

IRRADIATION-INDUCED GROWTH OF ADVANCED ZIRCONIUM ALLOYS

*Josef Běláč¹, Stanislav Linhart¹, Radomír Řeháček¹,
Alexander Y. Shevyakov² Anatoly A. Gusev²
Pavel Pešek³,*

¹ – ALVEL, a.s., Brno, Czech Republic

² – SC VNIINM, Moscow, Russian Federation

³ – UJV Řež, Husinec-Řež, Czech Republic



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PRESENTATION OUTLINE

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- ***MCA project***
 - ***Brief introduction***
 - ***Status and perspectives***

- ***Results***
 - ***Neutron fluence evaluation***
 - ***Irradiation-induced growth***

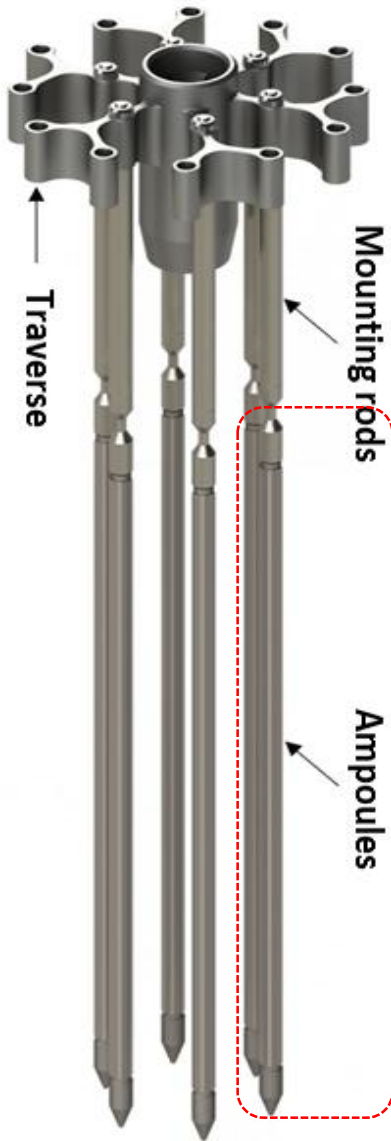
- ***Conclusions and future plans***

MCA PROJECT (1)

