# *Analysis of Accident Tolerant Fuel Using RELAP5-3D*

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# *Outline*

- LWRS/RISA/ERP Project

- Near-term ATF Technology

- ERP-RA methodology

- RELAP5-3D code M&S

- Application to PWR SBO

- Conclusions

# *LWRS/RISA/ERP Project*

- US DOE Light Water Reactor Sustainability Program (LWRS) – Risk-Informed Safety Analysis (RISA) – Enhanced Resilient Plant (ERP) is a multi-years effort led by INL for better **characterize the safety margins** of the existing US LWR fleet

  – Use RISA methodology and tools

  – Scope: enhance existing reactors **active** and **passive** safety features

  – Ultimate goal: **increase LWR economics and reliability**

- First step of LWRS/RISA/ERP: study the effects of introduction of near-term Accident Tolerant Fuel (ATF)

# Near-term ATF Technology 1/2

- Several ATF technological options being developed: $U_2Si_3$, Cr-doped $UO_2$, SiC clads, Cr-coated clads, FeCrAl clads, metallic fuel

- Near-Term ATF: to be introduced in the reactor cores during the next refueling outages (first half of 2020s) by several US electric utilities

- Two technologies investigated by LWRS/RISA/ERP:

  - FeCrAl clad + $UO_2$: clad alloy of Fe, Cr, Al (69/21.6/4.9 weight%)

  - Chromium-coated clad + $UO_2$: coating of tens of um of Zr-clad with Chromium

# *Near-term ATF Technology 2/2*

- Both FeCrAl and Cr-coated clads should provide superior resistance to oxidation by steam at high temperatures

  – reduce the risk of fuel failures

  – reduce $H_2$ production during accidental transients

  – provide some extra coping time



- Several experiments being carried out in the USA (ATR, ORNL, etc.) for better characterizing the properties of these new materials

- Need to quantify the risk reductions and the safety margin improvements
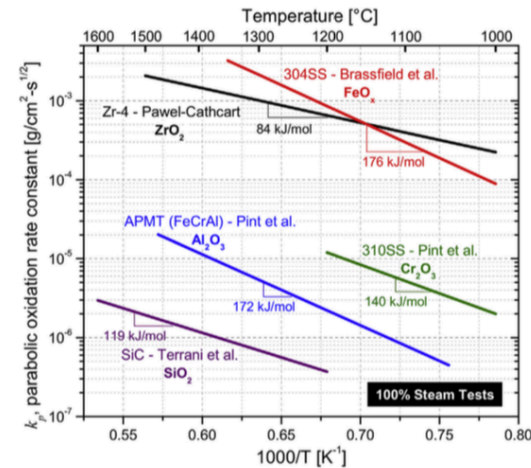
# *ERP-Risk Analysis methodology*

- ERP-Risk Analysis (RA) methodology uses state-of-the-art computer codes to perform **integrated deterministic-probabilistic** analysis

- Starting from a base PRA model, quantify the ΔCDF and ΔLERF derived from the proposed NPP enhancement

- SBO and LBLOCA analyzed in FY2018

- Different PRA methodologies (Dynamic and Classical PRA) and tools used (RAVEN, SAPHIRE)

- RELAP5-3D constitutes the workhorse for the system TH analyses



**ERP-RA application**
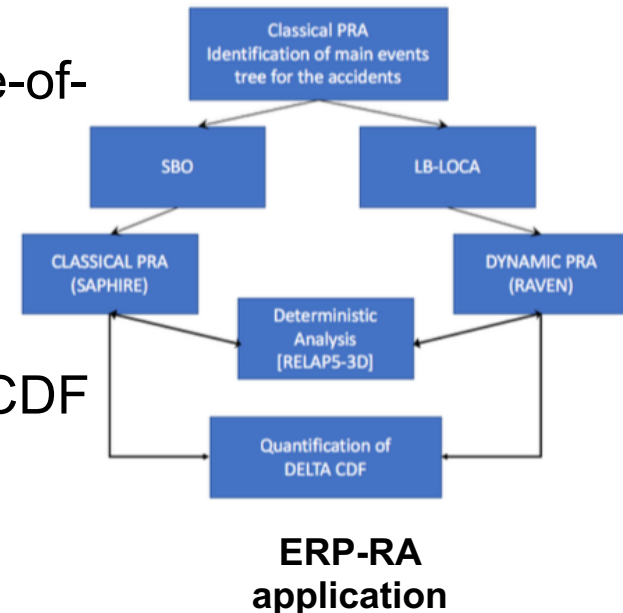
# RELAP5-3D Modeling & Simulation

- SBO simulations until core damage by RELAP5-3D → imply modeling of the early phases of the fuel damage

- Need of modifications to RELAP5-3D metal-water reaction model, in order to correctly study the near-term ATF clads

- RELAP5-3D metal-water reaction model is allowing calculation of one (generic) oxidation reaction
  - Card 1CCCG003 (metal-water) to be modified
  - 1CCCG001 (gap conductance) + 1CCG011 (Gap deformation) to be used

- ATF challenges:
  - Two/three different **oxidation reactions** possible
    - FeCrAl and Cr-coating reactions
    - Fe reaction (above a threshold temperature)
    - Zr (internal surface of clad-coated)

# *RELAP5-3D Modeling & Simulation*

- RELAP5-3D metal-water reaction based on a correlation developed by

  Cathcart et alii, 1977

$$\Delta r^{n+1} = \left[ (\Delta r^n)^2 + (K\Delta t)e^{-(\Delta E/RT)} \right]^{1/2}$$

