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Análisis de escenarios DEC con reinundación de núcleo para combustible ATF cromado: estudio de la integridad de las barras de control (ATF-DEC)

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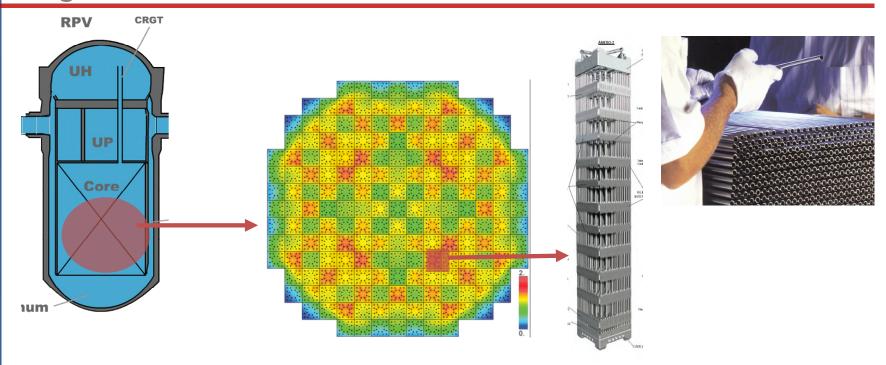
bravo.ivangabriel@gmail.com







Seguridad Nuclear, la vaina



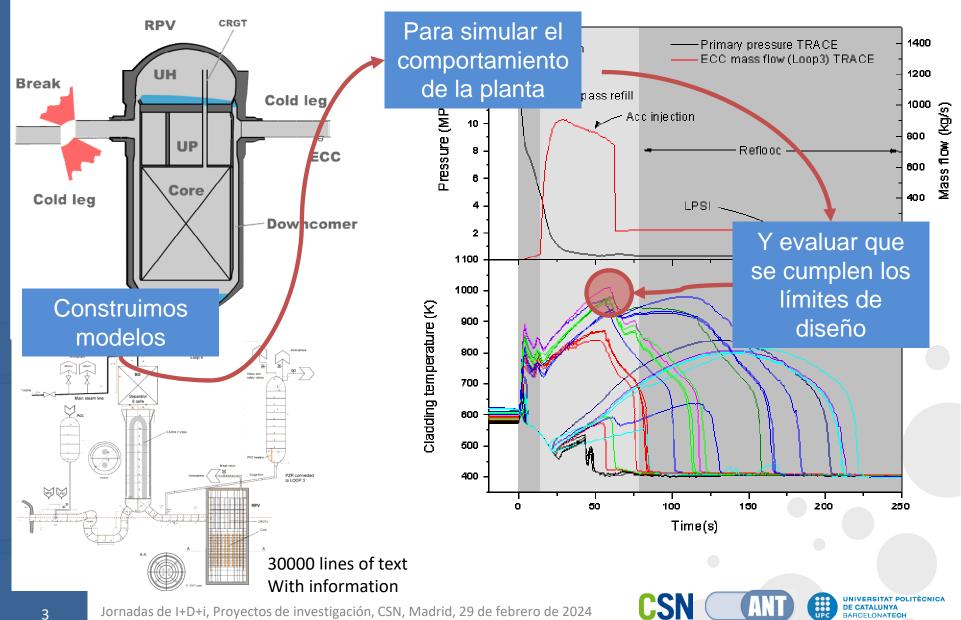
- Límites de Seguridad:
 - Alta temperatura 1477 K (1204 C)
 - 17 % de oxidación







Escenarios base de diseño: LOCA



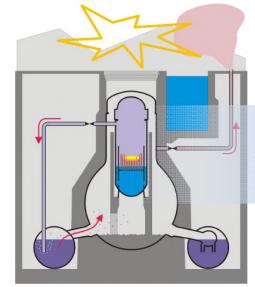


Pero luego... Fukushima





SBO de larga duración











Acciones post-Fukushima

- Stress tests
- Potenciar el concepto DEC (Extensión de diseño)
- Elemento de combustible ATF

| Level 1 | Level 2 | | Level 3 | Lev | rel 4 / Level 5 | |
|--------------------------------|-----------------------------------|--|---|---|--|--|
| Operational states | | | Accident conditions | | | |
| Normal operation ¹⁾ | AOOs ²⁾ | Within design basis accidents ³⁾ | | Beyond design bases accidents | | |
| | 2 2 3 4 4 4 4 | a) | DBAs | DEC without core melt ⁴⁾ | DEC with core melt - Severe accidents ⁵⁾ | |
| | >10 ⁻² events per year | 10-2 | ² - 10 ⁻⁶ events per year | 10 ⁻² - 10 ⁻⁶ events per year | < 10 ⁻⁶ events per year | |