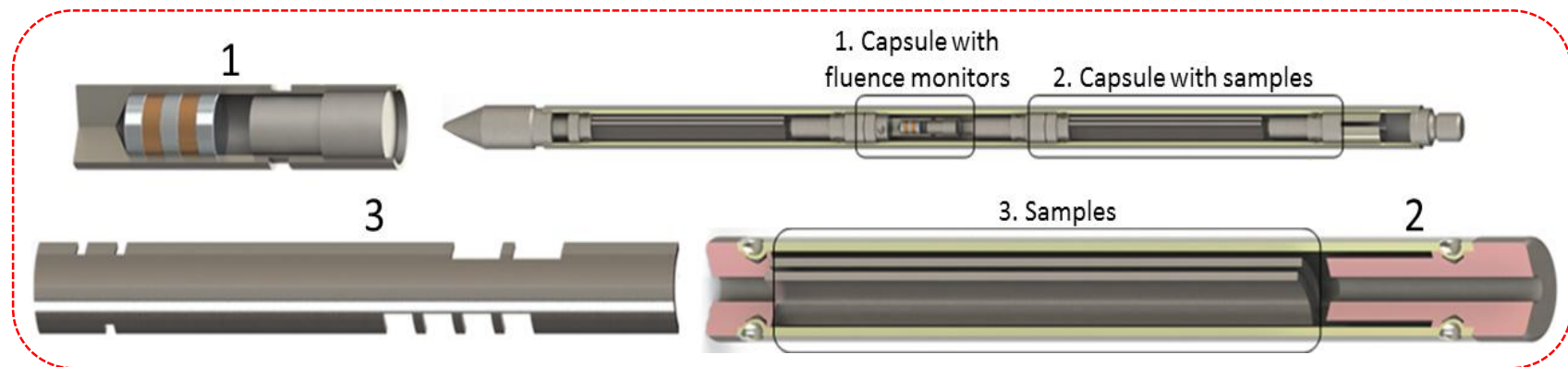
INTRODUCTION

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- Main goal: to study the irradiation induced growth of advanced zirconium-based alloys and their microstructural changes during the irradiation in VVER core;
- 6 Material Cluster Assemblies (MCA), manufactured in 2012, loaded into Temelín NPP Unit 1 core in 2014;
- 6 ampoules, 6 different alloys, 3 types of heat treatment, 3 types of fluence monitors.

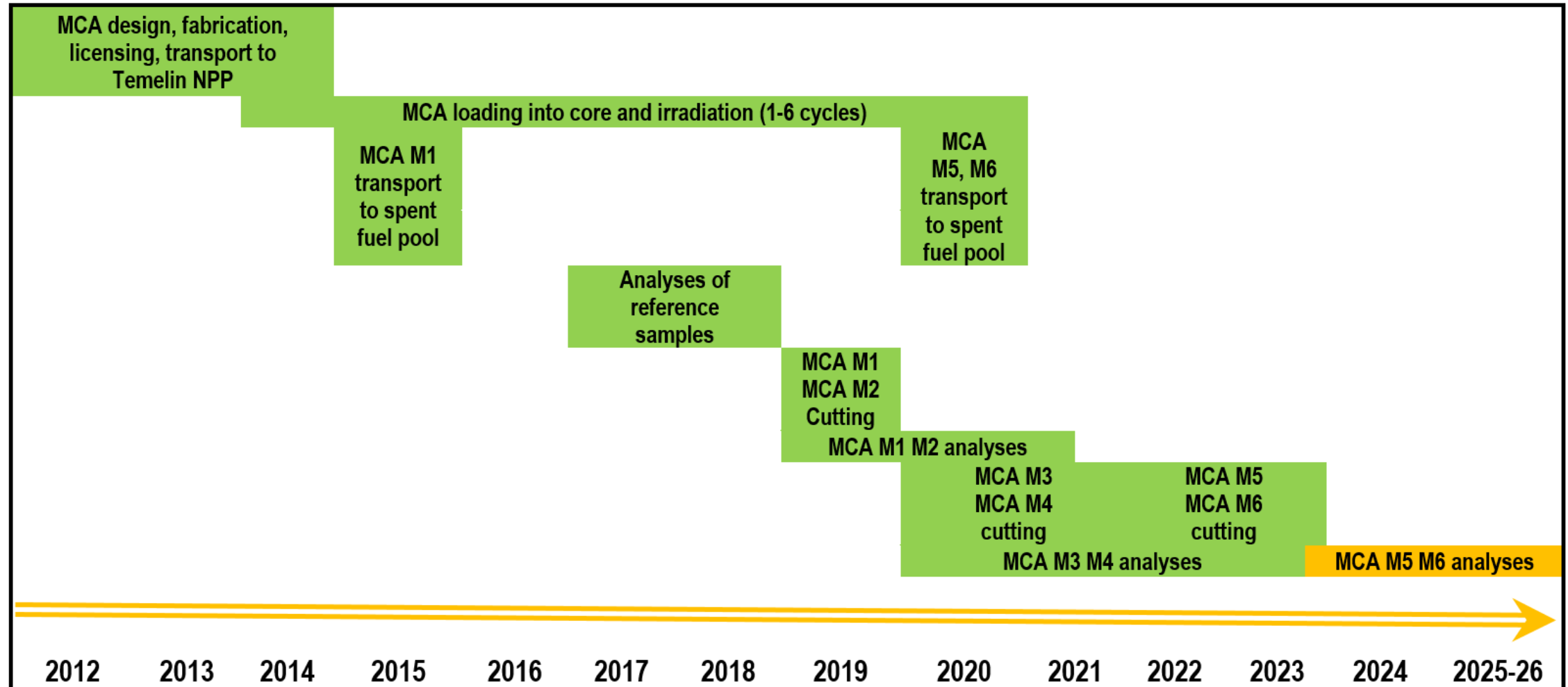


MCA PROJECT (2)

