2021 IRUG Users Seminar

Risk-Informed ATF Analysis for Generic PWR & BWR

LWRS
LIGHT WATER REACTOR SUSTAINABILITY

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Risk-Informed Approaches and Tools in ATF analysis

Deterministic

- Unquantified probabilities
- Design-basis accidents
- Defense in depth and safety margins
- Regulatory burden
- Incomplete

RELAP5-3D, BISON

Risk-Informed

"Combination of deterministic and risk-based approaches through a deliberative processes"

Risk-Based

- Quantified probabilities
- Thousands of accident sequences
- Realistic
- Incomplete

SAPHIRE, EMRALD, RAVEN

Benefits of Risk-informed Approach

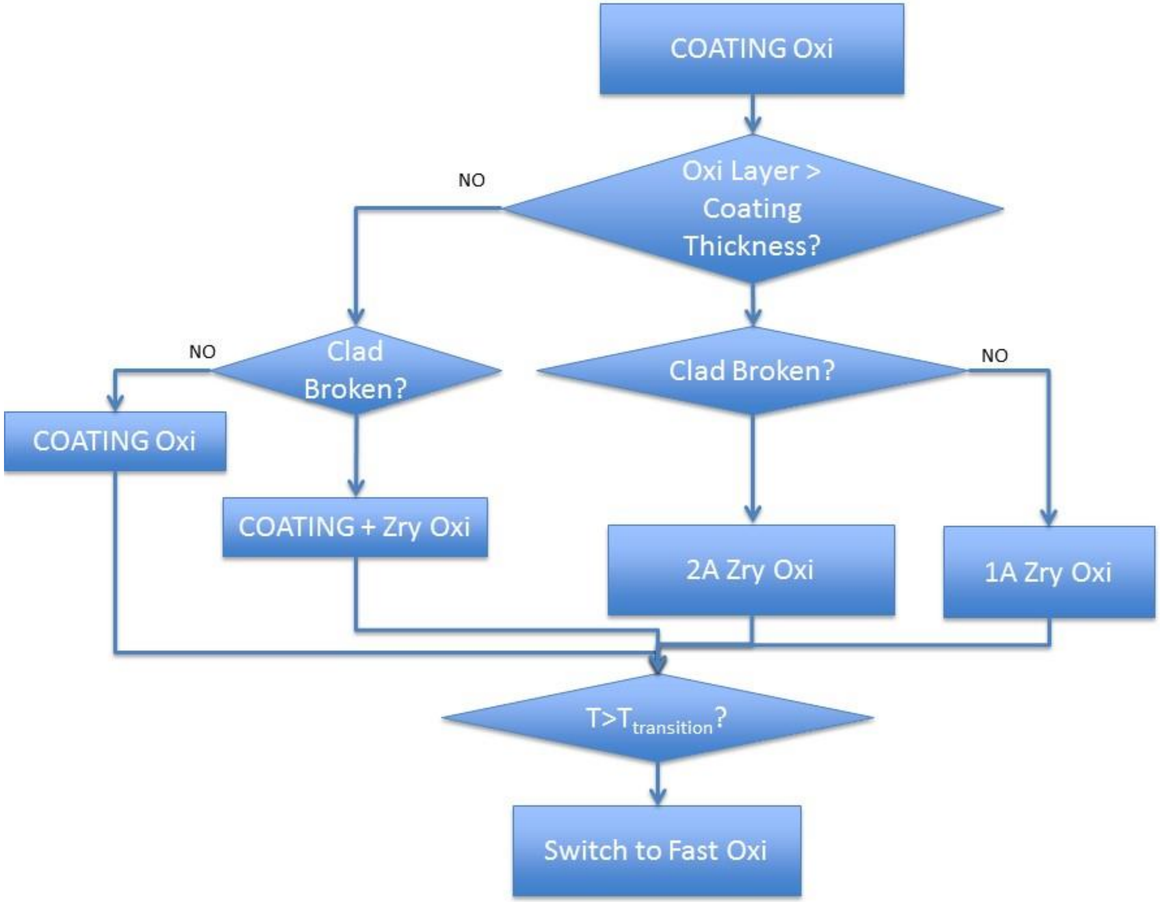
"Science-based margin optimization and minimized over-conservatism"

