IMPLEMENTATION OF ACCIDENT TOLERANT FUELS IN MELCOR: STABILITY, PERFORMANCE, AND LIMITATIONS

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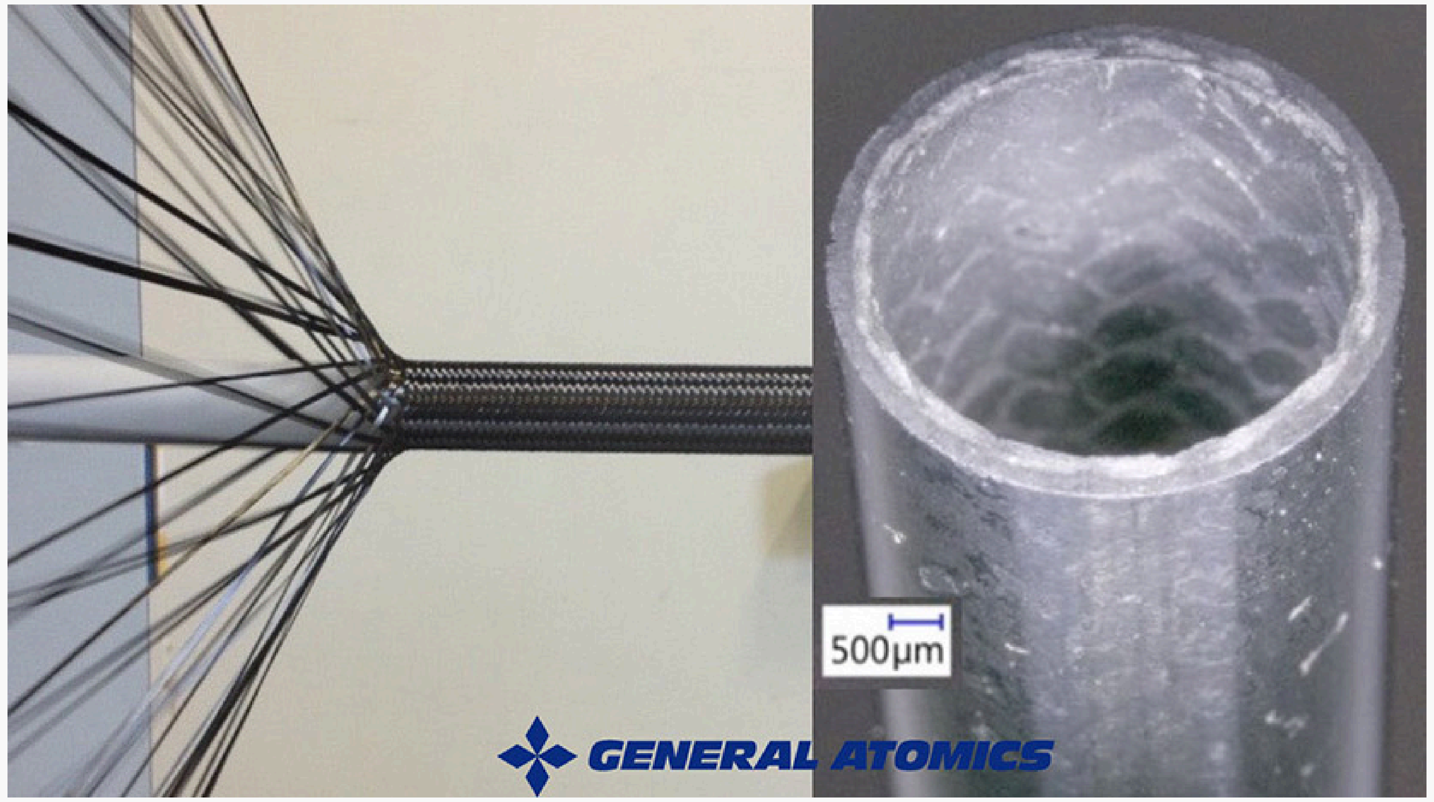
CONTENTS

INTRODUCTION TO ATF



- **Short term** - Coated Zirconium alloys (Framatome, KNF,...)
  - Separate coating material (component) not applicable in MELCOR
  - “hybrid” of Zirconium alloy and coating material with oxidation properties of the coating
- **Long term** - New cladding materials
  - **SiC** (Framatome, General Atomics)
  - **FeCrAl** (Oak Ridge National Laboratory)

IMPLEMENTATION

ATF cladding implemented to MELCOR as a User Defined Material in pair of **material - oxide**

01 Thermophysical properties

Enthalpy, specific heat, thermal conductivity - models based on publicly available data - NIST JANAF, articles

02 Oxidation models

Oxidation models and kinetics defined under Generalized Oxidation Modelling

Reaction equations based on observed reactions with **steam**, oxidation kinetics parameters (Arrhenius correlation) derived from experiments in high-pressure environments