TIMELINE

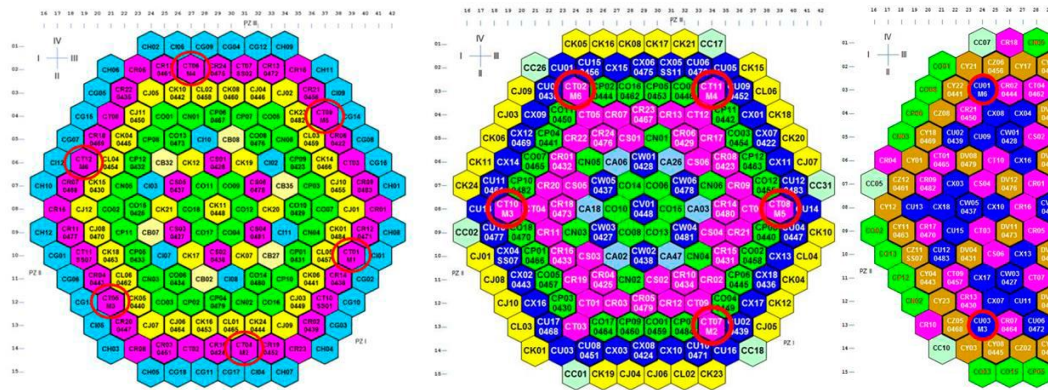
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- **Irradiation:** Temelin NPP, Unit 1,
5 cycles, 6 different values of neutron fluence.
- **Irradiation temperature** = approx. 320°C.
- **Positions for MCA placement** in each cycle of irradiation were chosen to maximize the fast neutron fluence ($E \geq 0.1$ MeV) given the limitations implied by the core and reactor design.



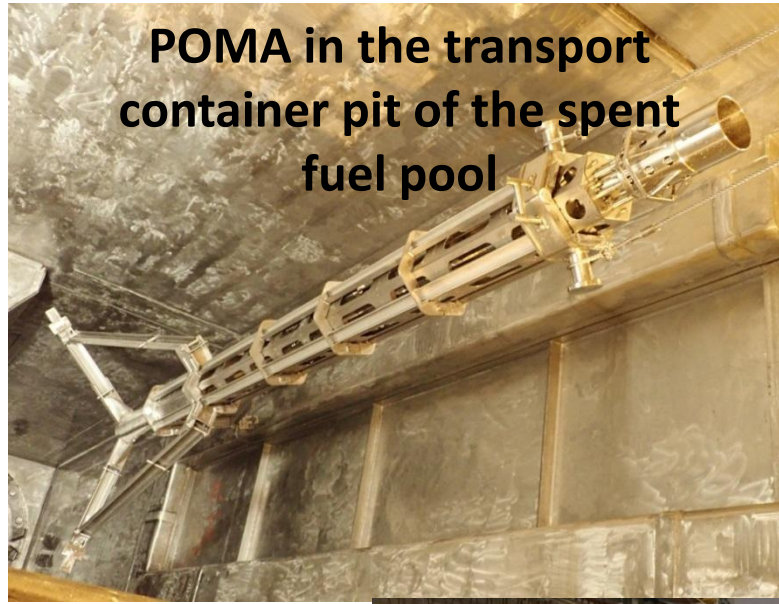
U1C17 (5th cycle)

MCA PROJECT (4)

SEPARATION OF SAMPLES

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Separation of irradiated samples and their loading into the shielded transport container

MCA PROJECT (5)

TRANSPORT OF SAMPLES

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PIE RESULTS (1)

