Federal Environmental, Industrial and Nuclear Supervision Service

Scientific and Engineering Centre
for Nuclear and Radiation Safety

EUROSAFE 2019

ETSON EUROPEAN TECHNICAL SAFETY ORGANISATIONS NETWORK

Actual issues of VVER reactor pressure vessel irradiation embrittlement assessment

Dr. Alexander Kryukov

OUTLINE

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RPV Radiation Damage

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Irradiation Embrittlement Mitigation by Annealing

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VVER RPV-440 life time long term operation

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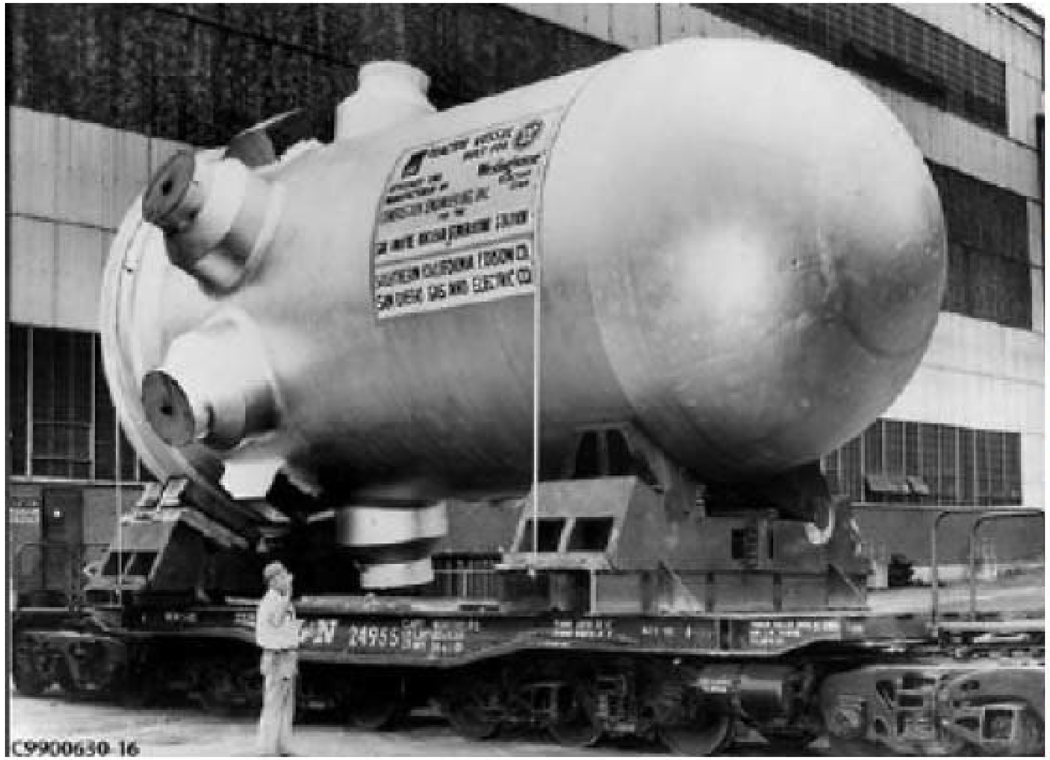
International STRUMAT project

TYPICAL PWR RPV



WWER-440 RPV

- Vessels may weigh up to 800t with wall thickness up to ~330mm.

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- Effects of several stressors from operating conditions

AGEING STRUCTURE

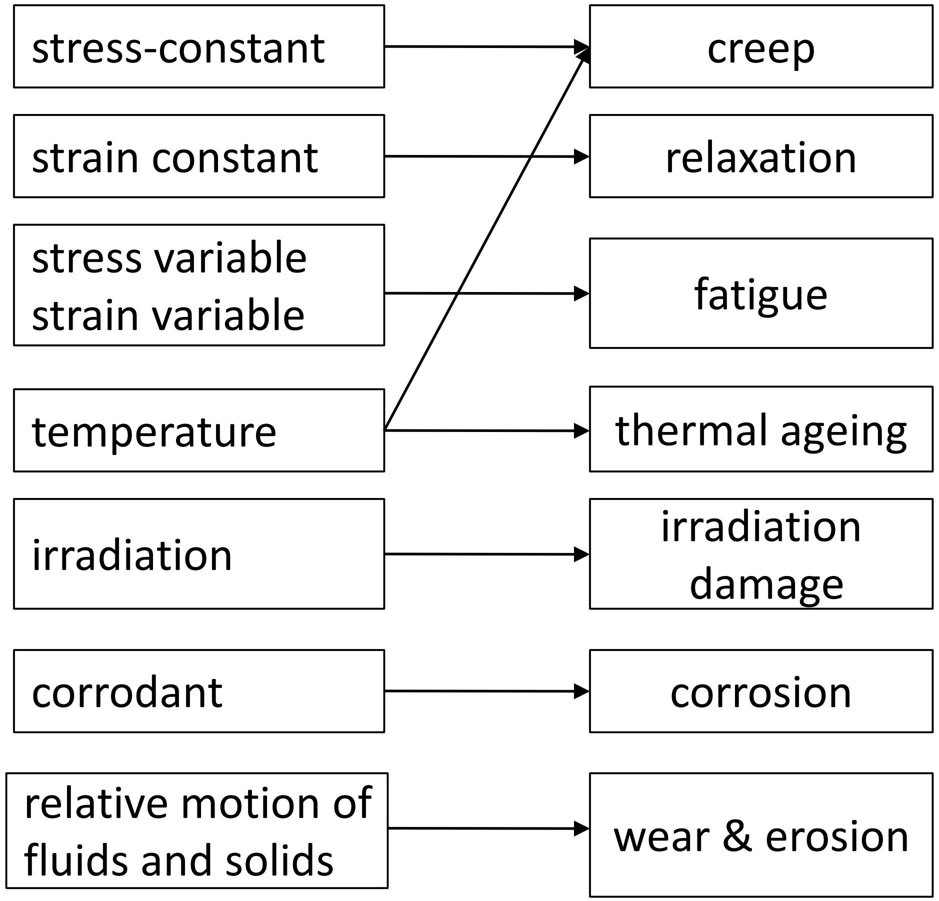
STRESSORS

- stress-constant
- strain constant
- stress variable strain variable
- temperature
- irradiation
- corrodant
- relative motion of fluids and solids

A major stressor in an ageing structure is time itself

AGEING STRUCTURE

STRESSORS | **AGEING MECHANISMS**



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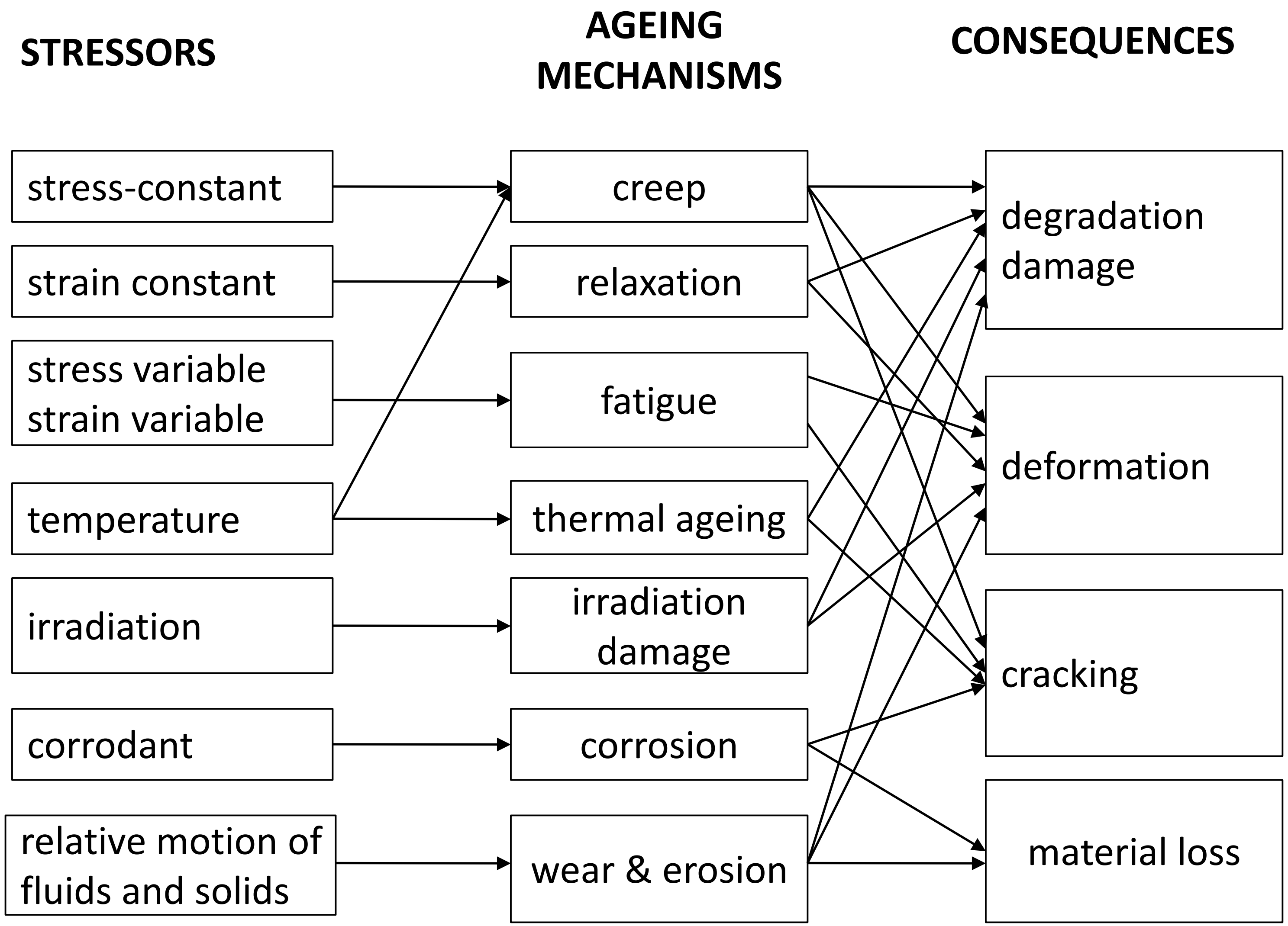

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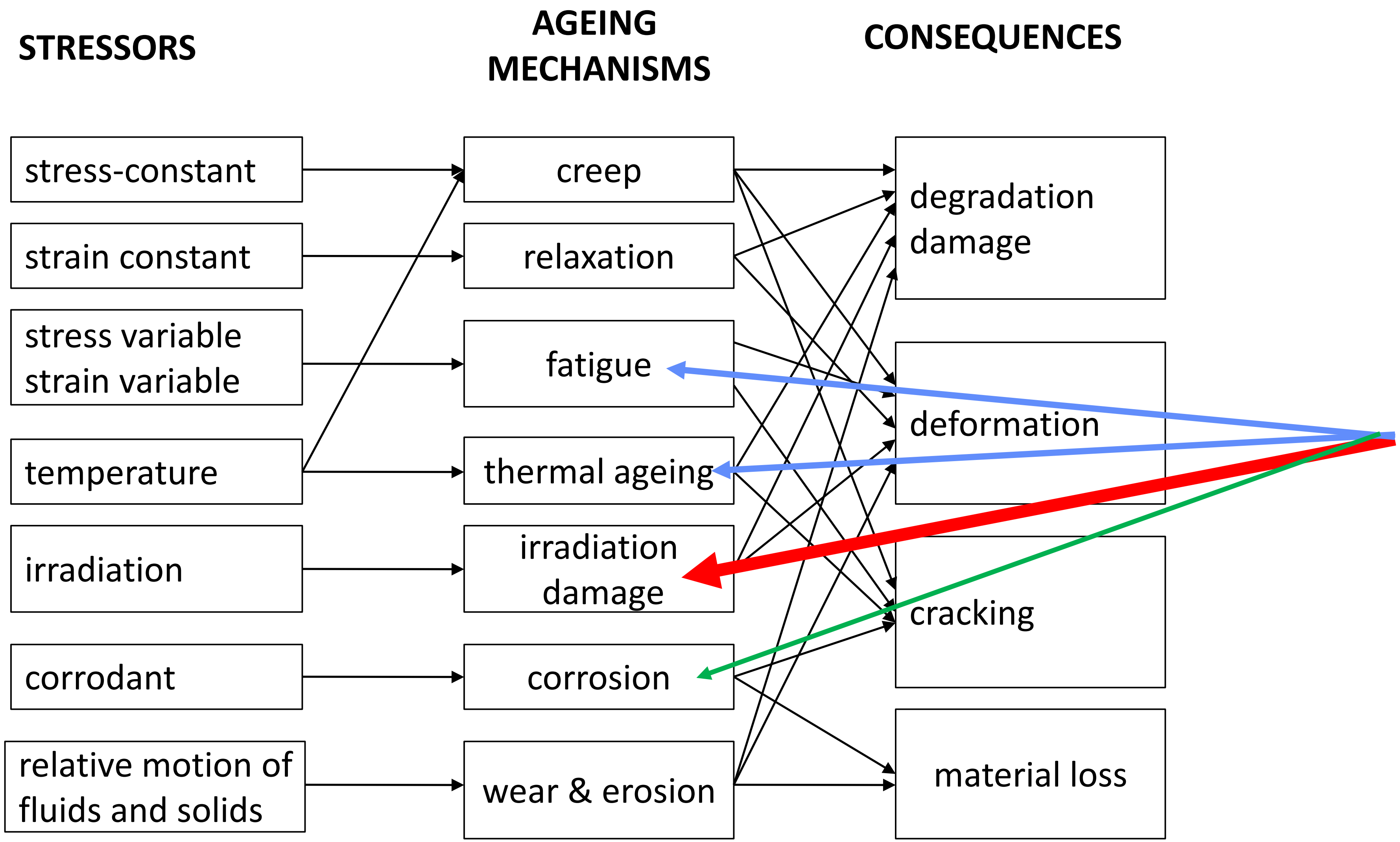

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RADIATION DAMAGE (Irradiation Embrittlement)

