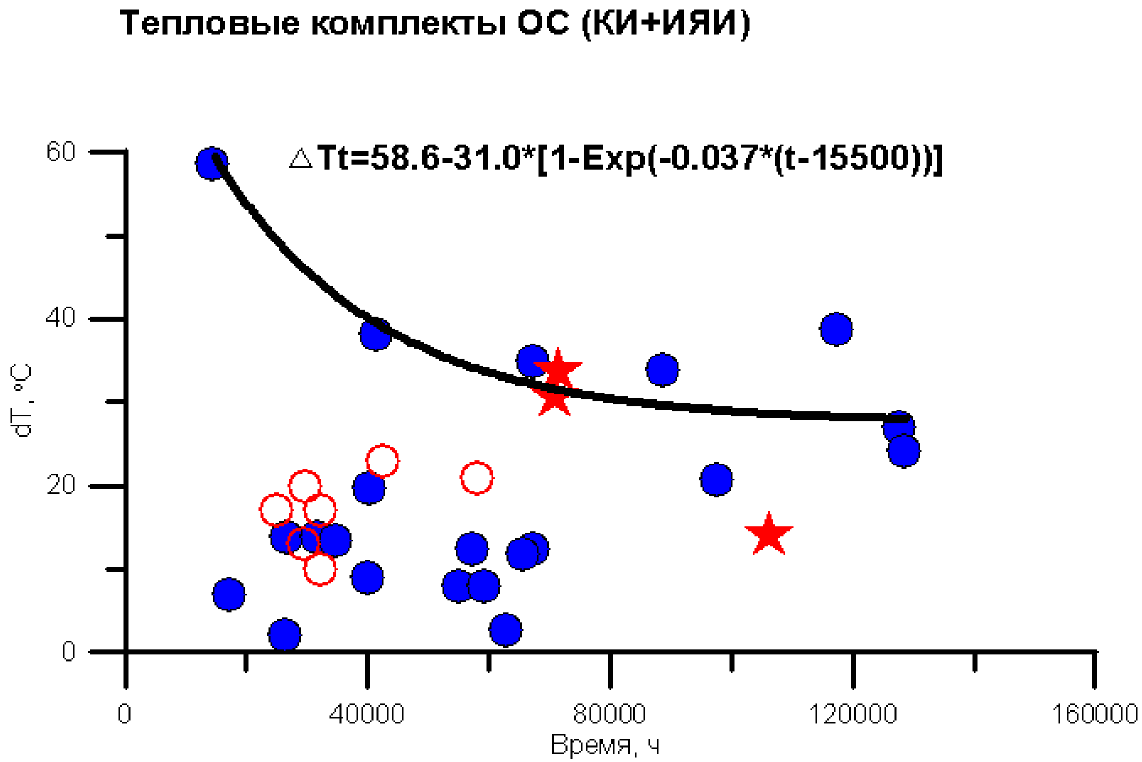
$$\Delta Tk = A*f1(Ni,Mn)*F0,9 + f2(t)$$

