

Aumento de márgenes de seguridad en centrales LWR mediante combustible tolerante a accidentes (ATF)

Jornada I+D+i

Proyectos de Investigación en SEGURIDAD NUCLEAR

MADRID, 11 DE JUNIO DE 2026

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Participantes

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- Sergio Courtin Vega (UPM à EAG)

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Coordinador Técnico (CSN): Miguel Sánchez Perea



Proyecto "Aumento de márgenes de seguridad en centrales LWR mediante combustible ATF" Subvención CSN: SUBV-16/2021

CAMP – CSN – NRC
TRACE
PWR - BWR

CSARP – CSN – NRC
MELCOR
PWR - BWR

SPAR – CSN
RiskSpectrum (RS)
PWR

TU User Group
TRANSURANUS
Modelos de barra

ISASMORE MCIU
TRACE
CAREM VVER-1000

ATF – CSN
TRACE TU MELCOR RS
PWR BWR VVER
NuScale

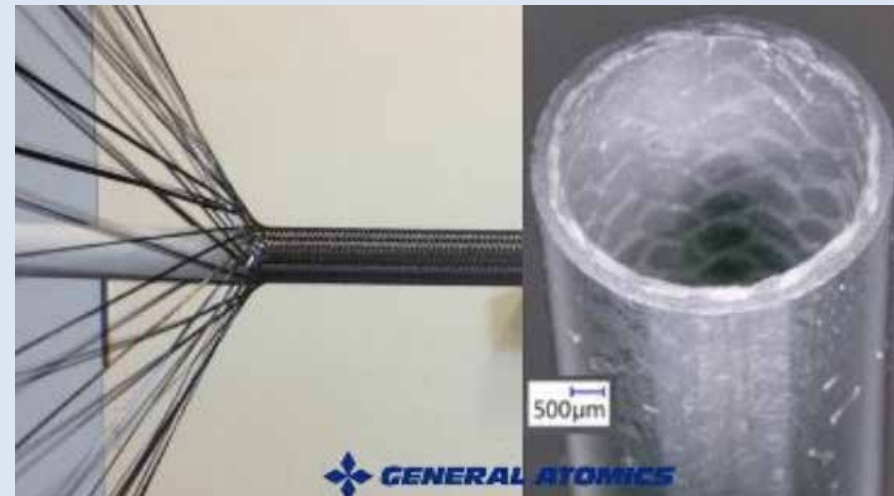
H2020 McSAFER
TRACE PARCS
NuScale

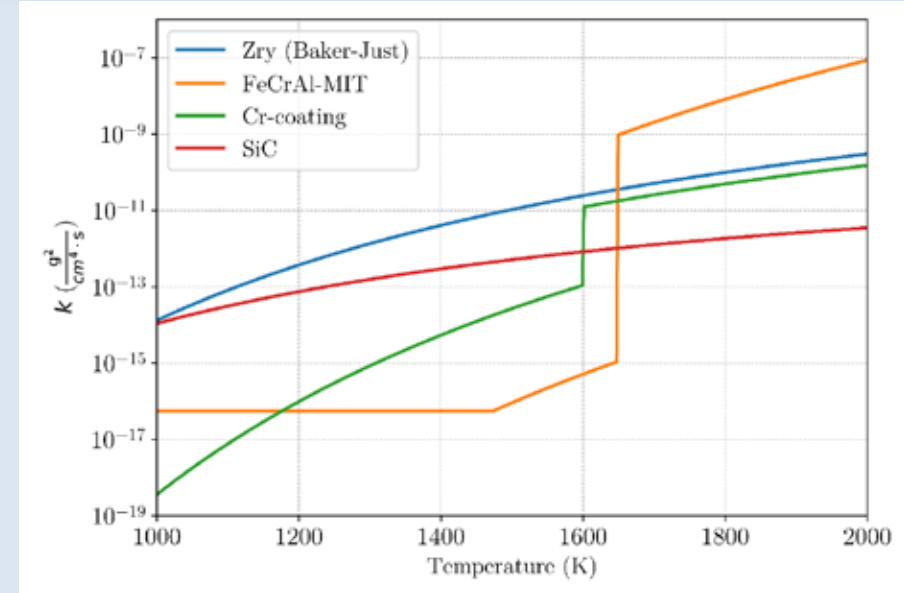
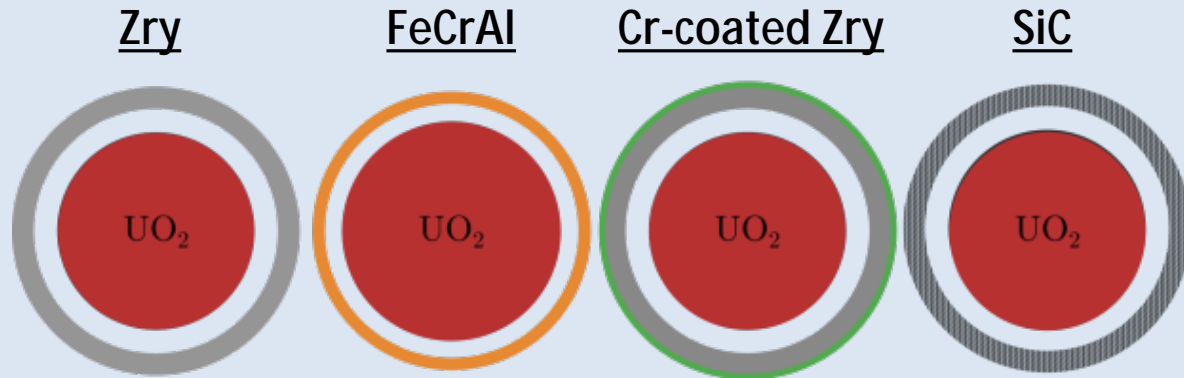
CRP IAEA ATF-TS
UPM – NFQ
TRACE TU MELCOR
PWR IFA QUENCH

Grupo CEIDEN - ATF
Grupo CEIDEN - SMRs

I-NERI Project
BNL– INL–UPM–NFQ
TRACE – TU – BISON
NuScale

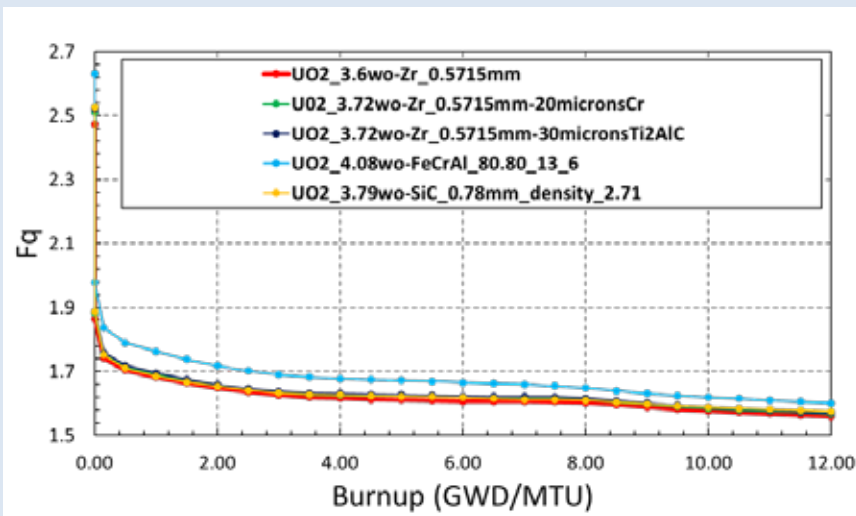
ATF	CLADDINGS	FUELS
EVOLUTIONARY (Near-term)	<ul style="list-style-type: none"> • Coated Zry cladding (Cr-Zry) • Advanced steels (e.g. FeCrAl) 	<ul style="list-style-type: none"> • Doped UO_2 (e.g Cr_2O_3) • High Thermal Conductivity UO_2 • Dual-cooled fuel
REVOLUTIONARY (Long-Term)	<ul style="list-style-type: none"> • Lined Mo-alloy • SiC Composite 	<ul style="list-style-type: none"> • High density fuels [UN] , $[U_3Si_2]$ • TRISO-SiC composite pellets



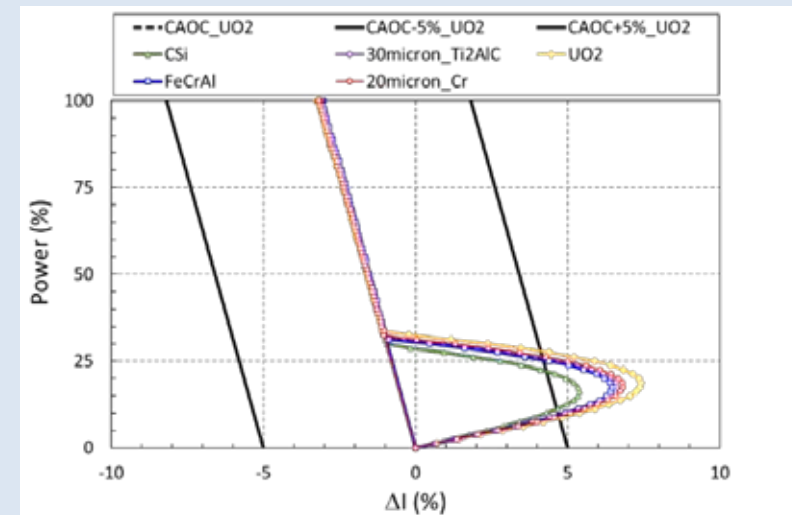


	PCT		ECR
Zry	1477 K		17%
Cr-coated Zry	1477 K	1605 K Eutectic Cr-Zr temperature	17% (burst) <i>Experimental tests show different ECR limits below and above 17% depending on the base cladding material</i>
FeCrAl	1477 K	1773 K Melting temperature	<i>FeCrAl is not affected by embrittlement due to hydrides and oxides (NEA-2022 ?) – new limit (?) – new experimental tests</i>
SiC	1973 K Decomposition and sublimation limits		<i>SiC failure mechanisms are also not related to oxidation</i>