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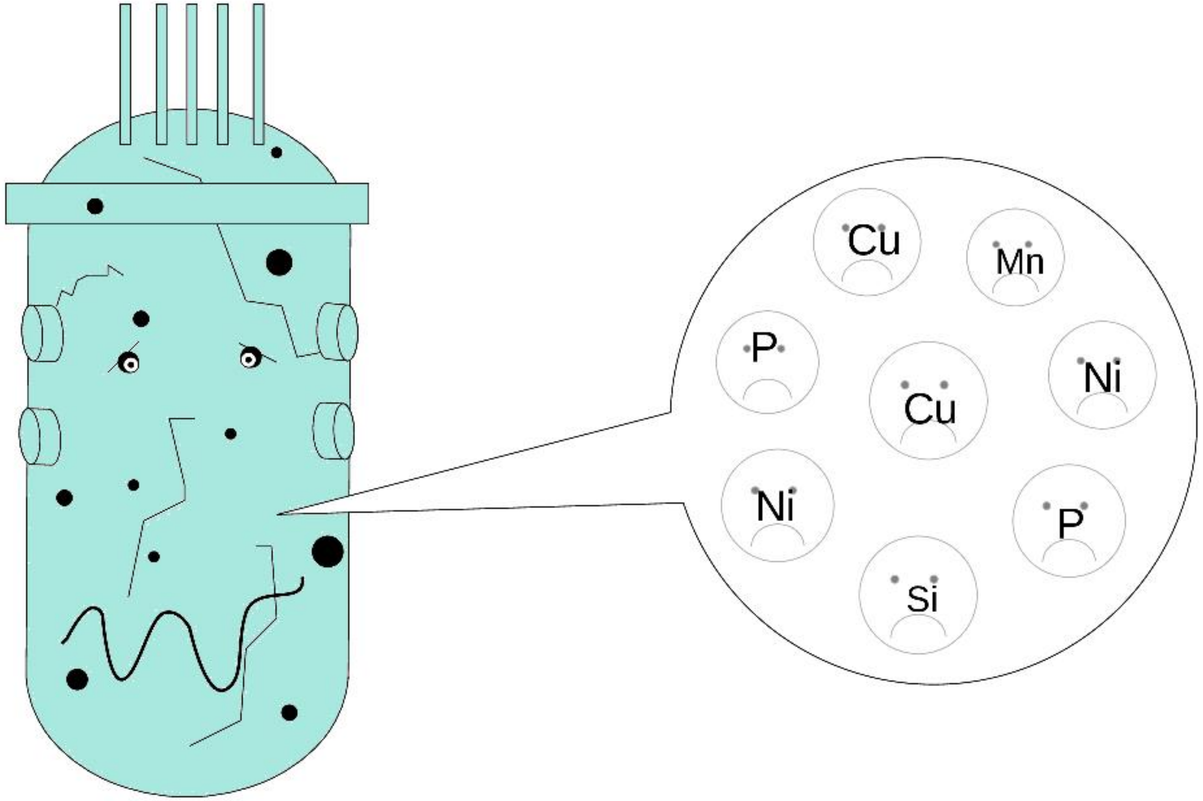
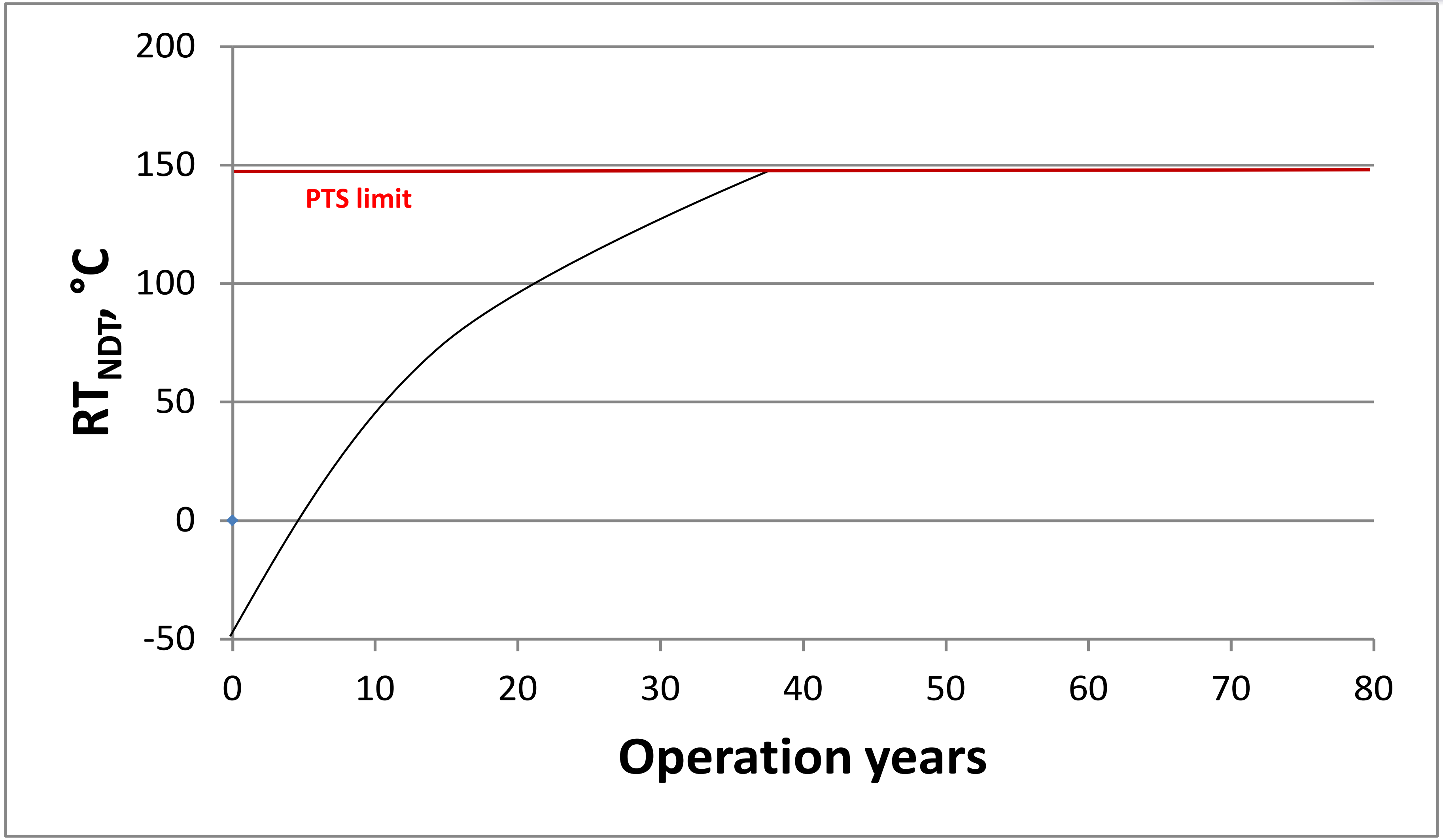
Most important ageing mechanism resulting to:

- Increase in strength properties
- Decrease in ductility and reduction of area
- Shift of impact and fracture toughness dependences to higher temperatures

Main influencing elements: Cu, P, Ni and Mn

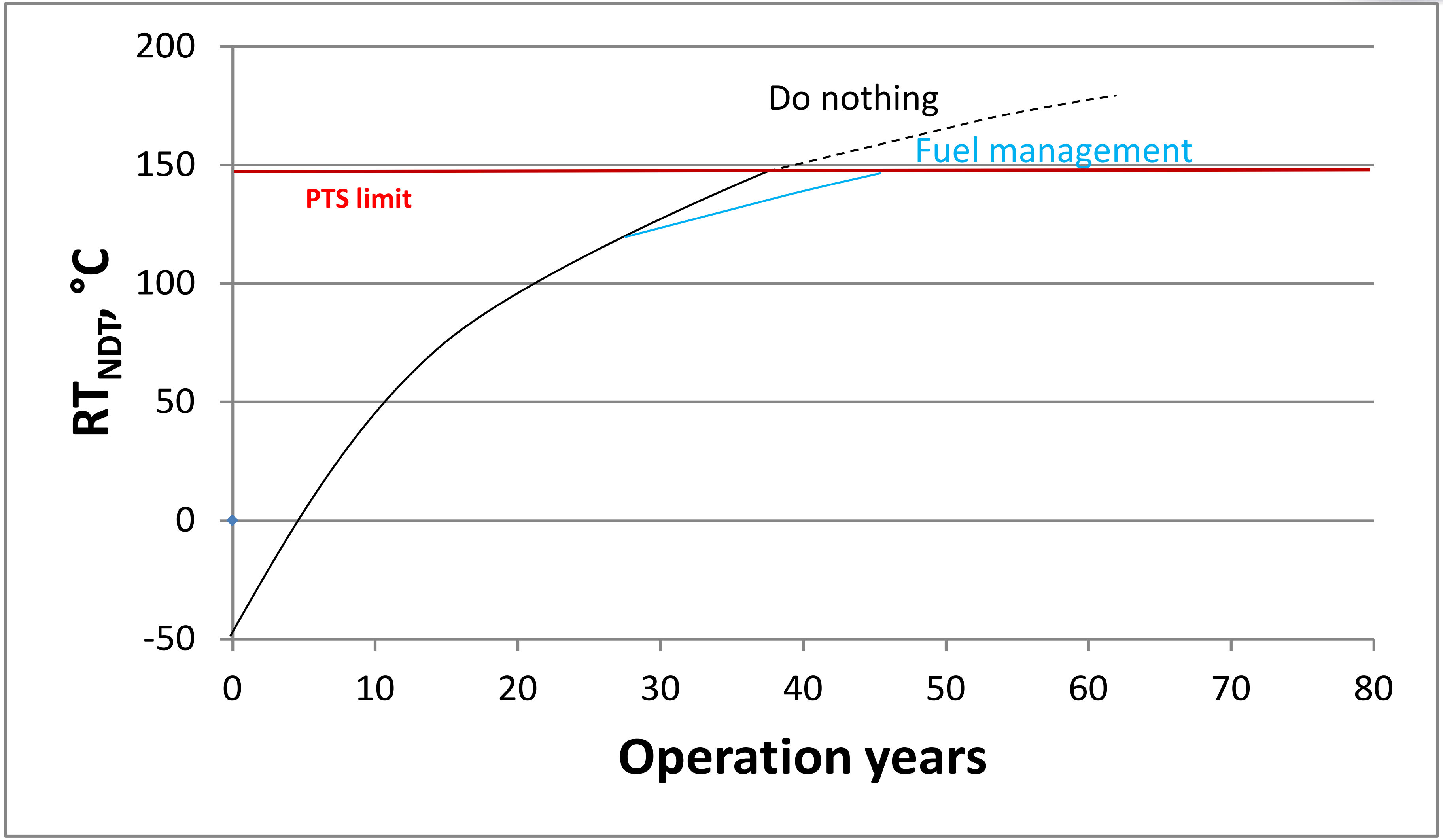


RPV ageing management



RPV ageing management

- Fuel management



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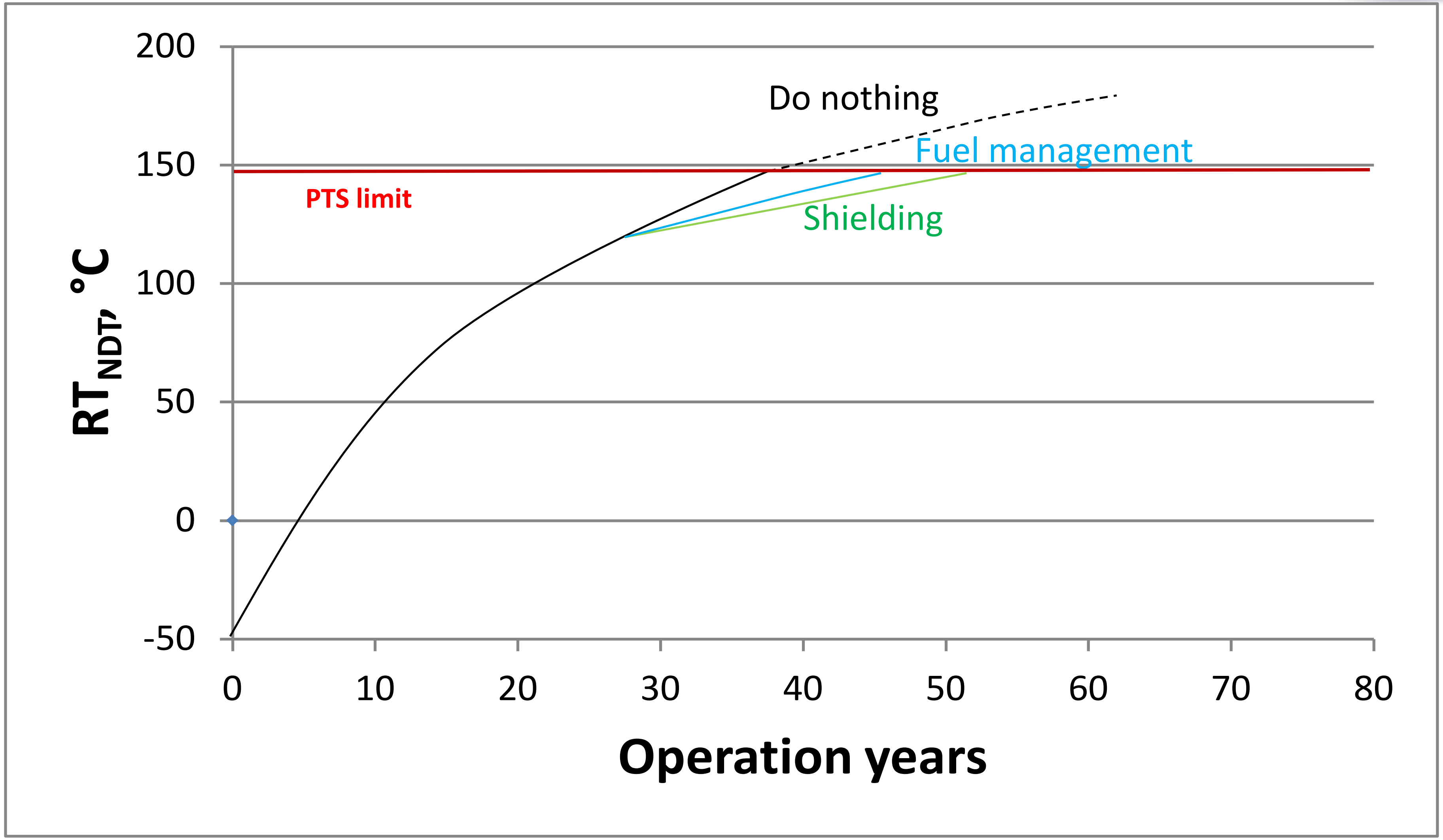
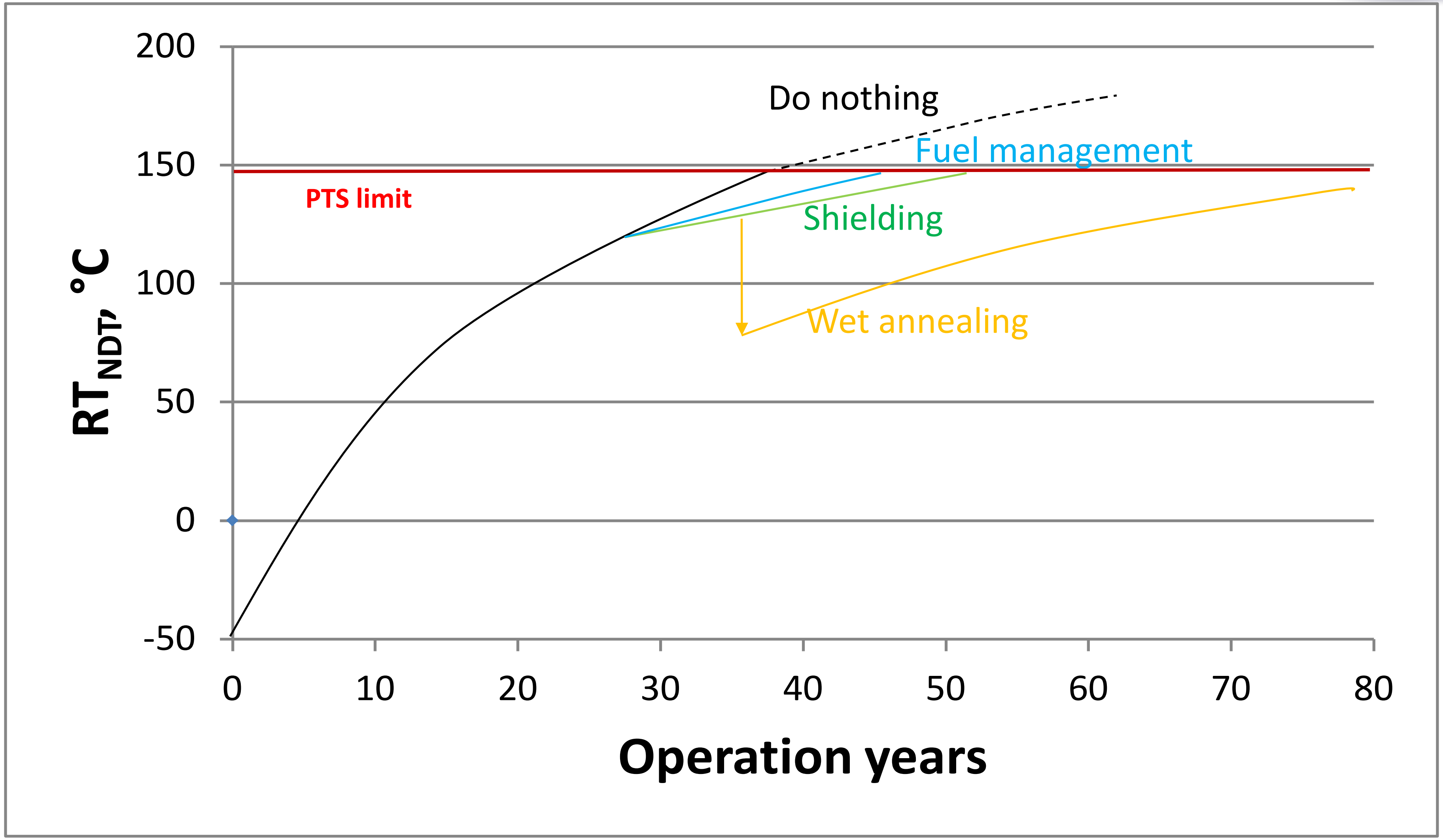
- RPV shielding



