Preliminary Analysis of the QUENCH-19 Test by means of the ASTEC Code

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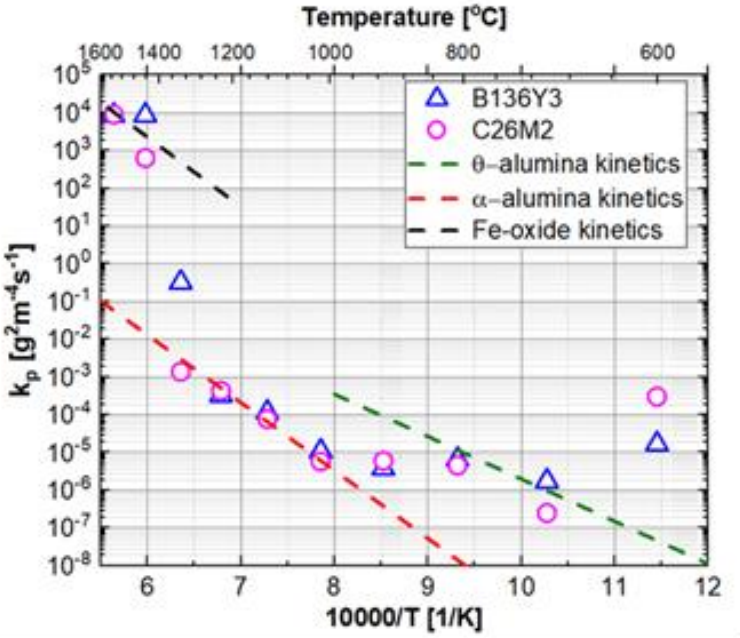
Motivation

- KIT strategy for severe accident (SA) analyses → continuous improvement of the codes to evaluate the radiological consequences of SAs in current and innovative NPPs.
- ATFs have the potential for improving the safety performance of large and integral LWRs during normal/transient operations and SA scenarios.
- **Efforts going on at KIT/INR to extend the ATF-related modelling capabilities (cladding) of the ASTEC code** to enable the safety assessment of the innovative reactor concepts employing such materials.
- Activities triggered by the KIT participation to the OECD/NEA QUENCH-ATF project and the IAEA CRP ATF-TS.
- **Focus on the implementation of the Steam/FeCrAl oxidation laws in ASTEC and analysis of the QUENCH-19 test.**

Modeling New Materials in the ASTEC Code

- User usually employs the data stored in the available material database, i.e. for Zry/ZrO_2
  - Thermo-physical properties.
  - Oxidation models, i.e. Cathcart, Prater-Courtright, Urbanic, Best-fit,..
- ASTEC is flexible enough to introduce new materials either by adjusting the properties of a default material or to fully define behavior and properties by scratch.
- **Approach:**
  - Implementation of the Steam/FeCrAl oxidation laws provided by the Quench experimental team in the ASTEC database (v2.2_b employed)
  - Same approach for KANTHAL APM

ASTEC: FeCrAl Oxidation Model



- **Fitting functions for weight gain provided by J. Stuckert (IAEA CRP ATF-TS)**

$$K = \begin{cases} 9.62 \times 10^{-12}\,[\mathrm{g^2/cm^4 s}], & T \leq 1473\ \mathrm{K} \\ A_B \exp\left(\frac{-E_B}{RT}\right), & 1473 < T < 1648\ \mathrm{K} \\ A_{Fe} \exp\left(\frac{-E_{Fe}}{RT}\right), & T \geq 1648\ \mathrm{K}\ (melting\ point\ of\ FeO) \end{cases}$$

A_B=3·10^9 g^2/cm^4 s **E_B=594354 J/mol**

A_{Fe}=2.4·10^6 g^2/cm^4 s **E_{Fe}=352513 J/mol**

C. KIM, C. TANG, M. GROSSE, M. STEINBRUECK, C. JANG, Y. MAENG, „OXIDATION KINETICS OF NUCLEAR GRADE FeCrAl ALLOYS IN STEAM IN THE TEMPERATURE RANGE 600-1500°C”, TopFuel 2021.