can give better fitting than

$$\Delta TTF = 33.5\ Ni^{1.35}\ Mn^{0.7}\ (0.64 - Si)\ F$$

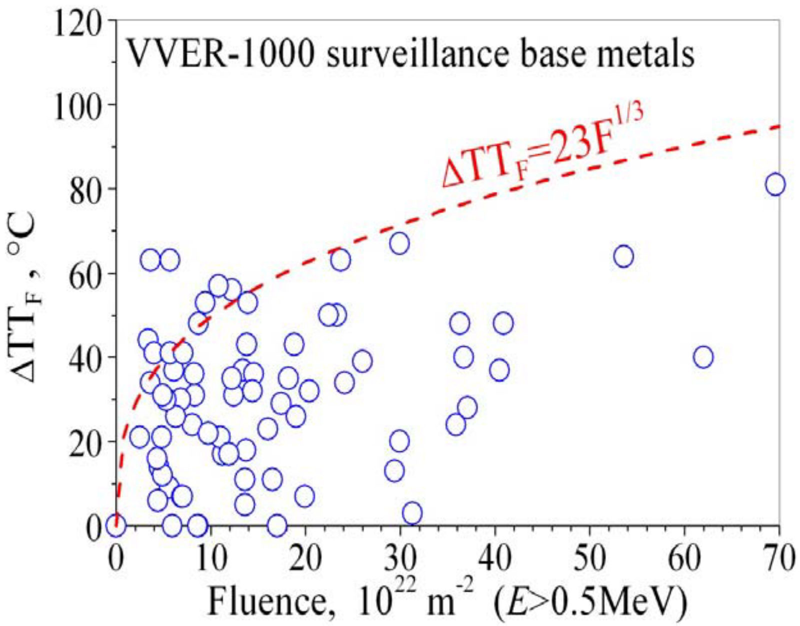
(Yu.NIKOLAEV, COVERS,BUDAPEST, 2007)

Thermal aging (ΔT_t) of VVER-1000 weld metal. Extracted thermal parts **in comparison with** SS results

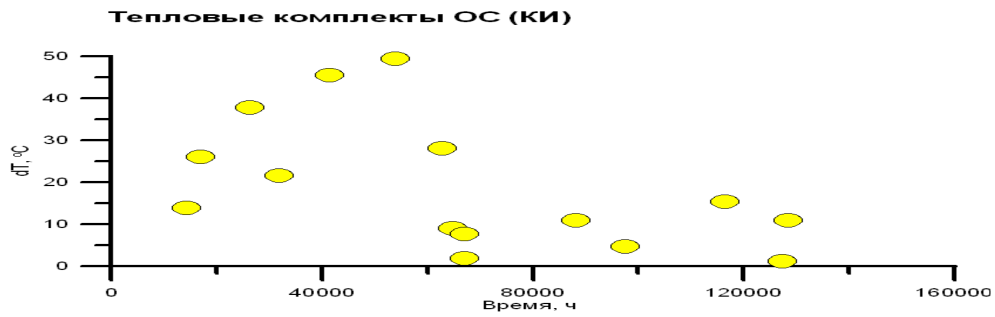


●-данные ОС КИ
○-данные ОС ИЯИ
★-данные полученные путем выделения термической части из ОС с высоким содержанием никеля.

Extraction of thermal ageing effect should have to be applied also for test results from base metals



Surveillance irradiated specimens



Surveiilance thermal ageing specimens

CONCLUSIONS

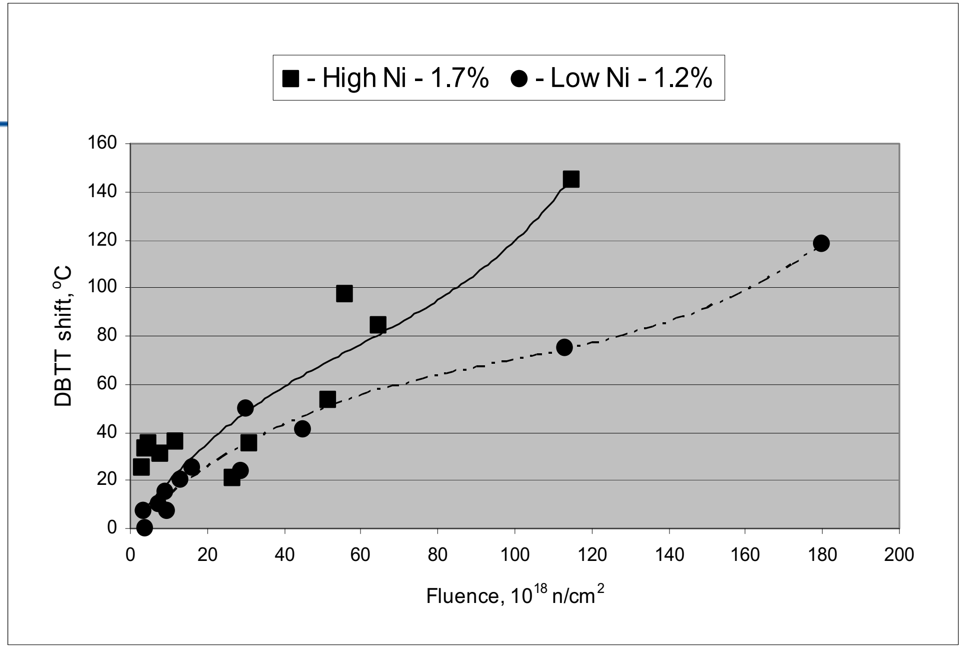
Preliminary analysis shows that such approach (i.e. taking into account effect of thermal asgeing) allows correct description of WWER-1000 RPV materials behaviour at different flux rates and different irradiation times – relation of the type