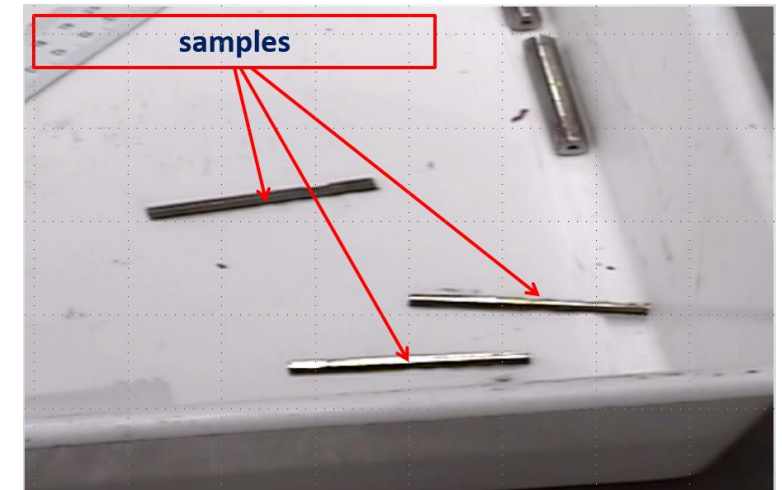
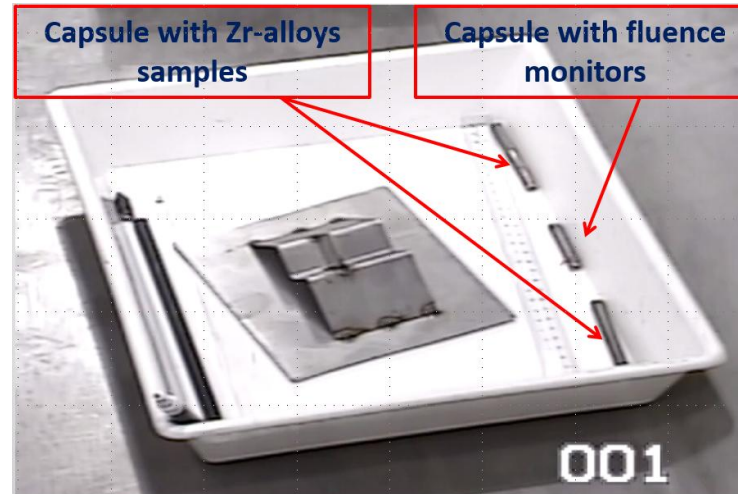
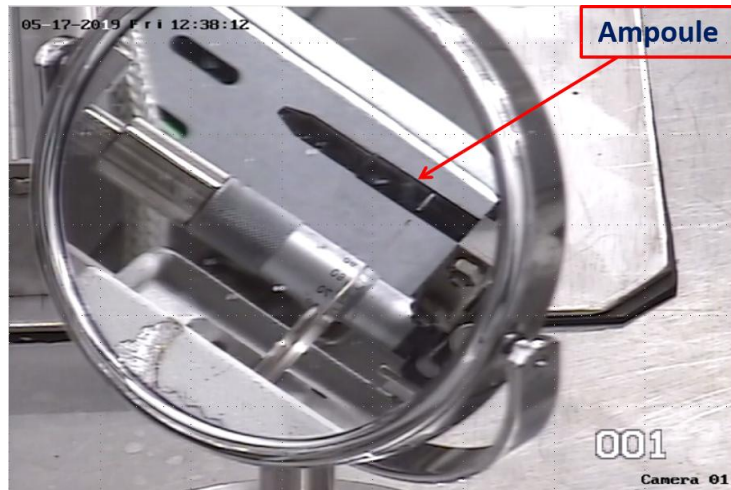
PIE OVERVIEW

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➤ **PIE**

- **Determination of neutron fluence based on the fluence monitor activities;**
- **Sample geometry measurement and evaluation;**
- **Transmission and scanning electron microscopy (TEM/SEM);**
- **Metallographic analysis and micro-hardness measurement;**
- **Mechanical tests (TR, AX, creep, nano-indentation) on base material of ampoules.**