ASTEC: FeCrAl Oxidation Model

- Modifying the laws for oxygen mass gain in the database.
- **Assumptions:**
  - **No information on the oxide thickness growth (similar law as mass gain used)**
  - **Δh of Zr employed**

$$m_o(t+dt) = S.\left(\left(\frac{m_o(t)}{S}\right)^{\frac{1}{model}} + AGAIN.e^{\frac{-BGAIN}{R.T}}dt\right)^{model}$$

$$e_{Zro2}(t+dt) = \left((e_{Zro2}(t))^{\frac{1}{model}} + ATHIC.e^{\frac{-BTHIC}{R.T}}dt\right)^{model}$$

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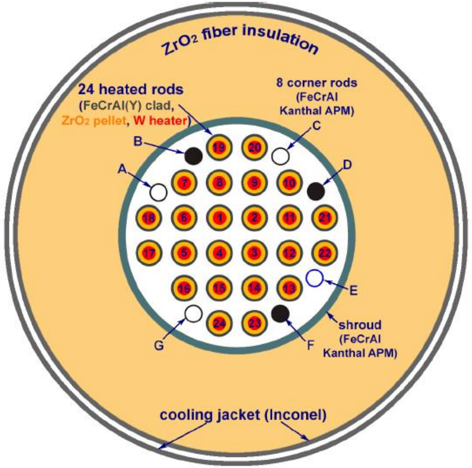
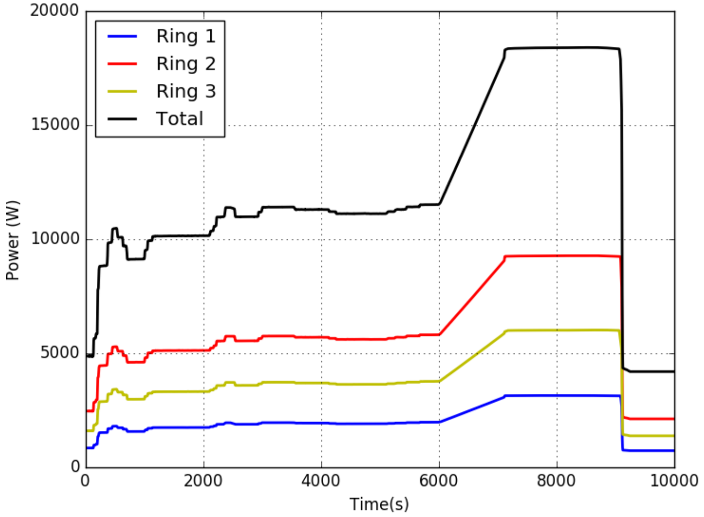
…..
STRUCTURE MODEL NAME 'BEST-FIT' LAW 'COEFF' VARIABLE 'T' VUNIT 'K' RUNLOW 0. RUNUPP 5000.
  SRG VALUE AGAIN 9.62D-10 BGAIN 0.0 ATHIC 2.252D-13 BTHIC 0.0 MODEL 0.5 TERM
  X  1473.K
  SRG VALUE AGAIN 3.0D+11 BGAIN 5.94354D5 ATHIC 3.371D3 BTHIC 5.94354D5 MODEL 0.5 TERM