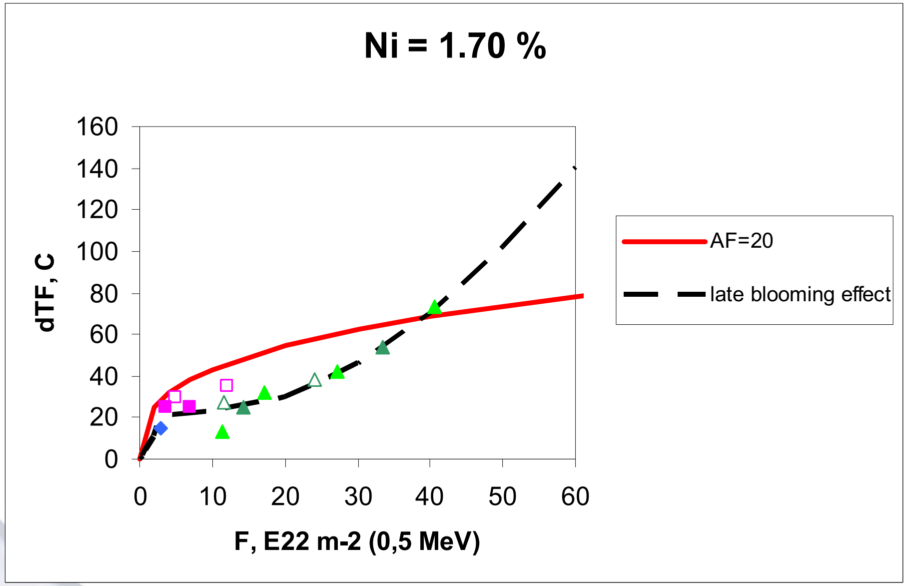
$$\Delta T_k = A * f_1(Ni, Mn, \ldots) * F^{0,9} + f_2(t)$$

should have to be evaluated from database of experimental results

This database should have to be extended and results (including neutron fluence) validated

FULLY OPEN QUESTION





what about LATE BLOOMING EFFECT ?!

Embrittlement trend curves

OPEN ISSUES:

