INL/MIS-21-64755-Revision-0

Quantitative Risk Analysis of High Safety-significant Safety-related DI&C Systems using IRADIC Technology

October 2021

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Changing the World's Energy Future

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

RISA Stakeholder Meeting

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10/14/2021

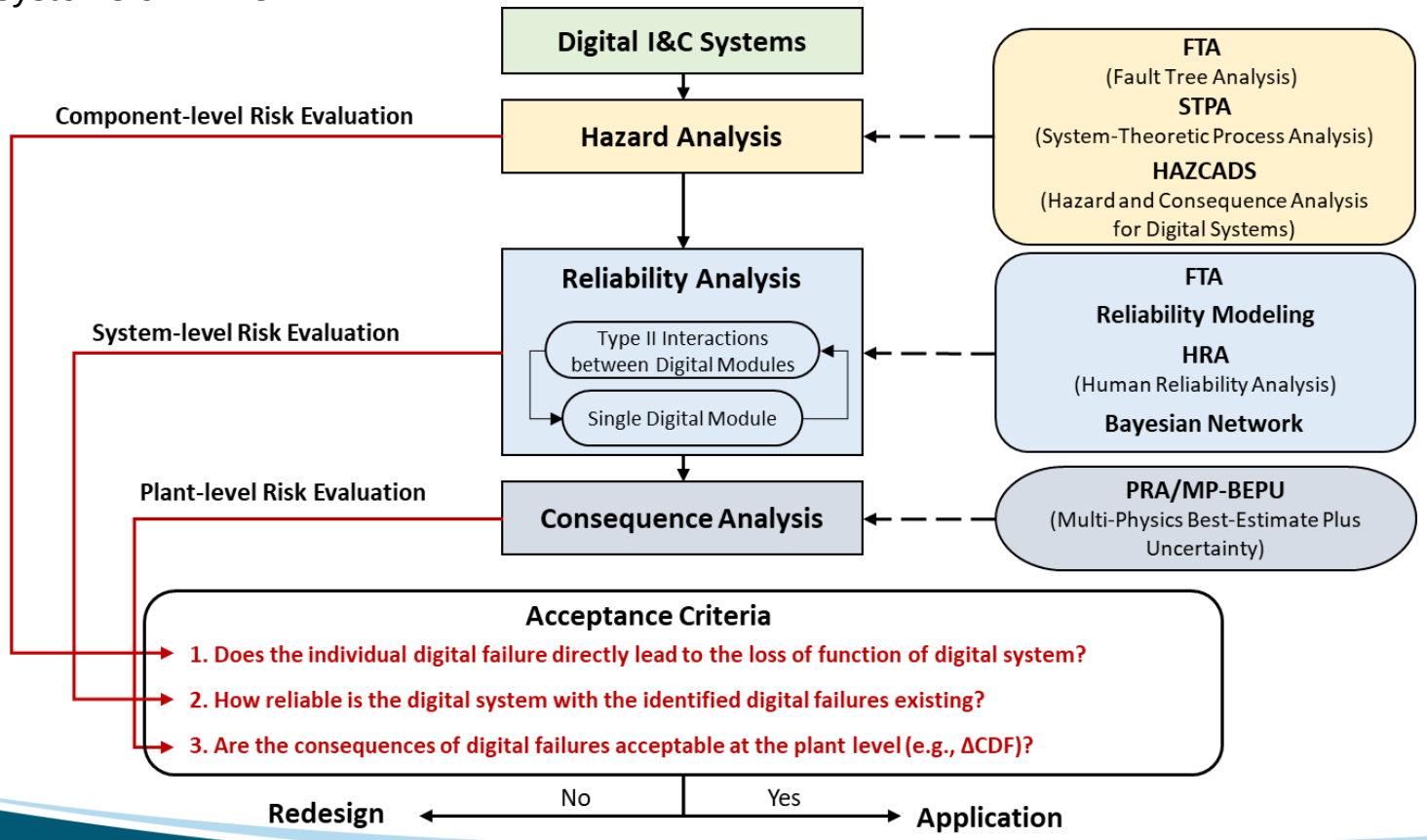
Challenges in Addressing CCF in HSSSR DI&C Systems