  X  1648.K
  SRG VALUE AGAIN 2.4D+08 BGAIN 3.52513D5 ATHIC 0.008682D0 BTHIC 3.52513D5 MODEL 0.5 TERM
 END
```

QUENCH-19 Test Conduct

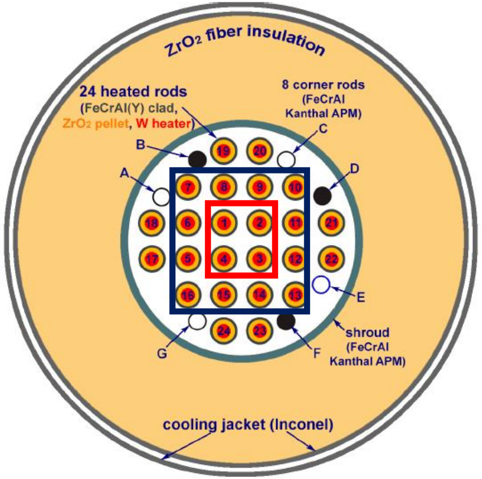


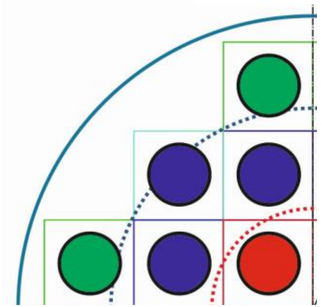
Phase 1: heating up to ~600 °C (4 kW).
Phase 2: power increase up to 11.5 kW (pre-oxidation).
Phase 3: power increased up to 18.12 kW (5 W/s) (T_{pct}~1500 °C).
Phase 4: power reduced to 4.1 kW.



- Atmosphere of Ar (3.45 g/s) and superheated steam (3.6 g/s).
- Reflooding at ~9100 s
  - Fast initial injection of 4 kg of water
  - Slow injection 48 ~ g/s of water

ASTEC Model of the QUENCH-19 Test

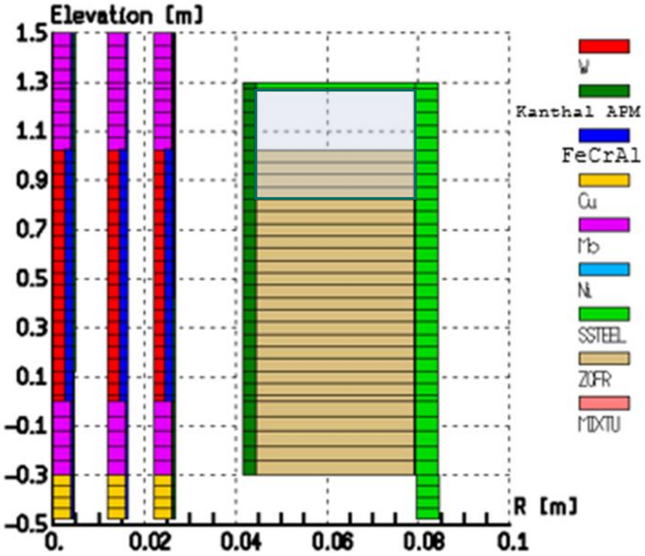




Ch. 3, 8 rods, r_{ext}= 41.5 cm

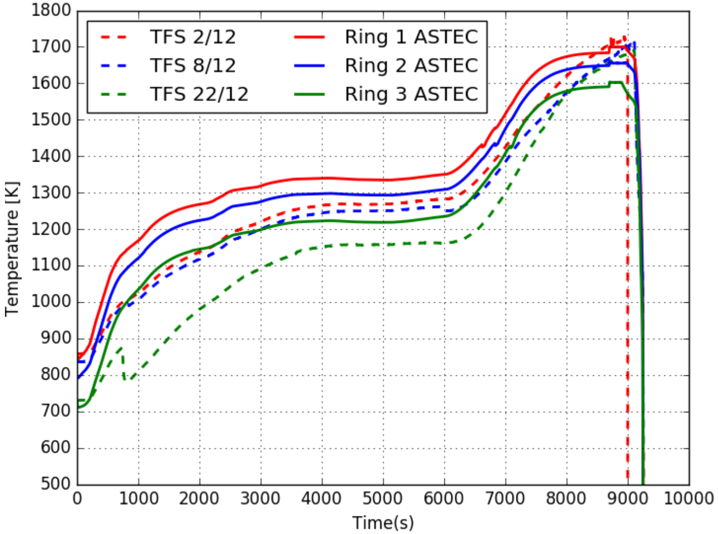
Ch. 2, 12 rods, r_{ext}= 28.4 cm

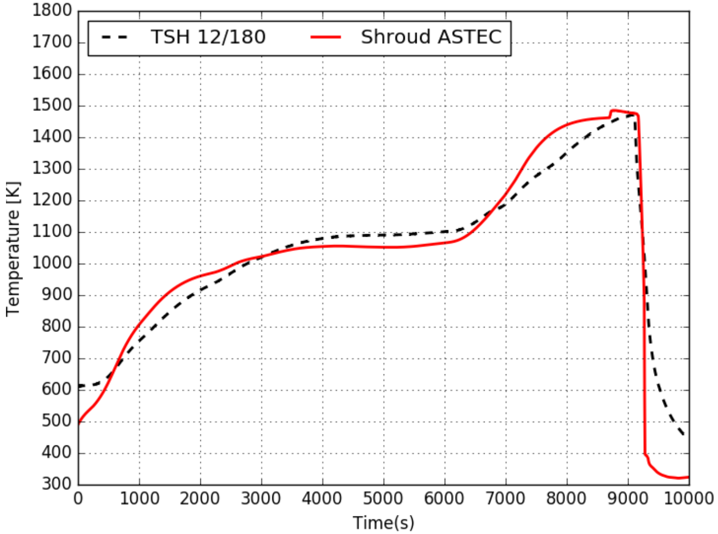