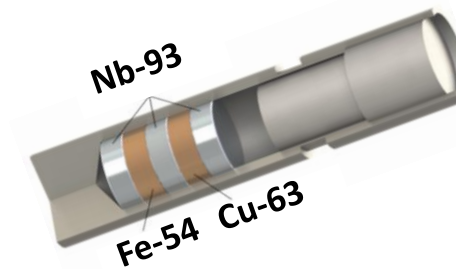
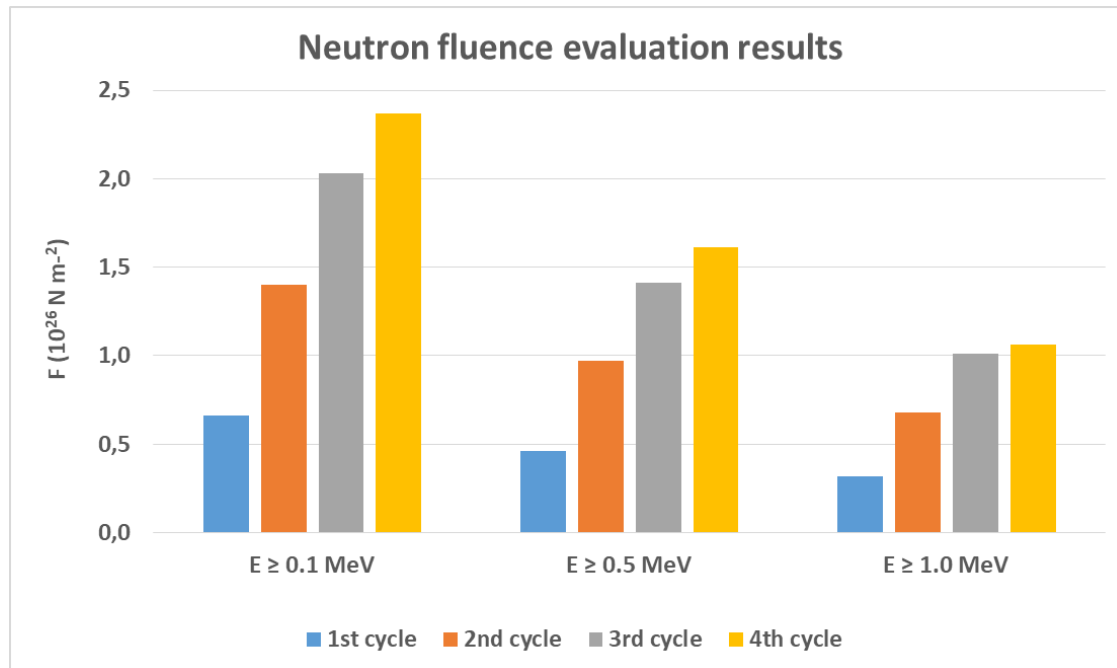
PIE RESULTS (2)

NEUTRON FLUENCE EVALUATION

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Material	Reaction	Half-life	Chemical purity, %	Isotope, %	Detector shape
Niobium	$^{93}\text{Nb}(n,n')^{93\text{m}}\text{Nb}$	16.12 years	99.9996	99.997	Ø 2.5×0.1 mm
	$^{93}\text{Nb}(n,\gamma)^{94}\text{Nb}$	20300 years			
Iron	$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	312.2 days	99.878	99.92	Ø 2.5×0.05 mm
Copper	$^{63}\text{Cu}(n,\alpha)^{60}\text{Co}$	1925.28 days	99.966	99.6	Ø 2.5×0.1 mm



1 cycle	2 cycles	3 cycles	4 cycles
5 dpa	10 dpa	15 dpa	18 dpa

PIE RESULTS (3)