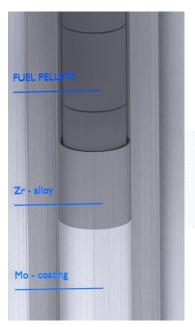




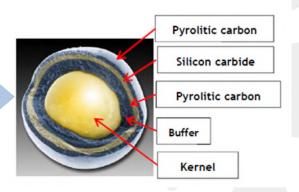
Elementos de combustible ATF

| Cladding designs | | | | Core components | |
|----------------------------|-------------------------------|-----------------|-------------------|--------------------------|--------|
| SiC and SiC/SiC composites | Coated and improved Zr-alloys | Advanced steels | Refractory metals | SiC/SiC channel boxes | ATCR |
| KAERI | UIUC | ORNL | EPRI | Toshiba | CRIEPI |
| Muroran | FJP (*) | GE | CGN | EPRI | AREVA |
| FJP (*) | KAERI | NFD | | | |
| KIT | IFE | | | | |
| ORNL | KIT | | | | |
| PSI | | | | | |
| Westinghouse | | |) j | | · 1 |

(*) French Joint Programme (CEA-AREVA-EDF).



TRISO fuel concept









Combustible UO₂/Zry con película cromada

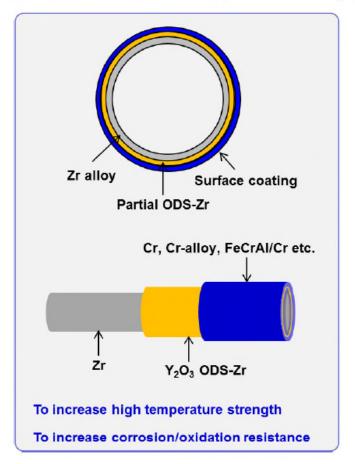
State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels

Figure 10.1. Schematic overview of KAERI's modified zirconium alloy ATF concept









- Fácil implementación
- Reducir la oxidación
- Mejor integridad mecánica
- Punto de fusión relativamente bajo 1500 K

Source: Kim et al., 2016.







Taxonomía europea

European Parliament backs nuclear and gas in EU taxonomy

06 July 2022



The proposed inclusion of certain nuclear and gas activities within the European Union's list of officially approved "green" investments is set to become law after an attempt to block it fails in the European Parliament.





- ¡La energía nuclear contribuye a la sostenibilidad del sistema energético!
- Pero... Con condiciones...
- Hay que incorporar los elementos de combustible ATF

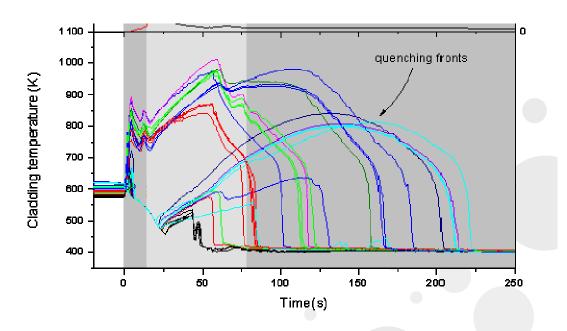






Objetivo principal del proyecto

- Capacidad para simular eventos frontera con elementos de combustible ATF de capa cromada
 - Cuantificar la oxidación
 - Evaluar el estado de las barras de control en estas condiciones