  - $\Delta t$ time step size
  - $K$ reaction rate constant
  - $\Delta E$ activation energy
  - $R$ gas constant
  - $T$ is clad temperature

- Amount of heat added ($Q$) to the clad surface

$$Q = \rho\pi \left[ (r_o - \Delta r^n)^2 - (r_o - \Delta r^{n+1})^2 \right] \frac{H}{W}$$

  - $r_0$ initial radius of unreacted clad
  - $H$ reaction heat release
  - $W$ molecular weight of cladding
  - $\rho$, clad density

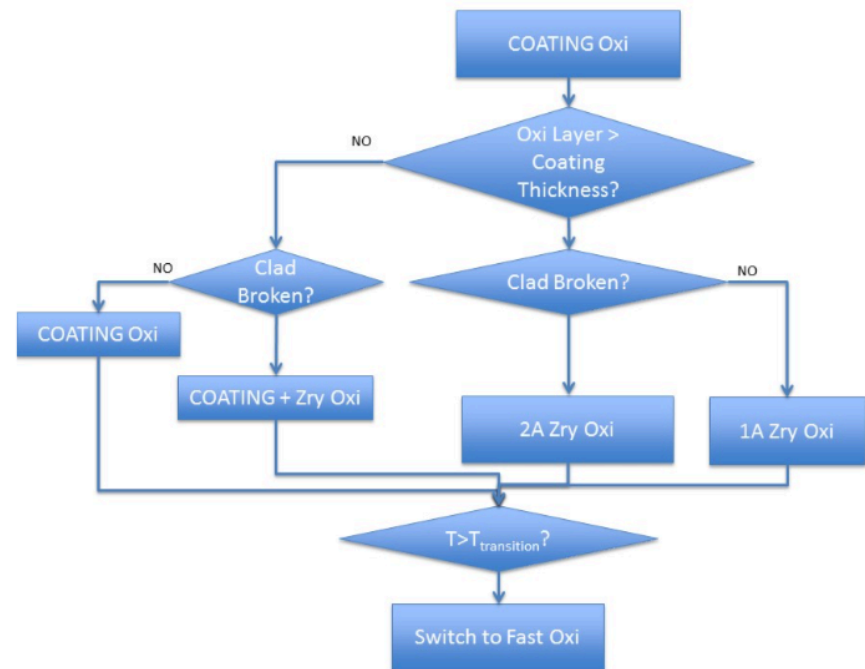# RELAP5-3D Modeling & Simulation

- Possible oxidation reactions
  - FeCrAl:  $2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2 + 67.3 \text{ MJ/kg mole}$
  - Chromium-coated:  $2Cr + 3H_2O \rightarrow Cr_2O_3 + 3H_2 + 64.84 \text{ MJ/kg mole}$
  - Iron Oxidation above 1773 K
  - Zr Oxidation

- Introduction of special "ATF cards" in RELAP5-3D input deck
  - 1CCCG002 (for coating)
  - 1CCCG005 (for high temperature reaction)
  - Words structures similar to 1CCCG003

- Modification of RELAP5-3D logic for taking into account possible clad ruptures



**RELAP5-3D Logic Path for the ATF Metal-Water Reaction Model**

# RELAP5-3D Modeling & Simulation

- INL-Generic PWR (IGPWR) defined for SBO analysis

- Main Characteristics:
  - 3 Loop PWR / NSSS by Westinghouse
  - Core average power: 2546 $MW_{th}$ [855 $MW_e$]
  - Core: 157 FA [15x15 Westinghouse FA]
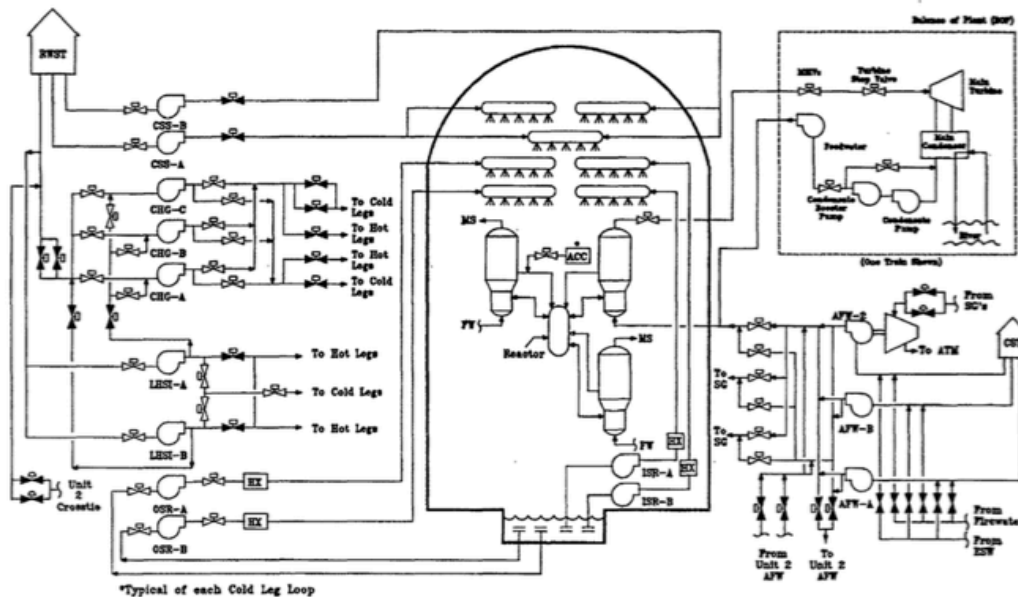