RPV ageing management

- Fuel management
- RPV shielding
- Thermal annealing
    - Wet annealing



RPV ageing management

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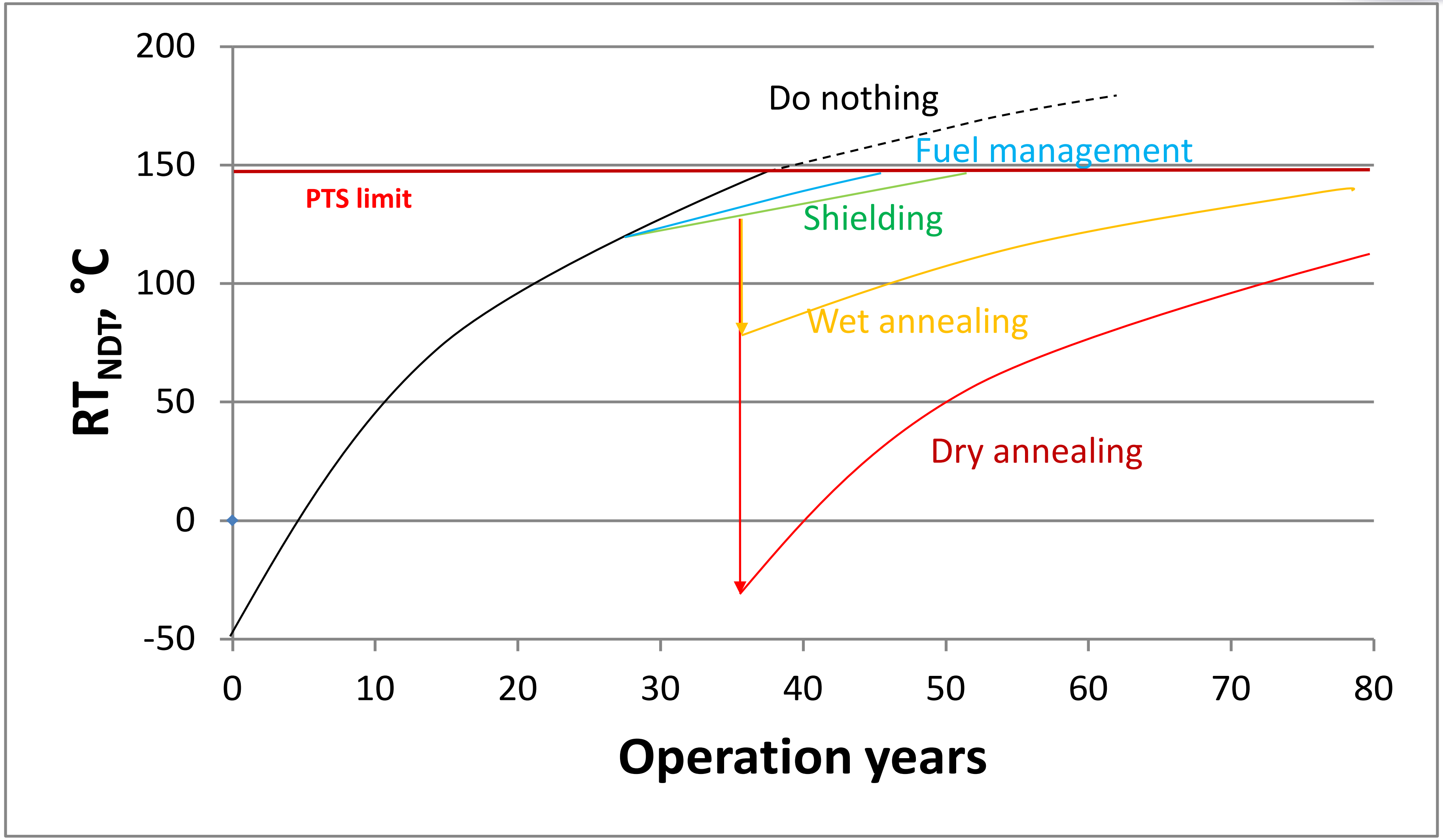
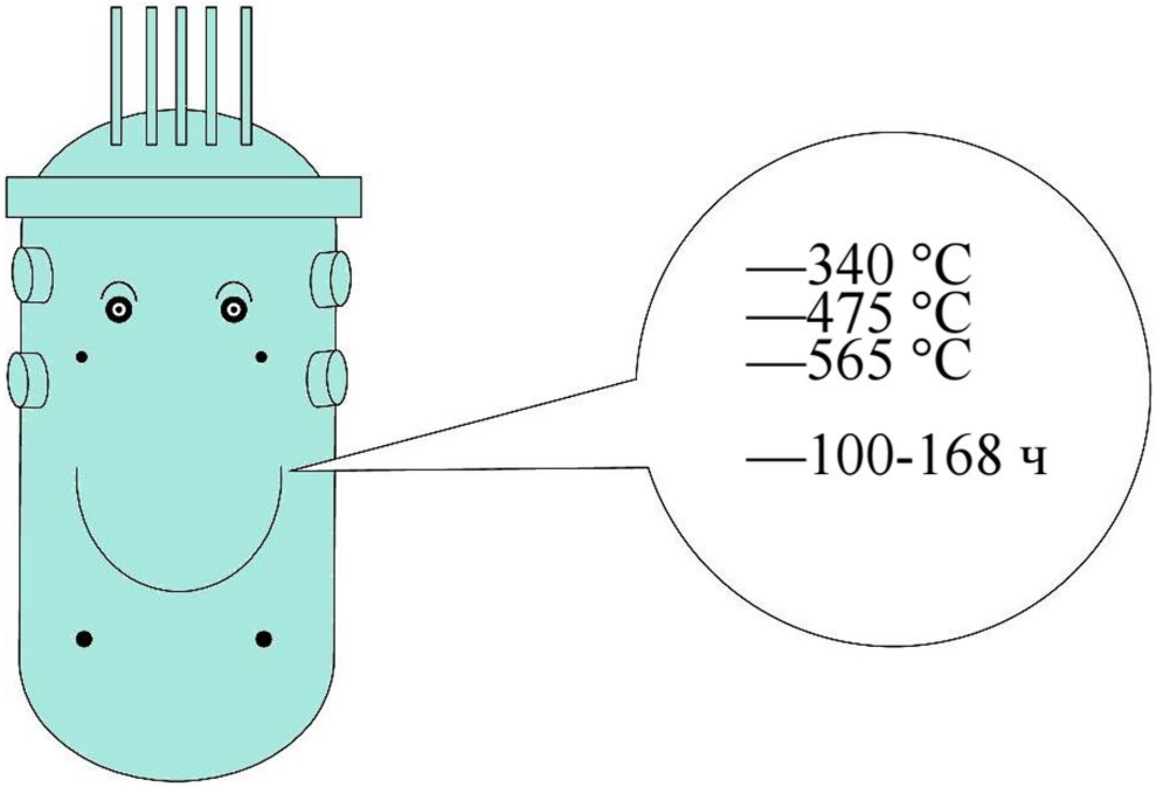
  - Wet annealing
  - Dry annealing



Annealing - most powerful solution

Irradiation embrittlement mitigation by thermal annealing



“Dry” annealing

High temperature (> 400 °C)

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Standard regime: **460-490 °C**, 100-168 hours

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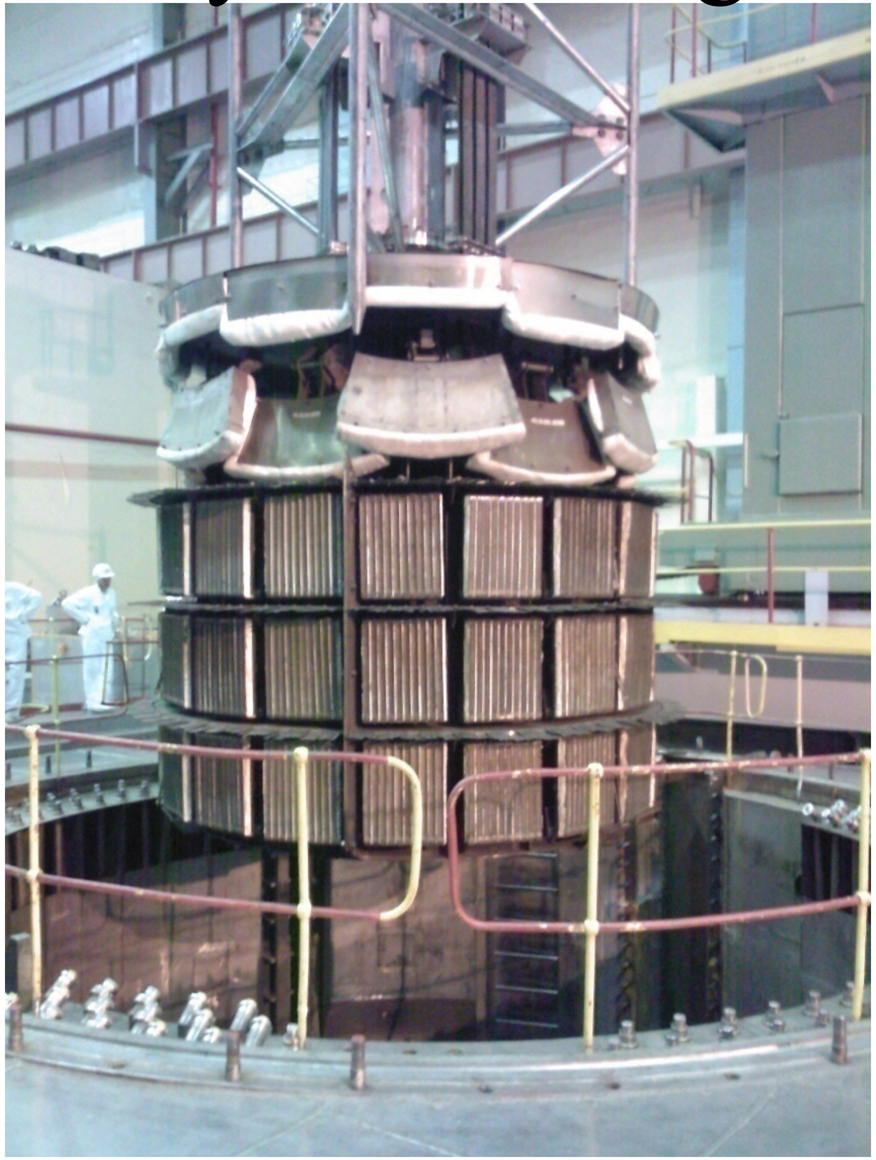
1st VVER-1000 RPV annealed in Russia in 2018:
550-580 °C, 100 hours

“Dry” annealing

~20 RPV VVER, 1987 – 2019
(460-490 ºC, 100-150 h.)



Extensive and expensive procedure

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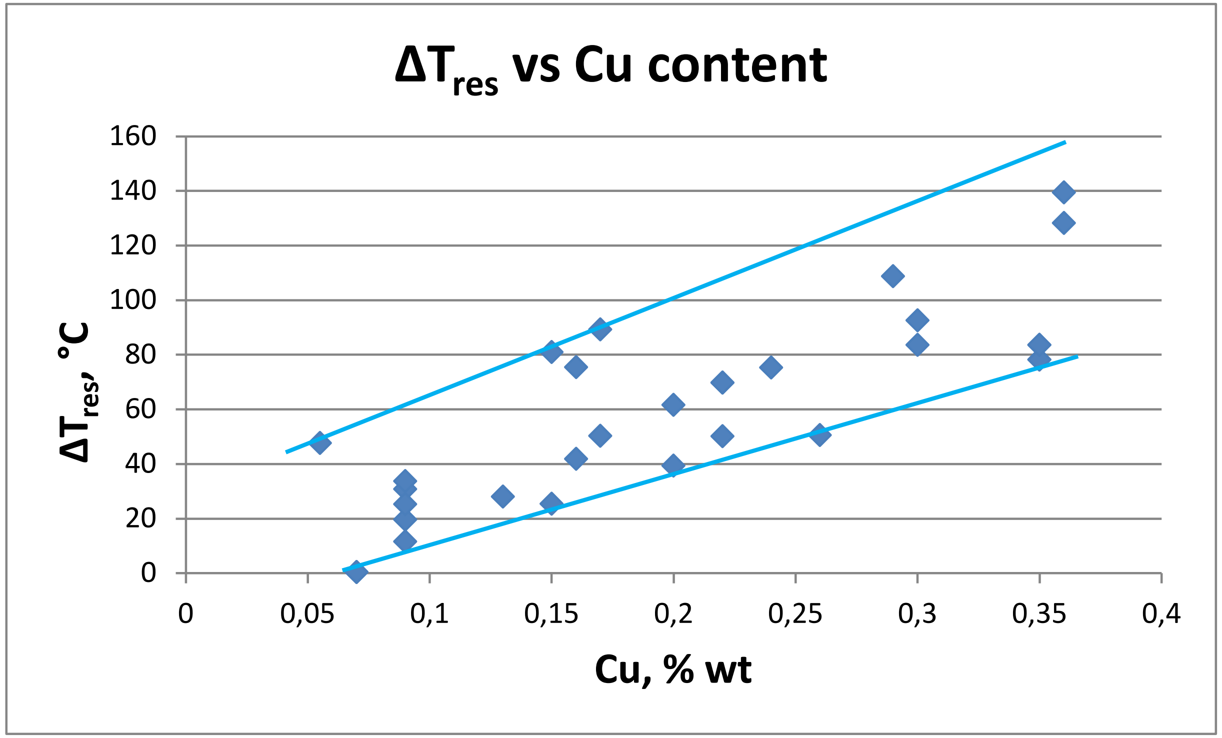
Conclusion in the 80s – “wet” annealing is not effective for high Cu steels