- $SiC + 3H_2O \rightarrow SiO_2 + 3H_2 + CO$

- $3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$
- $2Cr + 3H_2O \rightarrow Cr_2O_3 + 3H_2$
- $2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$

$$\frac{\mathrm{d}W^n}{\mathrm{d}t} = k_{p,H_2O} \cdot \exp\left(-\frac{E_a}{R \cdot T}\right)$$

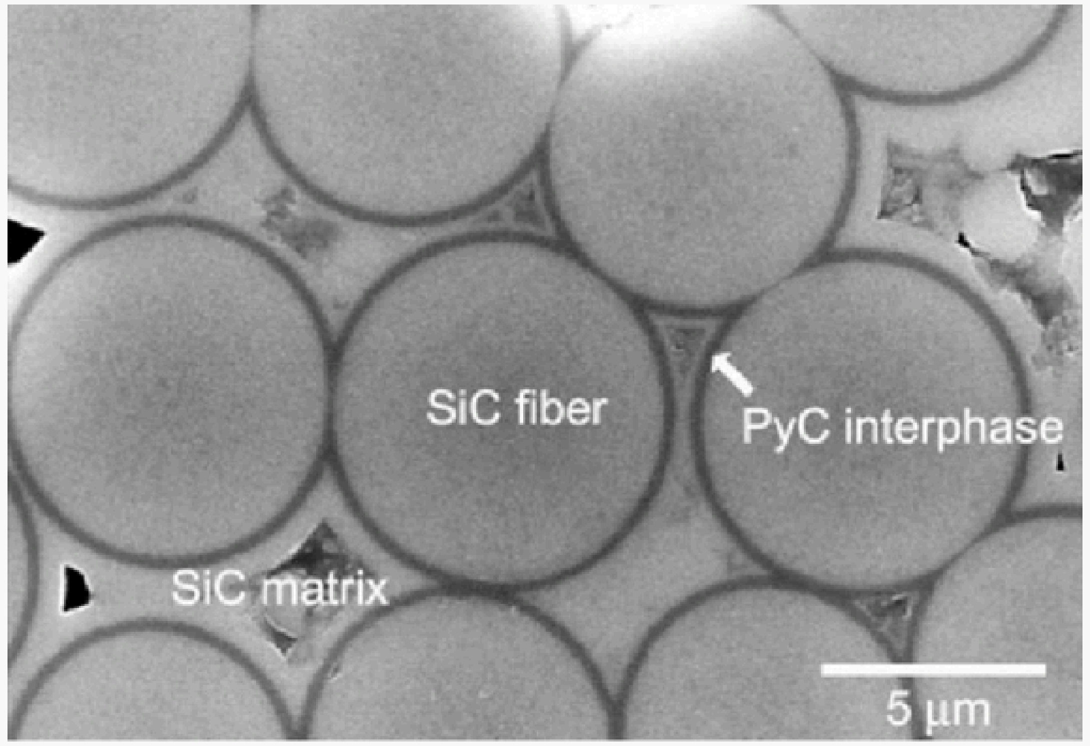
Material	$k_{p,H2O}$	E_a	n
SiC	0,03424	248000	1
FeCrAl	0,5213	260000	2
Zircaloy	87,9	138096	2

ASSUMPTIONS

01 SiC

Assumed as a fully dense material
- SiC cladding designs employ composite structures (SiC-SiC) - fibre winded rods with CVI method - improved mechanical properties over monolithic SiC, material properties are dependent on direction and location

Huge variance in thermal conductivity data
- design, production methods, purity and intended use



02 FeCrAl - C35M

C35M alloy is composed of 6 elements

Formation of FeCrAl-ox of 3 compounds
- Oxides formed from the alloy – Fe_3O_4, Cr_2O_3 and Al_2O_3
- Exact oxidation kinetics is not publicly available, replaced with Kanthal APMT kinetics

BEHAVIOUR AND STABILITY DURING SIMULATIONS

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

01 Encountered issues

ENERGY ERROR in COR package

Convergence problems - FeCrAl - complex oxidations and melting

- Time step reduction down to 0,5E-12, step cycling

02 Measures

Time step reduction

Multiple oxidation kinetics models

Interpolation and extrapolation of thermophysical properties outside of MELCOR

LIMITATIONS OF ATF MODELLING

Handling of complex oxidations - FeCrAl

- Thermophysical properties pre-defined with respect to oxidation kinetics
  - Each oxide formation depends on temperature and exposure time
  - Change in formation can't impact the defined OXIDE composition (FeCrAl-ox)

- Oxidation of complex alloys leads to formation of oxide mixture
  - FeCrAl oxidation leads to formation of multiple oxide layers that prevent further oxidation - protective mechanism