"Support risk-informed licensing and regulatory system development"

"Consequently, improves safety and economics for longer-term operation"

RELAP5-3D Enhancements for ATF

- The Cathcart correlation (using parabolic rate law) developed for Zr cladding has been generalized for coated cladding and FeCrAl cladding
- The materials properties for coatings and FeCrAl were obtained from published papers and reports
- Details can be found in C. Parisi, et al., "Risk-Informed Safety Analysis for Accident Tolerant Fuel", *Nuclear Science and Engineering* Vol. 194, 2020

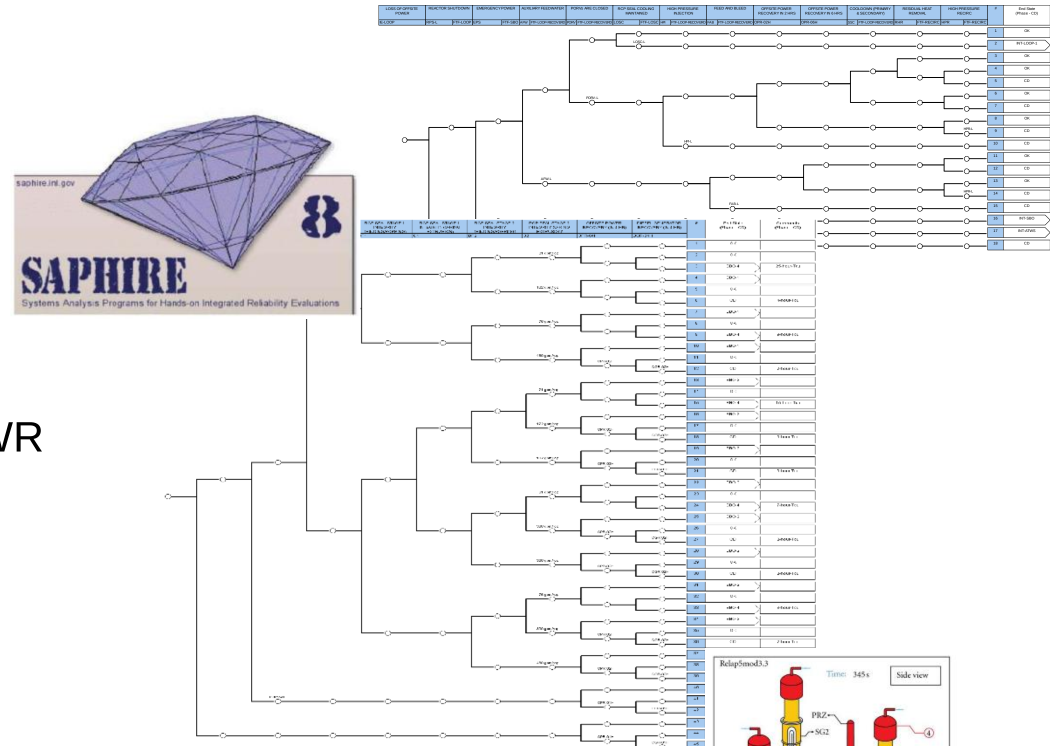


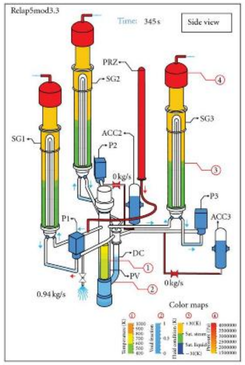
Logic Path for the Metal-Water Reaction Model Coding in RELAP5-3D