<u>Residual</u> after annealing (at 343ºC) T_k shift depends on Cu content (PWR steels)



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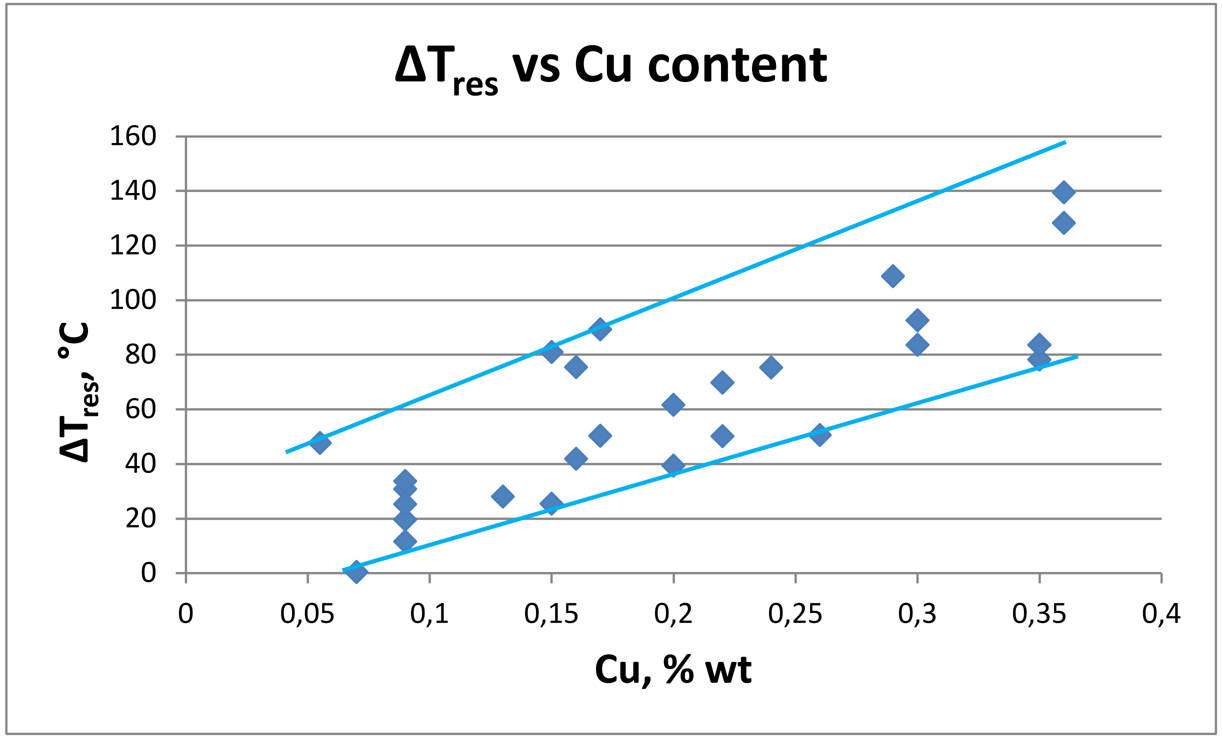

Wet annealing is effective for low Cu PWR RPV steels

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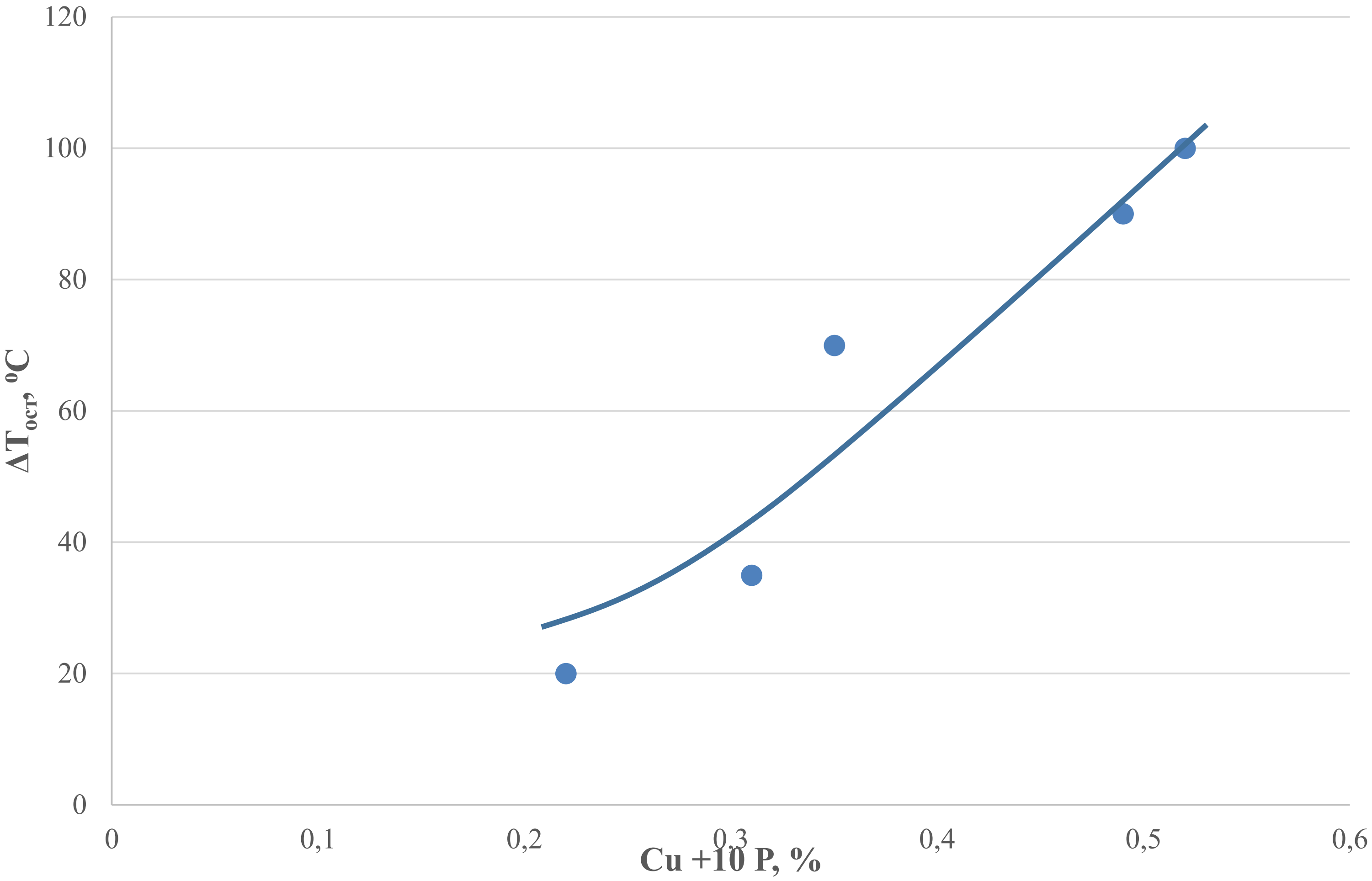

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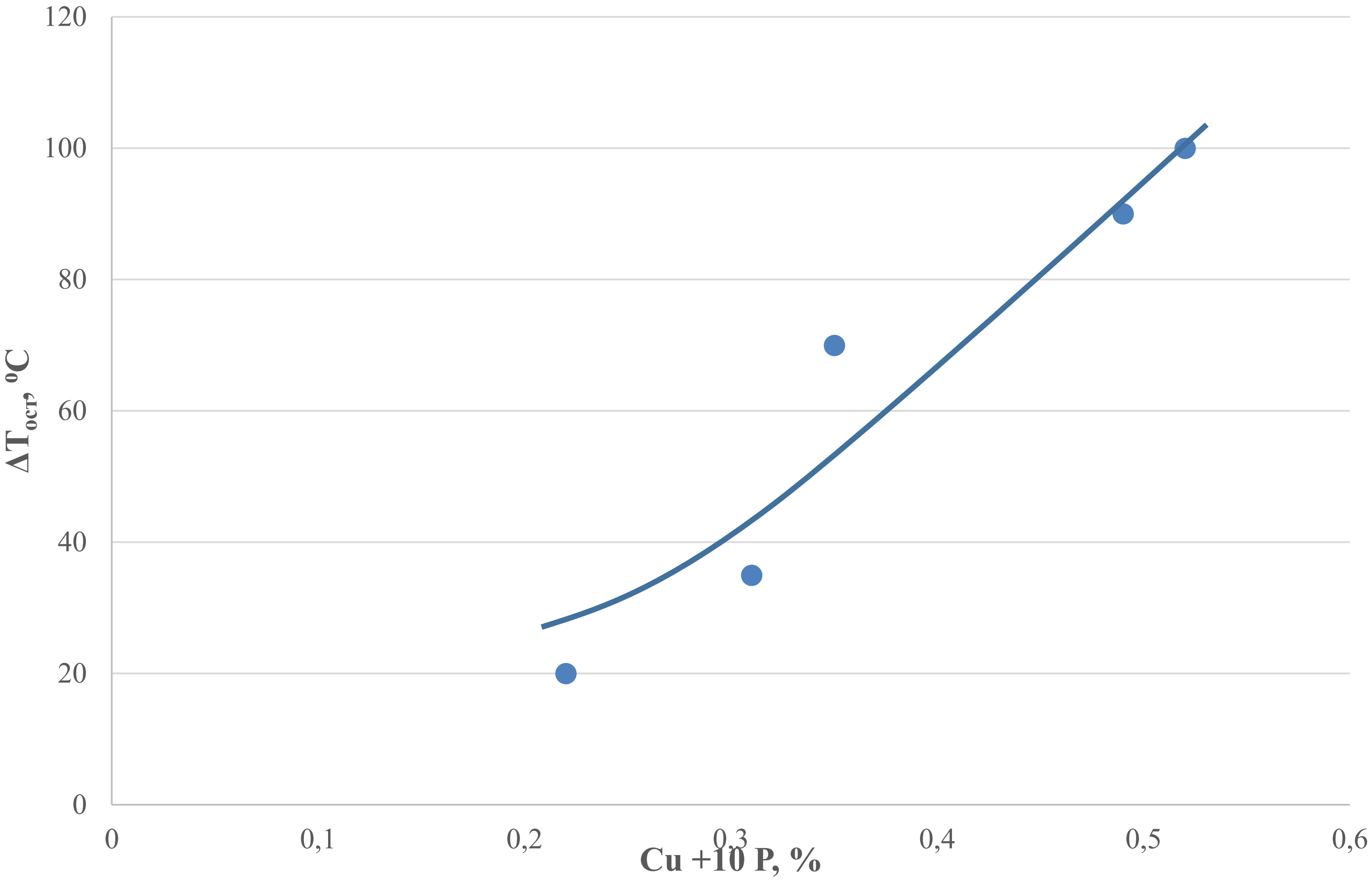

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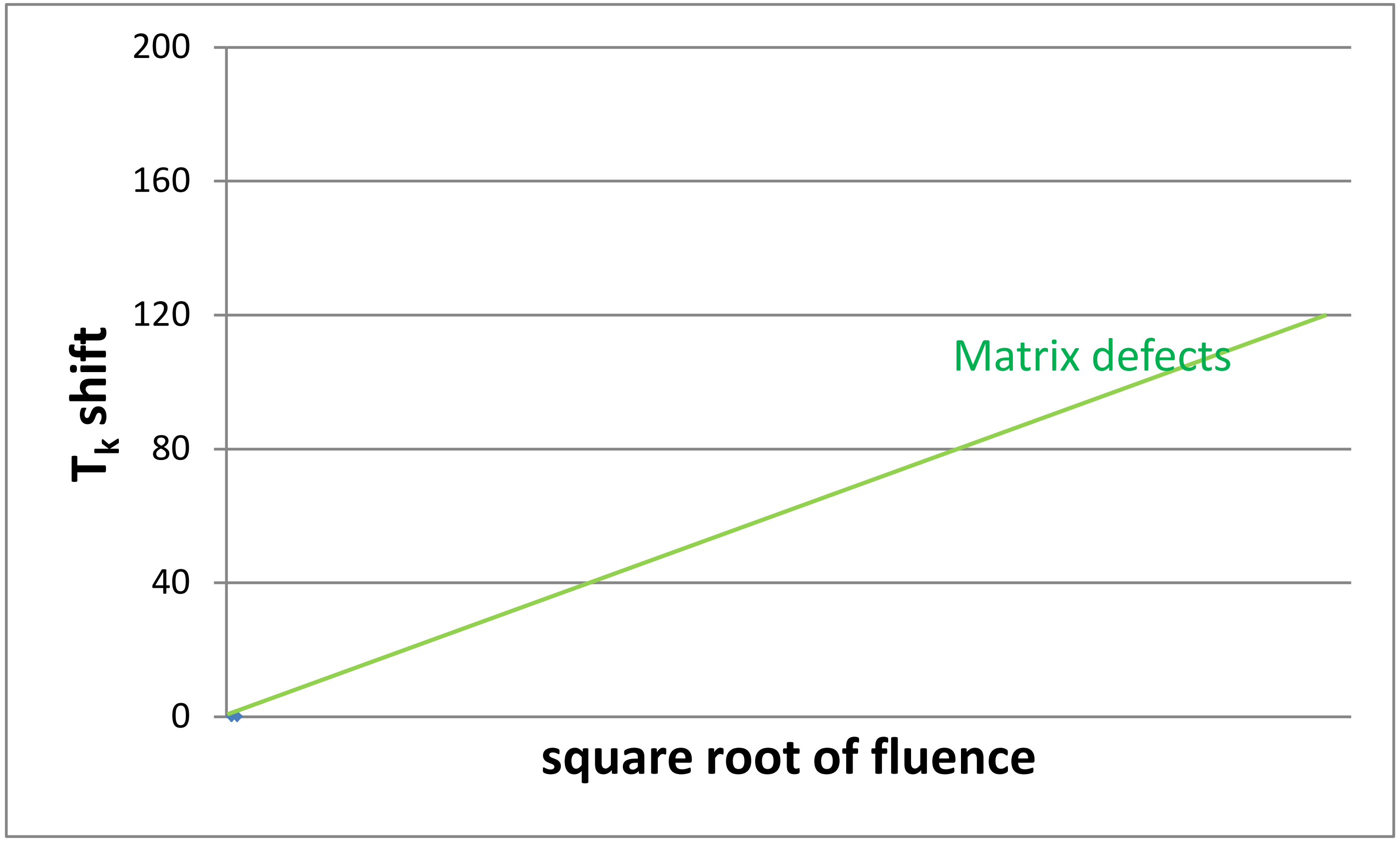
T_k shift recovery due to "wet" annealing - matrix defect elimination