Oxides formed can't be further volatilized

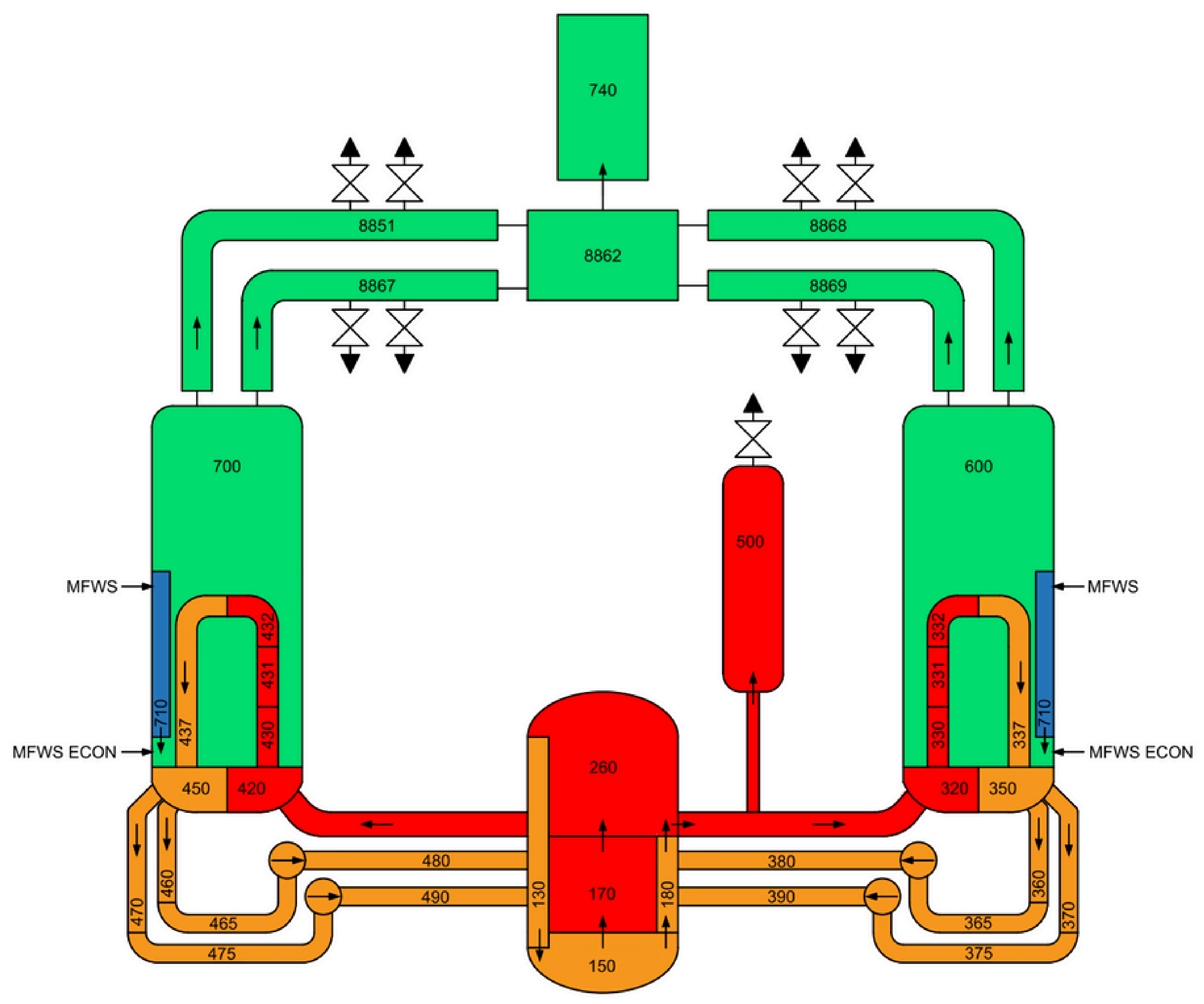
- Limits the analysis of SiC oxidation
  - SiO_2 is further volatilized in steam environment to $Si(OH)_4$