Investigación bibliográfica de los modelos de oxidación

Paso 1

Evaluación de las necesidades del código RELAP/SCDAP y diseño de nuevos modelos

Paso 2

Implementación de un nuevo modelo de **Paso 3** oxidación

Proyecto ATF

Paso 4

V&V del nuevo modelo

Paso 5

Paso 6

Exploración de casos frontera entre **escenarios DEC-A y DEC-B**

Cuantificación de la oxidación de vaina y estado final de las barras de control







Investigación bibliográfica de los modelos de oxidación

Paso 1

Evaluación de las necesidades del código RELAP/SCDAP y diseño de nuevos modelos

Paso 2

Proyecto ATF







RELAP/SCDAPSIM/MOD3.4

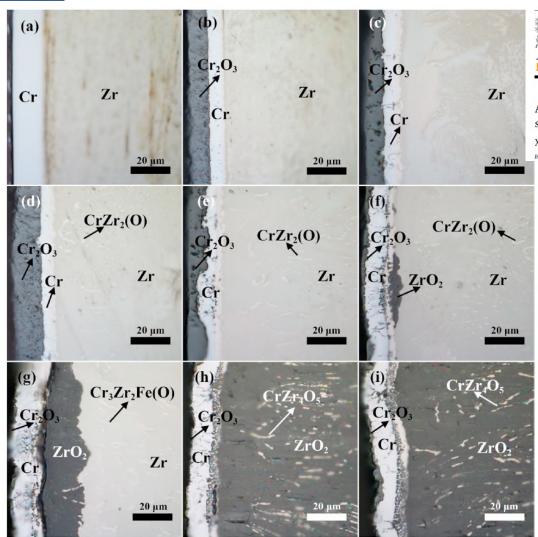
- Código de sistema para casos de daño severo
- RELAP5MOD3.2 + SCDAP + FRAP-T6 (MATPRO)
- Puede simular condiciones del sistema para:
 - Base de diseño
 - DEC-A
 - DEC-B







El mecanismo de oxidación



Contents lists available at ScienceDirect

Corrosion Science

ELSEVIER journal homepage: www.elsevier.com/locate/corsci

A systematic study of the oxidation behavior of Cr coatings on Zry4 substrates in high temperature steam environment

Xiaochun Han, Chen Chen, Yongqiang Tan, Wanlin Feng, Shuming Peng, Haibin Zhang*

Innovation Research Team for Advanced Ceramics, Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang, 621900, China

Ref [8]

Optical microscope images of the cross-section morphologies of samples before and after oxidation. (a) as-grown; (b) 30 min; (c) 60 min; (d) 75 min; (e) 90 min; (f) 120 min; (g) 150 min; (h) 210 min; (i) 240 min.

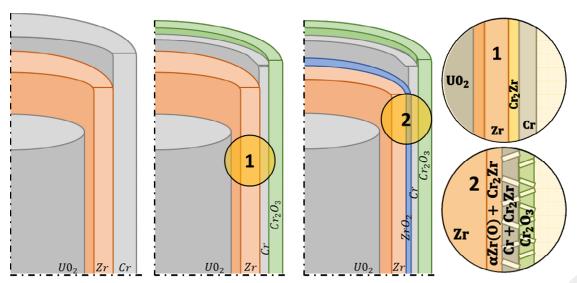


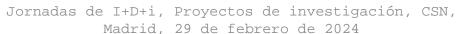




Modelización de la capa cromada

- Revisión de modelos previos y datos experimentales
- Modelo simplificado de oxidación:
 - $k_{Cr} \approx k_{Zr} C_{Cr} \approx C_{Zr}$
 - No se consideran efectos de estrés
 - Se asume el modelo de deformación propio de Zircaloy (SCDAP)
 - El coating se añade a la capa de Zircaloy
 - La oxidación del Cr se modela calculando el grosor de la capa oxidada, los cambios energéticos y de masa así como la producción de hidrógeno
 - La oxidación del Zircaloy se ve afectada por la oxidación del Cr











Modelo de oxidación implementado

- Se imponen dos límites:
 - LC1: Límite en el cual la capa está completamente oxidada
 - LC2: Temperatura a la cual se funde el eutéctico
- Base del modelo:
 - Modelo de oxidación parabólica [6]:

$$\frac{d\delta}{dt} = \frac{A}{\delta} e^{-\frac{B}{T}} \tag{1}$$

Where: δ weight gain/ layer thickness $[kg/m^2 \text{ or } m]$

t time [s]

T temperature [K]