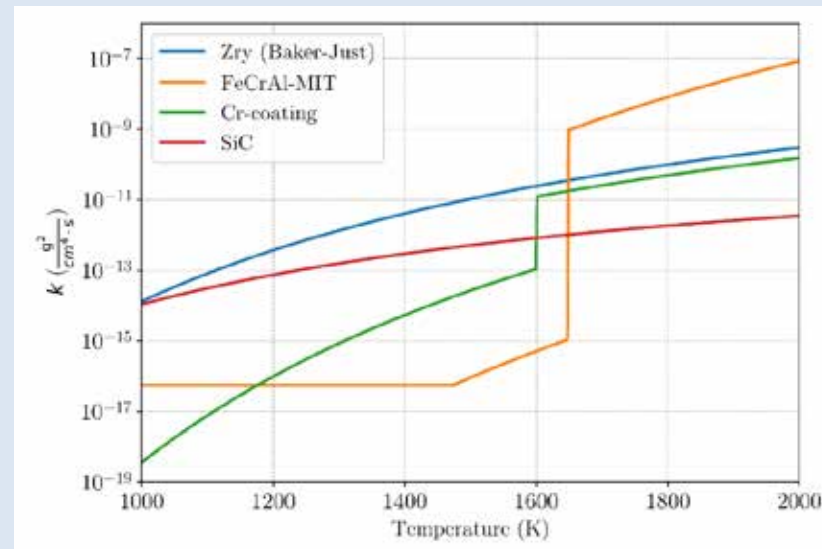
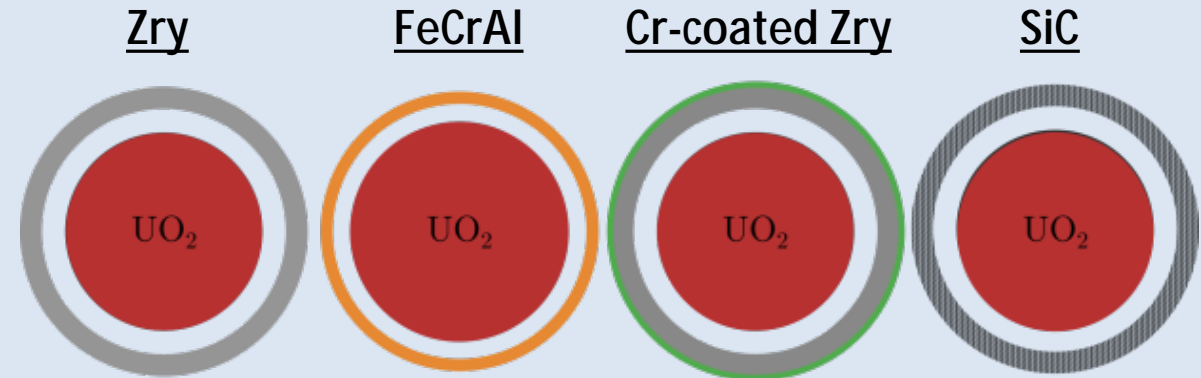
- Obtención de las secciones eficaces de los distintos materiales (**recubrimiento de Cr, FeCrAl, SiC**)
- Aplicado a un PWR-W en el modelo disponible en el sistema **SEANAP** (ETSII – UPM)
- El combustible ATF se ha considerado solo en el combustible nuevo de un ciclo, con ajuste del enriquecimiento
- Los resultados muestran que el **Cr-Zry** tiene un comportamiento muy próximo al combustible convencional.
- El **FeCrAl** presenta una **penalización neutrónica** significativa debido a su absorción neutrónica. Requiere un $\Delta\%U-235 \approx +0,33$ w/o, coeficientes de reactividad menos negativos y menor valor de los bancos de control, lo que puede reducir ligeramente los márgenes neutrónicos.
- Desde el punto de vista operacional, las **maniobras de parada y retorno a potencia** pueden realizarse **de forma similar a las del combustible convencional**, cumpliendo las ETFs. No obstante, el **FeCrAl** presenta cierta ventaja operativa al reducir las necesidades de boración/dilución en este tipo de maniobras.



Maniobra de retorno a potencia (5 %/h) tras una parada de 9 h al final de ciclo con vainas ATF.

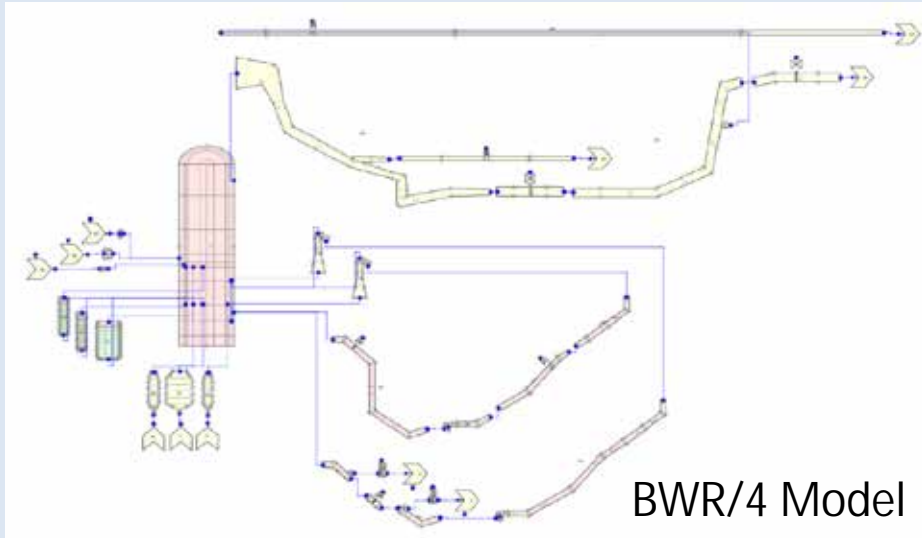


- Zry. Cladding thickness: 570 μm
- FeCrAl. Properties and models were incorporated in an in-house version of the TRACE code: density, oxidation rate, Young modulus, high-temperature creep strain, Poison's ratio, burst stress criterion, yield stress, ultimate tensile strength, thermal expansion coefficient and thermal conductivity. Cladding thickness: 385 μm
- Cr-coated Zry. The capability of TRACE to consider multiple cladding materials was considered. The thickness of the Cr layer is 25 μm and it is hypothesized that, in general, Cr-coated Zry cladding would exhibit a similar behavior to bare Zry cladding. Only strain/burst models has been modified.
- SiC. This cladding material is included in TRACE5 patch9. There is no ballooning or burst in SiC.

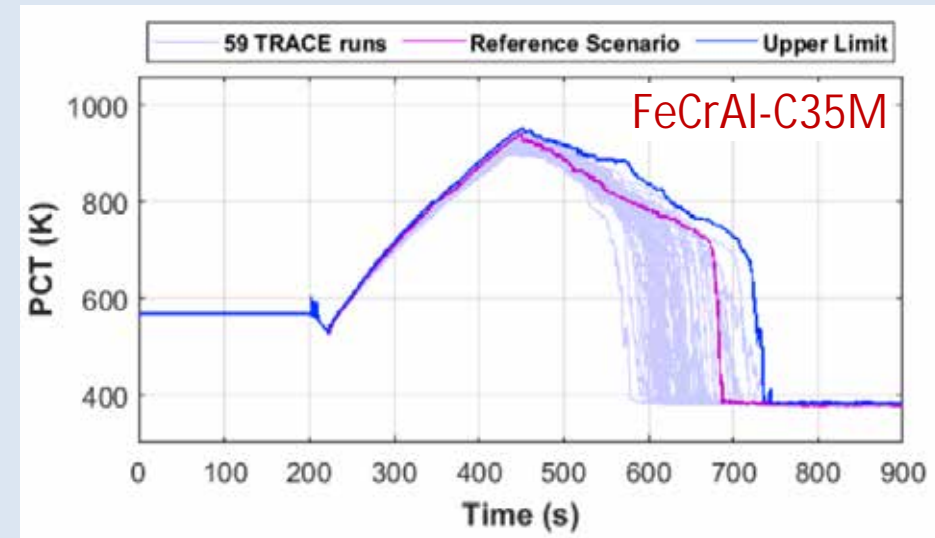
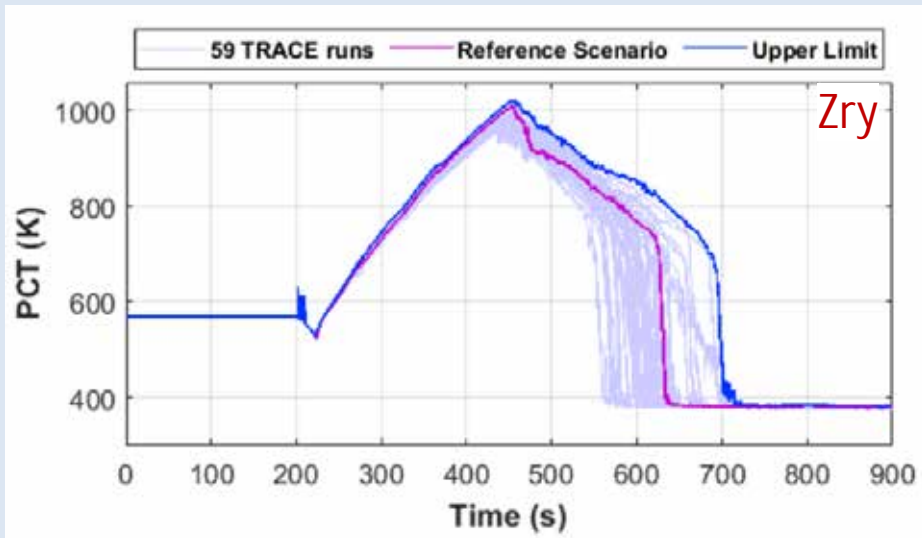


Parabolic oxidation rate



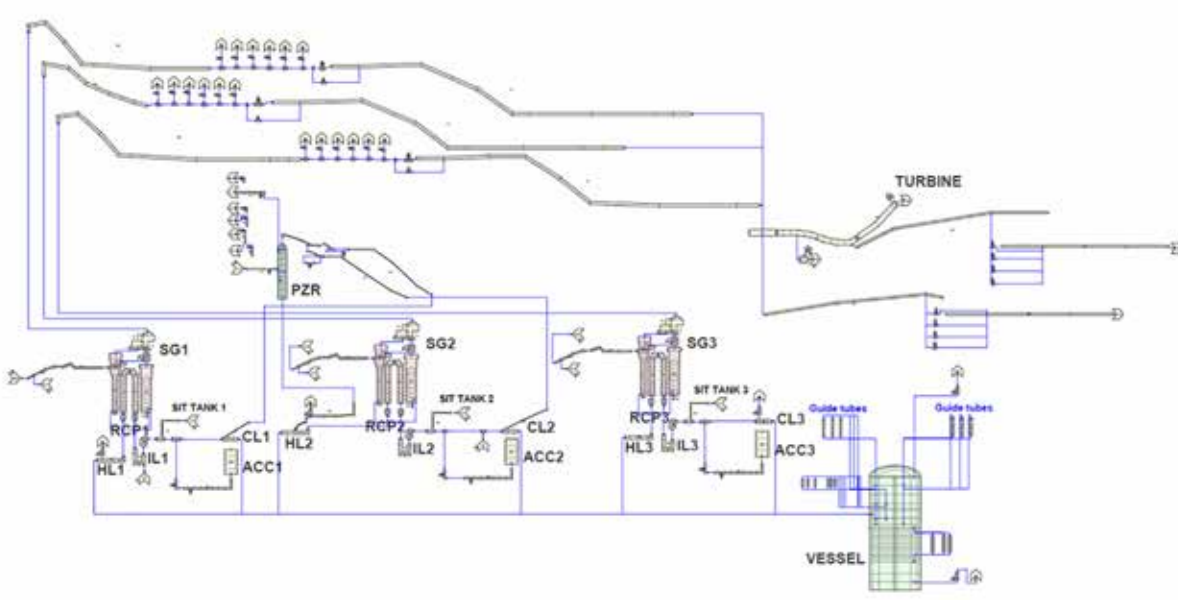


- Under LBLOCA conditions, **FeCrAl-C35M** cladding exhibits a lower peak temperature rise ($\Delta PCT \approx 60$ K), a slower cooling rate, and a delayed quenching temperature compared with Zircaloy, indicating an **improved heat removal capability**.
- The **Sobol indices** complement the **PRCC results** from Wilks analysis by revealing not only the direct influence of each parameter through the first-order index, but also their **combined interaction effects**, captured by the total-effect index.