Risk-Informed ATF Analysis for a Generic PWR

Plant-Level Scenario-Based Risk Analysis for Near-Term ATF Concepts

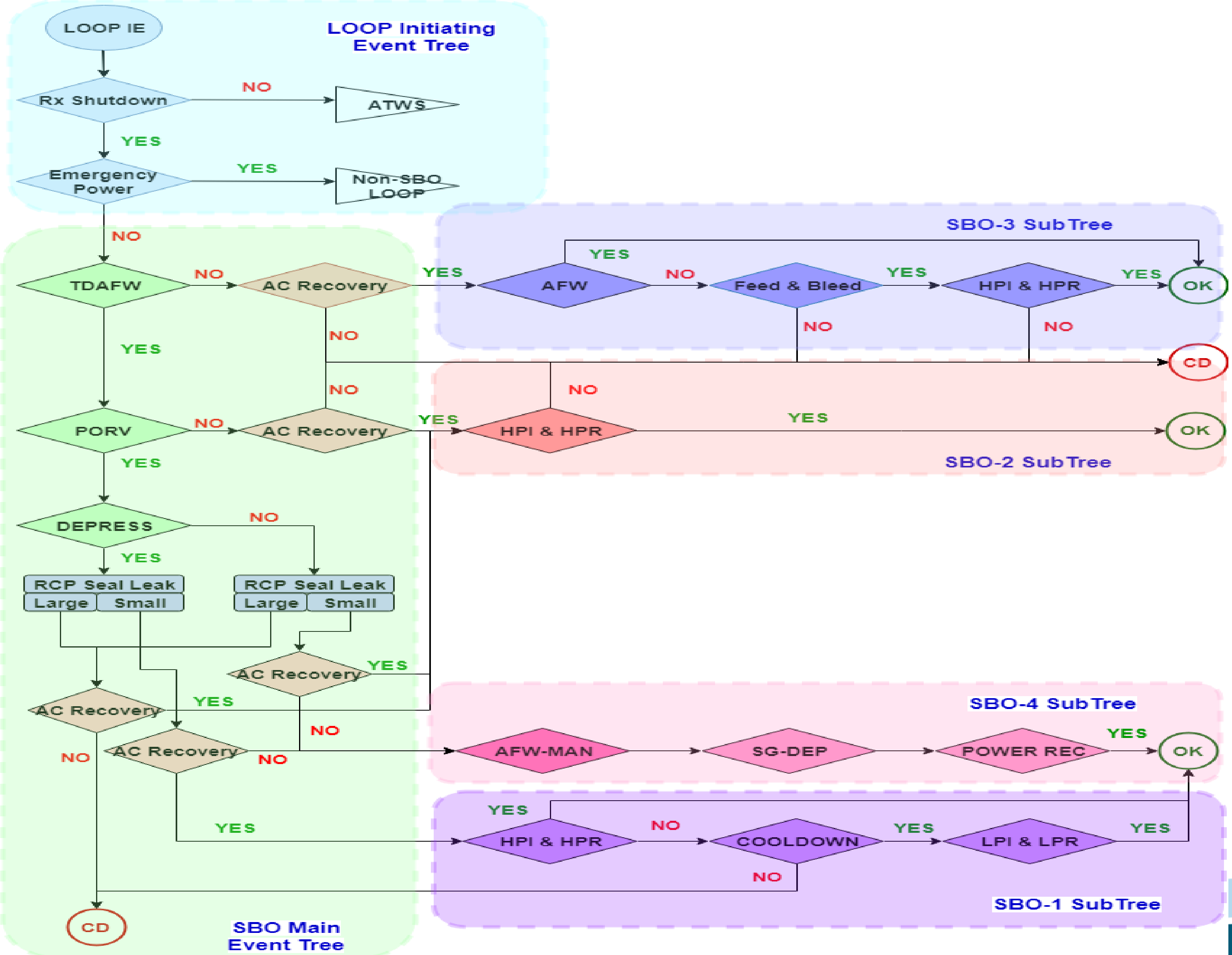
- **Generic SAPHIRE PRA Model**
  - 3-Loop PWR
  - SPAR-level details
    - Typical IEs/ETs/FTs
    - Industry Average Data
- **Best-Estimate**
  - RELAP5-3D Model for a 3-Loop PWR
  - BISON for fuels performance
- **Near-Term ATF Designs**
  - UO_2/FeCrAl & UO_2/Cr-Coated Zr
- **Risk Metrics**
  - Time to Reach Clad Melting Temperature
  - Time to Reach 0.5 kg H_2
  - CDF