Ch. 1, 4 rods, r_{ext}=14.2 cm



- Accidental presence of 4 l water the gap between the shroud and the cooling jacket modelled (J. Stuckert).

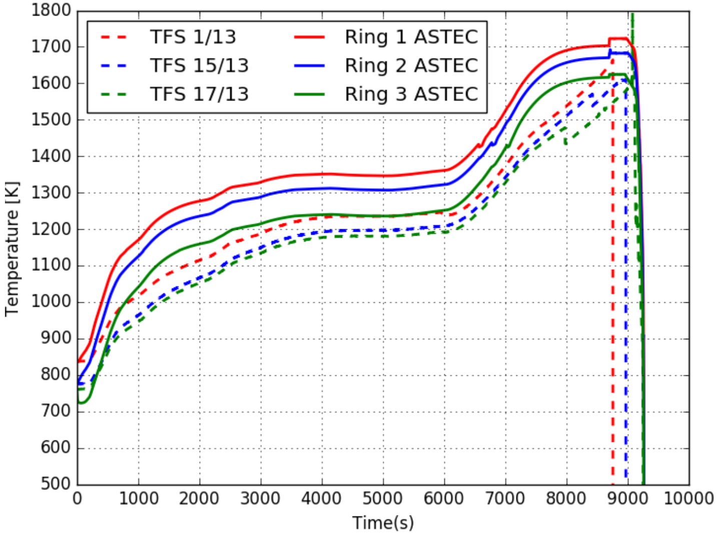
Results: Clad and Shroud Temp. @850 mm Height

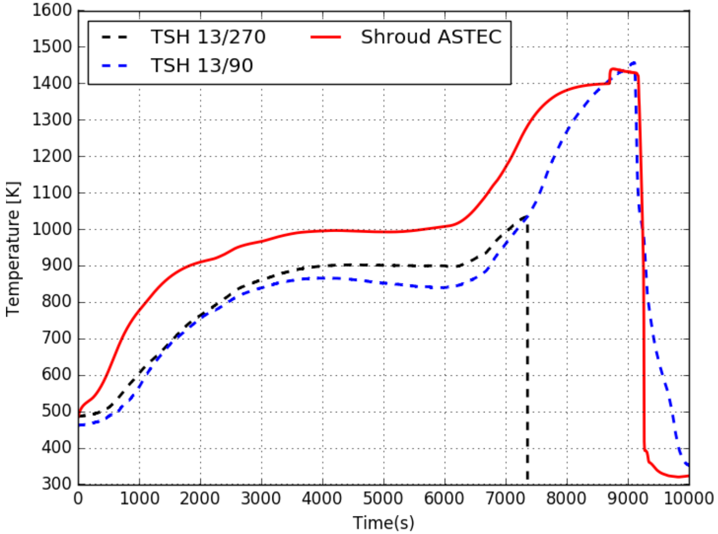




- **Clad**
  - Results exceed the exp. of about 100 degree in the pre-oxidation phase in Ring 1.
  - Better agreement in Ring 2 and 3.
  - Max. temperatures reasonably well reproduced in Ring 1 and 2 (deviation of ~ 100 degree in Ring 3).
- **Shroud**
  - Experimental results reasonably well reproduced.

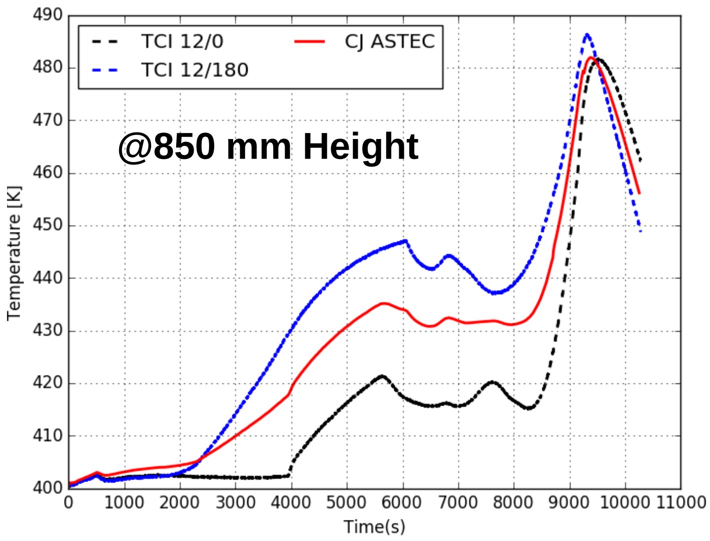
Results: Clad and Shroud Temp. @950 mm Height

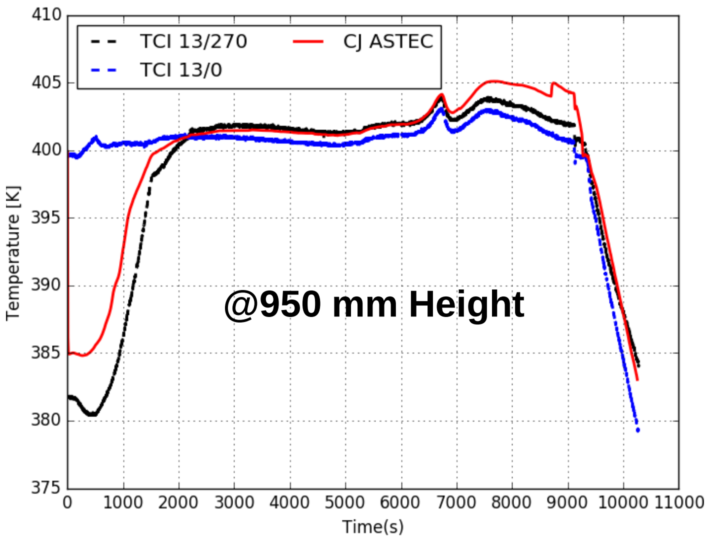




- **Clad**
- Results exceed the exp. of about 100 degree in the pre-oxidation phase in Ring 1 and 2.
- Better agreement in Ring 3.