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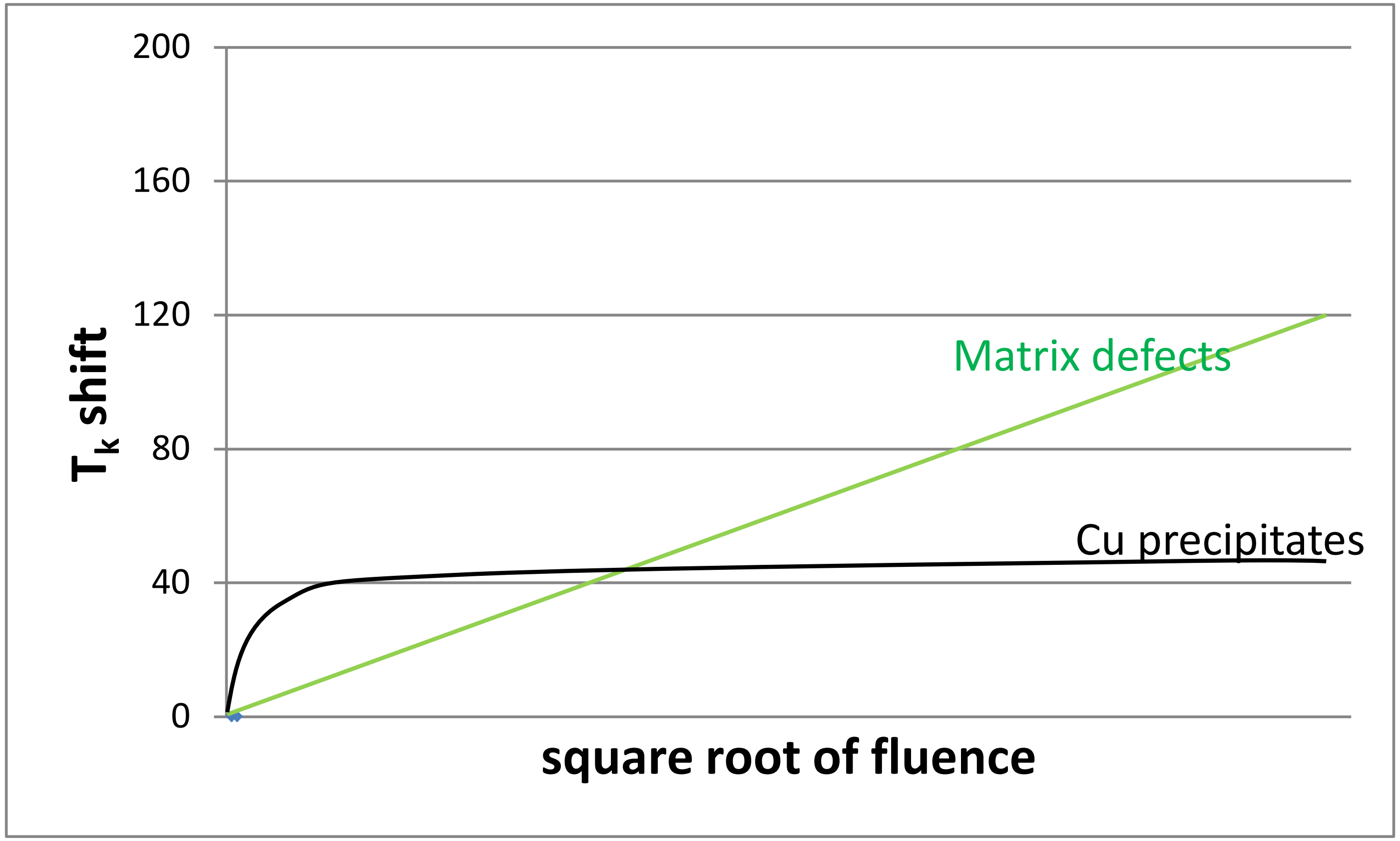

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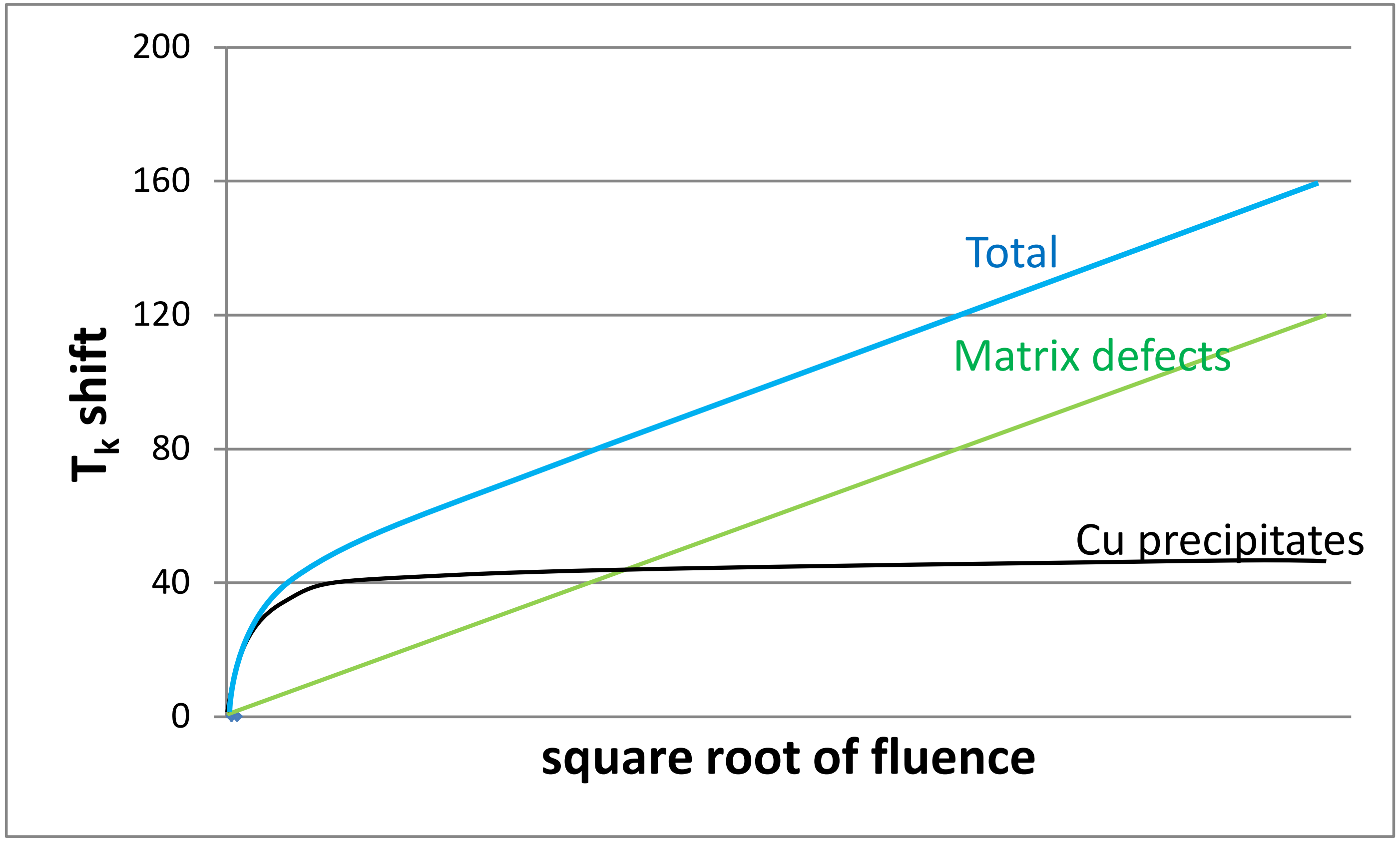

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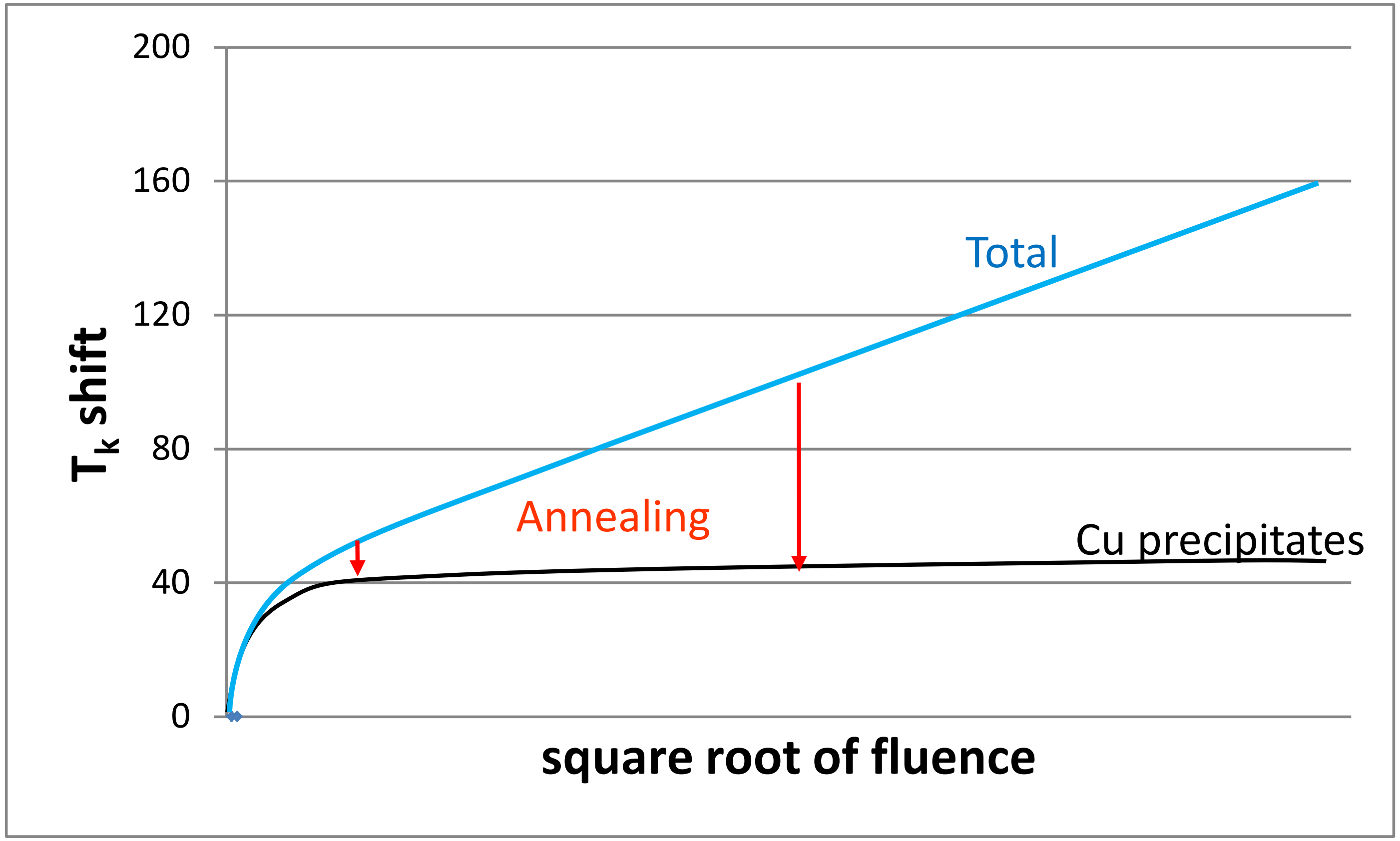
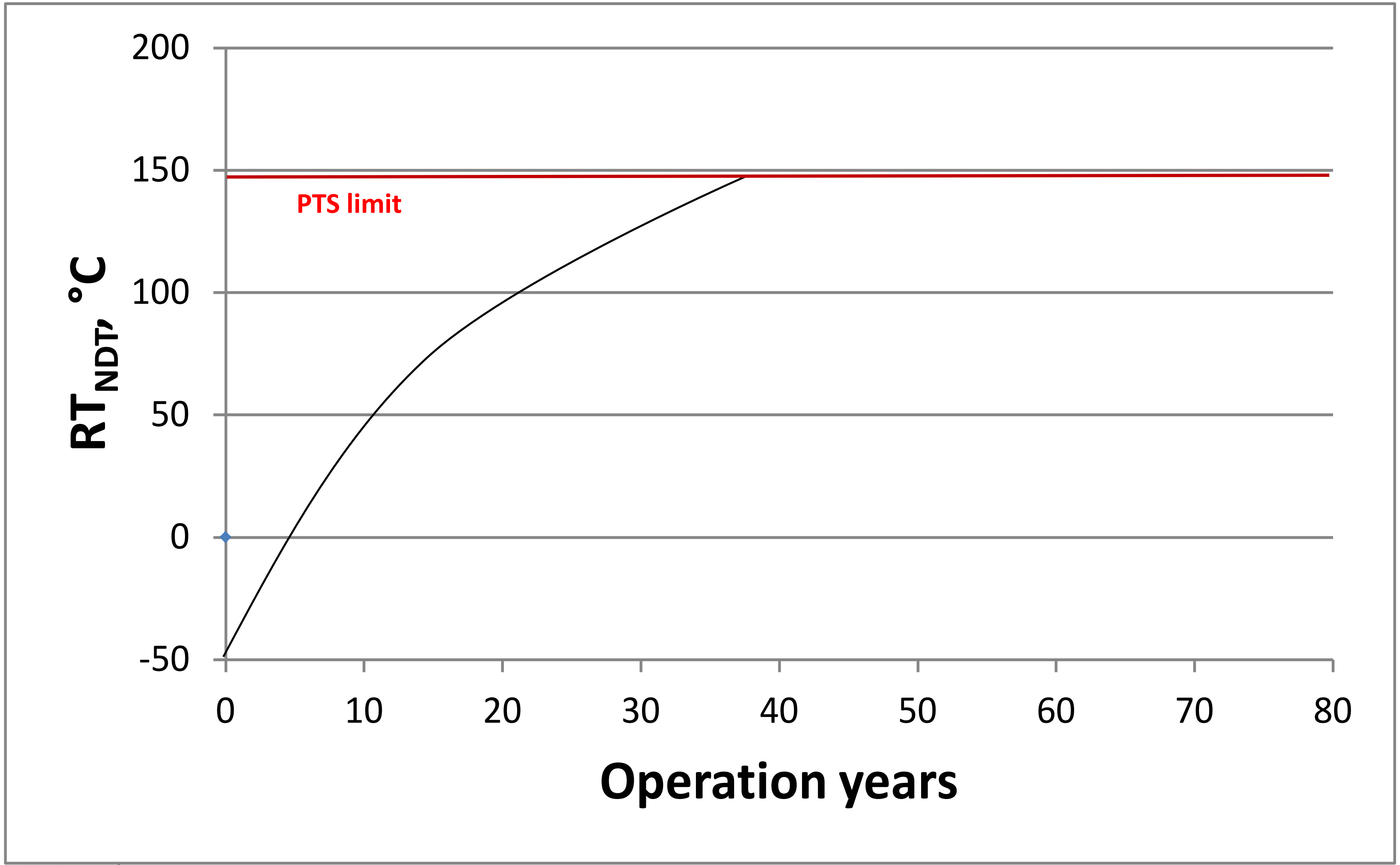