INL/EXT-18-51436, Plant-Level Scenario-Based Risk Analysis for Enhanced Resilient PWR – SBO and LBLOCA, September 2018

ATF Risk Impact Analysis – PWR SBO



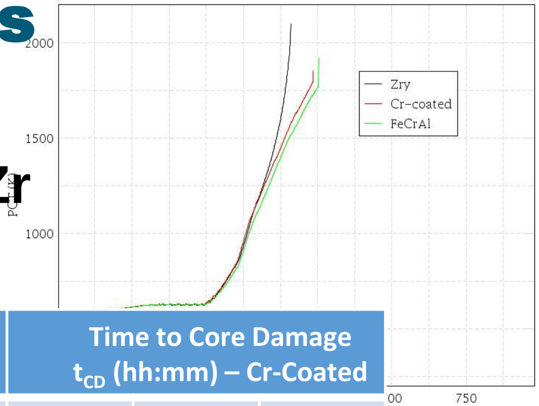
PWR SBO Scenarios

- The SBO PRA model was quantified with SAPHIRE 8
- Non-zero SBO sequences were reviewed to develop scenarios for RELAP5-3D simulations
- Main SBO Scenarios:
  - **SBO-1.0**: TDAFP success, No PORV remained open, 21gpm/RCP leakage, Rapid Secondary Depressurization success, No offsite power recovery and TDAFP stops after DC battery depletes
  - **SBO-2.0**: 21gpm->76gpm
  - **SBO-3.0**: 21gpm->182gpm
  - **SBO-4.0**: 21gpm->480gpm
  - **SBO-5.1**: 300gpm, Rapid Secondary Depressurization fails
  - **SBO-6.0**: TDAFP success, PORV remained opened, No offsite power recovery and TDAFP stops after DC battery depletes
  - **SBO-7.0**: TDAFP fails, No offsite power recovery (Unmitigated STSBO)

More comprehensive assessment for ATF than industry sponsored analyses

SBO RELAP5-3D Results

- **Time to Core Damage: FeCrAl & Cr-Coated vs. Zr**



	Scenario Description				Time to Core Damage t_{CD} (hh:mm) - FeCrAl			Time to Core Damage t_{CD} (hh:mm) – Cr-Coated		
					Zr	FeCrAl	Δt	Zr	FeCrAl	Δt
SBO-1.0	TDAFW runs 4 hrs	PORV Closed	Depress.	21 gpm	10:32	10:51	**0:19**	10:32	10:47	**0:15**
SBO-2.0	TDAFW runs 4 hrs	PORV Closed	Depress.	76 gpm	10:17	10:36	**0:19**	10:17	10:29	**0:12**
SBO-3.0	TDAFW runs 4 hrs	PORV Closed	Depress.	182 gpm	10:22	10:43	**0:21**	10:22	10:30	**0:08**
SBO-4.0	TDAFW runs 4 hrs	PORV Closed	Depress.	480 gpm	5:25	5:46	**0:21**	5:25	5:29	**0:04**
SBO-5.1	TDAFW runs 4 hrs	PORV Closed	No Depress.	300 gpm	4:42	4:51	**0:09**	4:42	4:47	**0:05**
SBO-6.0	TDAFW runs 4 hrs	PORV Opened	NA	21 gpm	1:16	1:23	**0:07**	1:16	1:18	**0:02**
SBO-7.0	No TDAFW	NA	NA	21 gpm	2:35	2:41	**0:06**	2:35	2:38	**0:03**

Cr-Coated and FeCrAl ATF provide modest increase in coping time for SBO events (< 1h additional coping time). This is consistent with industry sponsored studies.