**IGPWR ESF**

| Parameter | Value (SI units) | Value (British units) |
|---|---|---|
| Core Power [$MW_{th}$] | 2,546 | |
| Reactor Inlet / Outlet Temperature [°C / °F] | 282 / 319 | 540/ 606 |
| Number of Fuel Assemblies | 157 | |
| Rod Array | 15x15 | |
| RCS Coolant Flow [kg/s / $lb_m$/hr] | 12,738 | 101.6E+8 |
| Nominal RCS Pressure [MPa /psia] | 15.5 | 2,250 |
| MCP seal water injection [$m^3$/s / gpm] | 3.78E-3 | 8 |
| MCP seal water return [$m^3$/s / gpm] | 1.42E-3 | 3 |
| MCP Power [MW / hp] | 5.22 | 7,000 |
| Number of SG | 3 | |
| PRZ PORV set points op./clos. [MPa / psig] | 16.2 / 15.7 | 2,350 / 2,280 |
| PRZ PORV capacity [kg/s / $lb_m$/hr] | 2 x 22.5 | 2 x 179,000 |
| PRZ SV set points op./clos. [MPa / psig] | 16.4 / 17.7 | 2,375 / 2,575 |
| PRZ SV capacity [kg/s / $lb_m$/hr] | 3 x 37.0 | 3 x 293,330 |
| Relief Tank Rupture Disc capacity [kg/s / $lb_m$/hr] | 113.4 | 9.0E+5 |
| Relief Tank Rupture Disc set point op. [MPa / psid] | 6.89 | 1000 |
| Relief Tank Total Volume [$m^3$ / $ft^3$] | 36.8 | 1300 |
| Relief Tank Water Volume [$m^3$ / $ft^3$] | 25.5 | 900 |
| SG PORV capacity [kg/s / $lb_m$/hr] | 1 x 47.0 | 1 x 3.73E+5 |
| SG PORV set points op./clos. [MPa / psig] | 7.24 / 6.89 | 1,050 / 1,000 |
| SG SV capacity [kg/s / $lb_m$/hr] | 5 x 94.0 | 5 x 7.46E+5 |
| SG SV set points op./clos. [MPa / psig] | 8.16 / 7.53 | 1,184 / 1,092 |
| Secondary Pressure [MPa / psia] | 5.49 | 796 |
| Secondary Side Water Mass @ HFP [kg / $lb_m$] | 41,639 | 91,798 |
| SG Volume [$m^3$ / $ft^3$] | 166 | 5,868 |

# *RELAP5-3D Modeling & Simulation*

- Modeling of the Primary/Secondary side
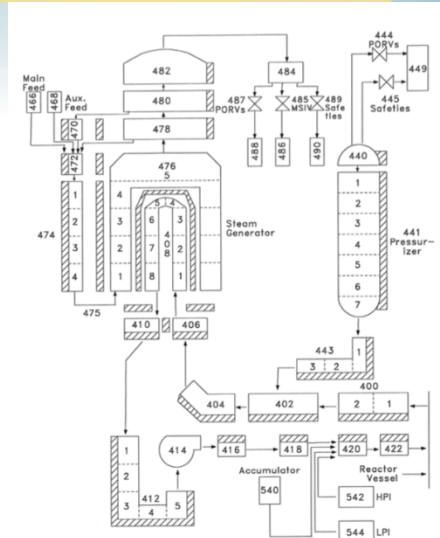
    - **Primary System**

        - RPV, 3 main circulation circuits (SGs, MCPs, HLs and CLs, PRZ)
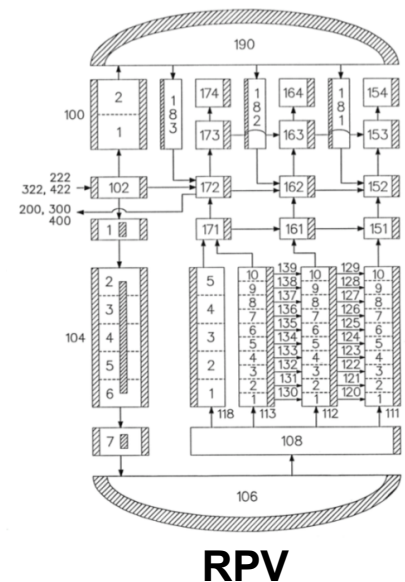
    - **Secondary side**

        - Steam Lines until MSIV, MFW/AFW inlet

    - **Core configuration**

        - 3 hydraulic channels connected with junctions (cross flow simulation) →representing 3 different core zones: central, middle and outer core zones [different power]

**Primary/Secondary side**

**RPV**

# RELAP5-3D Modeling & Simulation

- RELAP5-3D parameters for Fuel Clads

| Parameter | Clad Type | | |
|---|---|---|---|
| | Zry | Cr-coated | FeCrAl |
| Reaction Rate Constant ($m^2$ Metal/s) | 9.166E-7 | 1.409E-5 | 2.444E-5 |
| Reaction Heat Release (J/Kg mole) | 5.94E+8 | 6.48E+7 | 6.73E+7 |
| Activation Energy (cal/mole) | 35,890 | 66,890 | 82,218 |
| Clad Density ($kg/m^3$) | 6,500 | 7,190 | 6,860 |
| Clad thickness ($\mu m$) | 617 | 617 | 309 |
| Clad coating thickness ($\mu m$) | N/A | 20 | N/A |
| Gas Gap thickness ($\mu m$) | 95 | 95 | 95 |
| Pellet outer radius (mm) | 4.6469 | 4.6469 | 4.9555 |
| Fuel pin outer radius (mm) | 5.3594 | 5.3594 | 5.3594 |