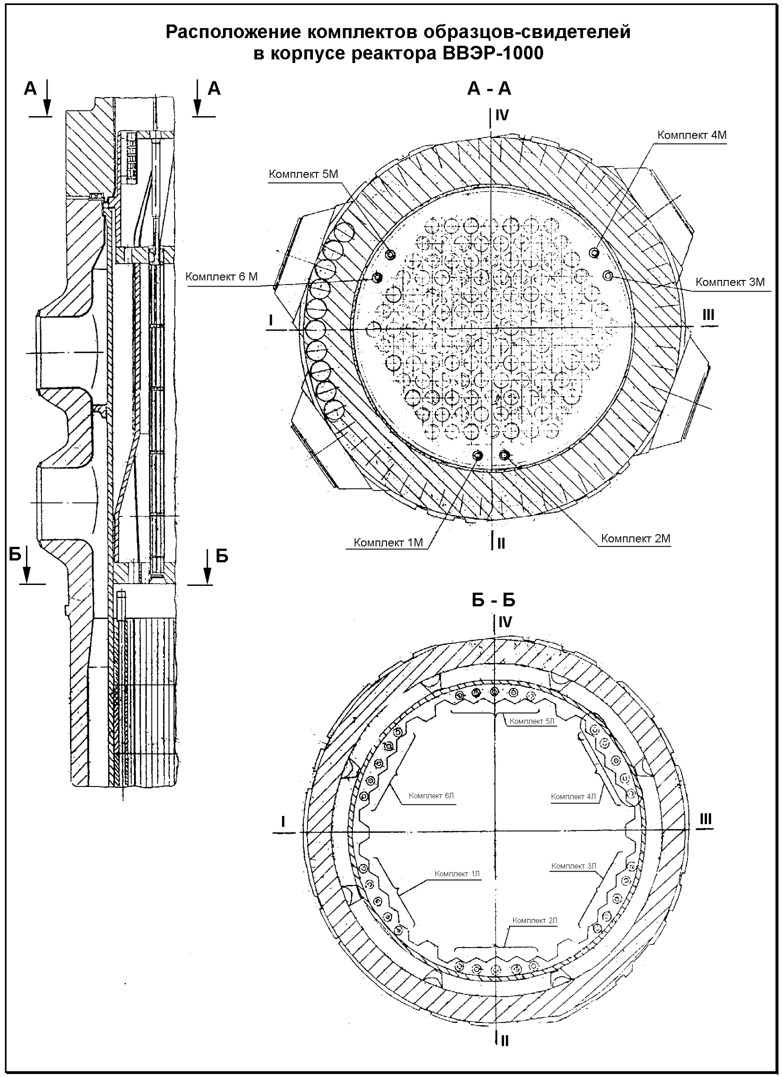
WWER-440:

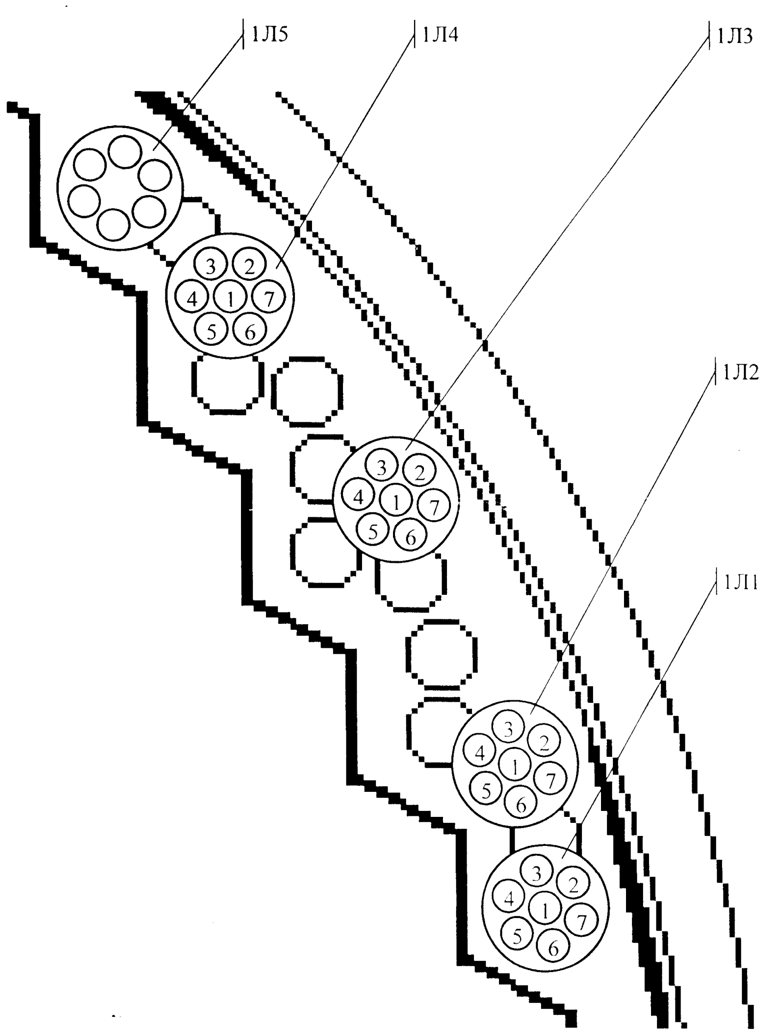
- TREND CURVES WITH SUFFICIENT RELIABILITY EXIST

WWER-1000:

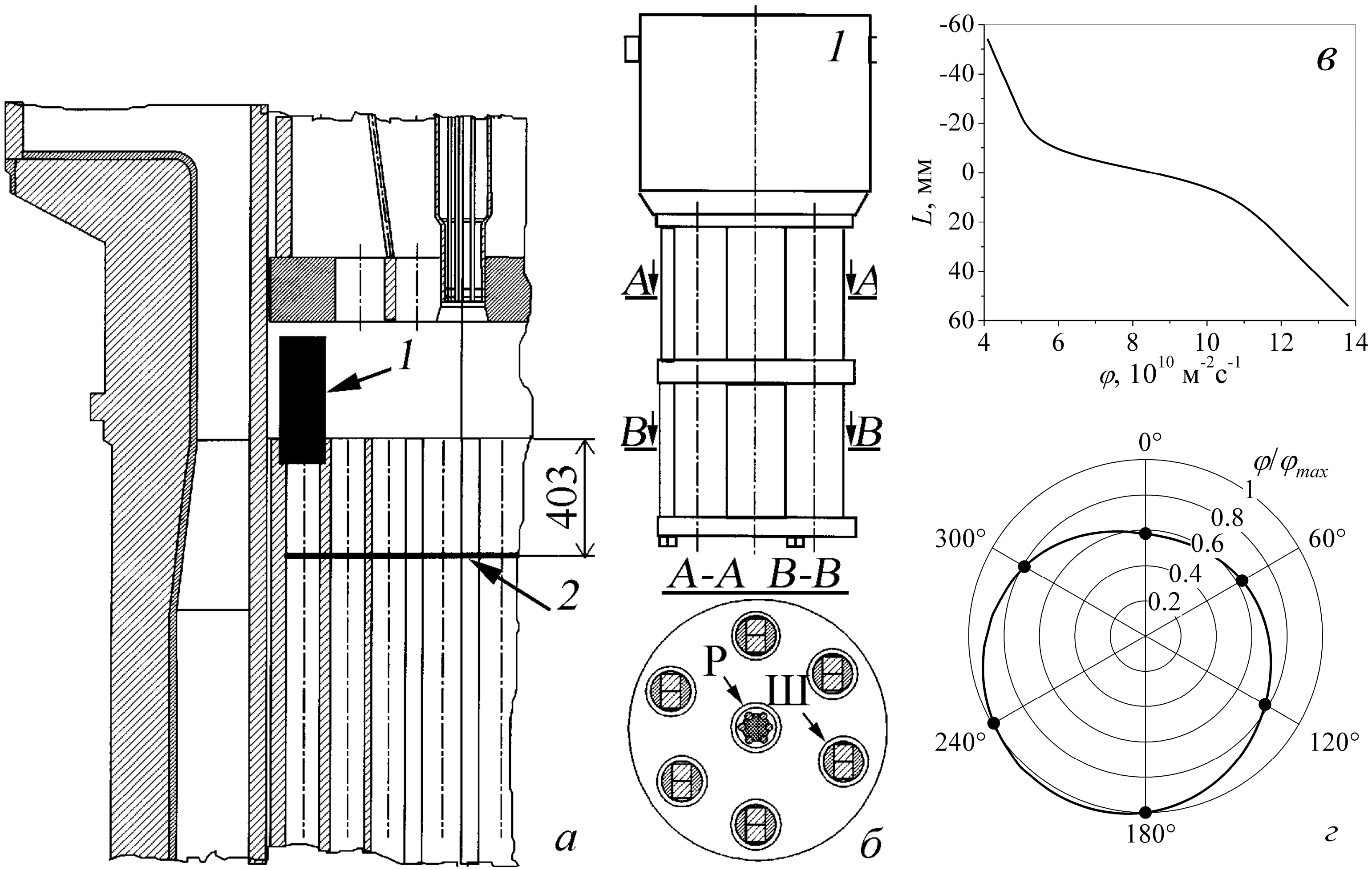
-NOT SUFFICIENTLY LARGE DATABASE
-PROBLEMS WITH STANDARD SURVEILLANCE PROGRAMME TESTING, DATA EVALUATION, spectral energy effect
-SYNERGISTIC EFFECT OF THERMAL AGEING
-SYNERGISTIC EFFECT OF Ni, Mn, Si, etc.(?) -
-FEW DATA FOR EOL FLUENCE AND PLEX
-„LATE BLOOMING EFFECT“ for high F, high Ni (thresholds) - ?