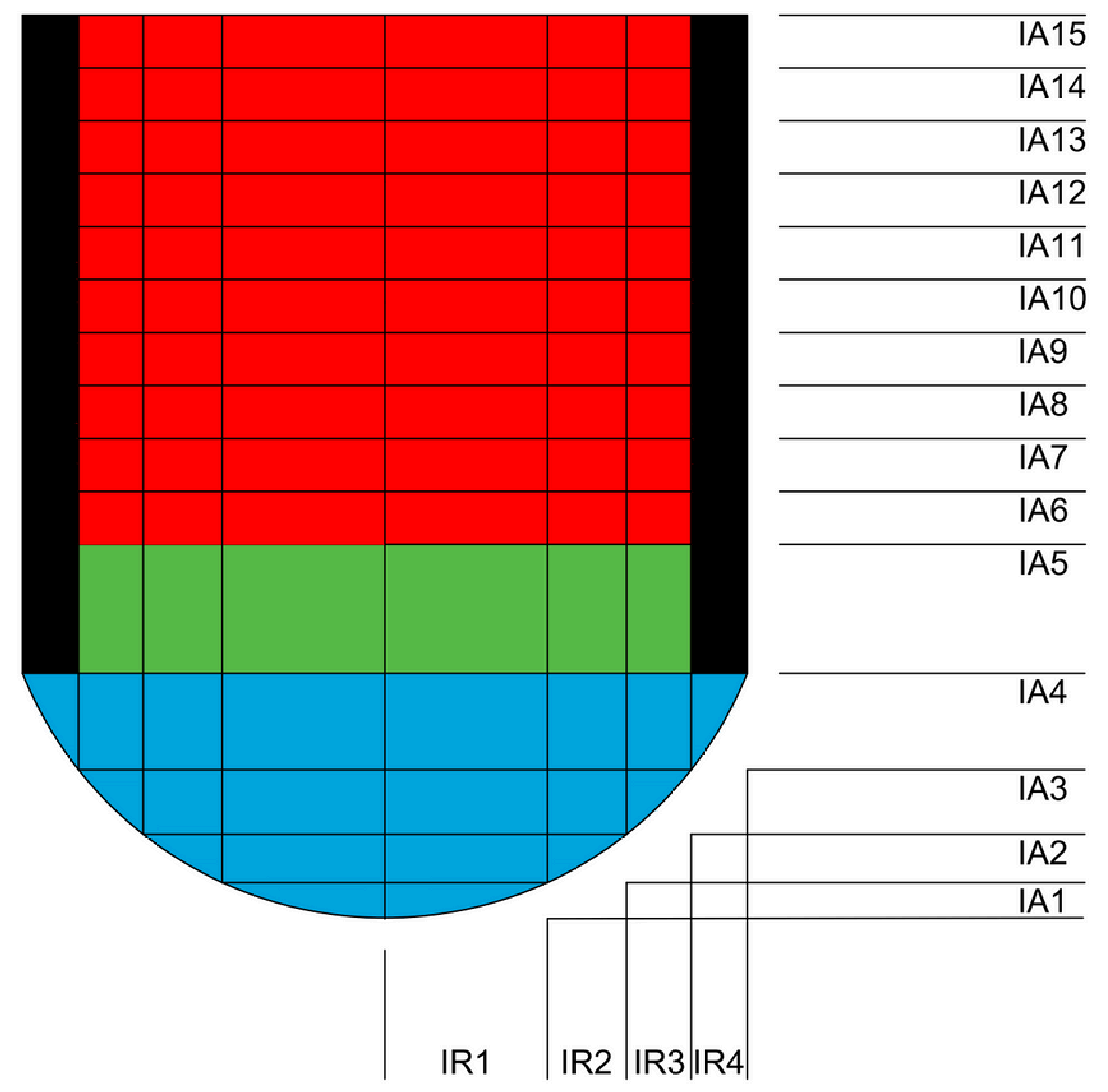
Eutectic behaviour is not available for UDM