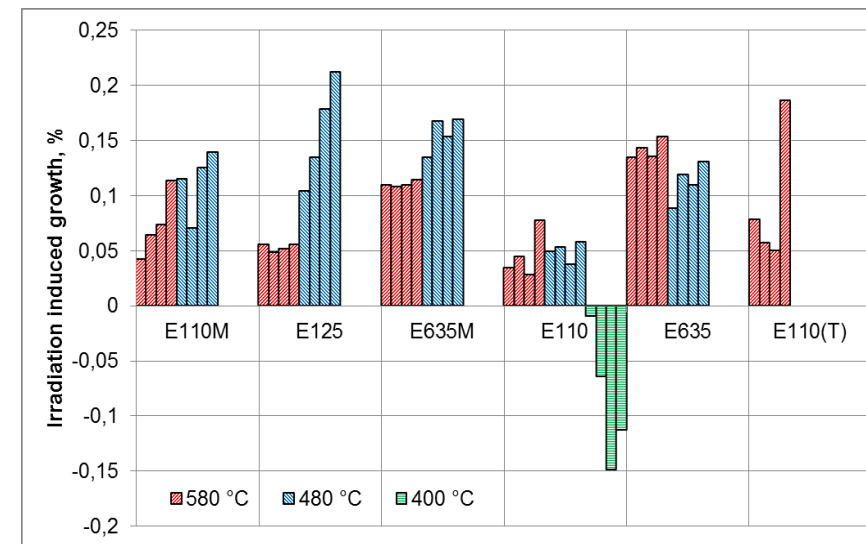
IIG RESULTS - OVERVIEW

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The irradiation induced growth (IIG) of the samples was calculated as the average value of the change in the samples length after irradiation relative to the initial length before irradiation.

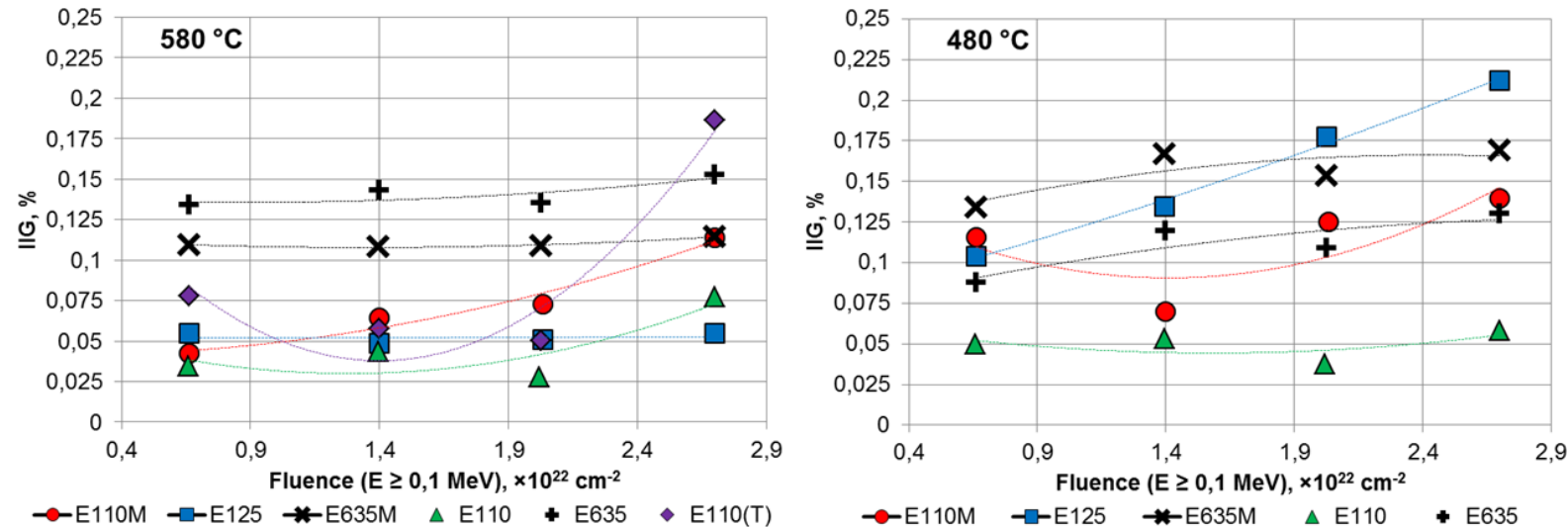
Alloy	T, °C	1 cycle	2 cycles	3 cycles	4 cycles
		IIG, %			
E110M	580	0.05	0.06	0.07	0.11
	480	0.10	0.07	0.12	0.14
E125	580	0.05	0.05	0.05	0.06
	480	0.10	0.13	0.18	0.21
E635M	580	0.11	0.11	0.11	0.11
	480	0.12	0.17	0.15	0.17
E110	580	0.06	0.04	0.03	0.08
	480	0.06	0.05	0.04	0.06
	400	-0.01	-0.06	-0.15	-0.11
E635	580	0.13	0.14	0.14	0.15
	480	0.10	0.12	0.11	0.13
E110(T)	580	0.08	0.06	0.05	0.18