VVER-1000/V-320 STANDARD PROGRAMME





VVER-1000/V-320 STANDARD PROGRAMME VARIATION IN NEUTRON FIELD IN ONE LEVEL COULD BE UP TO 180 – 200 %



INTEGRATED SURVEILLANCE PROGRAMME FOR VVER-1000/V-320

- LOCATED IN TEMELIN NPP
- SURVEILLANCE MATERIALS FROM

MATERIALS IRRADIATED IN ETE:

UKRAINE:

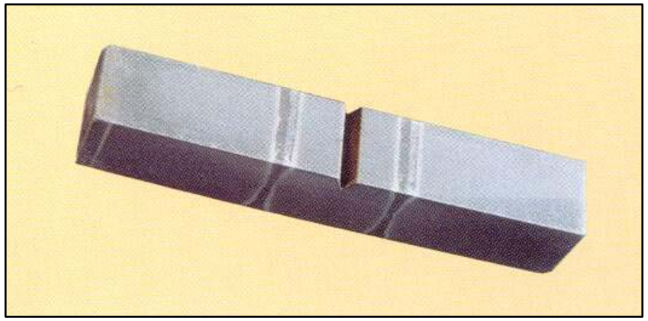
- ROVNO – 3
- ROVNO – 4
- KHMELNITSKY – 3
- ZAPOROZHYE – 6