No sublimation modelling - SiC vaporizes at high temperatures

PLANT MODEL

Based on APR1400 reactor design ~4000 MWt



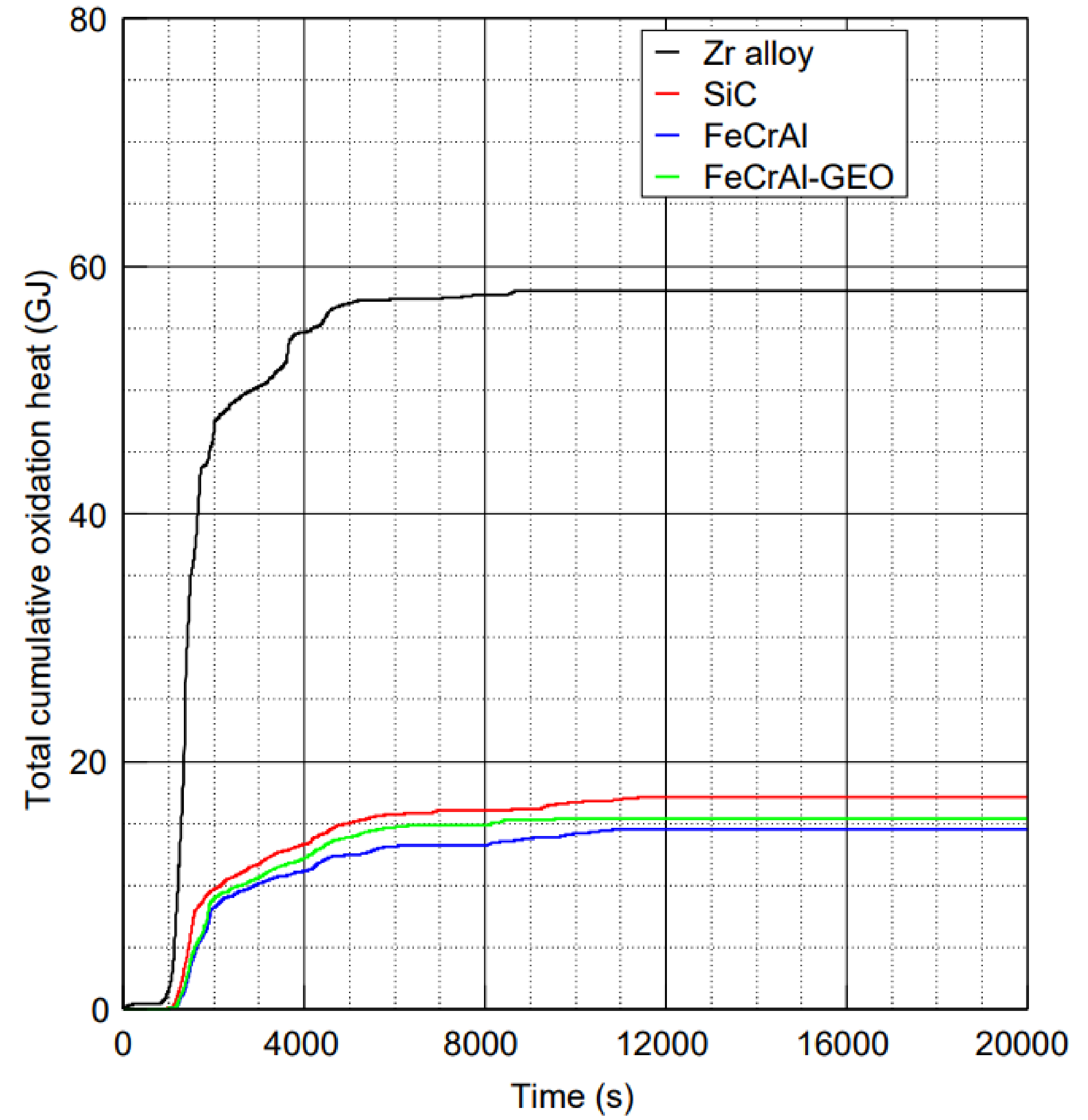


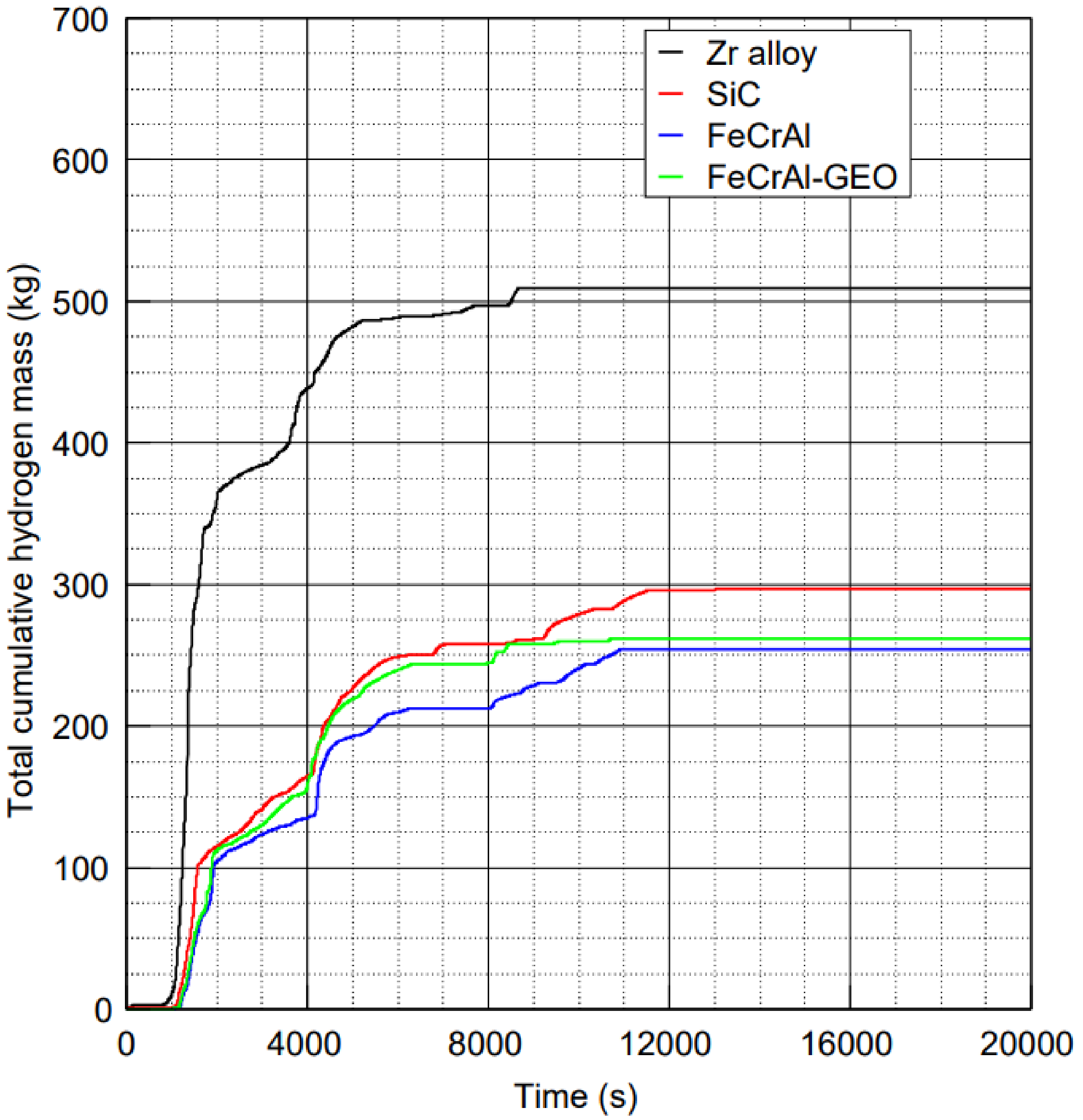
RESULTS - r2024.0.0

Unmitigated LB LOCA

Significant decrease of oxidation heat and hydrogen produced