- Failure Criteria for different Transients, for SBO looking to the maximum clad damage

| Clad Type | Failure Criteria | |
|---|---|---|
| | LB-LOCA | SBO |
| Zircaloy | PCT>1477 K | PCT>2100 K |
| ATF - FeCrAl | PCT>1804 K | PCT>1804 K |
| ATF - Cr | PCT>1804 K | PCT>1804 K |

# *RELAP5-3D Modeling & Simulation*

- RELAP5-3D provisions for SBO analysis

  - Creep Model: Larson-Miller model added via dedicated control-variables for major components (CL, HL, PRZ surge line)

  - Special Control Logic for operator actions and main events

| Procedure/Event | RELAP5-3D Control Logic |
|---|---|
| SGs depressurization | Start at t=+5,400 s (+1.5 hr), depressurize and cool-down with 100 F/hr (~55 C/hr) rate |
| Battery depletion | Selected by the safety analyst (4-8 hr). Disable TD-AFW injection and SG/PRZ PORVs |
| TD-AFW black-start | Restart TD-AFW and SG PORVs |
| Feed & Bleed on Secondary Side | Inject water from the ECST and bleed steam via SG PORVs. Keep the SGs depressurized at 0.923 MPa. Stop if ECST water or batteries are depleted. |
| Kerr pump injection on the primary side | Inject ~ 4 Kg/s of borated water from RWST after successful primary side depressurization. Injection continuing until: $P_{primary} <= 2.0$ MPa. |
| ECCS injection | HPI/LPI + Recirculation mode if AC available. Accumulators injection if $P_{primary} < 4.0$ MPa |
| MCP Seal LOCA | 21-480 gpm, depending on the transient |

# *Application to SBO analysis*

- Analysis started from SAPHIRE code generic PWR PRA model for SBO

  - Start with Loss-of-Offsite Power (LOOP) event

    - 888 sequences

    - Further reduced and regrouped in **four** SBO sub-events trees (304 sequences) → Total CDF: 8.21E-7/year

    - Grid related sequences identified + very low probability sequences removed → 15 main SBO sequences to be studied by RELAP5-3D