The IIG of the samples annealed at temperatures of 580 and 480 °C are positive, while for the sample from E110 alloy annealed at 400 °C is negative. This is consistently observed after each of the four irradiation cycles. This behavior of the E110 alloy is explained by the fact that holding for 3.5 hours at a temperature of 400 °C is insufficient for complete stress relief. Perhaps, negative values of the IIG indicate that the material relaxation from stress relief under irradiation during the achieved operating time exceeds the effect of the increase in size due to irradiation growth. However, this result requires additional study and analysis.

PIE RESULTS (4)

IIG RESULTS – MATERIAL BEHAVIOR



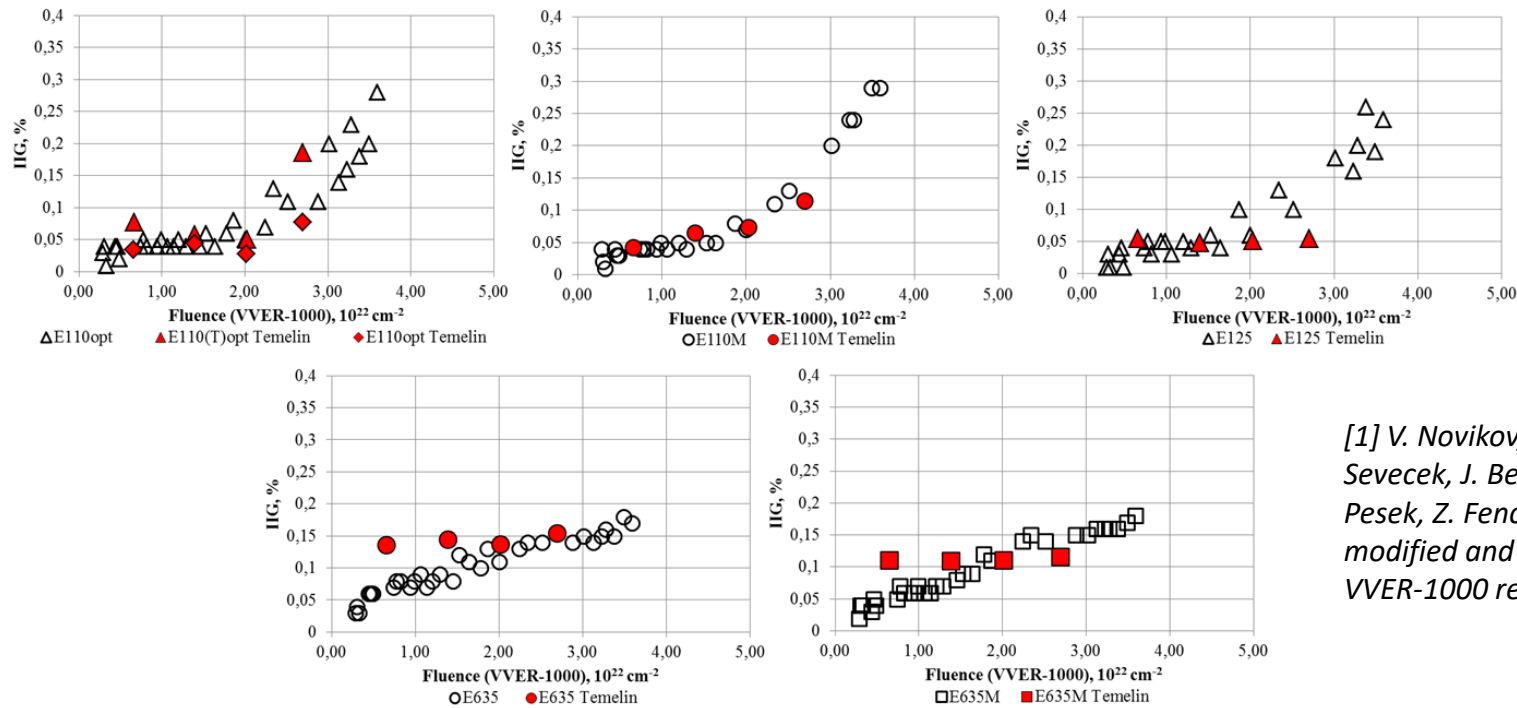
- For the first three irradiation cycles, the samples from multicomponent alloys had a significant length increase in comparison with binary alloys for the recrystallized state of the studied materials.
- After the third irradiation cycle, the stage of accelerated growth begins for binary alloys.
- The increased IIG values of the samples in the partially recrystallized state can be associated with the presence of a developed dislocation structure of the materials after low-temperature annealing (480 °C).