SBO RELAP5-3D Results

- H_2 Production, FeCrAl & Cr-Coated vs. Zr.

	Scenario Description				Total Hydrogrn (Kg) FeCrAl			Total Hydrogen (Kg) Cr-Coated		
					Zry	FeCrAl	%	Zry	Cr-coated	%
SBO-1.0	TDAFW runs 4 hrs	PORV Closed	Depress.	21 gpm	98.1	3.0	3.1	98.1	0.3	0.3
SBO-2.0	TDAFW runs 4 hrs	PORV Closed	Depress.	76 gpm	98.8	1.6	1.6	98.8	0.3	0.3
SBO-3.0	TDAFW runs 4 hrs	PORV Closed	Depress.	182 gpm	77.1	2.8	3.6	77.1	10.6	13.7
SBO-4.0	TDAFW runs 4 hrs	PORV Closed	Depress.	480 gpm	17.6	2.0	11.4	17.6	6.2	35.2
SBO-5.1	TDAFW runs 4 hrs	PORV Closed	No Depress.	300 gpm	31.5	2.0	6.3	31.5	8.1	25.7
SBO-6.0	TDAFW runs 4 hrs	PORV Opened	NA	21 gpm	17.7	1.9	10.7	17.7	5.2	29.4
SBO-7.0	No TDAFW	NA	NA	21 gpm	88.0	2.4	2.7	88.0	11.3	12.8

FeCrAl and Cr-Coated ATF provide significantly reduced H_2 generation during severe accident conditions. This also is consistent with industry sponsored studies.

PWR SBO PRA Results

	PRA Results for FeCrAl				PRA Results for Cr-Coated			
	CDF_0	CDF'	ΔCDF	ΔCDF%	CDF_0	CDF'	ΔCDF	ΔCDF%
SBO-1.0	1.57E-07	1.49E-07	-7.83E-09	-5%	1.57E-07	1.49E-07	-7.83E-09	-5%
SBO-2.0	1.91E-09	1.81E-09	-9.53E-11	-5%	1.91E-09	1.81E-09	-9.53E-11	-5%
SBO-3.0	1.30E-07	1.24E-07	-6.52E-09	-5%	1.30E-07	1.30E-07	0.00E+00	0%
SBO-3.1	5.84E-10	5.26E-10	-5.84E-11	-10%	5.84E-10	5.84E-10	0.00E+00	0%
SBO-4.0	4.37E-09	3.93E-09	-4.37E-10	-10%	4.37E-09	4.37E-09	0.00E+00	0%
SBO-5.1	1.10E-09	1.10E-09	0.00E+00	0%	1.10E-09	1.10E-09	0.00E+00	0%
SBO-6.0	2.32E-09	2.32E-09	0.00E+00	0%	2.32E-09	2.32E-09	0.00E+00	0%
SBO-7.0	5.42E-08	5.42E-08	0.00E+00	0%	5.42E-08	5.42E-08	0.00E+00	0%
Total	**3.51E-07**	**3.37E-07**	**-1.49E-08**	**-4%**	**3.51E-07**	**3.44E-07**	**-7.93E-09**	**-2%**

Estimated CDF reductions also consistent with industry sponsored studies.