# *Application to SBO analysis*

- Example of SAPHIRE PRA model
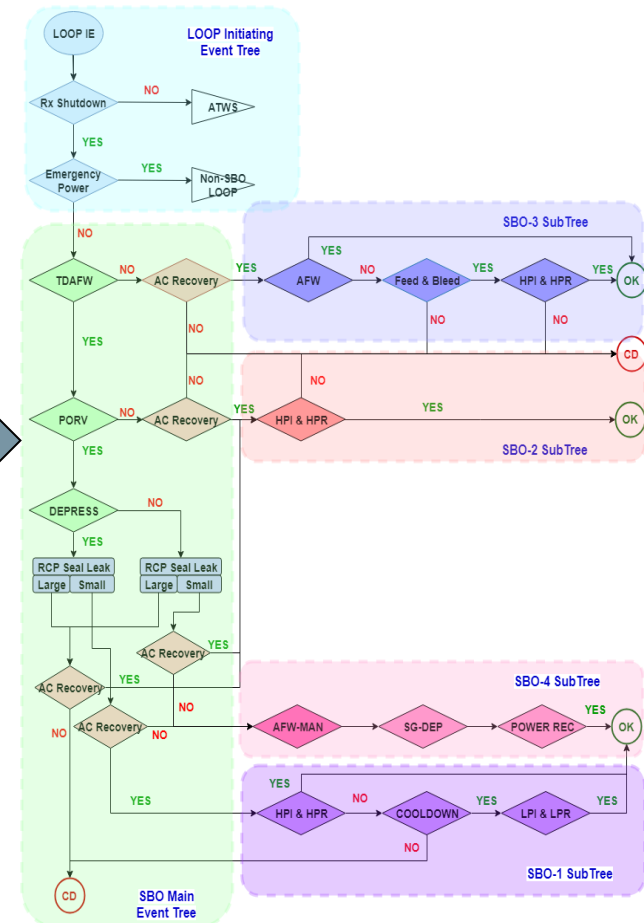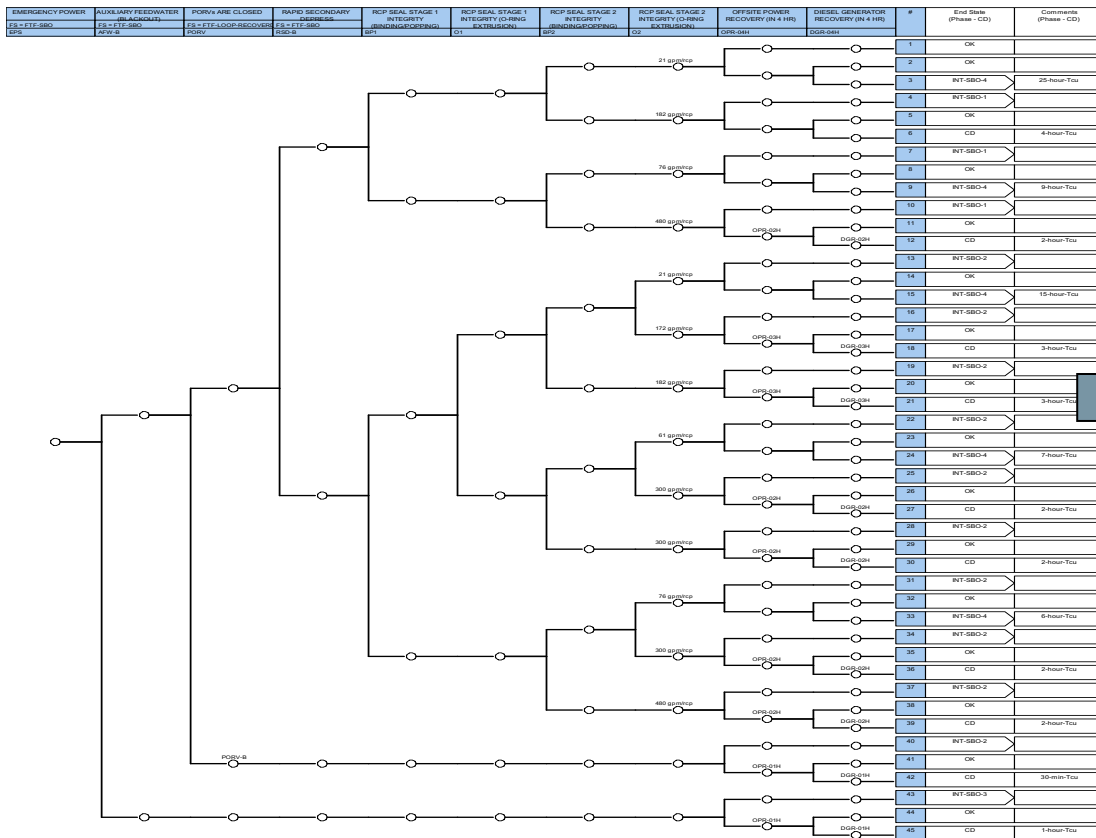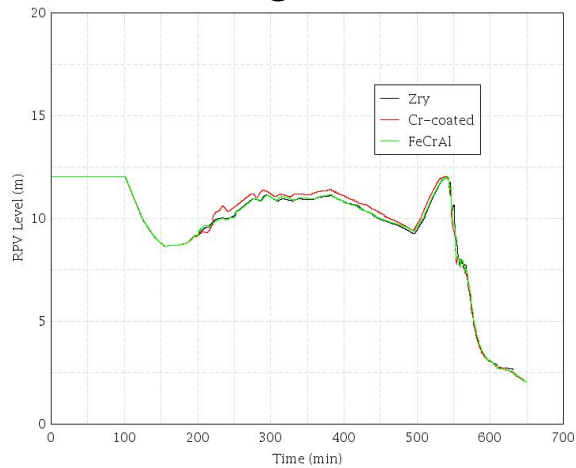
# *Application to SBO analysis*

- **15 Grid-related SBO sequences**

| R5-3D Scenario | Scenario Boundary Conditions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TD AFW availability | PRZ PORV Closed | Rapid Secondary Side Depressurization | RCP seal LOCA | AC Power recovery | Recovery Actions | | |
| SBO-1.0 | YES | YES | RSD | 21gpm/RCP | 4Hrs No | No AFW-MAN | | |
| SBO-1.2 | YES | YES | RSD | 21gpm/RCP | 4Hrs No | AFW-MAN | No SG Depre. | No Late OPR |
| SBO-2.0 | YES | YES | RSD | 76gpm/RCP | 4Hrs No | No AFW-MAN | | |
| SBO-2.2 | YES | YES | RSD | 76gpm/RCP | 4Hrs No | AFW-MAN | No SG Depre. | No Late OPR |
| SBO-2.3 | YES | YES | RSD | 76gpm/RCP | 4Hrs Yes | HPI | Cooldown | No LPR |
| SBO-3.0 | YES | YES | RSD | 182gpm/RCP | 4Hrs No | | | |
| SBO-3.1 | YES | YES | No RSD | 182gpm/RCP | 3Hrs No | | | |
| SBO-3.3 | YES | YES | RSD | 182gpm/RCP | 4Hrs Yes | HPI | Cooldown | No LPR |
| SBO-4.0 | YES | YES | RSD | 480gpm/RCP | 2Hrs No | | | |
| SBO-4.3 | YES | YES | RSD | 480gpm/RCP | 2Hrs Yes | HPI | Cooldown | No LPR |
| SBO-5.1 | YES | YES | No RSD | 300gpm/RCP | 2Hrs No | | | |
| SBO-6.0 | YES | NO | NA | NA | 1Hr No | | | |
| SBO-6.3 | YES | NO | NA | NA | 1Hr Yes | HPI | No HPR | |
| SBO-7.0 | NO | NA | NA | NA | 1Hr No | | | |
| SBO-7.3 | NO | NA | NA | 300gpm/RCP | 1Hr Yes | AFW | No HPI | |

- Batteries for TD-AFW and SG PORV valve actuations assumed to last 4 hrs maximum