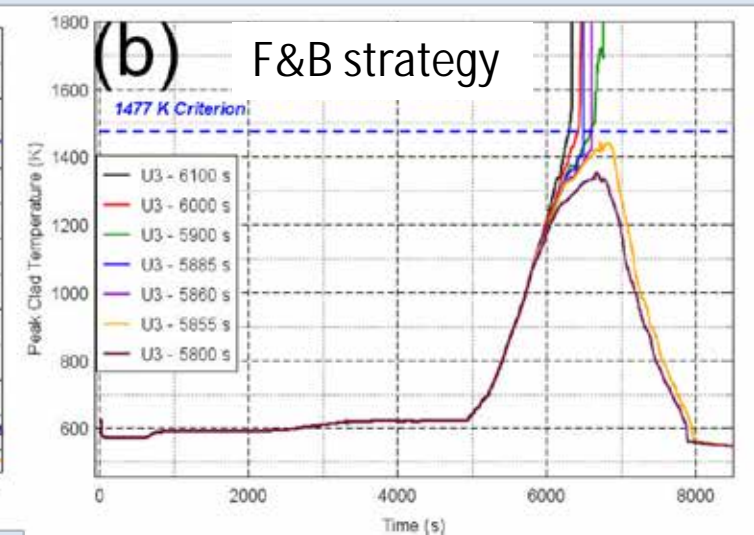
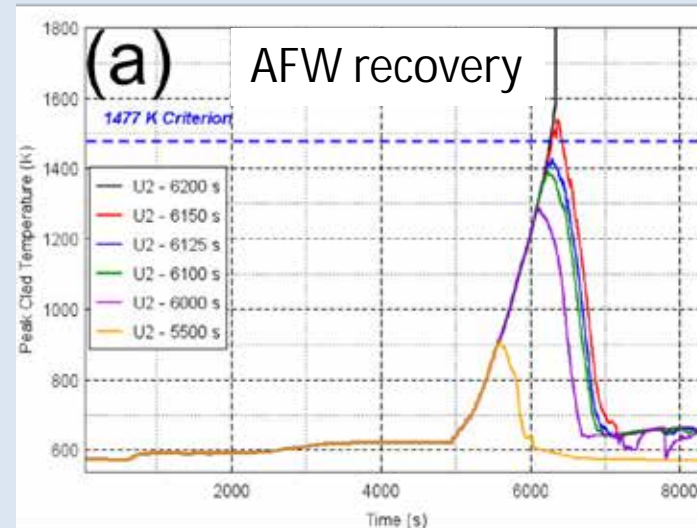
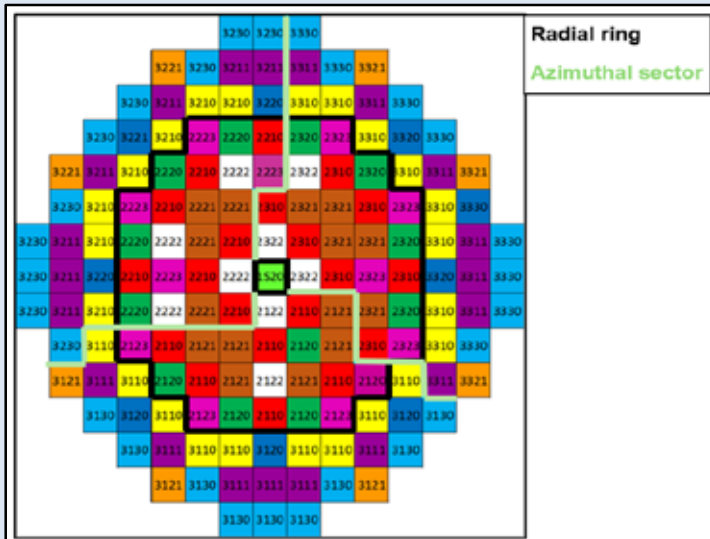


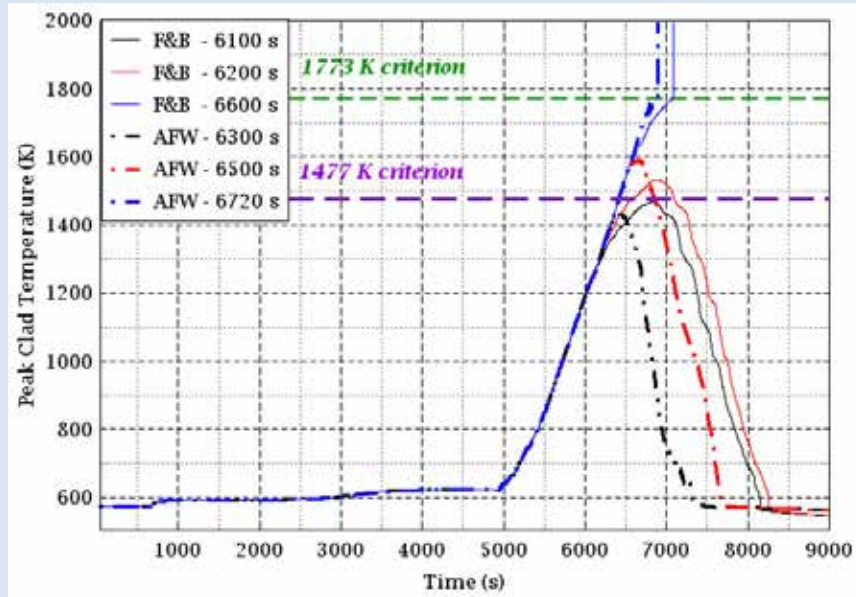
Actividades Realizadas.

Secuencias de TLFW en PWR

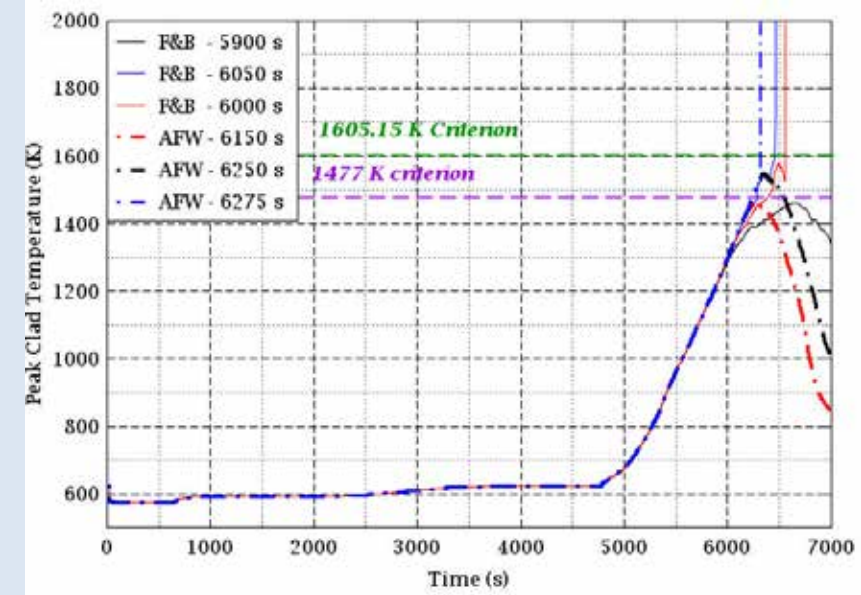


Total loss of Feed Water	Reactor trip	AFW recovery	Feed & Bleed	H. P. Recirc.	Seq	State
TLFW	Z	A	F	HPR		
					1	Success
					2	Success
					3	Damage
					4	Damage
					5	ATWS





FeCrAl cladding



Cr-coated Zry cladding

Cladding Type	t_{A1} (min)	t_{A2} (min)	Δt_{A1} (min)	Δt_{A2} (min)
Opt. Zirlo	97.5	-	-	-
Cr- coated Zry	98.3	100.0	0.8	2.5
FeCrAl	101.7	106.6	4.2	9.1

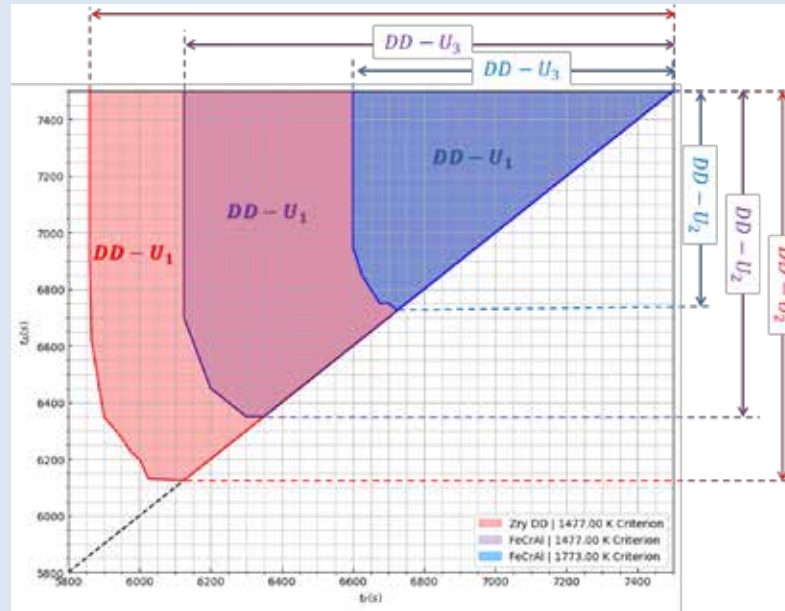
Time available with **F&B strategy** for different types of cladding

Cladding Type	t_{A1} (min)	t_{A2} (min)	Δt_{A1} (min)	Δt_{A2} (min)
Opt. Zirlo	100.0	-	-	-
Cr- coated Zry	102.5	104.2	2.5	4.2
FeCrAl	105.0	111.7	5.0	11.7

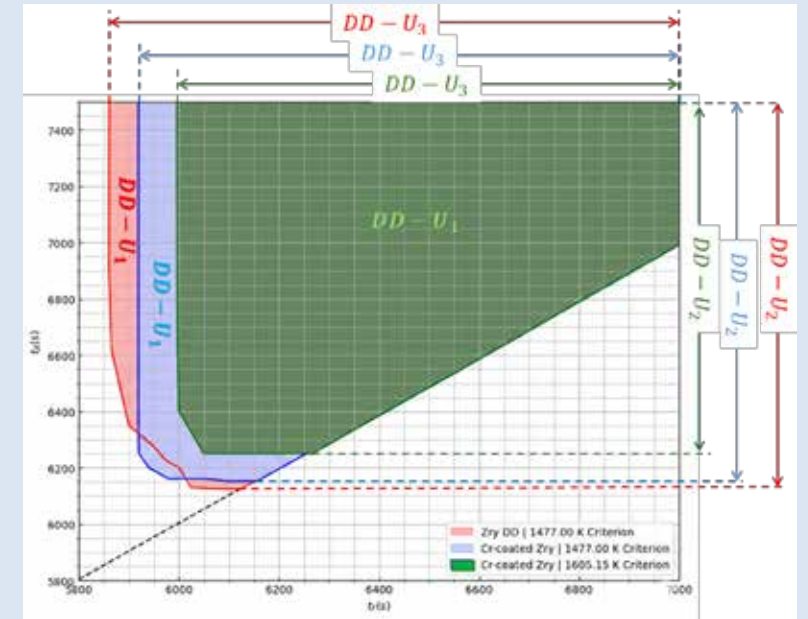
Time available with **AFW recovery** for different types of cladding