Other Scenarios

- ATF impact in other Scenarios analyzed
  - Loss of Feedwater
  - PWR Locked Rotor
  - ATWS
  - Turbine Trip
  - SBLOCA
  - Steam Generator Tube Rupture
  - Main Steam Line Break
- Results are similar with those from SBO
  - Modest increase in time to core damage with FeCrAl and Cr-coated ATF designs
  - The hydrogen production with ATF is one or two order of magnitude lower
  - The timing to release significant hydrogen production (0.5 Kg) is delayed about 0.5 hour to 1 hours with ATF

1. INL/EXT-19-53556, Risk-Informed Analysis for an Enhanced Resilient PWR with ATF, FLEX, and Passive Cooling, August 2019.
2. INL/EXT 19-56215, Evaluation of the Benefits of ATF, FLEX, and Passive Cooling System for an Enhanced Resilient PWR Model, October 2019.

Near-Term ATF Risk Assessment Summary for a Generic PWR

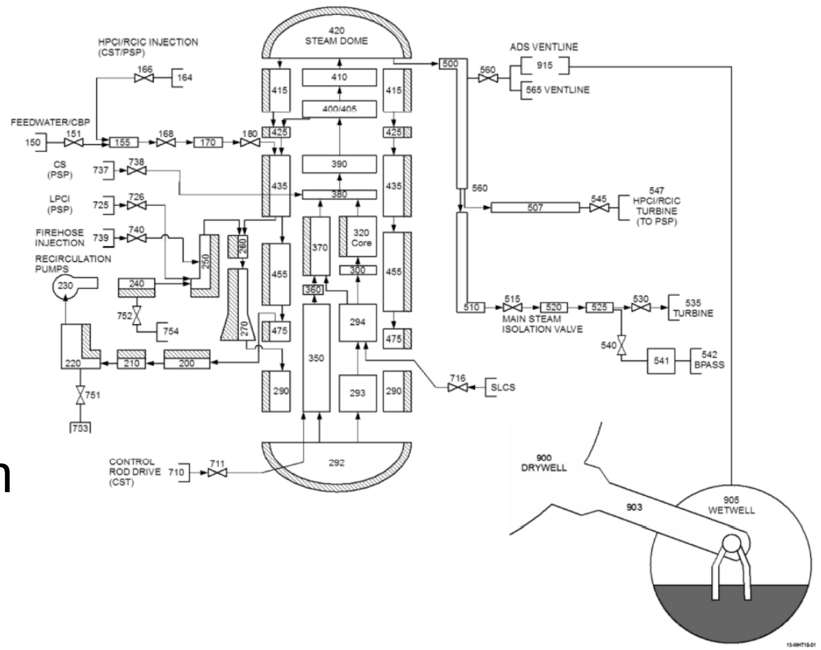
- There is moderate increase of the time to core damage with FeCrAl and Cr-coated ATF designs
- Other than SBO, the results do not warrant a change of the PRA model (event tree, fault tree, success criteria, or human reliability analysis)
- The estimated CDF reduction for SBO from the modest coping time increase is about 4% for FeCrAl and 2% for Cr-Coated
- Significant risk benefits brought by ATF
  - The hydrogen production with ATF is one or two order of magnitude lower
  - The timing to release significant hydrogen production (0.5 Kg) is delayed about 0.5 hour to 1.5 hours with ATF

The PRA models for the existing Zr fuel would bound the implementation of the near-term ATF for PWRs.

Risk-Informed ATF Analysis for a Generic BWR

Risk-Informed ATF Analysis for a Generic BWR

- **Generic SAPHIRE PRA model for a BWR (9 SBO scenarios)**
- **RELAP5 model for a generic BWR based on a BWR4**
  - Rated Thermal Power: 3293 MWth
  - # of Fuel Assemblies (Bundles): 764
  - Core Mass Flow Rate: 11510 Kg/s
  - Safety Systems: ADS, SRVs, HPCI, RCIC, LPCI, CS, SLCS, Firehose Injection, Control Rod Drive Hydraulic System
  - Analysis is based on 10x10 fuel design
  - Calculations were done at BOC, MOC and EOC



INL/EXT-20-59906, Risk-Informed ATF and FLEX Analysis for an Enhanced Resilient BWR Under Design-Basis and Beyond-Design-Basis Accidents, September 2020.