- **Some technical challenges remain in software common cause failure (CCF) analysis in the high safety-significant safety-related (HSSSR) DI&C systems:**
  - **Are current methods able to capture potential CCFs in DI&C systems?**
    - Various methods: FMEA, FTA, STPA, HAZCADS, HAZOP…
    - Software should not be analyzed in isolation from the complete digital system.
    - Not easy to identify new failure modes in single software and interactions between different components in a DI&C system ("Type II interaction").
  - **Is qualitative evaluation sufficient for addressing software CCFs in HSSSR DI&C systems?**
    - Most of the STPA-based approaches focus on the identification of software failures but not the quantification of their probabilities.
    - Instead, a conservative bounding assessment is performed to evaluate their impacts to plant safety (e.g., Δ Core Damage Frequency, [CDF]), which may lead to an underestimation of safety margins gained by plant digitalization.
  - **How to quantitatively evaluate CCF-related impacts to DI&C systems and plant response?**
    - This proposes a need to develop an integrated strategy to include both qualitative hazard analysis and quantitative reliability and consequence analysis for addressing software CCF issues in the HSSSR DI&C systems of nuclear power plants (NPPs).

Schematic of Integrated Risk Assessment Technology for Digital I&C Systems (IRADIC)

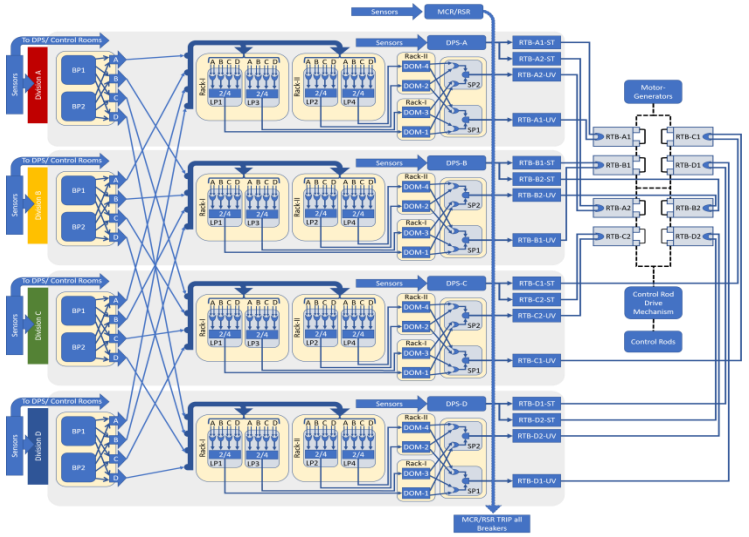
INL-IRADIC Technology:

- Provide an integrated and best-estimate capability to address new technical issues quantitatively, accurately, and efficiently in plant modernization progress, such as software CCFs in HSSSR DI&C systems of NPPs.



How IRADIC Could Support Industry for Risk Informing HSSSR DI&C Designs or Upgrades?

- We expect **IRADIC** to become an integrated risk-informed tool for vendors and utilities to meet regulatory requirements and **optimize the diversity and defense-in-depth (D3) applications in the DI&C designs and upgrades.**
  - **Quantitative vs. Qualitative**
    - Software Failure Probability ⟶ DI&C System Failure Probability ⟶ ΔCDF
  - **Balance of risk and cost in design stage**
    - Management strategy of CCFs
      - All elimination vs. selective elimination
    - Level of redundancy
      - 4 divisions vs. 2 divisions
      - 4 vs. 2 local coincidence logic processors per division
    - Level of diversity
      - Design: Analog? Digital? Both?
      - Software: Design requirements, programming language…
      - Equipment: Manufacturers, designs, architectures…