ISA Approach

- CSN – UPM – NFAQ
- DPSA: PSA + DSA
- J.M. Izquierdo et al



Damage Domain for different FeCrAl acceptance criteria



Damage Domain for different Cr-coated Zry acceptance criteria

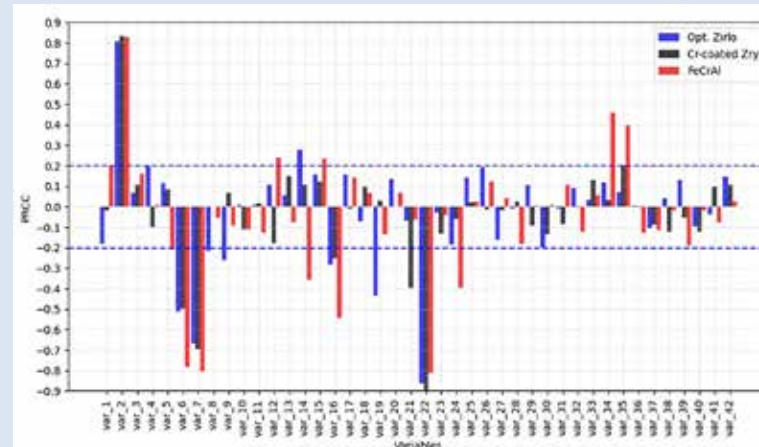
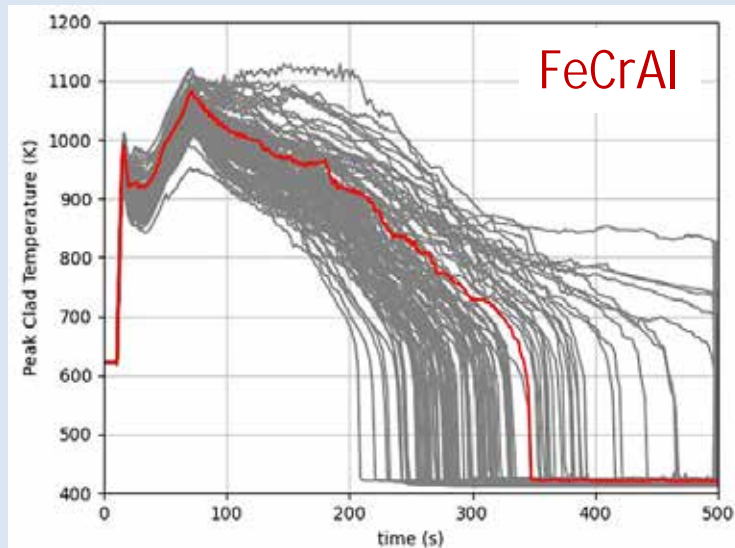
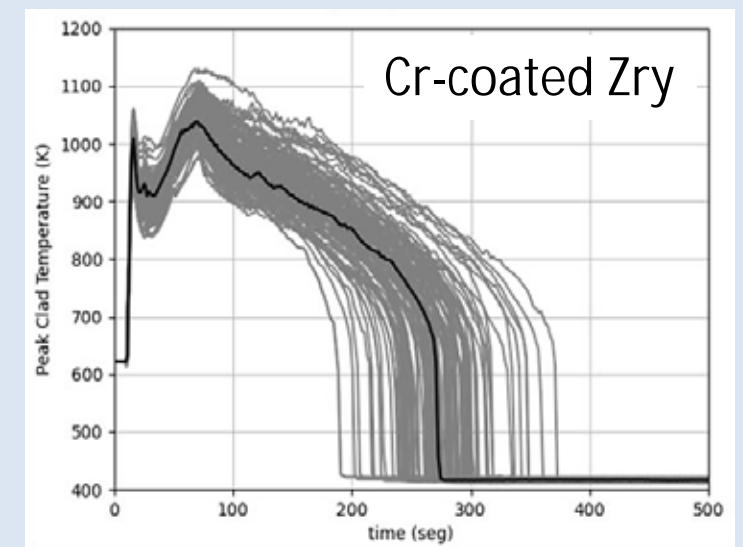
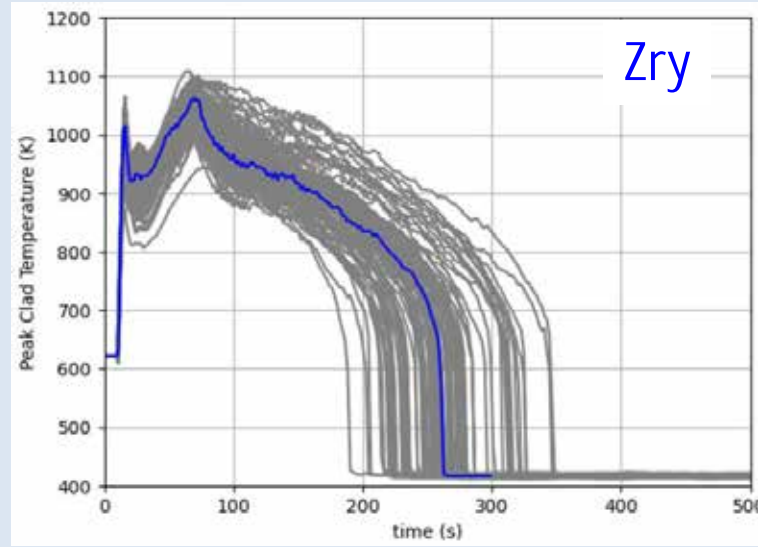
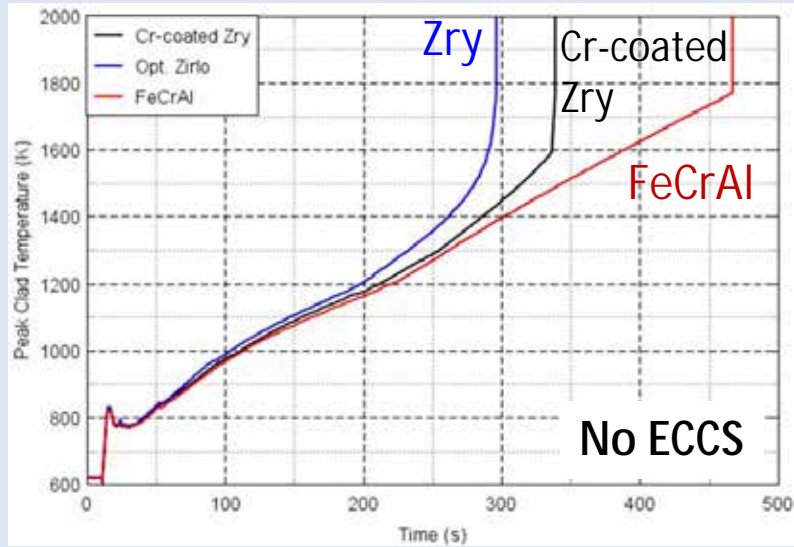
Cladding material	Acceptance criterion	DEP	DEF (1/y)	Δ DEF (%)
Opt. Zirlo	1477 K	7.14E-04	1.43E-07	-
Cr coated Zry	1477 K	6.95E-04	1.39E-07	3%
	1605.15 K	6.66E-04	1.33E-07	7%
FeCrAl	1477 K	6.38E-04	1.28E-07	10%
	1773 K	5.26E-04	1.05E-07	27%

David Canal, César Queral, Javier Magán, Emilio Castro-González, Jorge Sánchez-Torrijos.

“Quantification of the risk reduction due to the implementation of ATF claddings in Total Loss Feed Water sequences”. Nuclear Engineering and Design **2026**

Actividades Realizadas.