VVER-440 life time long operation

RPV irradiation embrittlement



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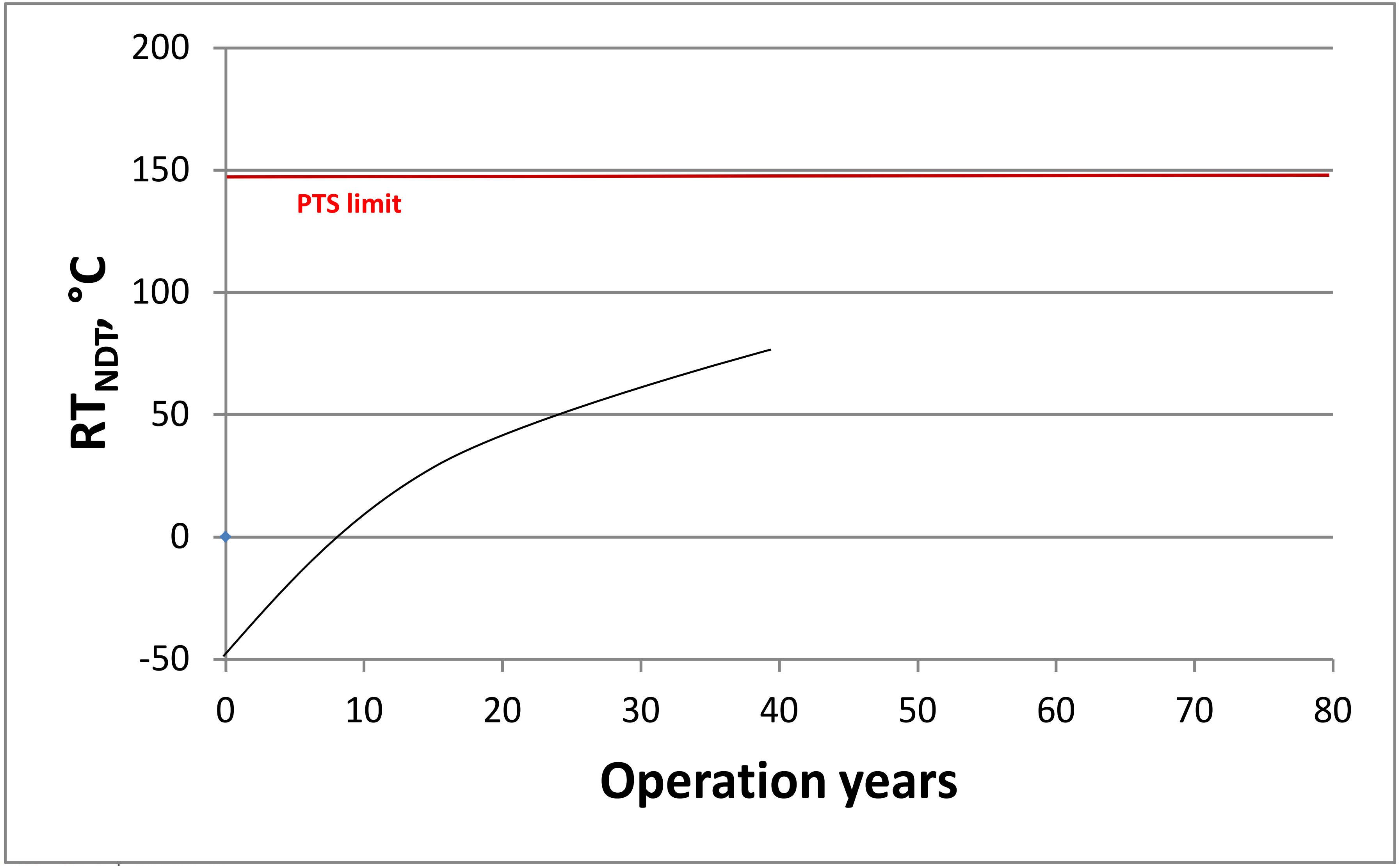

VVER RPV-440 life time long term operation

1960s

VVER-440 RPV design fluence:

- 2,4 10^{20} cm^{-2} for base metal
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- Validation of Tk vs fluence dependences for flunce more $3x10^{20}$ cm^{-2}

Objective – VVER-440 RPV integrity validation at neutron fluence up to $5x10^{20}$ cm^{-2} (~ 80 years operation)

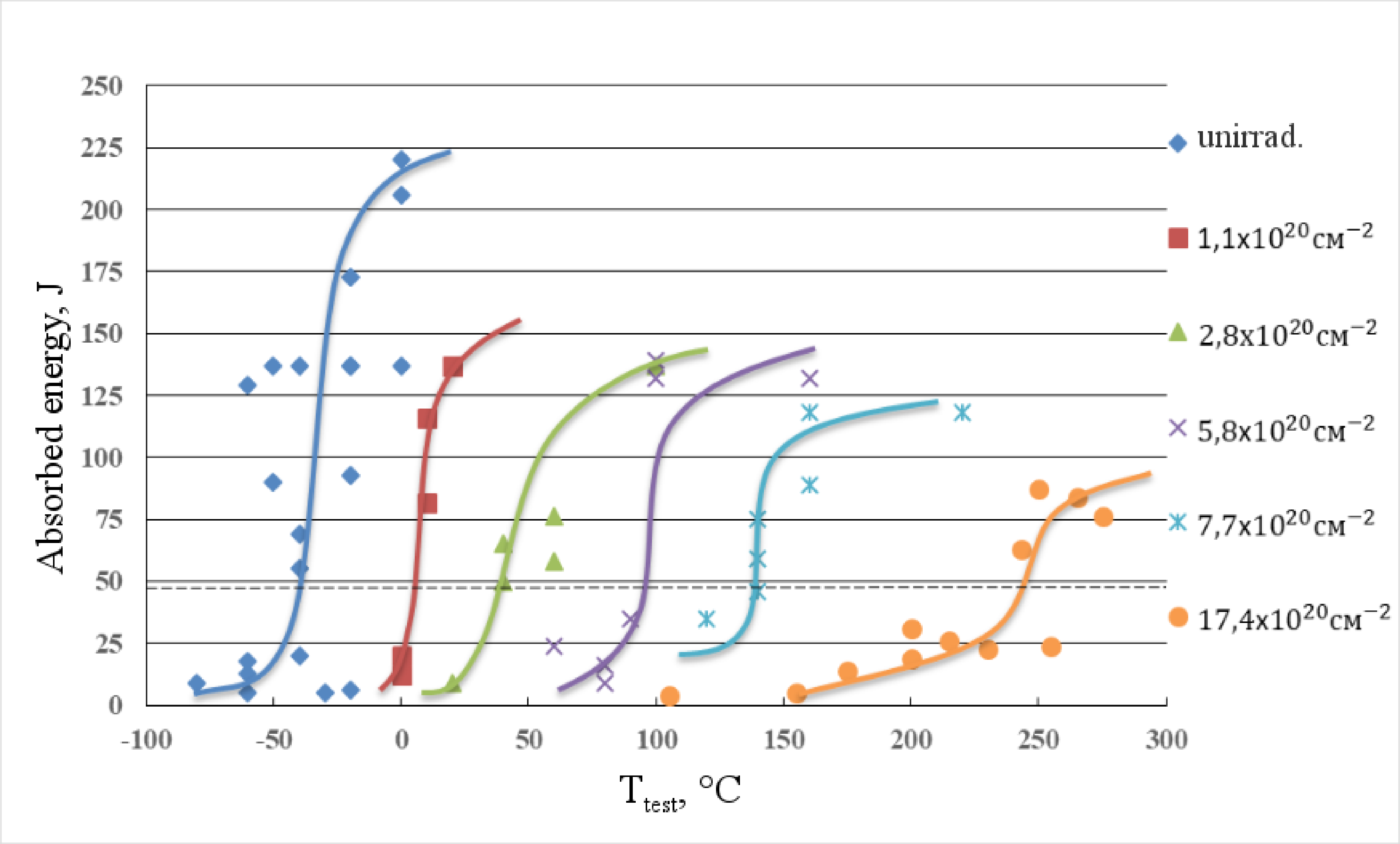
The highest contents of impurities and fluence values both in the worldwide used RPV steels and in the **IAEA Database**

Reactor type	Cu $_{max}$, wt %	P $_{max}$, wt %	Ni $_{max}$, wt %	Mn $_{max}$, wt %	Fluence $_{max}$, n/cm^2
PWR	0.42	0.025	1.2	2.1	3.7 x 10^{19}, E>1 MeV
VVER	0.20	0.042	1.9	1.3	2.4 x 10^{20}, E>0.5 MeV
Surveillance data	0.35	0.035	1.9	2.1	~15 x 10^{20}, E>0.5 MeV
Research programme data	0.4	0.045	2.8	2.0	~20 x 10^{20}, E>0.5 MeV

IAEA database for VVER-440 RPV surveillance test results

№	Country	NPP	Unit
1	Armenia	Mezhamor	2
2	Russia	Kola	3
3	Russia	Kola	4
4	Ukraine	Rovno	1
5	Ukraine	Rovno	2
6	Hungary	Paks	1
7	Hungary	Paks	2
8	Hungary	Paks	3
9	Hungary	Paks	4
10	Slovak Republic	Bohunice	3
11	Slovak Republic	Bohunice	4
12	Czech Republic	Dukovany	1
13	Czech Republic	Dukovany	2
14	Czech Republic	Dukovany	3
15	Czech Republic	Dukovany	4

Rovno 2 base metal surveillance results



Analysis of highly irradiated surveillance specimens results

Group of steels	Phosphorus content	Cupper content
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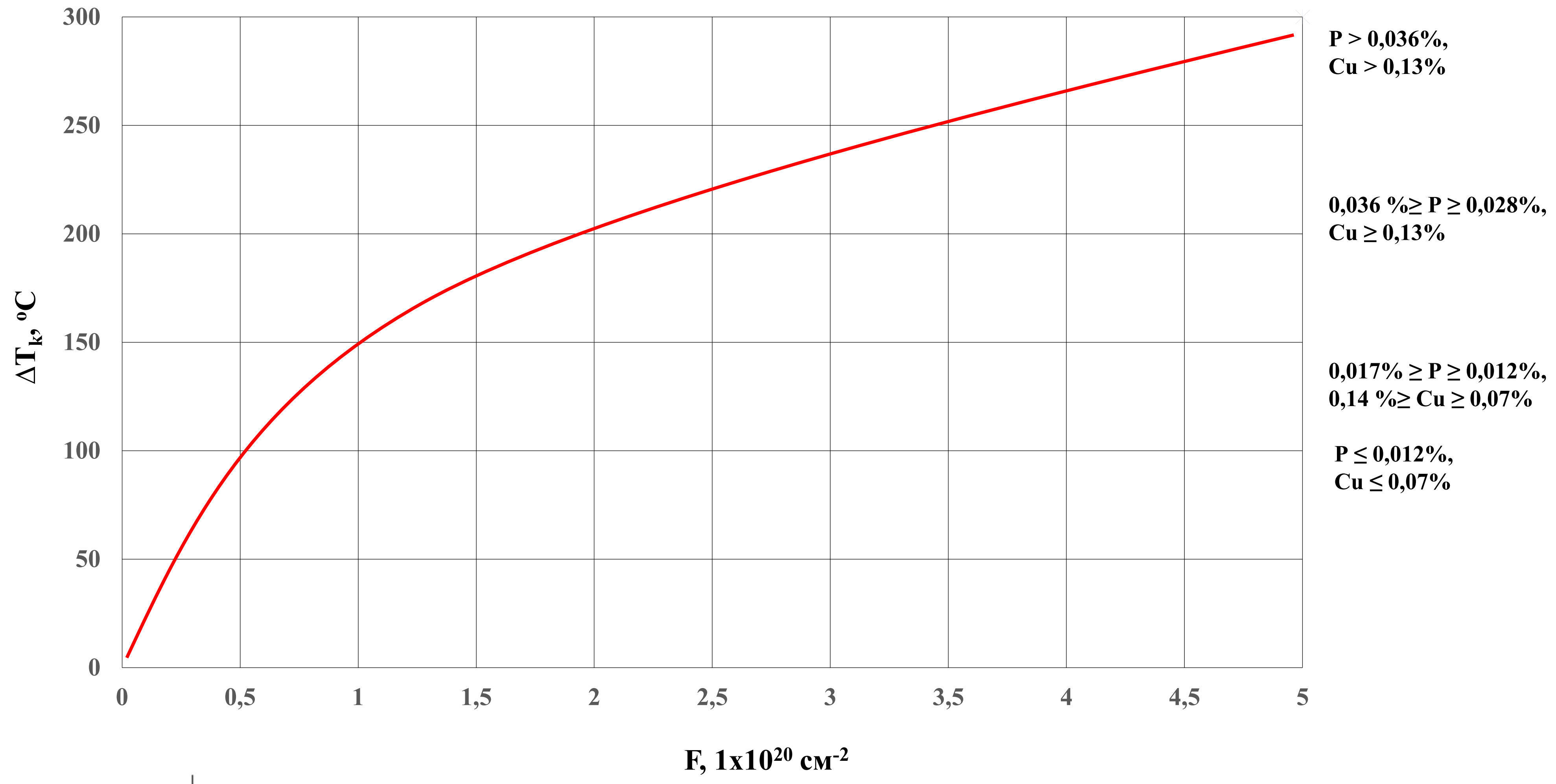
Highly "dirty"	P > 0,036%,	Cu > 0,13%