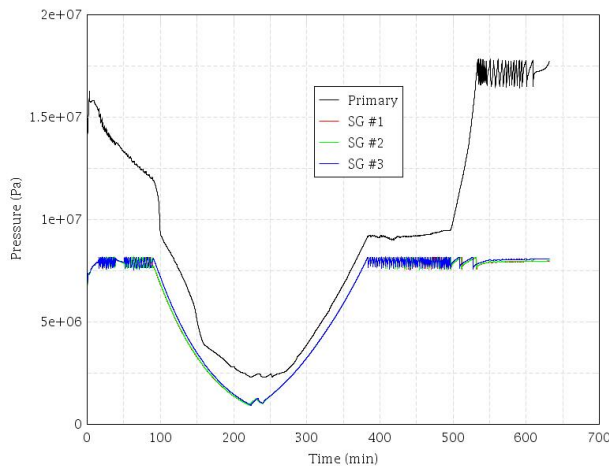# *Application to SBO analysis*
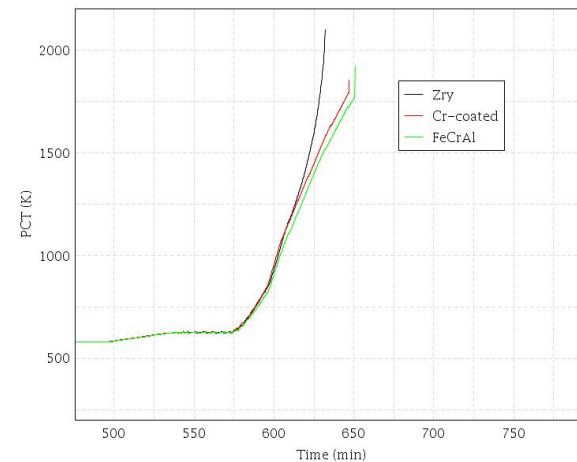
- Sequence 1.0, Long Term-SBO (~ 10.5 hrs)
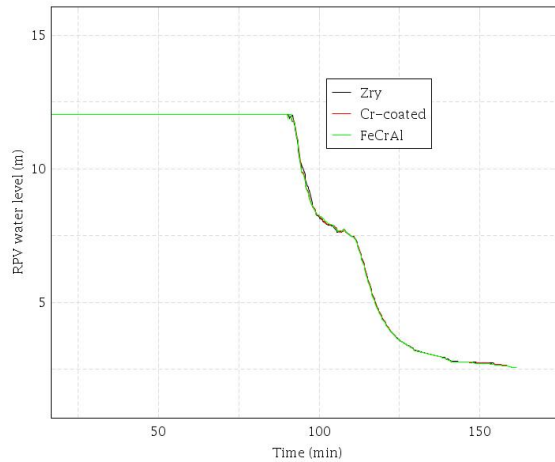