A, B parabolic rate constants

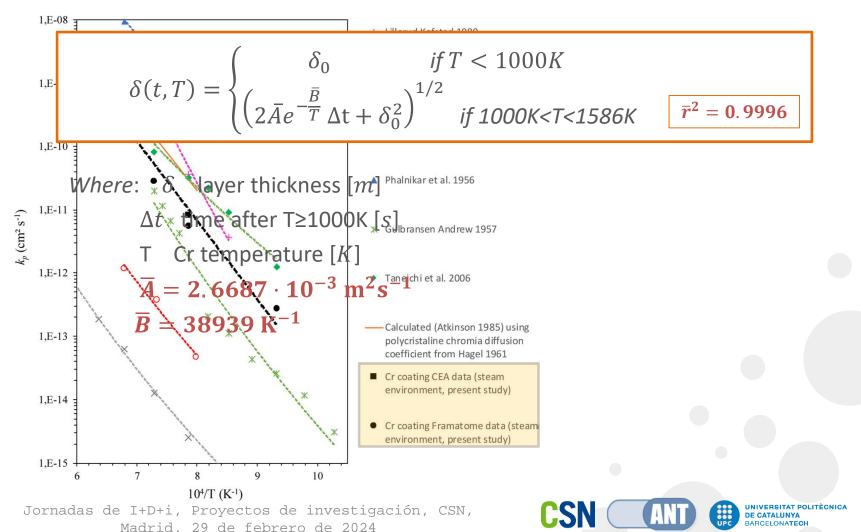






Modelo de oxidación implementado

• Estimación de las constantes parabólicas a partir de datos experimentales de FRAMATOME y CEA [7]





Paso 3

Implementación de un nuevo modelo de oxidación

Paso 4

V&V del nuevo modelo







Implementación y verificación

| Fase | Condiciones | Oxidación del cromo | Oxidación del zirconio | Verif. |
|------|---|---|--|--------|
| #1 | T _{Cr} < 1000K | $\delta_{c_{r_2 o_3}} = w_{c_{r_2 o_3}} = 0$ | $\delta_{c_{r_2o_3}} = w_{c_{r_2o_3}} = 0$ | OK |
| #2 | 1000K ≤ T_{Cr} < 1586K ^(*) , δ_{Cr2O3} < ϵ_1 $t(T_{Cr} \ge 1000K)$ < 1.5h | $\delta_{c_{r_2o_3}}$ Ecuación 1 $w_{c_{r_2o_3}}^c$ Ecuación 2 | Sin oxidación, 0% $\delta_{zr_{o_2}} = 0.0 \cdot \delta_{zr}^{non-coated}$ $w_{zr_{o_2}}^{ro} = 0.0 \cdot w_{zr_{o_2}}^{ron-coated}$ | OK |
| #3 | 1000K ≤ T_{Cr} < 1586K ^(*) , δ_{Cr2O3} < ϵ_1 1.5h < t(T_{Cr} ≥1000K) ≤ 3h | $\delta_{c_{r_2}o_3} = 10 \% \delta_{c_{r_2}o_3(^{\ell_1.5h})}$ $W_{c_{r_2}o_3} = 0 \% W_{c_{r_2}o_3,^{\ell_1.5h}}$ | 10% de la oxidación de Zr sin recubrimiento: $\delta_{z_{r_{o_{2}}}} = 0.1 \cdot \delta_{z_{r_{o_{1}}}}^{non-coated}$ $w_{z_{r_{o_{2}}}}^{r_{o_{2}}} = 0.1 \cdot w_{z_{r_{o_{2}}}}^{rflon-coated}$ | ОК |
| #4 | 1000K ≤ T_{Cr} < 1586K ^(*) , δ_{Cr203} < ϵ_1 t(from T_{Cr} ≥1000K) > 3h | | 25% de la oxidación de Zr sin recubrimiento: $\delta_{z_{r_{o_2}}} = 0.25 \cdot \delta_{non-coated}^{non-coated}$ $w_{z_{r_{o_2}}}^{z_{r_{o_2}}} = 0.25 \cdot w_{z_{r_{o_2}}}^{n\theta n-coated}$ | OK |
| #5 | $\delta_{\text{Cr2O3}} \ge \epsilon_1$ | $w_{c_{r_2 o_3}} = 0$ $\frac{\delta_{c_{r_2 o_3}}}{\frac{dw_{c_{r_2 o_3}}}{dt}} = 0$ | 100% de la oxidación de Zr sin recubrimiento: $\delta_{zr} = \delta_{non-coated}^{non-coated} + \varepsilon_{1}$ $w_{zr_{o_{2}}} = w_{zr_{o_{2}}}^{non-coated} + w_{Cr_{2}O_{3}}(\varepsilon_{1})$ | OK |
| #6 | T _{Cr} ≥1586K | $\delta_{c_{r_2o_3}} = 0 \ w_{c_{r_2o_3}}^{c_{r_2o_3}} = 0 \ rac{dw_{r_2o_3}^{c_{r_2o_3}}}{dt^2} = 0$ | 100% de la oxidación de Zr sin recubrimiento: $\delta_{zr_{O_2}} = \delta_{zr_{O_2}}^{non-coated} + \varepsilon_1 \\ w_{zr_{O_2}} = w_{zr_{O_2}}^{non-coated} + w_{Cr_2O_3}(\varepsilon_1)$ | ОК |