PIE RESULTS (5)

IIG RESULTS – COMPARISON TEMELIN NPP / BOR-60

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[1] V. Novikov, V. Markelov, A. Shevyakov, A. Gusev, S. Linhart, M. Sevecek, J. Belac, R. Rehacek, V. Stary, A. Shishkin, M. Grekhov, P. Pesek, Z. Fencel, P. Halodova: A study of irradiation – induced growth of modified and advanced Zr-Nb system alloys after irradiation in the VVER-1000 reactor core at Temelin NPP, ASTM 1645, 520, 2022

- For the studied samples, a high degree of convergence of the IIG results obtained in the BOR-60 reactor and under industrial operating conditions is observed.
- For some alloys (E635M and E635), there is a deviation of the first irradiation cycle results in the VVER-1000 reactor at the Temelin NPP from the data set obtained in the BOR-60 reactor.

CONCLUSIONS

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- **MCA project status:** Irradiation has been completed;
PIE scheduled to be finished in 2026.
- **PIE:** 4 batches completely evaluated, the last two – in progress.
- **Irradiation Induced Growth:**
 - Binary alloys in the fully recrystallized state (580 °C – 3 h) show a high resistance to irradiation-induced microstructure change after three irradiation cycles in the VVER-1000 reactor (their deformation is at the level of up to 0.07 %).
 - After the third irradiation cycle, the stage of accelerated growth is observed for binary alloys (E110(T) alloy has the maximum deformation, which reaches a value of 0.18 %). E110 CW – negative values of IIG.
 - For the multicomponent alloys, irradiation growth is at the steady state (accelerated growth is not observed even after four cycles of irradiation).
 - The maximum IIG value of 0.15 % is observed for the recrystallized (580 °C – 3 h) alloy E635, which corresponds to the previously obtained results (for the corresponding level of the damaging dose) during irradiation in the fast-flux research reactor BOR-60.



FUTURE STEPS

MCA-ATF PROJECT

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- **MCA-ATF: Project (JEEP) under the framework of OECD-NEA FIDES II;**
- **Goal of the project: Irradiation and PIE of Cr-coated ATF fuel claddings from different vendors, comparison of various materials with a different coating method / technique;**
- **Core Group: ALVEL, CVŘ, UJV, Framatone, Westinghouse, NNL, ENSI, EPRI, KEPCO NF;**
- **Duration:** **pre-characterization and preparation phase: 2024 – 2026;**
 scheduled irradiation (Temelin NPP): 2026 – 2029;
 Separation of samples: 2029 & 2030;
 PIE: 2030 - 2032

ACKNOWLEDGEMENTS

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QUESTIONS ?