RPV level
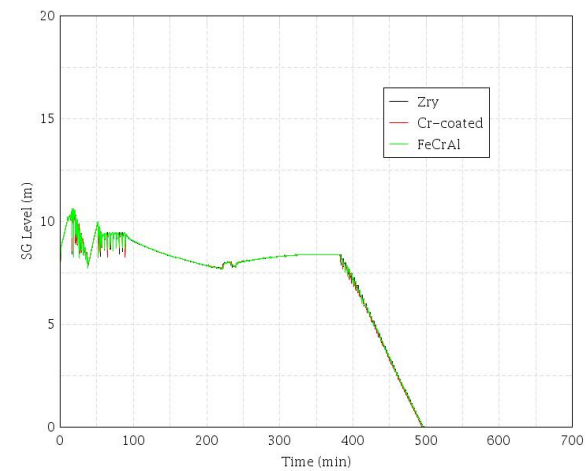


SG1 level



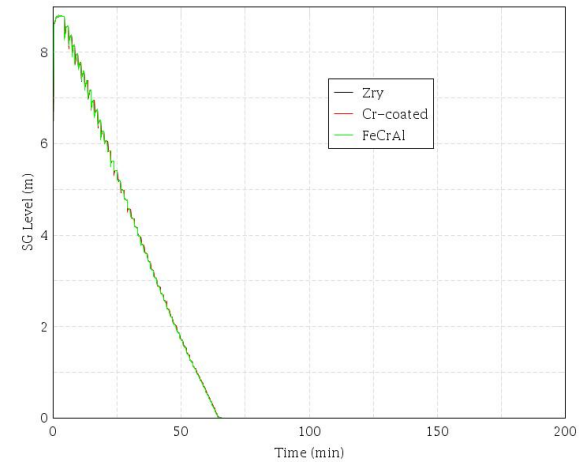System pressures



PCT trend

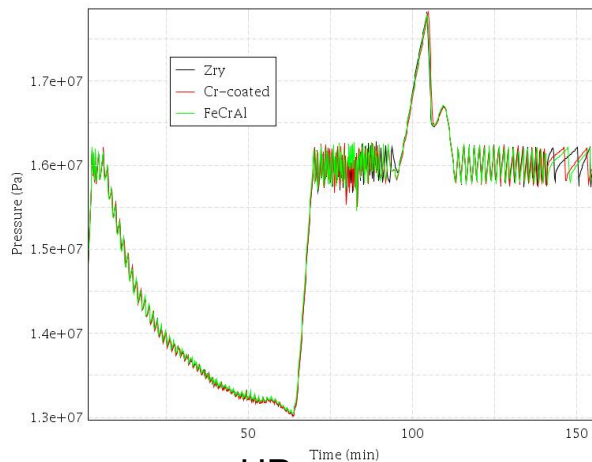# *Application to SBO analysis*

- Sequence 7.0, Short Term-SBO (~2.5 hrs)
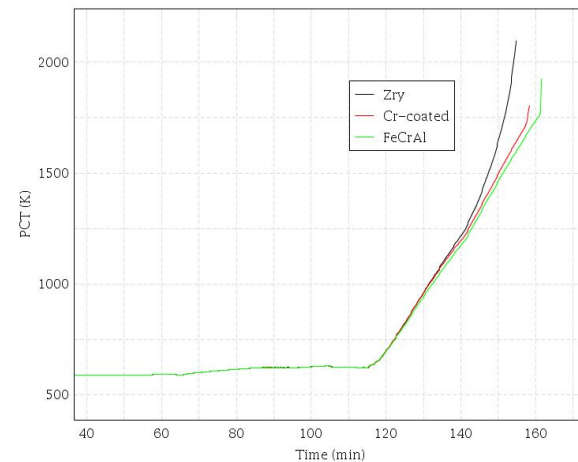


RPV level



SG1 level



UP pressure



PCT trend

# *Application to SBO analysis*

- Summary of SBO scenarios w/o AC Power Recovery - Zry vs FeCrAl
  - Time to core damage
  - Timing of 0.5 Kg $H_2$ production

| | Scenario Description | | | | Time to Core Damage $t_{CD}$ (hh:mm) | | | Timing of 0.5 Kg H2 production tH2 (hh:mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Zry | FeCrAl | Δt | Zry | FeCr Al | Δt |
| SBO-1.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 21 gpm | 10:32 | 10:51 | 0:19 | 10:01 | 10:45 | 0:44 |
| SBO-1.3 | TDAFW runs 8 hrs | PORV Closed | Depress. | 21 gpm | 15:40 | 16:49 | 1:09 | 15:02 | 15:35 | 0:51 |
| SBO-2.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 76 gpm | 10:17 | 10:36 | 0:19 | 9:45 | 10:31 | 0:46 |
| SBO-3.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 182 gpm | 10:22 | 10:43 | 0:21 | 9:48 | 10:37 | 0:49 |
| SBO-3.1 | TDAFW runs 4 hrs | PORV Closed | No Depress. | 182 gpm | 7:10 | 7:26 | 0:16 | 6:47 | 7:23 | 0:36 |
| SBO-4.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 480 gpm | 5:25 | 5:46 | 0:21 | 5:10 | 5:46 | 0:36 |
| SBO-5.1 | TDAFW runs 4 hrs | PORV Closed | No Depress. | 300 gpm | 4:42 | 4:51 | 0:03 | 4:26 | 4:51 | 0:25 |
| SBO-6.0 | TDAFW runs 4 hrs | PORV Opened | NA | 21 gpm | 1:16 | 1:23 | 0:07 | 1:07 | 1:23 | 0:16 |
| SBO-6.1 | TDAFW runs 4 hrs | PORV Opened | Depress. | 21 gpm | 5:19 | 5:40 | 0:21 | 1:17 | 5:40 | 4:23 |
| SBO-7.0 | No TDAFW | NA | NA | 21 gpm | 2:35 | 2:41 | 0:06 | 2:11 | 2:39 | 0:28 |

# *Application to SBO analysis*

- Summary of SBO scenarios w/o AC Power Recovery - Zry vs Cr-coated
  - Time to core damage
  - Timing of 0.5 Kg $H_2$ production

| | | | | | Time to Core Damage $t_{CD}$ (hh:mm) | | | Timing of 0.5 Kg H2 production tH2 (hh:mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario Description | | | Zry | Cr-coated | Δt | Zry | Cr-coated | Δt |
| SBO-1.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 21 gpm | 10:32 | 10:47 | **0:15** | 10:01 | N/A | **N/A** |
| SBO-1.3 | TDAFW runs 8 hrs | PORV Closed | Depress. | 21 gpm | 15:40 | 15:55 | **0:15** | 15:02 | N/A | **N/A** |
| SBO-2.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 76 gpm | 10:17 | 10:29 | **0:12** | 9:45 | N/A | **N/A** |
| SBO-3.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 182 gpm | 10:22 | 10:30 | **0:08** | 9:48 | 10:28 | **0:40** |
| SBO-3.1 | TDAFW runs 4 hrs | PORV Closed | No Depress. | 182 gpm | 7:10 | 7:19 | **0:09** | 6:47 | 7:09 | **0:22** |
| SBO-4.0 | TDAFW runs 4 hrs | PORV Closed | Depress. | 480 gpm | 5:25 | 5:29 | **0:04** | 5:10 | 5:18 | **0:08** |
| SBO-5.1 | TDAFW runs 4 hrs | PORV Closed | No Depress. | 300 gpm | 4:42 | 4:47 | **0:05** | 4:26 | 4:31 | **0:05** |
| SBO-6.0 | TDAFW runs 4 hrs | PORV Opened | NA | 21 gpm | 1:16 | 1:18 | **0:02** | 1:07 | 1:09 | **0:02** |
| SBO-6.1 | TDAFW runs 4 hrs | PORV Opened | Depress. | 21 gpm | 5:19 | 5:21 | **0:02** | 1:17 | 5:11 | **3:54** |
| SBO-7.0 | No TDAFW | NA | NA | 21 gpm | 2:35 | 2:38 | **0:03** | 2:11 | 2:37 | **N/A** |