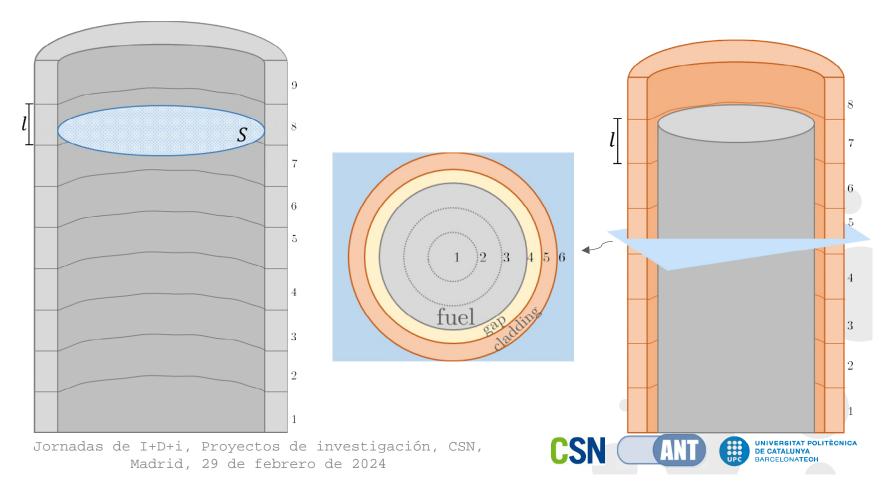
Modelo de verificación

• RELAP input:

- Vertical pipe
- 9 axial volumes
- $-S = 3.685 \cdot 10^{-3} m$

• SCDAP input:

- 8 axial nodes, 5 radial intervals
- 32 fuel rods
- -1 = 0.1143 m
- Decay power: experimental data [10]



Results and discussion

Cases under study, comparing:

Assessment 1. Coating variation with P(LBLOCA) = 39kW

→ Assessment 2. Power variation with 5µm Cr coating

| 2 | Dryout condition | Time after SCRAM | Reactor | Reactor |
|---|------------------|---------------------|-------------|-----------|
| | reached | [s] | Potter [/e] | perior [] |
| | LBLOCA: ~4% | 50 | 4.22% | 3.898E+04 |
| | IBLOCA: ∼2% | 1330 | 2.00% | 1.85E+04 |
| | SBLOCA: ~1.8% | 1930 | 1.80% | 1.66E+04 |
| | 1h | 3600 | 1.47% | 1.36E+04 |
| | 2h | 7200 | 1.21% | 1.12E+04 |
| | 4h | 14400 | 1.00% | 9.21E+03 |
| | 6h | 21600 | 0.89% | 8.27E+03 |
| | 10h | 36000 | 0.78% | 7.23E+03 |
| | 24h | 86400 | 0.61% | 5.60E+03 |
| | 72h | 259200 | 0.45% | 4.13E+03 |