Secuencias de LBLOCA en PWR



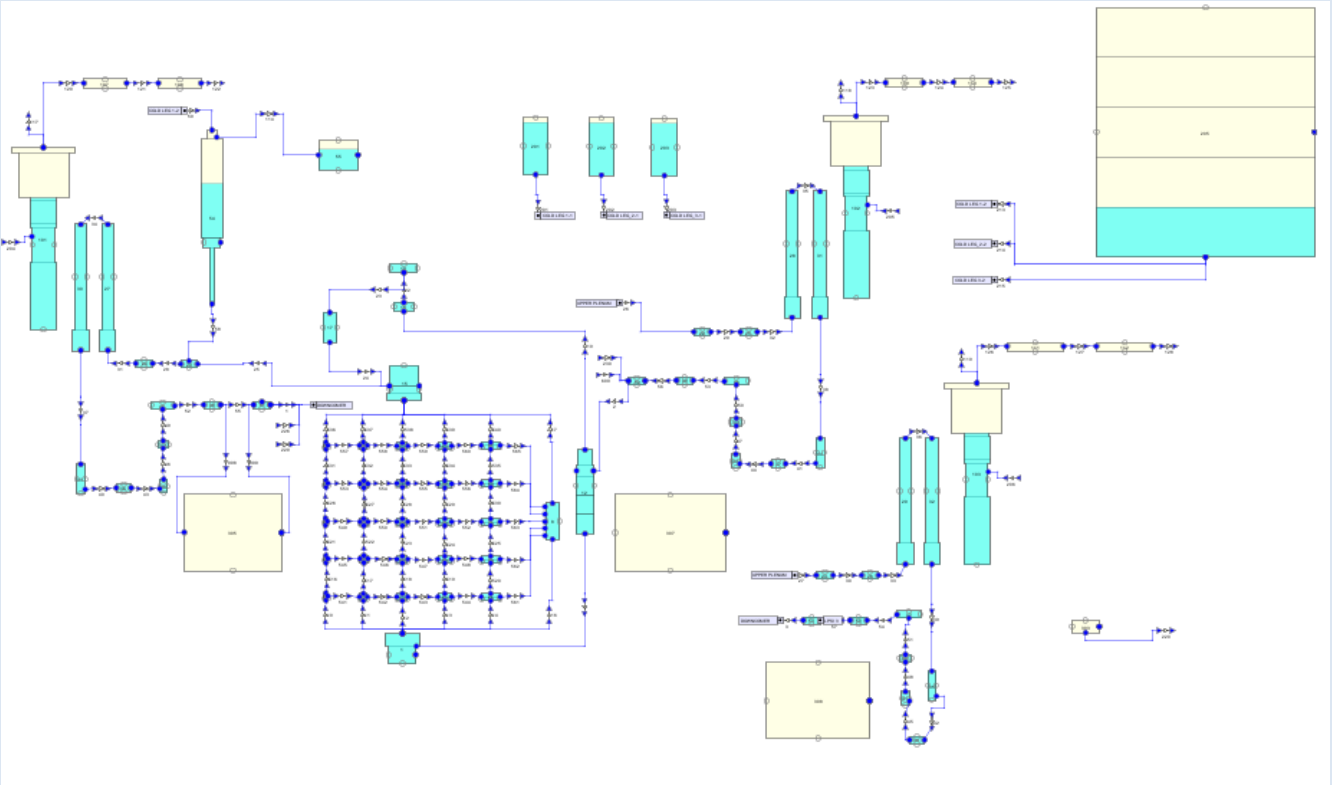
PRCC PCT Blowdown



PRCC PCT Reflood

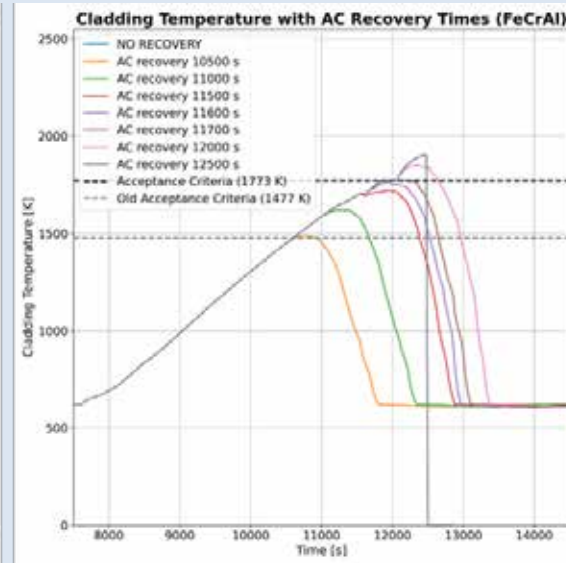
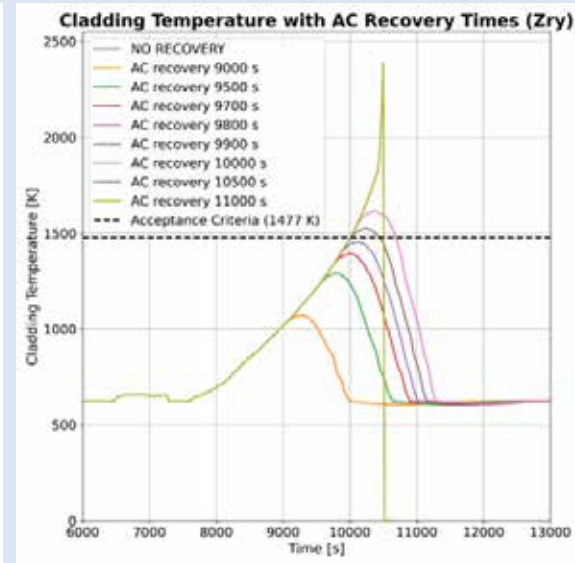
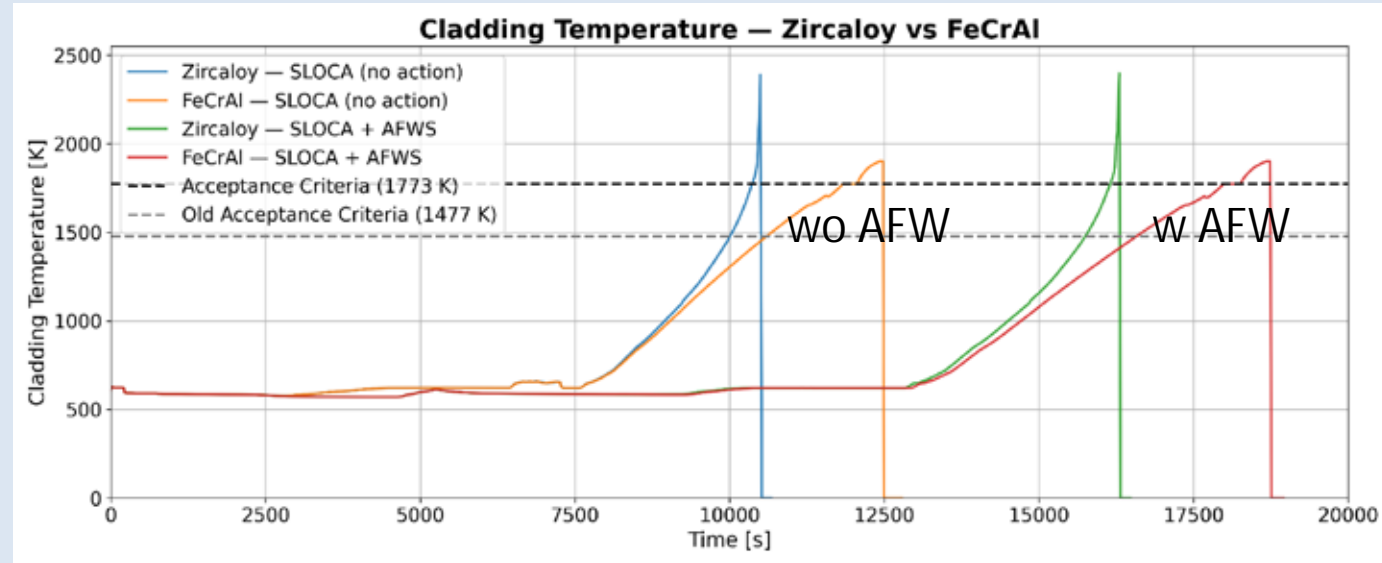
Actividades Realizadas.

Secuencias de SBO en PWR (MELCOR)



LOSS OF OFFSITE POWER	REACTOR PROTECTION SYSTEM	EMERGENCY POWER DG-A AND DG-B	AUXILIARY FEEDWATER	PASSIVE THERMAL SEALS	SEAL LOCA + FLOW RATE	POWER SUPPLY TO BATTERY CHARGES (BUS DC-B AND DC-D)	OFFSITE POWER RECOVERY	No.	Conseq.
LOOP	Z	DG	AF	TS	LS	LB	R-EX		
1								1	GT-LOOP
								2	S
								3	S
								4	CD
								5	SBLOCA
								6	CD
								7	SBLOCA
								8	CD
								9	SBLOCA
								10	CD
								11	ATWS

SBO
SLOCA
 $G_{1p} = 11.5 \text{ kg/s}$
 $G_{1p} = 30 \text{ kg/s}$
 $TA = 1.30 \text{ h}$

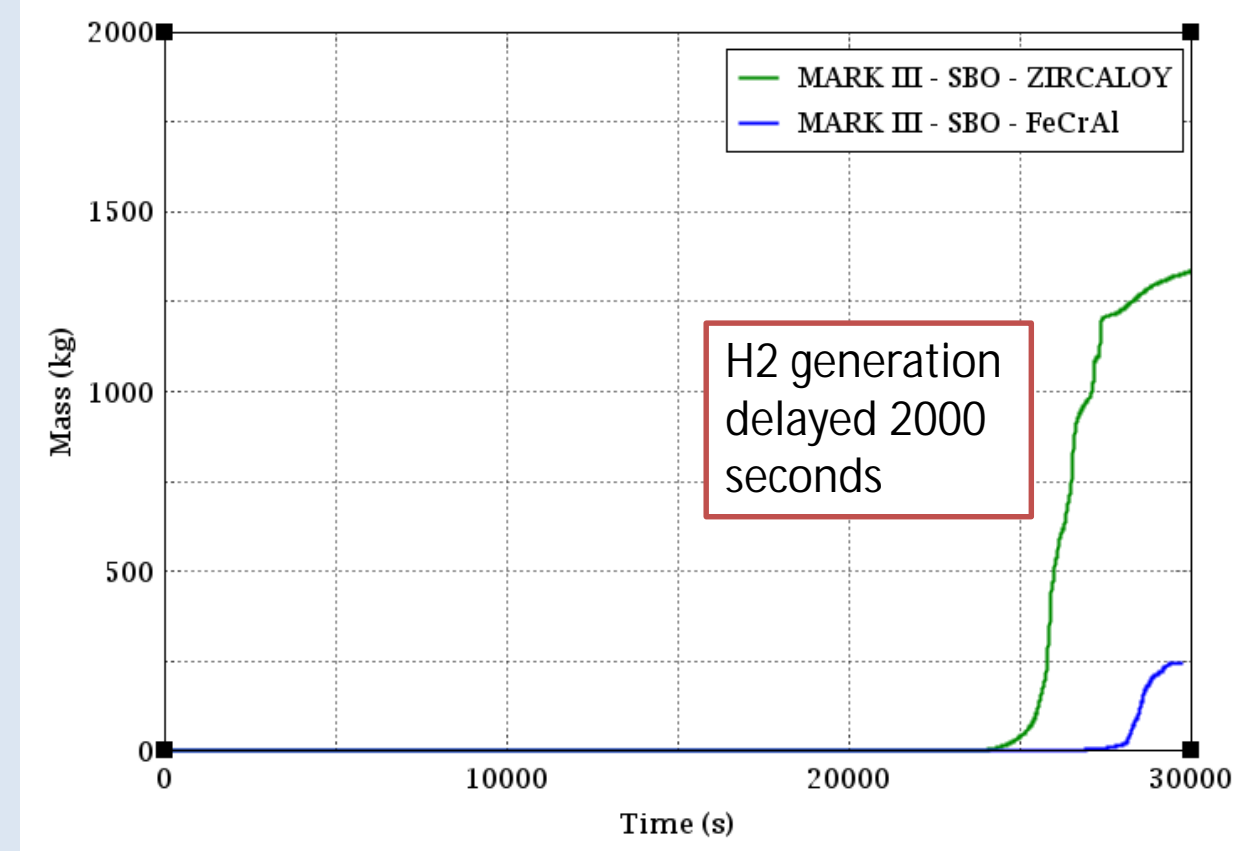
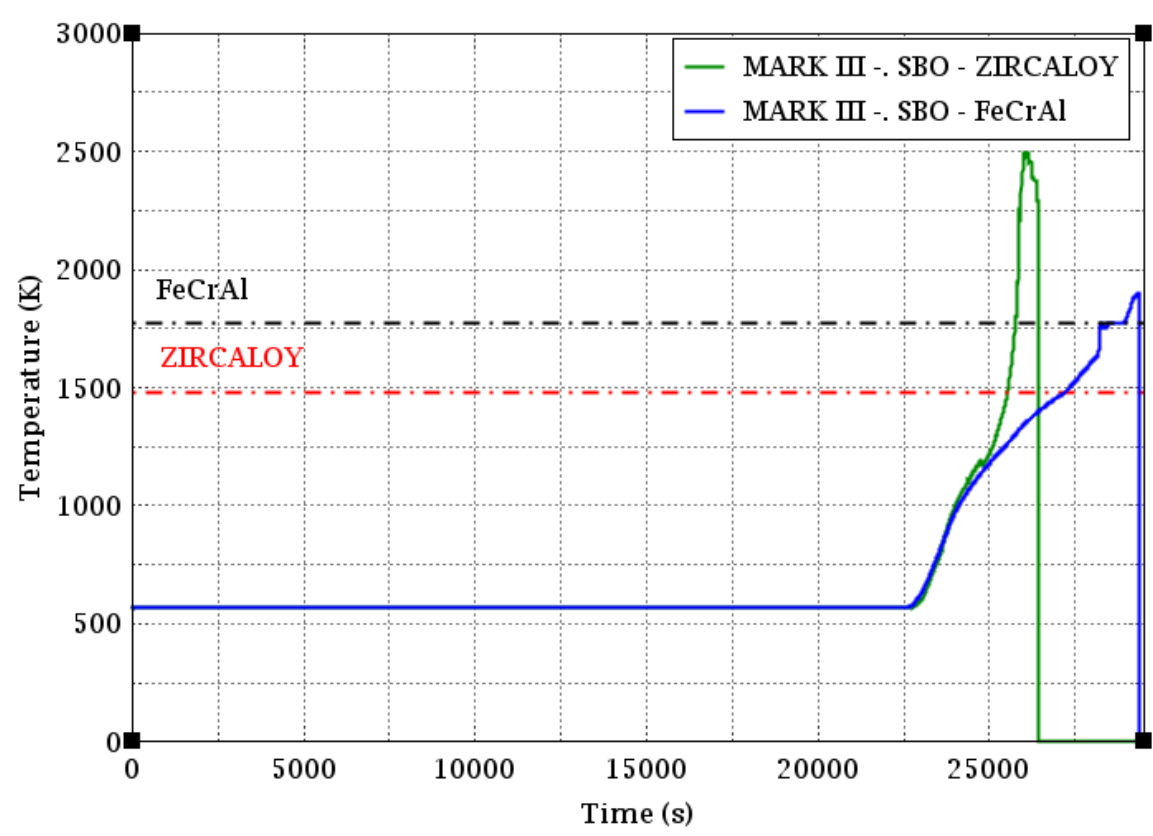


SBO + w/wo AFW + SLOCA ($G_{1P} = 11.5 \text{ kg/s}$)

SBO + wo AFW + SLOCA ($G_{1P} = 11.5 \text{ kg/s}$)

	SBO+SLOCA (w/o AFWS)	SBO+SLOCA (w AFWS)
Zry	10,020 s	15,760 s
FeCrAl (1477 K)	10,600 s	16,580 s
FeCrAl (1773 K)	11,840 s	18,000 s

También se han realizado diversos análisis con TRACE para Cr-coated Zry y FeCrAl



CD time	CD time FeCrAl
25800 s	27780 s (8%)



12th CONFERENCE ON
SEVERE ACCIDENTS RESEARCH
May 18-22, 2026 - Madrid, Spain
ERMSAR 2026