RUSSIA

- KALININ – 3

BULGARIA

- BELENE - 1



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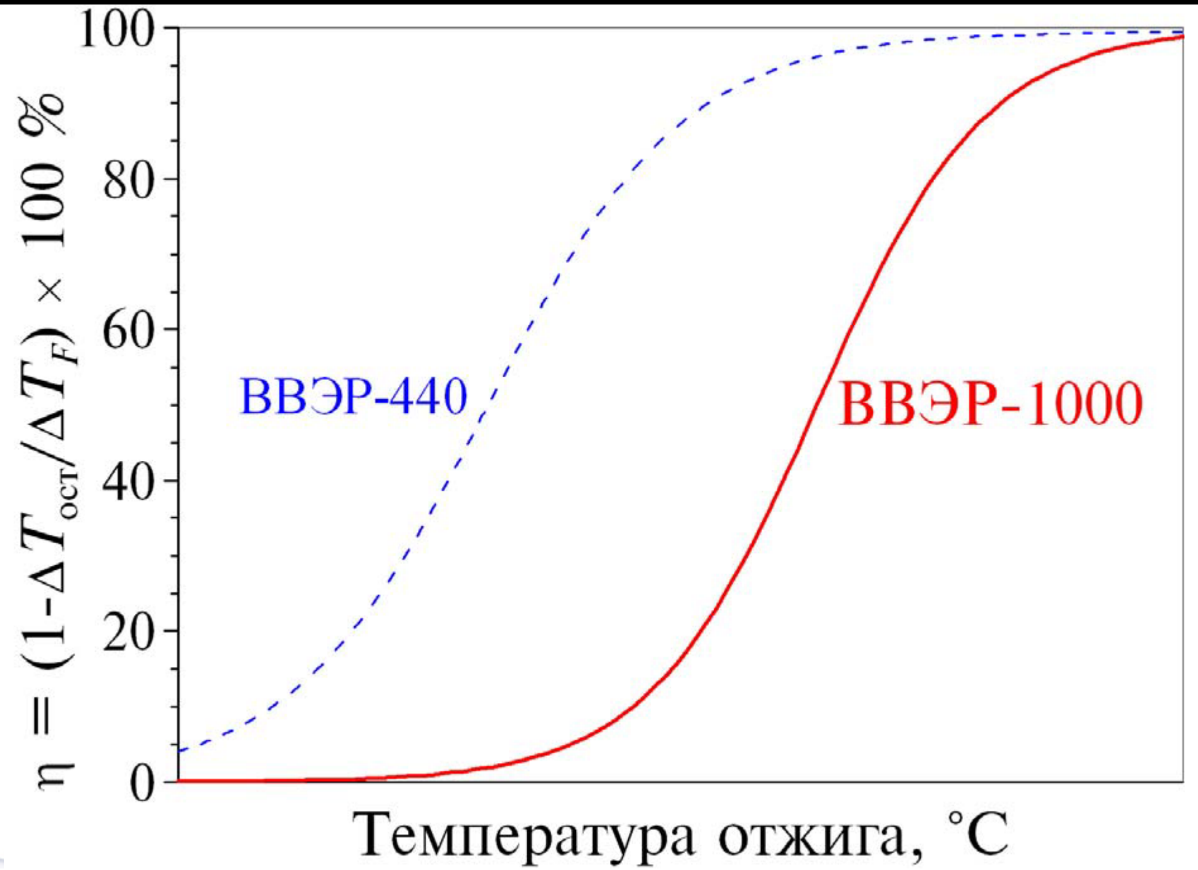
STROMBAKH - 10th CONFERENCE PROMETEY, 2008:

Analysis of results show that embrittlement of welds with Ni < 1.3% is lower than in base metal (green); welds with Ni > 1.7% (red) can limit its design lifetime – the only possible way for PLEX assurance is annealing of the RPV

Ni content in weld № 4	PLEX
1.70 - 1.88	TO ASSURE DESIGN LIFETIME AND PLEX-ANNEALING?
	Monitoring of radiation damage and loading for assurance of design lifetime and ANNEALING for PLEX
1.57 - 1.64	Monitoring of radiation damage and loading for assurance of design lifetime and Supplementary material qualification for PLEX
1.10 - 1.21	Design lifetime is assured PLEX based on Supplementary material qualification

OPEN ISSUE:

The only way for PLEX of RPVs with the most embrittled welds seems to be ANNEALING. This could be connected with additional problems, as recovery of properties in these materials of WWER-1000 RPVs will be PROBABLY reached at higher temperatures than in the case of WWER-440 RPV materials