- Slower oxidation kinetics of both ATF materials



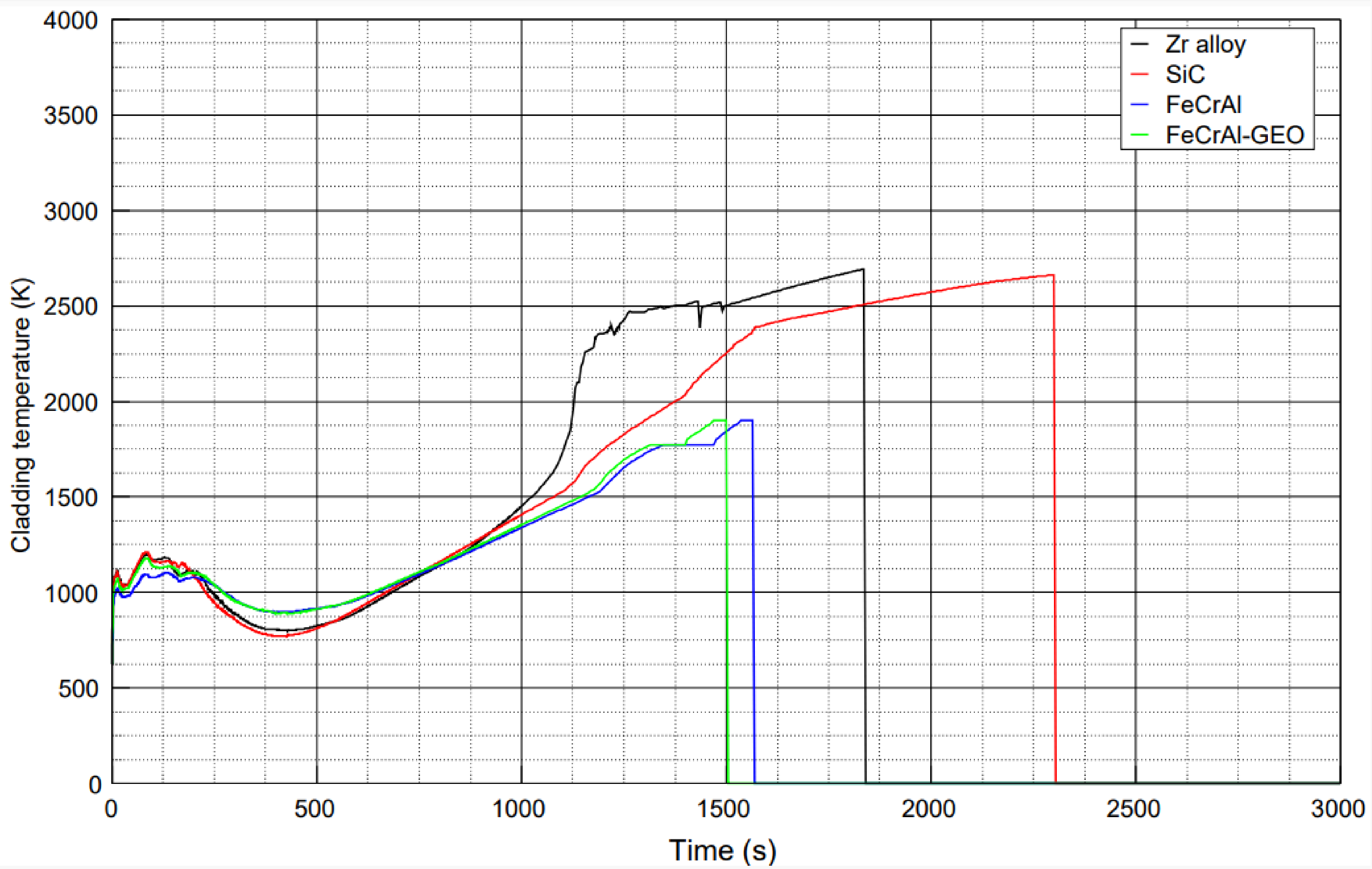


RESULTS - r2024.0.0

Unmitigated LB LOCA

Longest time to first clad failure of SiC
- Highest thermal conductivity and melting point (~3000 K)
- Fuel melts before clad - cell failure from damage function

Shortest time to first clad failure of FeCrAl