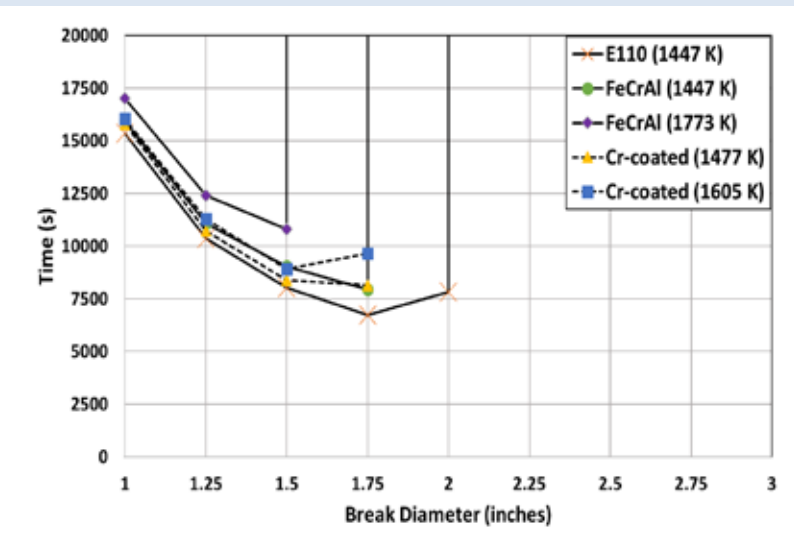
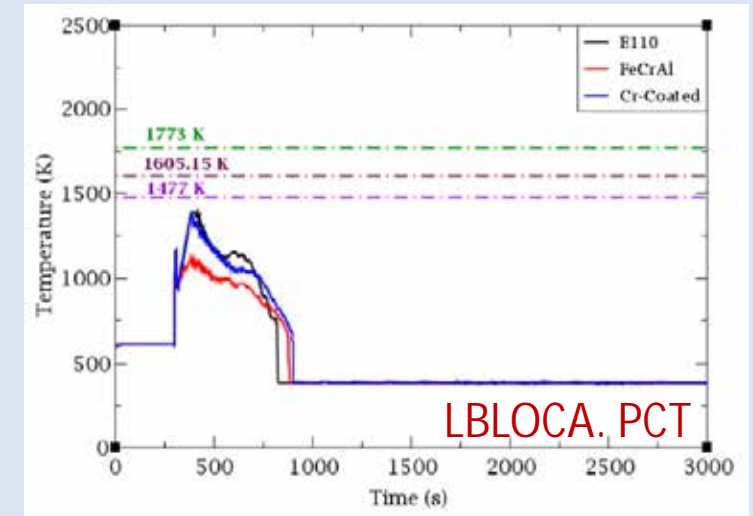
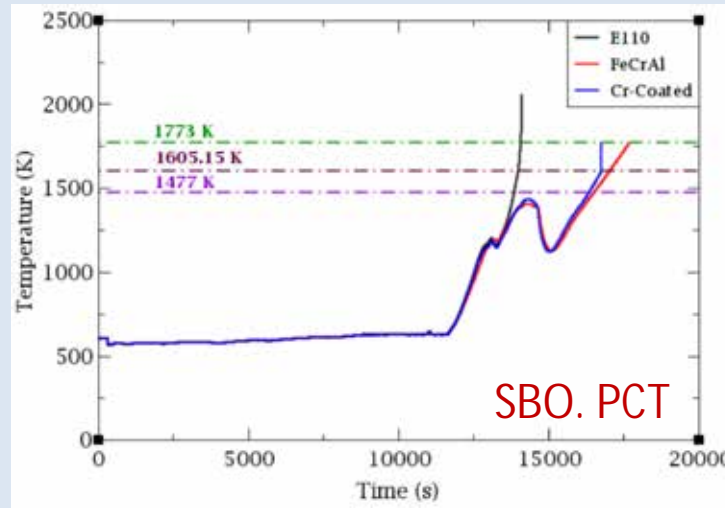
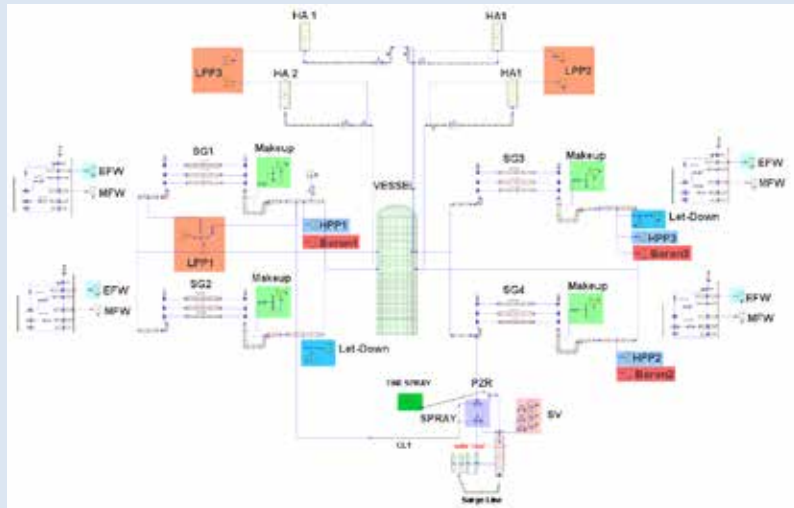


Evaluation of Accident Tolerant Fuel using MELCOR2.2 on Representative Accident Sequences in Typical Japanese PWR

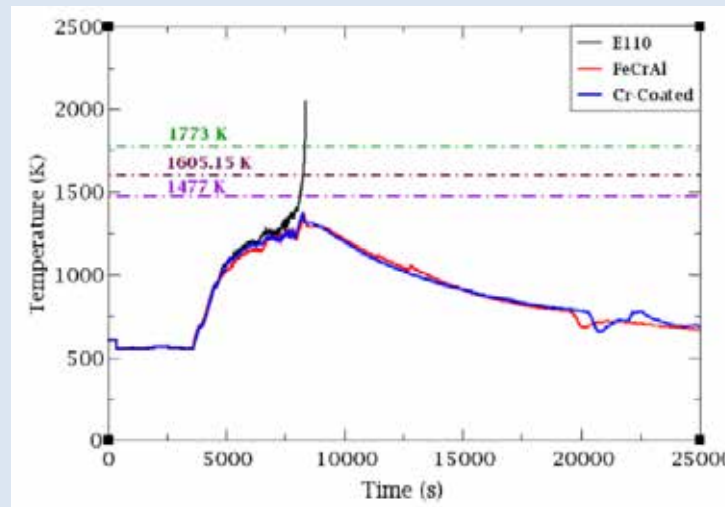
NRA, Masashi SEKINE, Junichi KANEKO, Wataru KIKUCHI, Retsu KOJO

SBO	Zircaloy	Cr-coating	FeCrAl-ORNL	FeCrAl-MIT	SiC
PCT [K]	2,497	2,499	1,804	1,901	2,900
Lower head failure timing [hr]	6.5	7.8	7.4	7.0	8.0
H ² mass [kg]	541	603	490	558	<u>611</u>

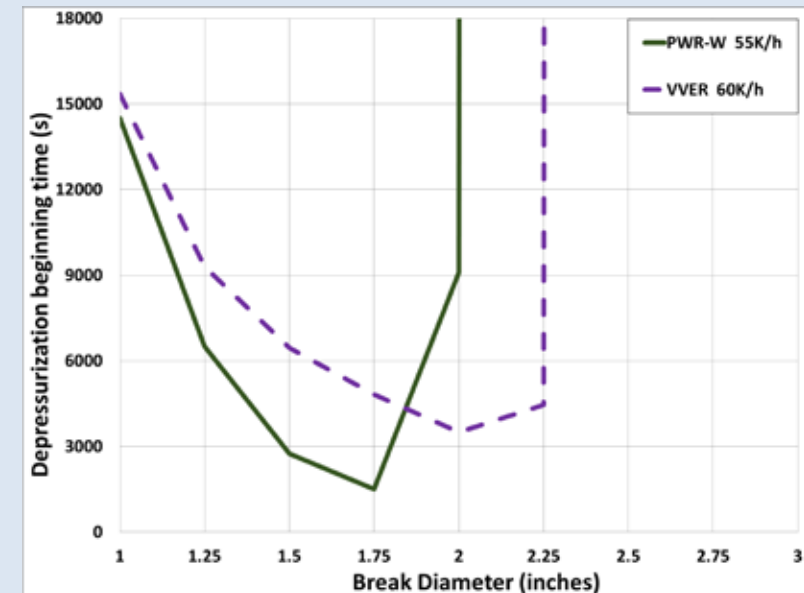
LOCA	Zircaloy	Cr-coating	FeCrAl-ORNL	FeCrAl-MIT	SiC
PCT [K]	2,497	2,499	1,804	1,901	2,900
Lower head failure timing [hr]	2.5	2.5	2.6	2.6	3.0
H ² mass [kg]	343	301	347	400	<u>450</u>



Damage Time. SBLOCA w HPSI failure



SBLOCA (2 in.) w HPSI failure.



Zry. PWR-3L .vs. VVER-1000



Sequence	E110 (1477 K) [s/min]	FeCrAl (1477 K) [s] (Δt) [min]	FeCrAl (1773 K) [s] (Δt) [min]
LBLOCA (No ECCS)	77 1.3	107 (0.5)	205 (2)
2 inches SBLOCA	7822 130.4	No damage	No damage
1 inches SBLOCA	15357 256	15927 (9.5)	17008 (27.5)
SBO	13546 226	16206 (44)	17386 (64)

Sequence	E110 (1477 K) [s/min]	Cr-coated Zry (1477 K) [s] (Δt) [min]	Cr-coated Zry (1605 K) [s] (Δt) [min]
LBLOCA (No ECCS)	77 1.3	90 (0.2)	113 (0.5)
2 inches SBLOCA	7822 130.4	No damage	No damage
1 inches SBLOCA	15357 256	15802 (7.5)	16032 (11)
SBO	13546 226	16041 (41.5)	16436 (48)

Elena Redondo-Valero, César Queral, Kevin Fernández-Cosials, Jorge Sánchez-Torrijos, David Canal, Emilio Castro-González, Victor Hugo Sánchez-Espinoza. **Comparative analysis of accidental sequences with conventional and Accident Tolerant Fuels (ATF) in VVER-1000 reactors.** Nuclear Engineering and Design, Volume 446, Part B, 2026.

- Collaboration between **CSN** and **UPM**.
- Generic Standardized Plant Analysis Risk (SPAR) model: SPAR-CSN
- 3-loop PWR-WEC design.
- PSA model independent from the industry, like to NRC SPAR models.