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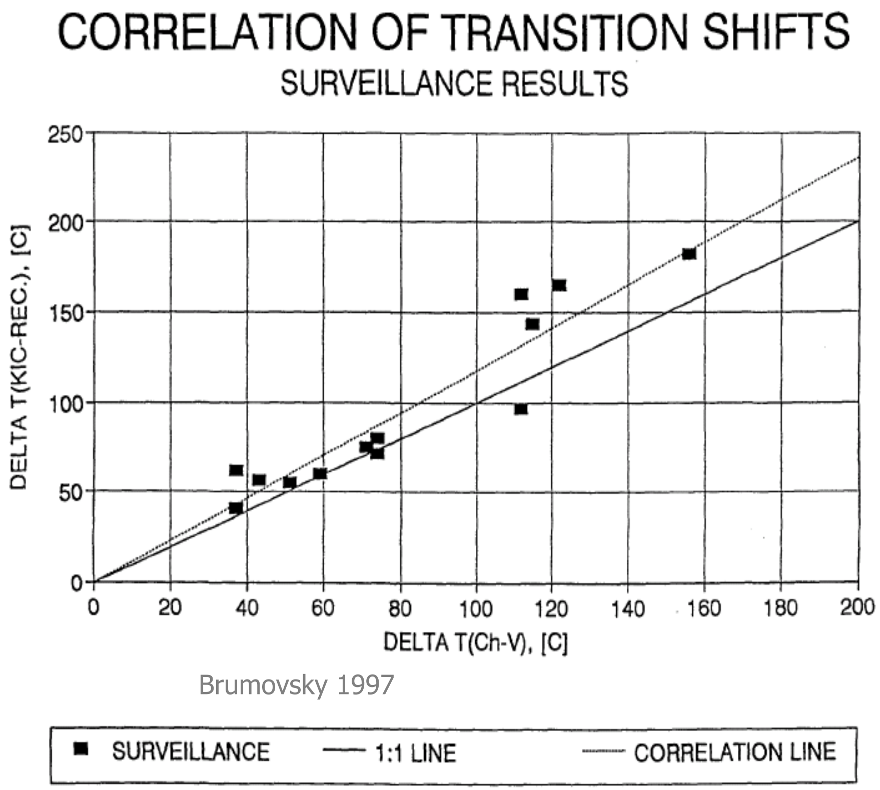
ANOTHER PRINCIPAL OPEN ISSUES:

- ALL THESE TREND CURVES ARE BASED ON CHARPY NOTCH IMPACT TESTS
- HOW THESE TREND WILL BE MODIFIED FOR STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURES, i.e. T0 etc.?
- ONLY LIMITED NUMBER OF CORRELATIONS EXISTS. e.g.
  – $\Delta T0 \approx 1{,}05\ \Delta Tk$

CORRELATION ΔTk – ΔT0

- (Brumovsky 1997) the higher is transition temperature shift, the higher is the difference between static and dynamic transition temperature shift.
  - These differences can be neglected up to VVER-440 EOL design neutron fluence
- Other authors also reported much higher fracture toughness shift than Charpy shifts,
  - Differences in flux between Charpy specimens and fracture toughness specimens (Ozsvald 1999)
  - Pre-cracking procedures (Ahlstrand 1993).



Brumovsky 1997

CORRELATION $\Delta Tk - \Delta T0$

IAEA-TECDOC-1442

Guidelines for prediction of irradiation embrittlement of operating WWER-440 reactor pressure vessels

If this cannot be determined directly by fracture toughness testing, then the following mixed way (i.e. combination of static fracture toughness and Charpy V-notch impact test results) may be conservatively used for determination of temperature T_0 during operation, i.e.

$$T_0^{operation} = T_0^{initial} + 1.1\ \Delta T_F \qquad (9.13)$$

where ΔT_F is determined by the same process as is shown in 9.3.1, i.e. using Charpy impact specimen testing and/or prediction using formula (8.14).

CONCLUSION

- PREDICTIVE FORMULAE FOR VVER-440 RPV MATERIALS FIT WELL WITH SURVEILLANCE SPECIMEN RESULTS
- SURVEILLANCE SPECIMEN PROGRAMMES (MAINLY SUPPLEMENTARY ONES) WELL MONITOR RPV MATERIAL CHANGES
- THERE IS A HIGH EXPERIENCE WITH RPV RECOVERY ANNEALING (13 UNITS)

CONCLUSION

- PREDICTIVE FORMULAE FOR VVER-1000 RPV MATERIALS ARE STILL IN PROGRESS
- STANDARD SURVEILLANCE SPECIMEN PROGRAMMES CAN GIVE ONLY LIMITED INFORMATION EVEN AFTER COMPLICATED RE-EVALUATION
- HIGH FLUENCE RESULTS WILL BE OBTAINED ONLY BY MODIFICATION OF THE PROGRAMME INSERTING NEW CAPSULES
- ONLY MODIFIED SURVEILLANCE PROGRAMMES (SKODA, OKB) CAN WELL MONITOR RPV MATERIAL CHANGES AND CAN GIVE RELIABLE INFORMATION

Thank you for your attention

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