Irradiation embrittlement of VVER-440 RPV steels



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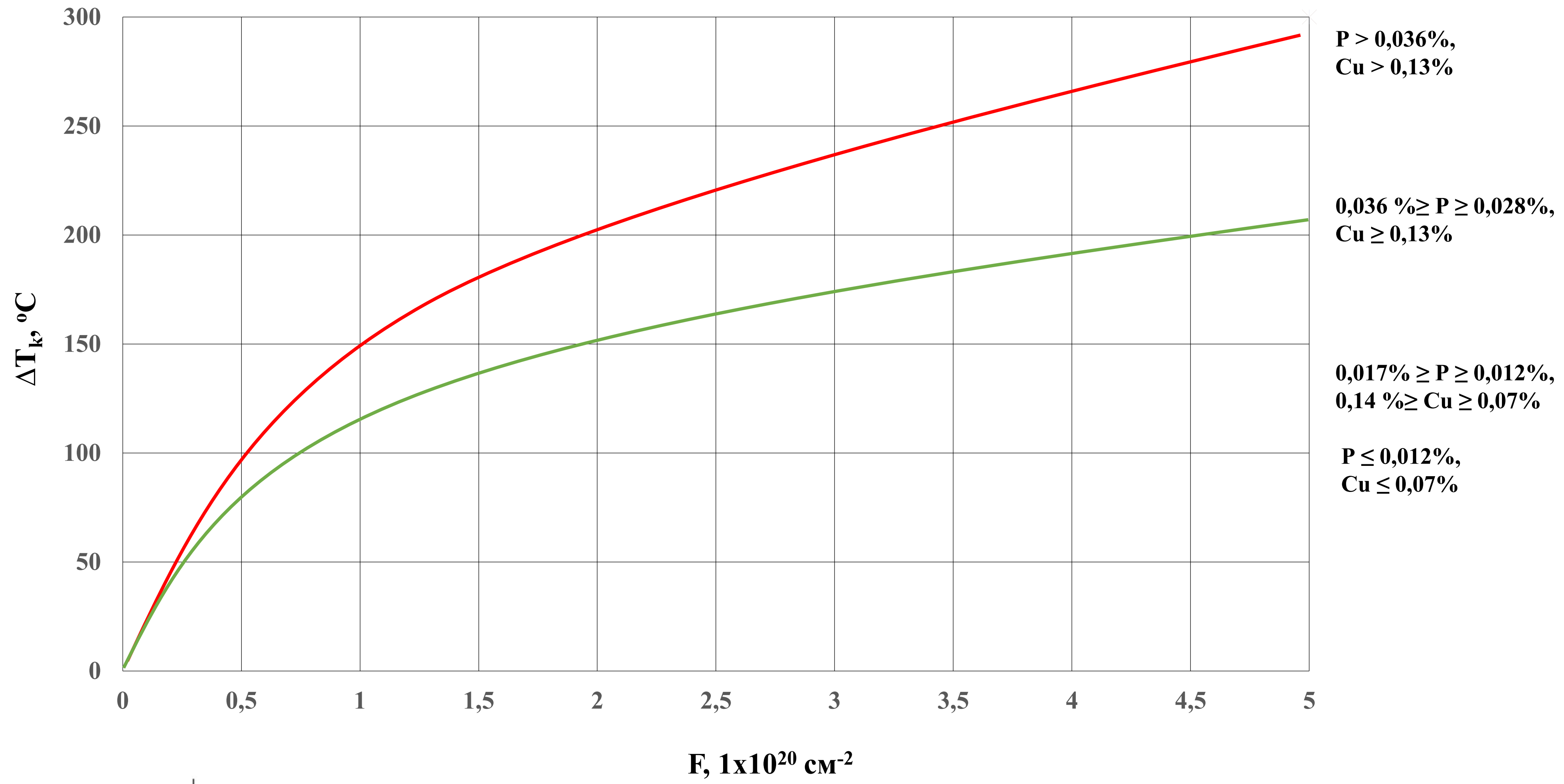

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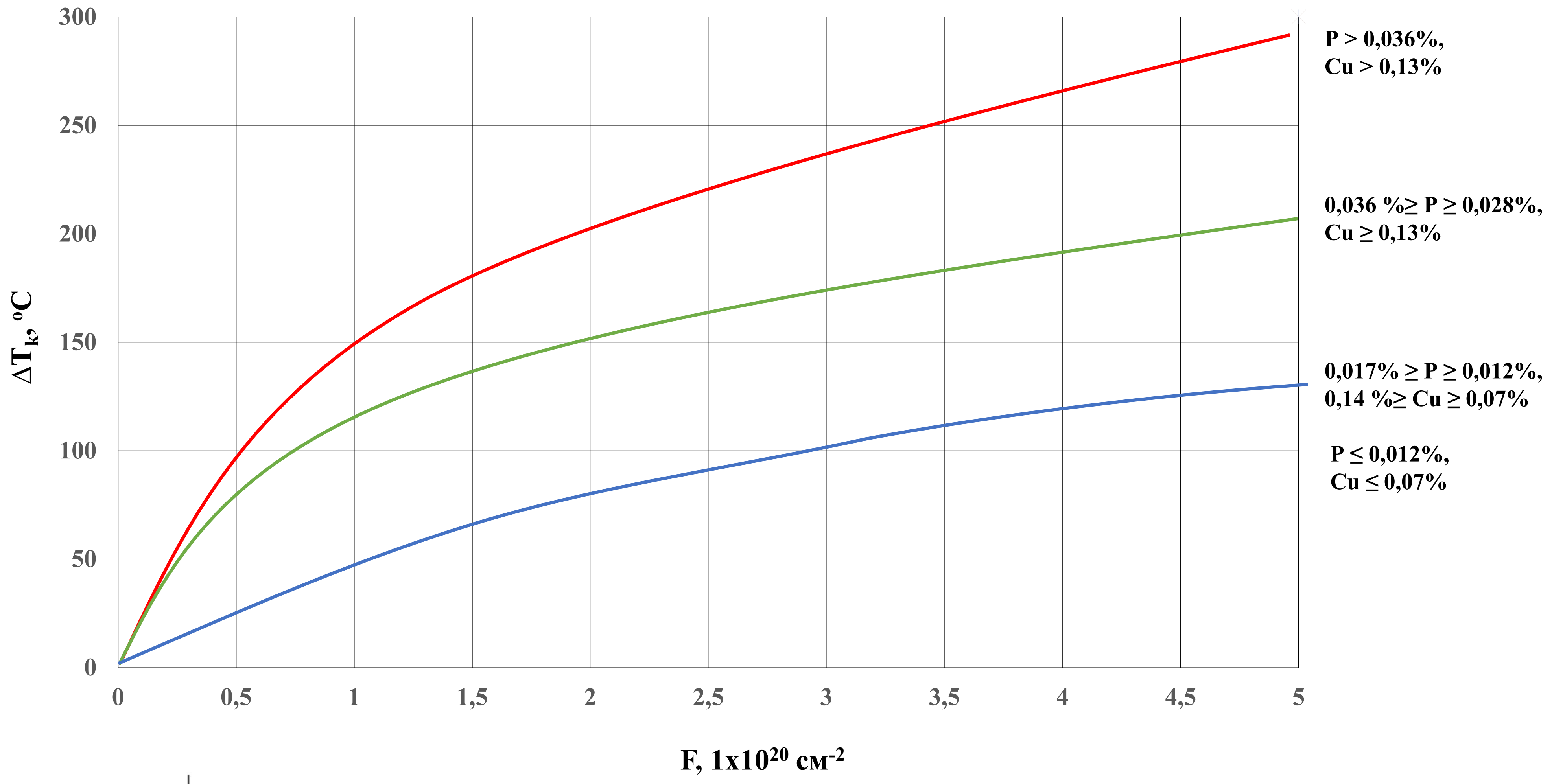

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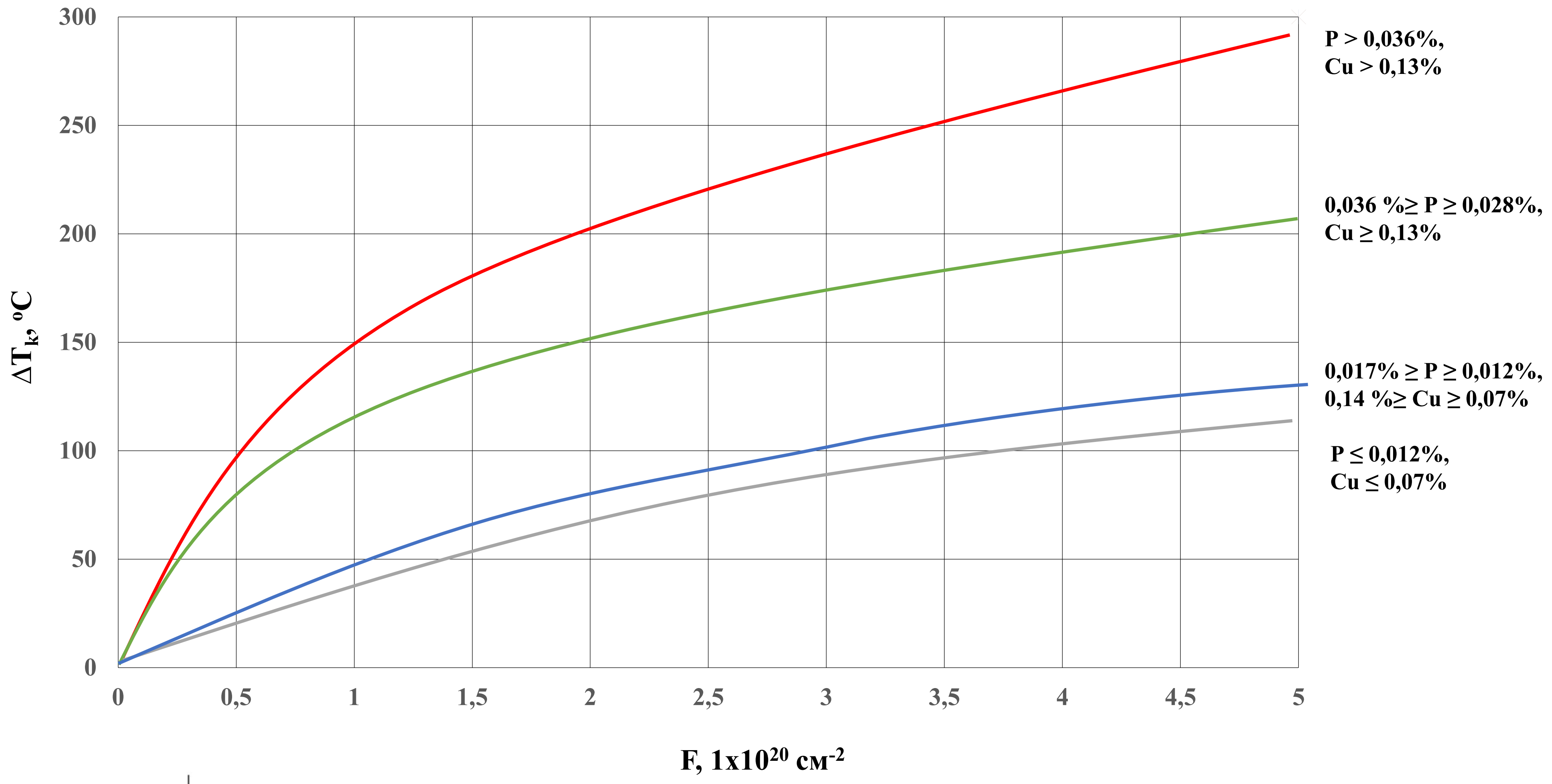

Results of highly irradiated surveillance data analysis

- Tк shift is not more 100 -130 °C for low Cu и P steels

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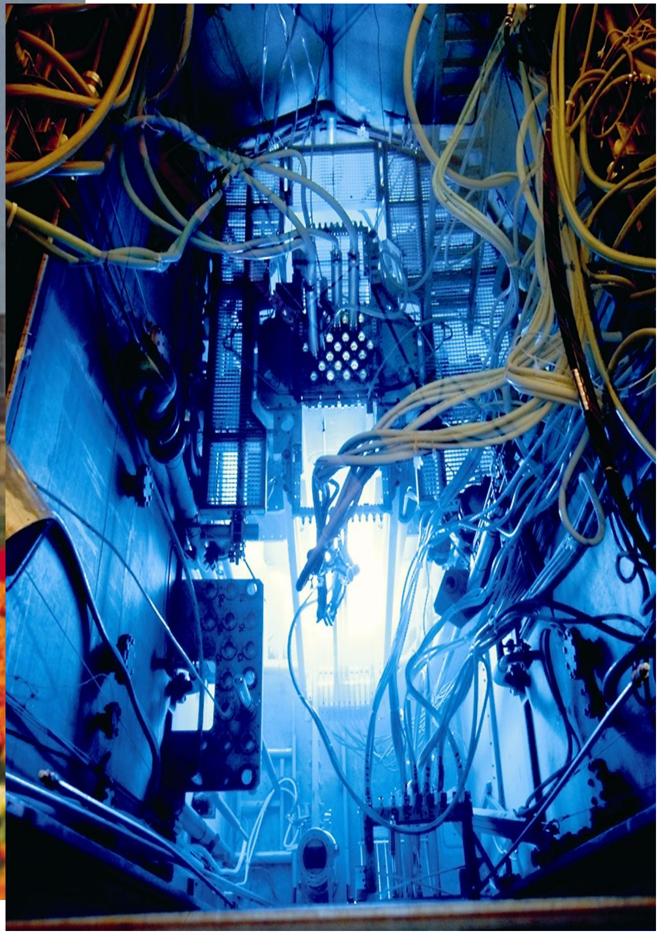
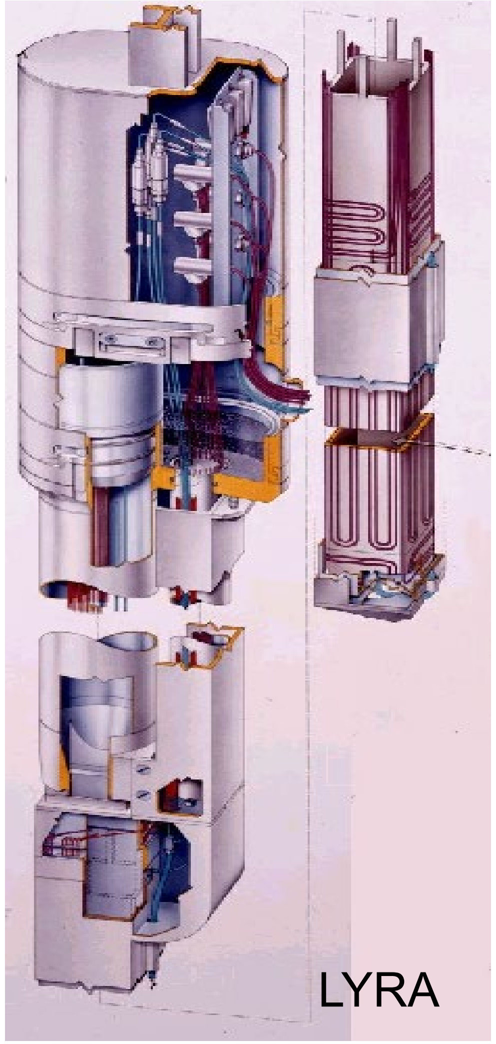
- Tк shift is not more 100 -130 °C for low Cu и P steels
- Lifetime of VVER-440 RPV could be validated up to fluence 5 x 10^{20} см$^{-2}$ (~ 80 years operation) without thermal annealing

STRUMAT

(**STRU**ctural **MAT**erials research for safe Long Term Operation of LWR NPPs)

Joined JRC – NRG project irradiation in HFR, Petten





Project aim – validation of irradiation embrittlement assessment for RPV long term operation

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Key point: establishment of synergistic interactions between Ni and Mn for low Cu RPV steels at high fluence