BWR SBO Scenarios

RELAP5-3D Scenario	Scenario Description	SBO PRA Sequence	CDF
SBO-1	No SRV Open, RCIC Success, but AC power not recovered in 4 hours, No RCIC/HPCI Black Run	LOOPWR:37-03-17	2.77E-07
SBO-1.1	No SRV Open, HPCI Success, but AC power not recovered in 4 hours, No RCIC/HPCI Black Run	LOOPWR:37-06-17	4.10E-08
SBO-1.2	One SRV Open, RCIC Success, but AC power not recovered in 4 hours	LOOPWR:37-11-3	2.65E-08
SBO-1.3	One SRV Open, HPCI Success, but AC power not recovered in 4 hours	LOOPWR:37-11-6	3.80E-09
SBO-2	No SRV Open, No RCIC/HPCI -> STSBO	LOOPWR:37-09	1.27E-08
SBO-2.1	One SRV Open, No RCIC or HPCI -> STSBO	LOOPWR:37-11-7	3.44E-09
SBO-3	Two or more SRV Open	LOOPWR:37-12	2.85E-09
SBO-4	No SRV Open, RCIC Success, AC Power Recovered, SPC Failed, DEP Success, containment venting system (CVS) failed, LI failed	LOOPWR:37-01-05	2.22E-11
SBO-4.1	No SRV Open, RCIC Success, AC Power Recovered, SPC Failed, DEP failed	LOOPWR:37-01-11	3.15E-12

Time to Core Damage Comparison for BWR SBO Scenarios

	Time to Core Damage t_{CD} (hh:mm) - FeCrAl			Time to Core Damage t_{CD} (hh:mm) – Cr-Coated		
	Zr	FeCrAl	Δt	Zr	Cr-Coated	Δt
SBO-1	6:59	7:19	0:20	6:59	7:11	0:12
SBO-1.1	8:21	8:49	0:18	8:21	8:30	0:09
SBO-1.2	7:31	7:47	0:16	7:31	7:38	0:07
SBO-1.3	10:37	10:53	0:16	10:37	10:52	0:15
SBO-2	1:14	1:24	0:10	1:14	1:19	0:05
SBO-2.1	1:02	1:11	0:09	1:02	1:07	0:05
SBO-3	0:31	0:35	0:04	0:31	0:32	0:01
SBO-4	10:20	10:33	0:13	10:20	10:21	0:01
SBO-4.1	11:56	12:46	0:50	11:56	12:38	0:42

Hydrogen Production Comparison for BWR SBO Scenarios

	Hydrogen Production (Kg) - FeCrAl			Hydrogen Production (Kg) – Cr-Coated		
	Zr	FeCrAl	%	Zr	Cr-Coated	%
SBO-1	31.02	0.55	1.8	31.02	6.05	19.5
SBO-1.1	32.24	0.65	2.0	32.24	6.23	19.3
SBO-1.2	26.35	0.33	1.3	26.35	11.11	42.2
SBO-1.3	26.20	0.41	1.6	26.20	5.19	19.8
SBO-2	24.08	0.30	1.2	24.08	4.11	17.1
SBO-2.1	46.25	0.44	1.0	46.25	5.44	11.8
SBO-3	10.30	0.07	0.7	10.30	1.12	10.9
SBO-4	13.07	0.13	1.0	13.07	1.91	14.6
SBO-4.1	34.05	1.10	3.2	34.05	7.25	21.3