# *Application to SBO analysis*

- Main differences found from the SBO sequence analysis

  - Extra coping time for ATF clad before CD ~ minutes → negligible, to be included in the uncertainty bands of the calculations

  - Extra coping time for the timing of 0.5 Kg $H_2$ production ~30 min for FeCrAl, depends on clad rupture time for Cr-coated → generally, less $H_2$ production for all sequences

  - **Outlier**: extra coping time before CD of ~1.15 hrs for FeCrAl-LT-SBO-1.3 (8 hrs battery time) →derived from creep rupture of the PRZ surge line → further injection of water from accumulators
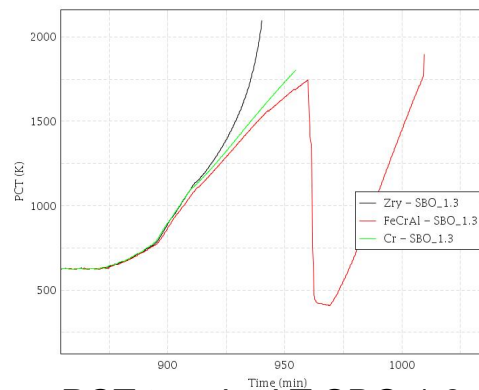


PCT trend – LT-SBO 1.3

# Application to SBO analysis

- Further investigations using RAVEN **Limit Surface Search** Algorithm

  - Exploring random parameters of the sequence SBO-3.0

    - Battery Lifetime: 4-8 hrs {uniform distribution}

    - Recovery Action timing: 10-15.5 hrs {uniform distribution}

  - Failure probability reduced by ~10%
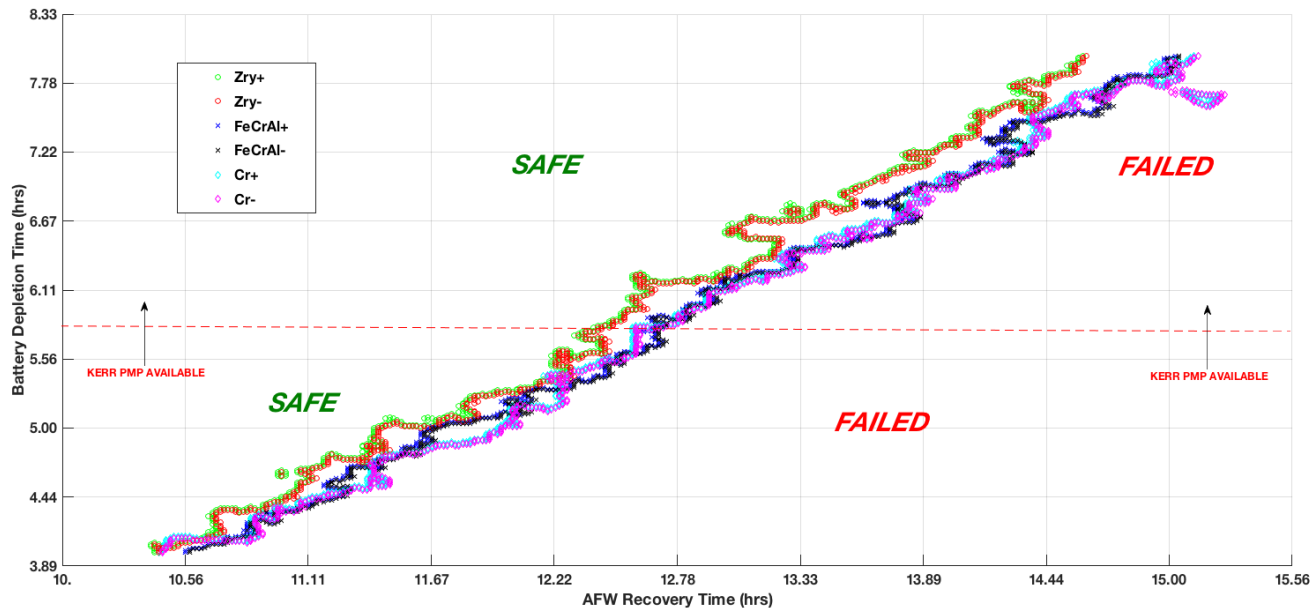
# *Application to SBO analysis*

- Final Risk Analysis performed by integrating in SAPHIRE model the RELAP5-3D results

  - Less than ~1 hr time difference does not warrant a change of the PRA SBO model

  - Introduction of coping time factor $F_{CT}$ (*m/n*), *m* extra coping time, *n* time to AC recovery

    - $CDF' = F_{CT}$ (*m/n*) $* CDF_0$

  - Extra coping time increases the chance of AC recovery

- Small extra coping time leads to minimal CDF reduction (2-4%)

# *Conclusions*

- LWRS/RISA/ERP project investigates passive and active ways for enhancing LWR fleet safety and economic profitability

- First investigation carried out for the near-term ATF

- RELAP5-3D has been modified for analyzing the oxidation reactions of two near-term ATF

- Coupling of deterministic/probabilistic approaches allowed to quantify reduction on CD

- LBLOCA and SBO analyses carried out for FY2018
  - No significant CDF reduction
  - Potential Risk improvements from the smaller $H_2$ production

-  Analyzing other AOO/DBA cases during FY2019 for having a clearer picture of the near-term ATF benefits