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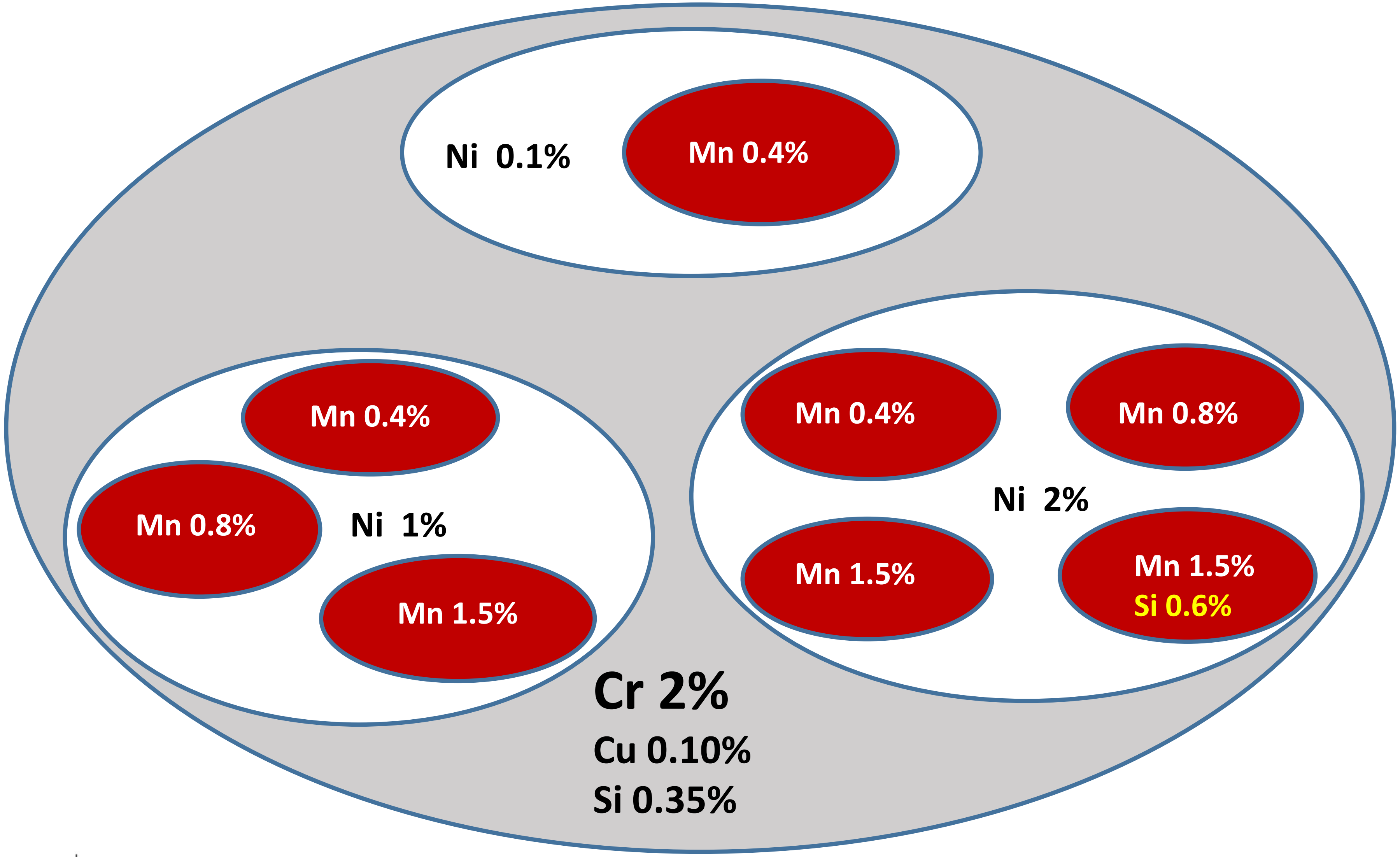
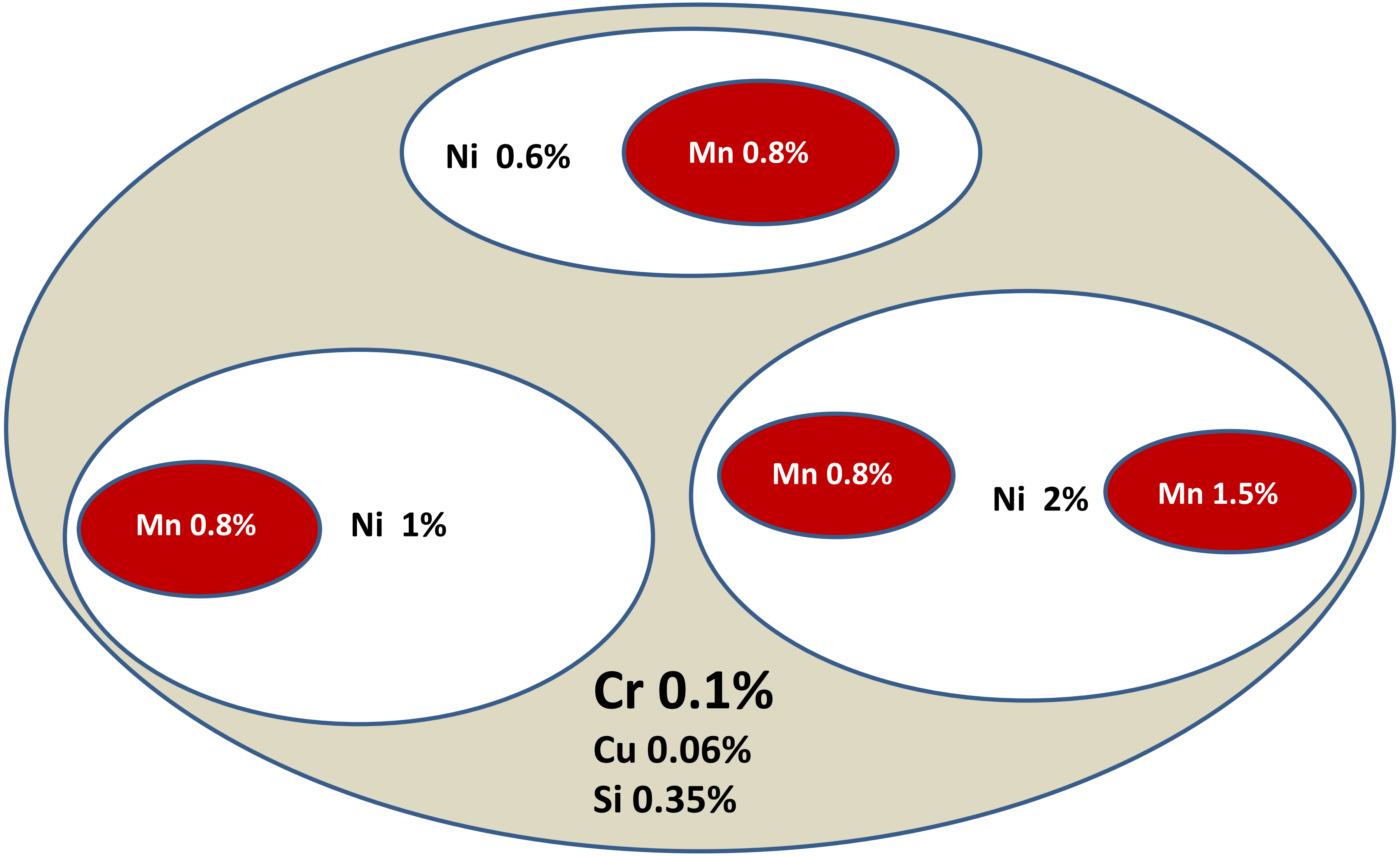
8 model steels
Ni & Mn variations in VVER RPVs



4 model steels
Ni & Mn variations in PWR RPVs



8 submerged arc welds
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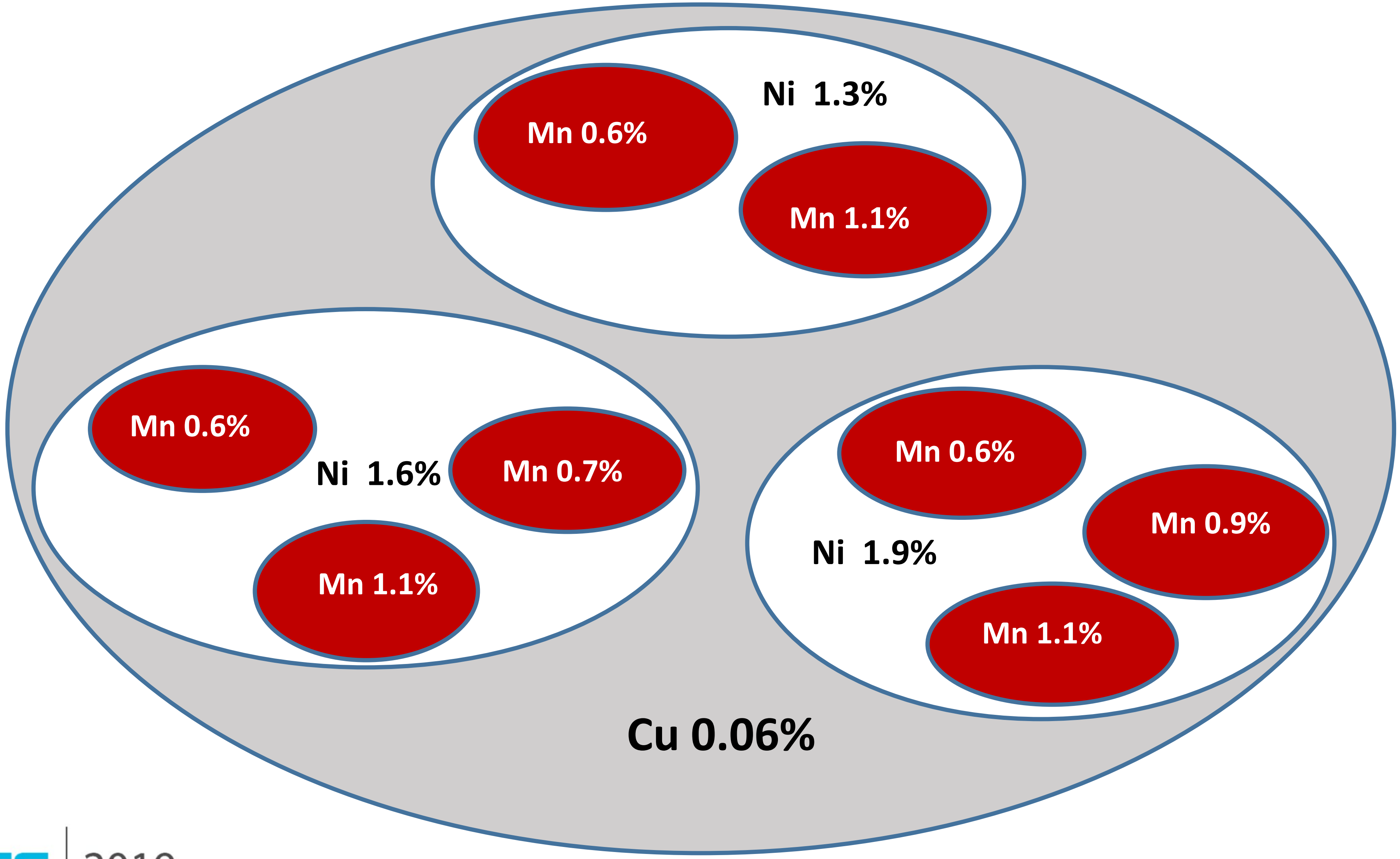
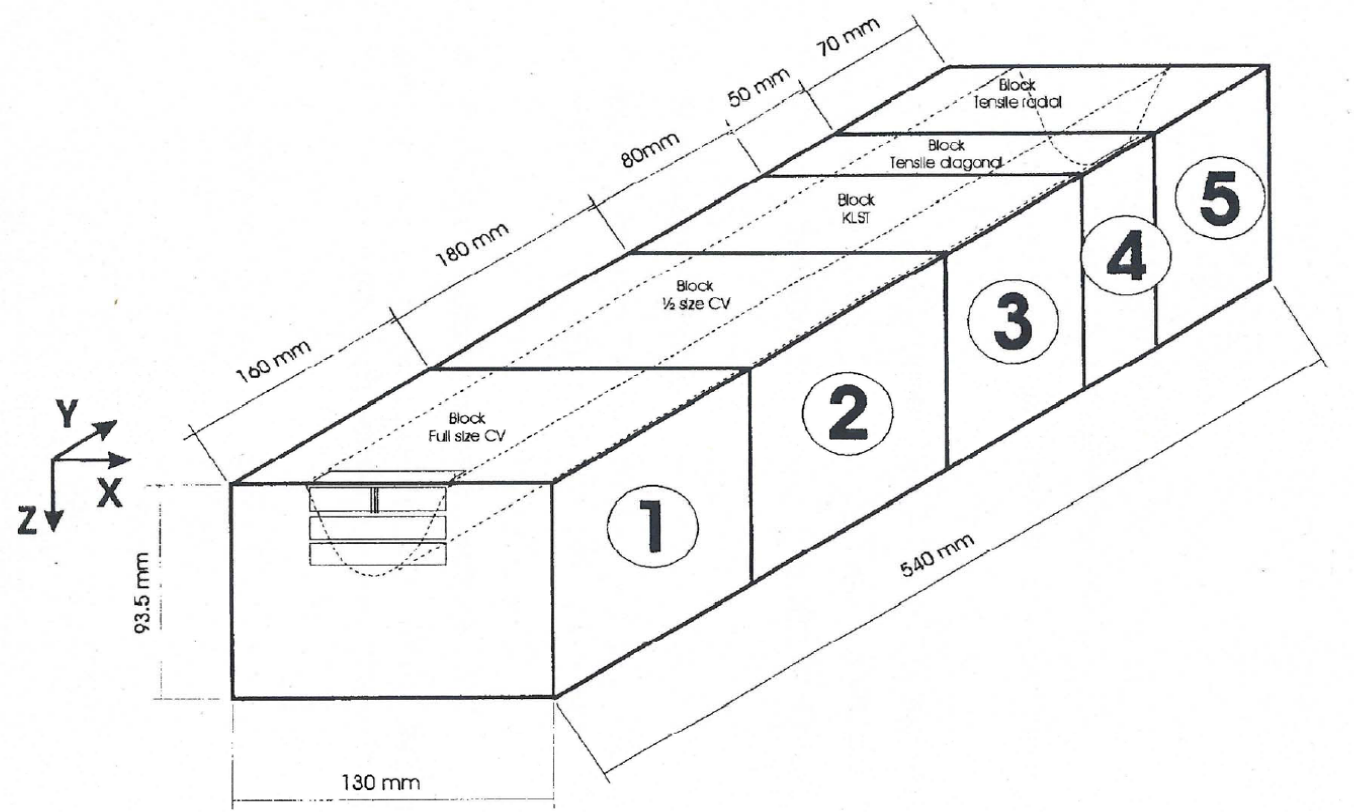


8 Low Cu high Ni&Mn submerged arc welds

- Skoda Plzen plant in Czech Republic
- 8 single V-preparation submerged arc welds in **190 mm thick plate**



KLST and tensile specimens, Charpy (4 welds),
slices 6x10x0.5 mm for microstructural examination

Project participants

Research centres:

- EC JRC (EU)
- NRG (The Netherlands)
- HZDR (Germany)
- VTT (Finland)
- Fraunhofer Institute for Nondestructive Testing (Germany)
- CIEMAT (Spain)
- UJV Rzez (Czech Republic)
- Hungarian Academy of Science Centre for Energy Research (Hungary)
- Bay Zoltan Nonprofit Ltd (Hungary)
- University of Manchester (UK)
- Kiev Institute for Nuclear Research (Ukraine)
- VUJE (Slovakia)
- Slovak University (Slovakia)

Regulators:

- STUK (Finland)
- United Kingdom Atomic Energy Authority
- SEC NRS (Russia)
- Analytical Research Bureau for NPP Safety (Ukraine)

SEC NRS role – scientific support of STRUMAT post irradiation examination

Conclusions

Radiation damage - most important RPV ageing mechanism

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RPV lifetime controlled by radiation damage of RPV beltline materials

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Irradiation embrittlement together with material initial properties determines RPV lifetime

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"Wet" annealing is effective for RPV steels with low P & Cu contents

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Basic resent event in ageing mechanism area - STRUMAT project aimed to validation of irradiation embrittlement for RPV long term operation