- Max. temperature reasonably well reproduced in Ring 1 and 3 (deviation of ~ 100 degree in Ring 2).
- **Shroud**
- Results exceed the exp. of about 100 degree in the pre-oxidation phase.
- Max. temperature reasonably well reproduced.

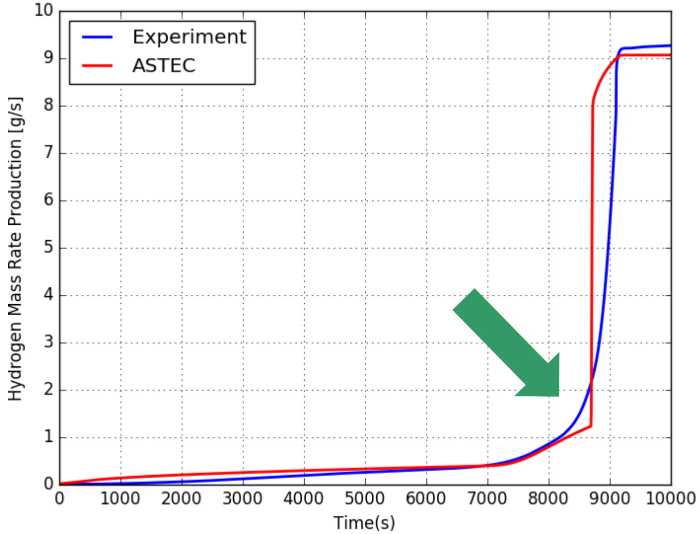
Results: Cooling Jacket Temperature

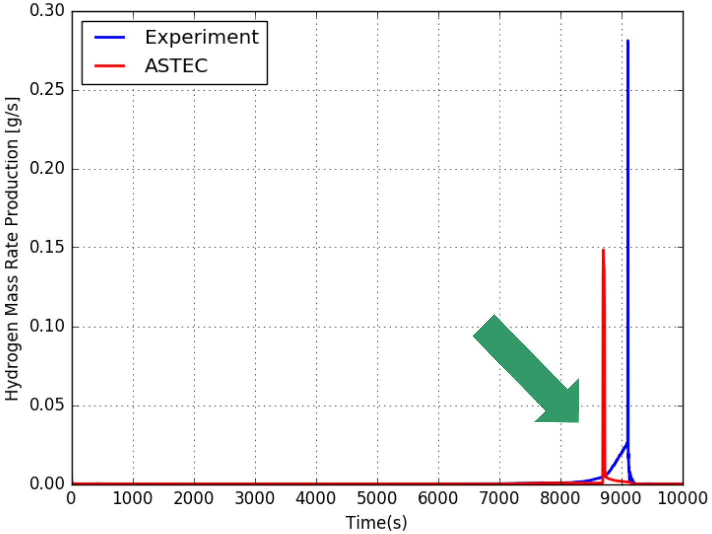




➢ **Experimental results reasonably well reproduced.**

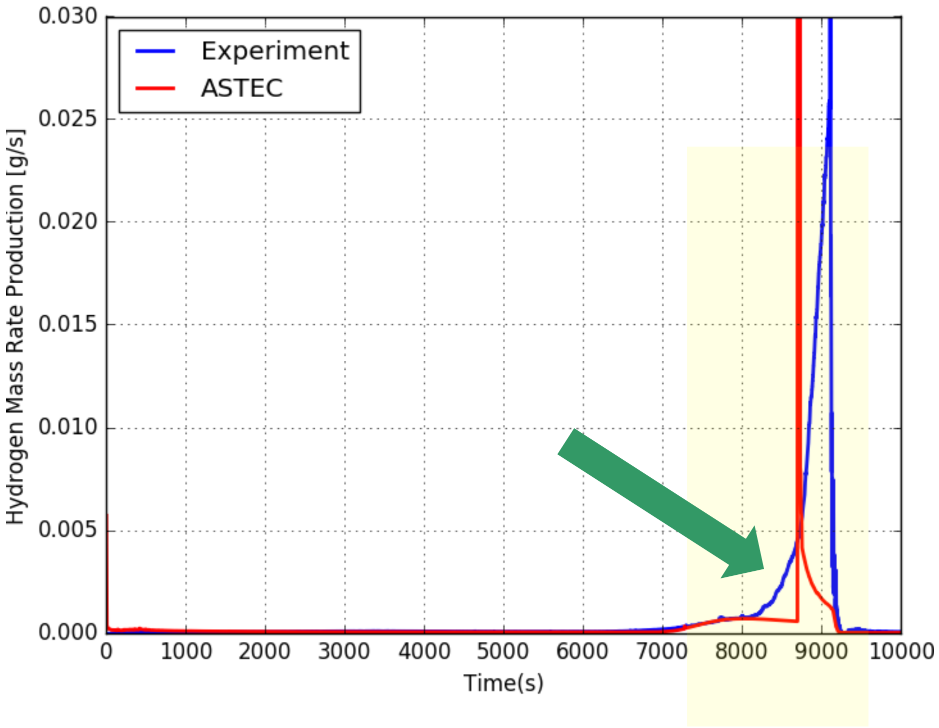
Results: Hydrogen Production





- **The final amount of H2 is reasonably well reproduced.**
- ASTEC results show a good agreement with exp. up about 8000 s.
- Escalation is anticipated in time with about 50% of the mass rate compared with the exp.
- **Transition to the escalation is not well reproduced.**

Results: Hydrogen Production



- ‘Smooth’ kinetics behavior is not reproduced.
- **Updating of the model related to the oxide thickness gain may improve the ASTEC vs. exp. agreement.**

Conclusion

- Efforts are going on to extend the capabilities of the ASTEC to model the ATFs.
- The Steam/FeCrAl oxidation laws implemented in the material database of the code (v2.2_b).
- The QUENCH-19 test has been analyzed
- **Overestimation of the clad temperatures (~100 degree) and acceptable agreement on the radial profile**
- **Acceptable ASTEC/Exp. agreement concerning the shroud temperatures**
- **H_2 generation** – ASTEC vs. Exp.
  - **Total amount reasonable well reproduced**
  - **The kinetics of the escalation is not well predicted**
- **Outlook**
  - **Refinement of the oxide thickness law necessary.**
  - **Participation to the OECD/NEA benchmark (blind phase) on ATF-1 experiment.**