- Lowest melting point (~1773 K)



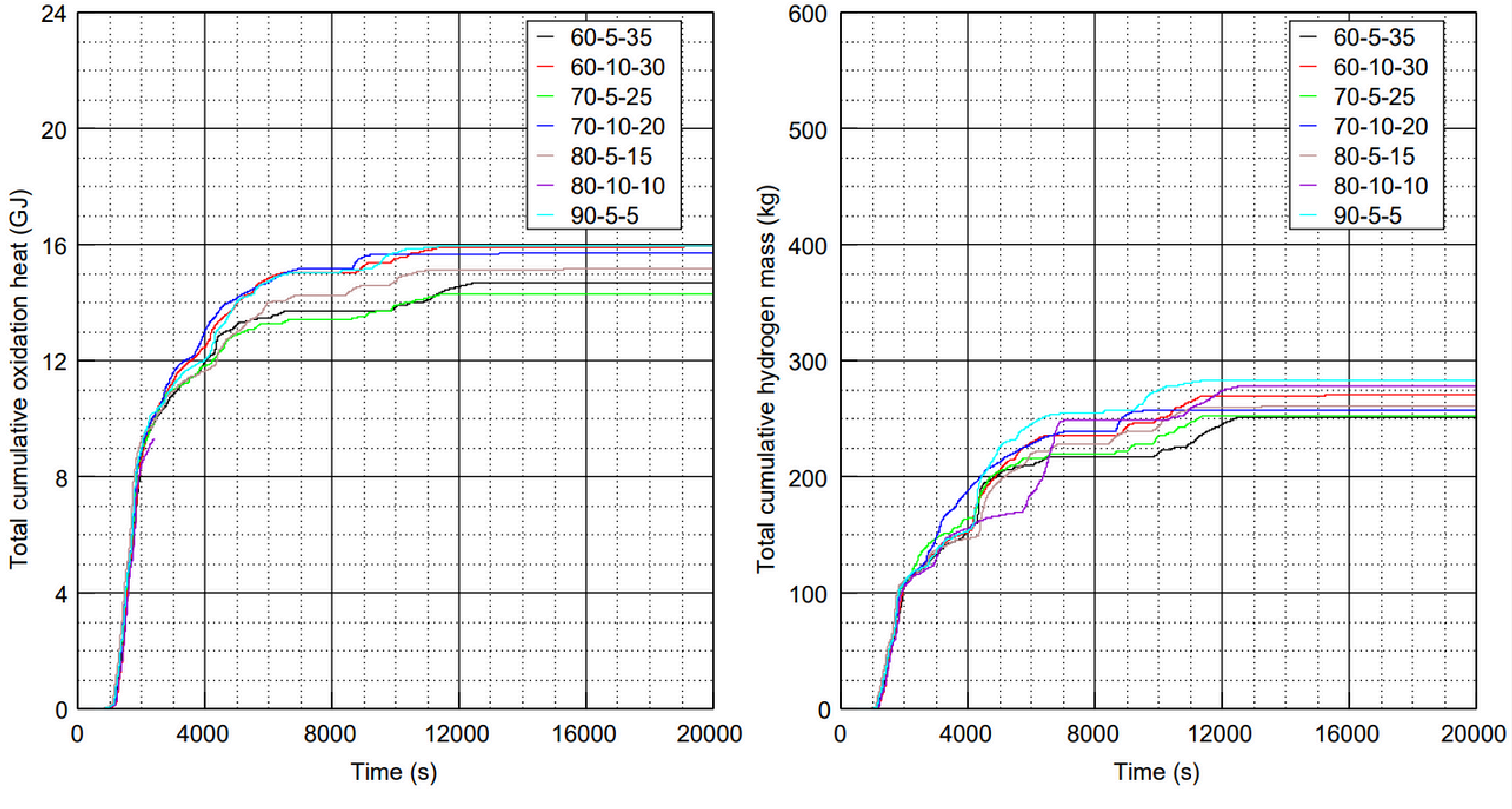
RESULTS - r2024.0.0

Unmitigated LB LOCA

Sensitivity study of oxide formation

- Defined oxide properties based on wt. % - adjusted kinetics to respect the preassumed formation
- Composition in plots is as: Al_2O_3 - Cr_2O_3 - Fe_3O_4