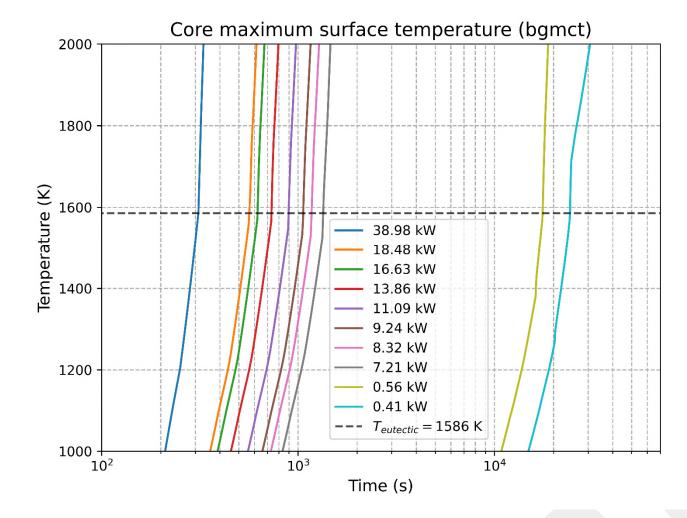




Results and discussion

Assessment 2: power variation

| Power | Tim e required |
|-------|----------------|
| | 1000 to 1586 K |
| (kW) | (m in) |
| 38.98 | 1.7 |
| 18.48 | 3.5 |
| 16.63 | 3.9 |
| 13.86 | 4.6 |
| 11.09 | 5.7 |
| 9.24 | 6.7 |
| 8.23 | 7.4 |
| 7.21 | 8.5 |
| 0.56 | 112.8 |
| 0.41 | 156.2 |









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Proyecto ATF

Paso 5

Paso 6

Exploración de casos frontera entre escenarios DEC-A y DEC-B

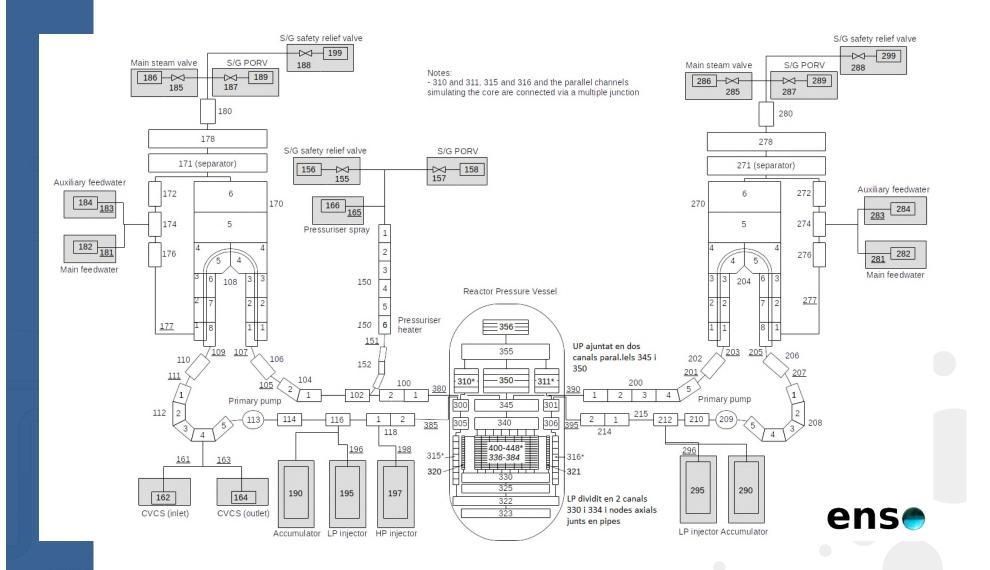
Cuantificación de la oxidación de vaina y estado final de las barras de control







Modelo Westinghouse 4 lazos









State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels

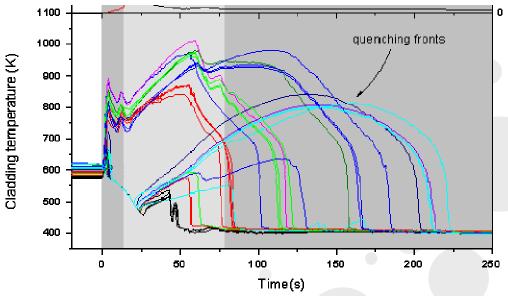
 Buscamos casos frontera donde la temperatura de vaina se encuentra alrededor del límite de diseño por tiempos prolongados:







 Familia de casos LOCA con limitaciones adicionales (DEC)









Conclusiones y próximos pasos

- Nuevo modelo de oxidación de capas cromadas: diseño, y verificación
 - Posible validación con futuros experimentos en DEGREE,
 CODEX y/o QUENCH
 - Exploración de escenarios frontera entre DEC-A y DEC-B
- Próximos pasos:
 - Cálculos con modelo Westinghouse 4-lazos
 - Cuantificación de la generación de hidrógeno con y sin la capa cromada
 - Análisis de la integridad de las barras de control







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