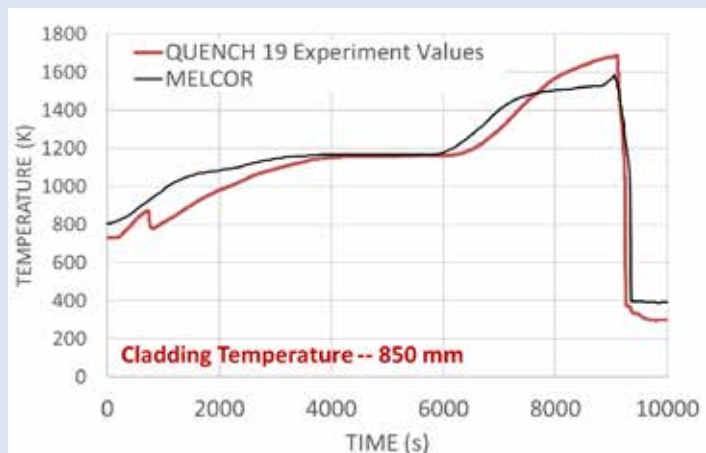
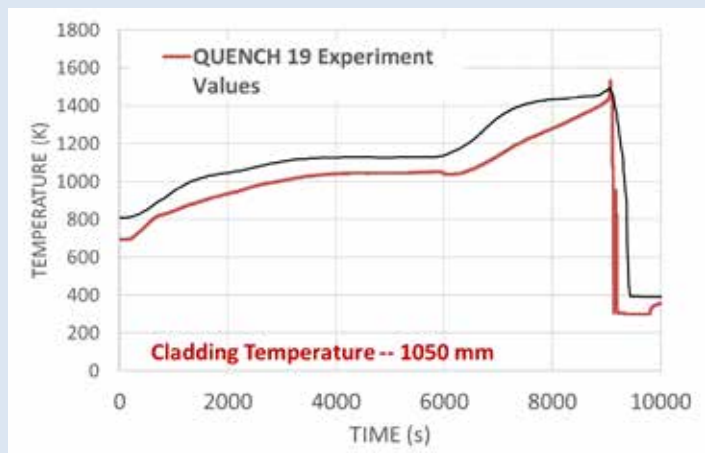
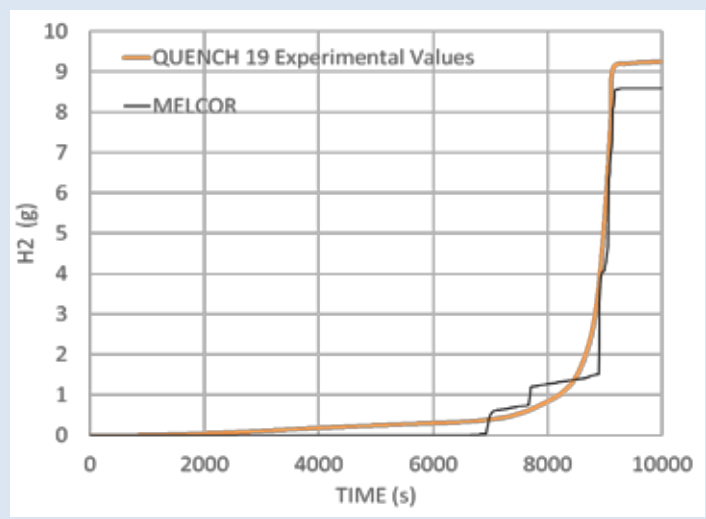
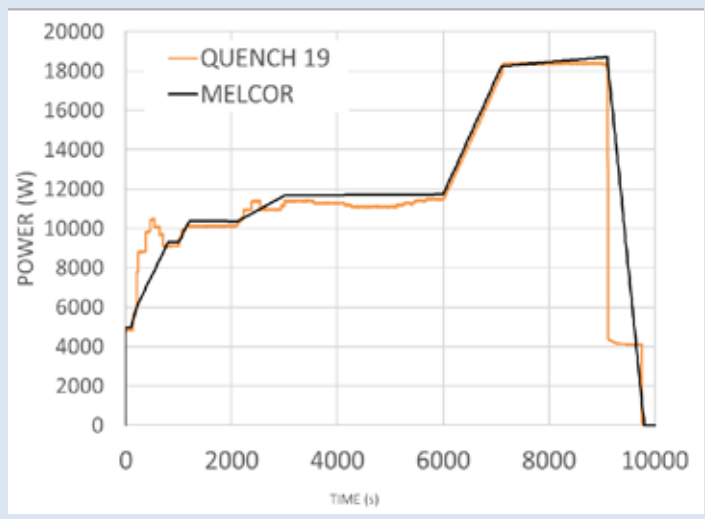
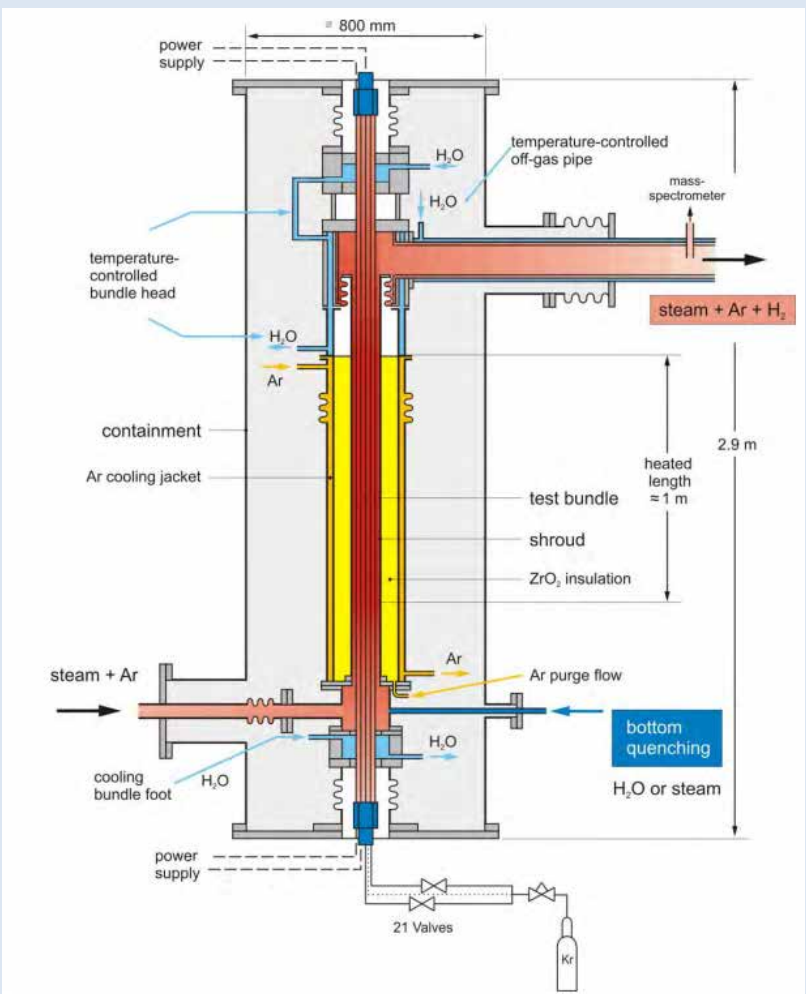
ID	Initiating event	ID	Initiating Event
LBLOCA	LOCA (> 6 in.)	MSLB-US	Main Steam Line Break upstream of MS isolation valves (MSIV)
MBLOCA	LOCA (2 in. to 6 in.)	MSLB-DS	Main Steam Line Break downstream of MSIV
SBLOCA	LOCA (3/8 in. to 2 in.)	SGTR	Steam Generator Tube Rupture
GT	General Transient	LCWA	Loss of a CW train
ATWS	Anticipated transient without SCRAM	LNSW	Loss of Non-essential Service Water System
LC	Loss of Condenser	LOOP/SBO	Loss of Offsite Power/ Station Blackout
LDC-A	Loss of emergency DC-A bus	LDC-B	Loss of emergency DC-B bus

Time to CD (min)	Increase in time available (min)	
	Cr-Coated	FeCrAl
50-80	2	6
130-160	5	10
300-350	10	21
500-550	12	50

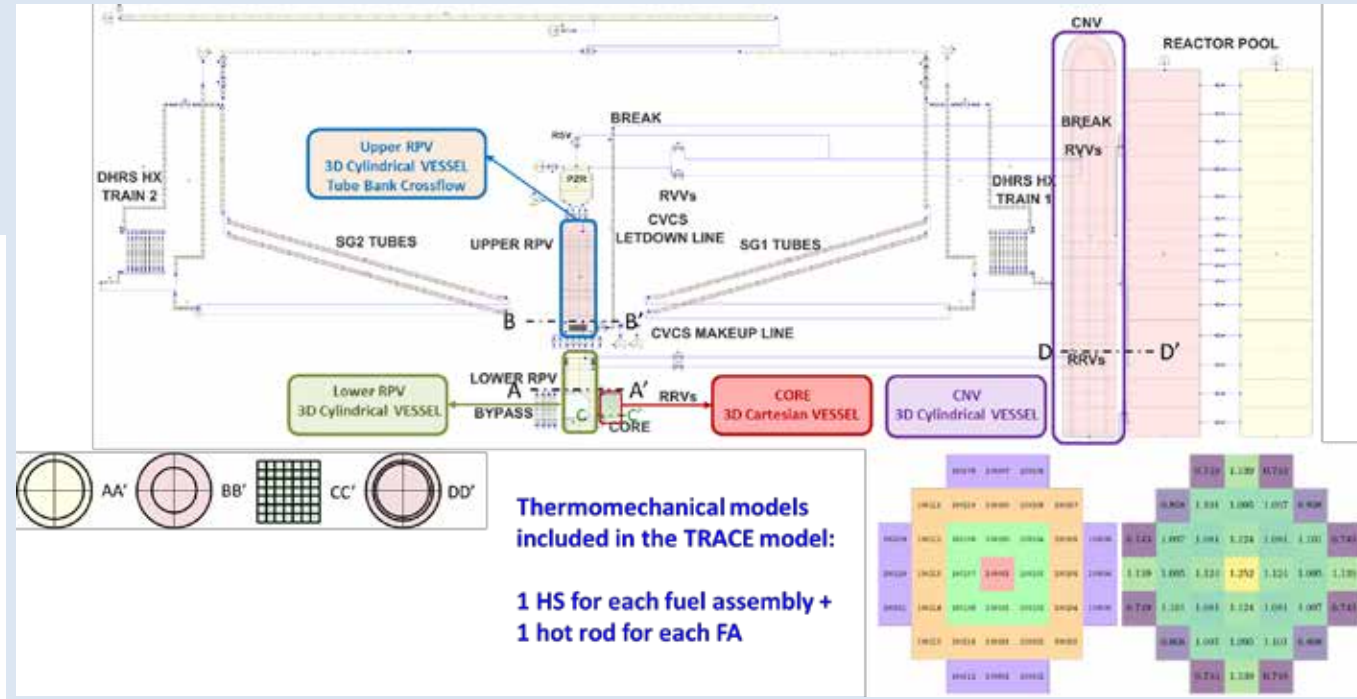
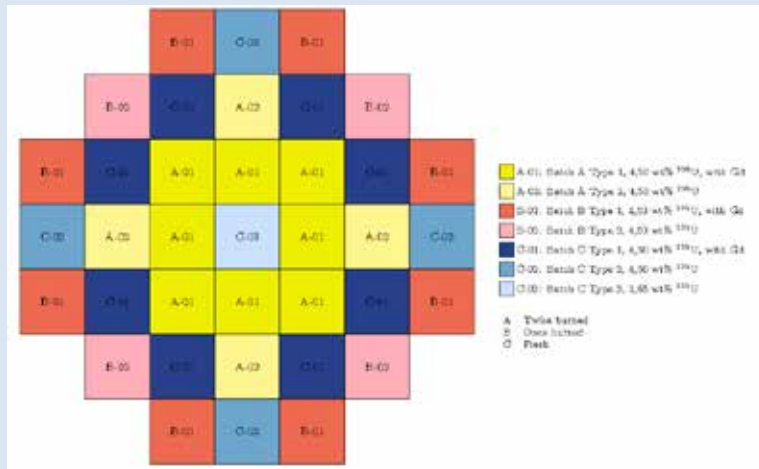
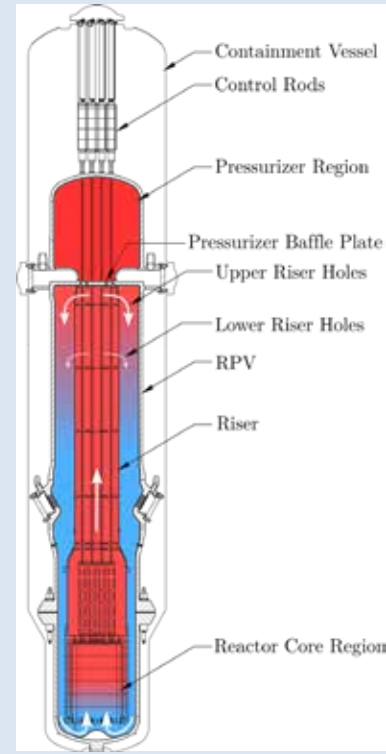
CDF Zry (1/y)	CDF Cr-Coated Zry (1/y)	Δ CDF Cr-Coated	CDF FeCrAl (1/y)	Δ CDF FeCrAl
5.5E-07	5.2E-07	-5%	4.9E-07	-10%