Increased Al_2O_3 formation leads to higher amount of oxidation heat and hydrogen released

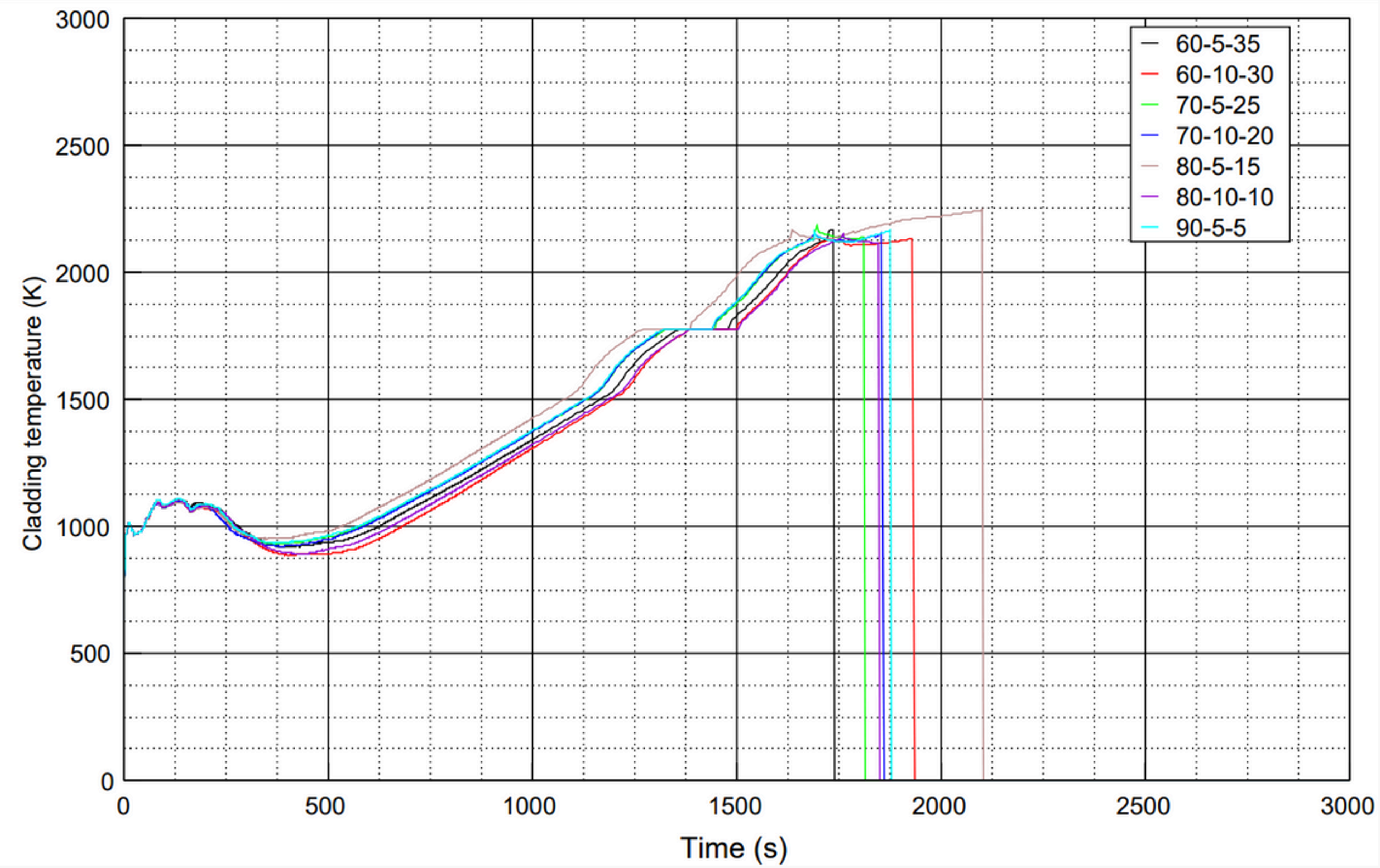


RESULTS - r2024.0.0

Unmitigated LB LOCA

Thermophysical properties of oxide formed close to those of Al_2O_3

- Higher thermal conductivity



FUTURE PLANS

Materials models revision - implementation of recent findings and use of new MELCOR capabilities

APR1400 model revision

- Use of advanced B4C model
  - Issues with B4C oxidation (no heat release or combustible gases production) - QUENCH 07-09
- Finer CORE nodalization

Modelling of “hybrid” cladding

Modelling of High density uranium

THANK YOU!!