BWR SBO PRA Results

	PRA Results for FeCrAl				PRA Results for Cr-Coated Cladding			
	CDF_0	CDF'	ΔCDF	ΔCDF%	CDF_0	CDF'	ΔCDF	ΔCDF%
SBO-1	2.77E-07	2.64E-07	-1.27E-08	-5%	2.77E-07	2.69E-07	-7.75E-09	-3%
SBO-1.1	4.10E-08	3.84E-08	-2.59E-09	-6%	4.10E-08	4.01E-08	-8.66E-10	-2%
SBO-1.2	2.65E-08	2.55E-08	-9.81E-10	-4%	2.65E-08	2.61E-08	-4.37E-10	-2%
SBO-1.3	3.80E-09	3.66E-09	-1.40E-10	-4%	3.80E-09	3.67E-09	-1.32E-10	-3%
SBO-2	1.27E-08	1.20E-08	-6.62E-10	-5%	1.27E-08	1.23E-08	-3.43E-10	-3%
SBO-2.1	3.44E-09	3.44E-09	0.00E+00	0%	3.44E-09	3.44E-09	0.00E+00	0%
SBO-3	2.85E-09	2.85E-09	0.00E+00	0%	2.85E-09	2.85E-09	0.00E+00	0%
SBO-4	2.22E-11	2.27E-11	5.00E-13	2%	2.22E-11	2.22E-11	3.94E-14	0%
SBO-4.1	3.15E-12	3.40E-12	2.55E-13	8%	3.15E-12	3.36E-12	2.17E-13	7%
Total	**3.67E-07**	**3.50E-07**	**-1.71E-08**	**-5%**	**3.67E-07**	**3.58E-07**	**-9.52E-09**	**-3%**

BWR MLOCA Scenarios for RELAP5-3D Calculations

RELAP5-3D Scenario	Scenario Description	RPS	VSS	HPCI	DEP	LPI & VA
MLOCA-1	Reactor Shutdown, Vapor Suppression Success, but HPCI and DEP Fail	Success	Success	Fail	Fail	
MLOCA-2	Reactor Shutdown, Vapor Suppression Success, HPCI Fails, DEP Success, but LPI and VA Fail	Success	Success	Fail	Success	Fail
MLOCA-3	Reactor Shutdown, Vapor Suppression Fails	Success	Fail			
MLOCA-4	Reactor Shutdown, Vapor Suppression Success, HPCI Success, but LPI and VA Fail	Success	Success	Success		Fail

Time to core damage gain ranges from 4.5 to 11 minutes for FeCrAl and 1 to 4 minutes for Cr-coated cladding. Significant reduction on hydrogen production (20 to 100 times lower for FeCrAl and 4 to 10 times lower for Cr-coated cladding).

Other Scenarios

- ATF impact in other Scenarios analyzed
  - Loss of Main Feedwater
  - General Transients
  - ATWS
  - Inadvertent open relief valve (IORV)
  - SBLOCA
- Results are similar with those from SBO
  - Modest increase in time to core damage with FeCrAl and Cr-coated ATF designs
  - The hydrogen production with ATF is a few times to two orders of magnitude lower

INL/EXT-21-#####, Risk-Informed Analysis for Enhanced Resilient Nuclear Power Plant with Initiatives including ATF, FLEX, and Advanced Battery Technology, September 2021.

Near-Term ATF Risk Assessment Summary for Generic BWR Analyses

- There is moderate increase of the time to core damage with FeCrAl and Cr-coated cladding ATF designs
- The estimated CDF reduction for SBO from the modest coping time increase is about 5% for FeCrAl and 3% for Cr-coated cladding
- Other than SBO, the results for other scenarios do not warrant a change of the PRA model (event tree, fault tree, success criteria, or human reliability analysis)
- Significant risk benefits brought by ATF
  - ❑ The hydrogen production with ATF is a few times to two order of magnitude lower

Future Work on Risk-Informed ATF Analysis

- **FY22**
  - Risk-informed analysis of ATF implementation with burnup extension and increased enrichment

LWRS

LIGHT WATER
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SUSTAINABILITY

Sustaining National Nuclear Assets

http://lwrs.inl.gov