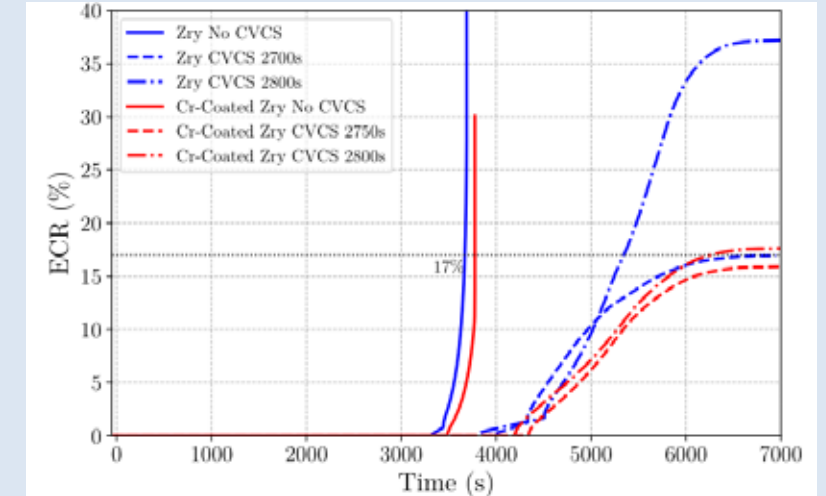
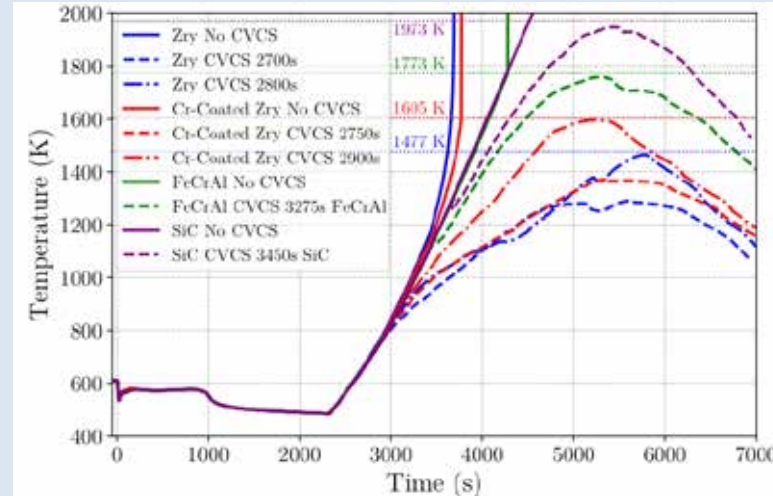
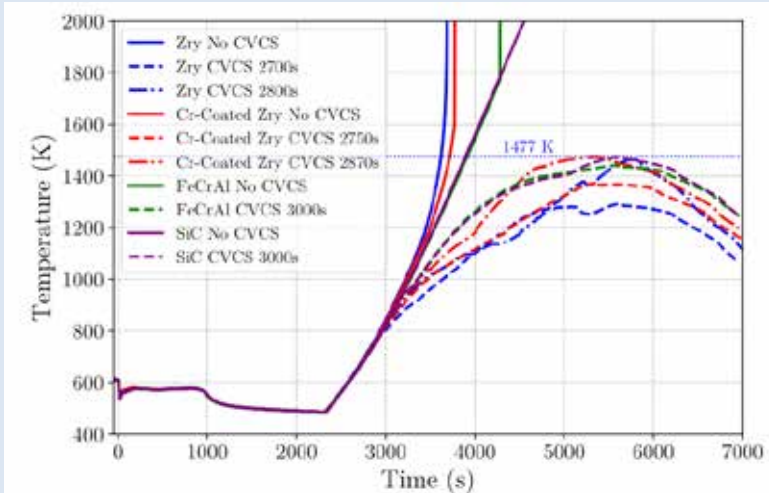
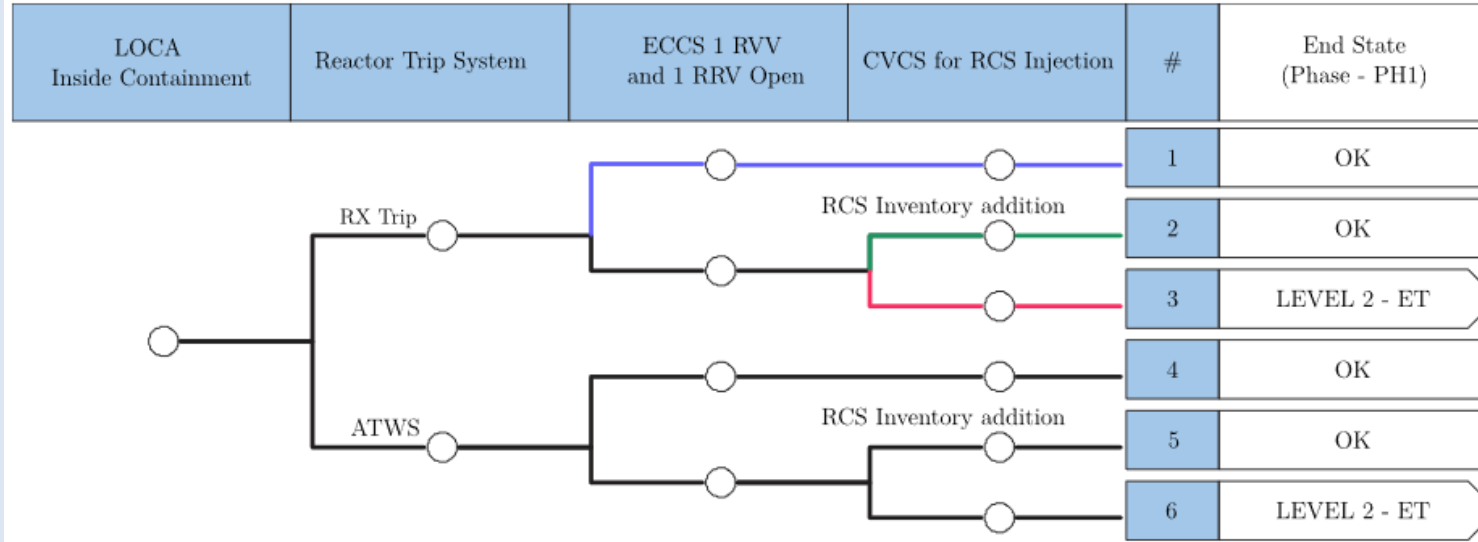
UPM – NFQ Activities:

- Experimental tests: PUZRY and FCA burst tests; impact of ATF in IFA 650.10 (BEPU **TRACE** and **TU**); QUENCH-19 (**MELCOR**)
- PWR LBLOCA and SBLOCA analyses (**TRACE**)



- Task 1: **Non-proprietary TRACE/PARCS model of NuScale**
- Task 2: **ATF material properties and models**
- Task 3: Risk-informed Accident Sequences. PRA model development
- Task 4: **Accident analysis. NuScale (TRACE). LOCA, SBO, ATWS, Loss of DC, Loss of support system; Generic Transient.**
- Task 5: Multi-physics Simulation of ATF Cladding Performance
- Task 6: Evaluation of Impact of ATF on SMRs





Material	t_{A-T1} (min)	t_{A-T2} (min)	t_{A-Ox} (min)	Δt_{A1} (min)	Δt_{A2} (min)
Zr _y	46.7	–	45	–	–
Cr-coated Zr _y	47.8	48.3	45.8	0.8	0.8
FeCrAl	50.0	54.6	–	5	9.6
SiC	50.0	56.7	–	5	11.7

1. *Descripción del combustible en reactores PWR/BWR*. César Queral (UPM).
2. *Fenomenología termomecánica propia del periodo de irradiación*. Jorge Sanchez Torrijos (UPM).
3. *LOCA en PWR/BWR/KWU. Fenomenología termomecánica durante accidentes con pérdida de refrigerante*. Jorge Sanchez Torrijos (UPM).
4. *Criterios de aceptación LOCA*. César Queral (UPM).
5. *Modelos termomecánicos incluidos en el código FRAPCON/FRAPTRAN/FAST*. Francisco Feria, Carlos Aguado, Pau Aragón (CIEMAT).
6. *Aplicaciones del código FALCON*. Roberto Plaza (IDOM).
7. *Modelos termomecánicos incluidos en el código TRANSURANUS*. Jorge Sanchez Torrijos (UPM).
8. *Pin-level multiphysics analysis of Light Water Reactors using TRANSURANUS coupled to Serpent and SUBCHANFLOW*. Manuel García. Karlsruhe Institute of Technology (KIT)
9. *Modelos termomecánicos incluidos en el código de sistemas TRACE. Fase de irradiación. Propiedades de los materiales*. Jorge Sanchez Torrijos (UPM).
10. *Modelos termomecánicos incluidos en el código de sistemas TRACE. Secuencias de LOCA*. Jorge Sanchez Torrijos (UPM).
11. *SCDAP/RELAP5 y RELAP5*. Raimon Pericas (ENSO).
12. *INTRODUCTION TO ATF CONCEPTS. APPLICATION TO MELCOR ANALYSIS*. Kevin Fernandez-Cosials (UPM).
13. *ACCIDENT-TOLERANT FUELS*. Pau Aragón (CIEMAT).

Curso INGENIA/UPM: Diseño de Reactores Nucleares - “Accident Tolerant Fuels for LWRs”

Segunda Jornada **CEIDEN – UPM**: “Accident Tolerant Fuels for LWRs”

Fecha: 20 de mayo de 2020, de 09:00 a 13:00h.

Presentaciones (disponibles en la web del CEIDEN):

- Introducción y Programa
- Arjan Plompen (JRC) – «The JEFF nuclear data file and the need for your development goals»
- Allan Simpson (UK NNL) – «Nuclear Data for ATF: A UK Perspective»
- Cedric Cozzo (PSI) – «PSI developments on ATF»
- Robert Kilger (GRS) – «Current neutronics activities on LWR ATF at GRS»
- **INGENIA UPM – «UPM – CDIO Project in Nuclear Engineering Education»**
- **INGENIA UPM – «PWR 3D Core Simulation using different ATF cladding materials»**
- **INGENIA UPM – «PWR 3D Core Simulation using different ATF fuels»**
- **INGENIA UPM – «Simulation of the Power Maneuvering of PWRs using new ATF»**
- Daniel Cano (CIEMAT) – «Emerging activities on nuclear data for ATF at CIEMAT»

<https://ceiden.com/programas/grupo-siren-simulacion-de-reactores-nucleares/segunda-jornada-ceiden-upm-accident-tolerant-fuels-for-lwrs/>

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5. Yago Martínez González, César Qeral, Jorge Sánchez-Torrijos, Arantxa Cuadra, David Canal, Emilio Castro, Kevin Fernández-Cosials. “**Analysis of Risk-Important LOCA Sequences in NuScale considering Accident Tolerant Fuels**”. Nuclear Engineering and Design, volume 453, **2026**.
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19. Rodrigo Rivilla, Kevin Fernández-Cosials, César Queral. **ANALYSIS OF ACCIDENTAL SEQUENCES ON A PWR REACTOR USING MELCOR CODE FOR DIFFERENT ADVANCE TECHNOLOGY FUELS**. 51 Reunión Anual de la Sociedad Nuclear Española, 24-26 de septiembre de 2025, Cáceres.
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1. Los materiales de vaina y combustible ATF muestran **características de gran interés en operación normal** y **AOO** que pueden permitir aumentos del enriquecimiento y/o el quemado y reducir el número de elementos en cada recarga.
2. Desde el punto de vista de las **secuencias accidentales** se observan incrementos de los tiempos disponibles dependientes de los materiales utilizados.
3. La **disminución del riesgo** es relativamente baja desde el punto de vista del APS nivel 1. También depende de la modelación e hipótesis realizadas sobre las acciones humanas.
4. Todavía es necesario realizar un amplio conjunto de **experimentos** para caracterizar adecuadamente estos materiales.
5. Es necesario participar en **nuevos proyectos nacionales e internacionales** relacionados con esta temática.
6. Por último, cabe destacar la **mejora de la formación** de un amplio conjunto de personas que hoy en día trabajan en el sector nuclear, incluyendo cuatro tesis doctorales.

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Dedicado a José María Izquierdo Rocha (1947–2023)