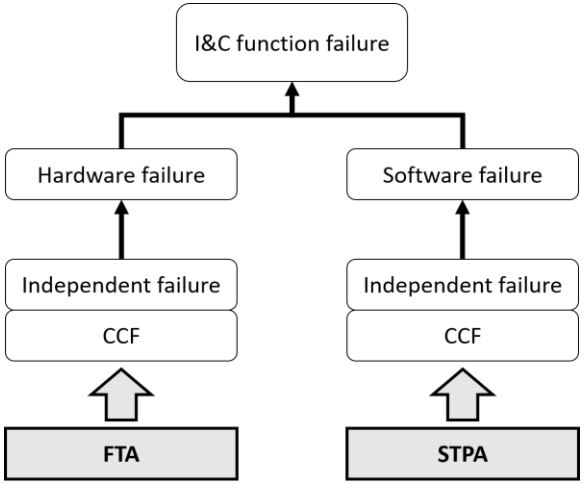


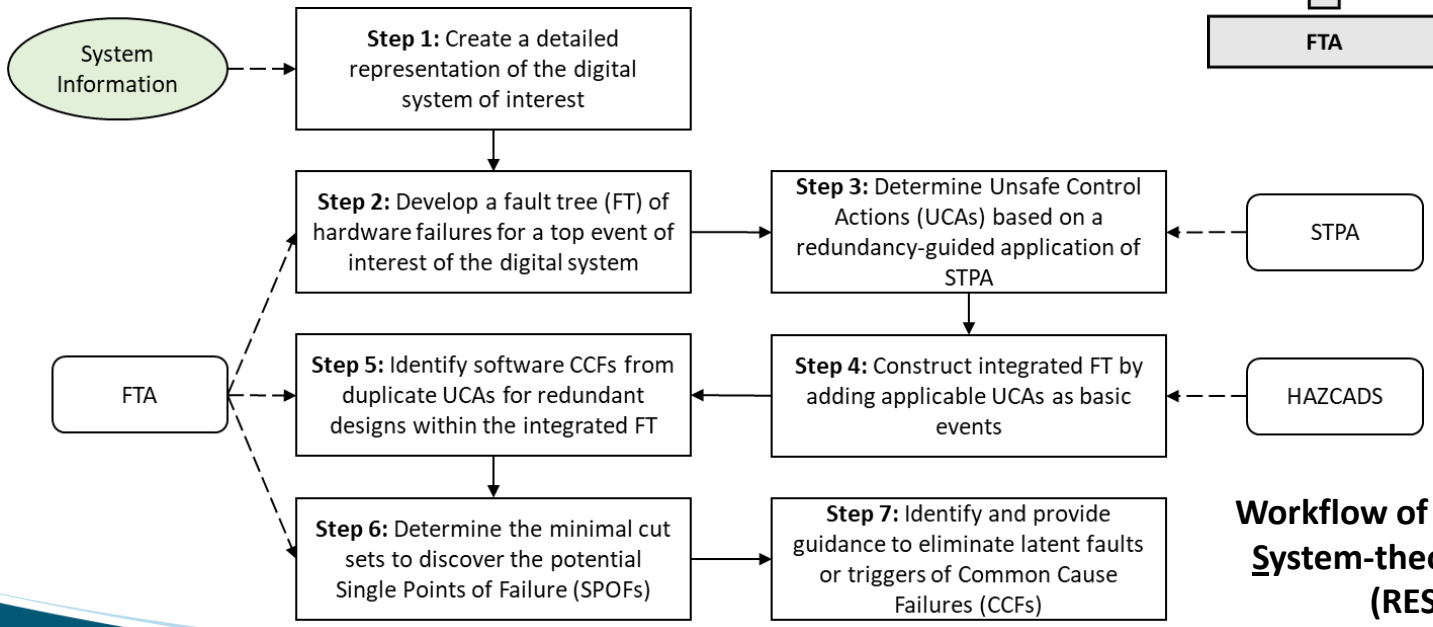
4-division digital Reactor Trip System

(I). Redundancy-guided System-theoretic Hazard Analysis

Hazard analysis in IRADIC:

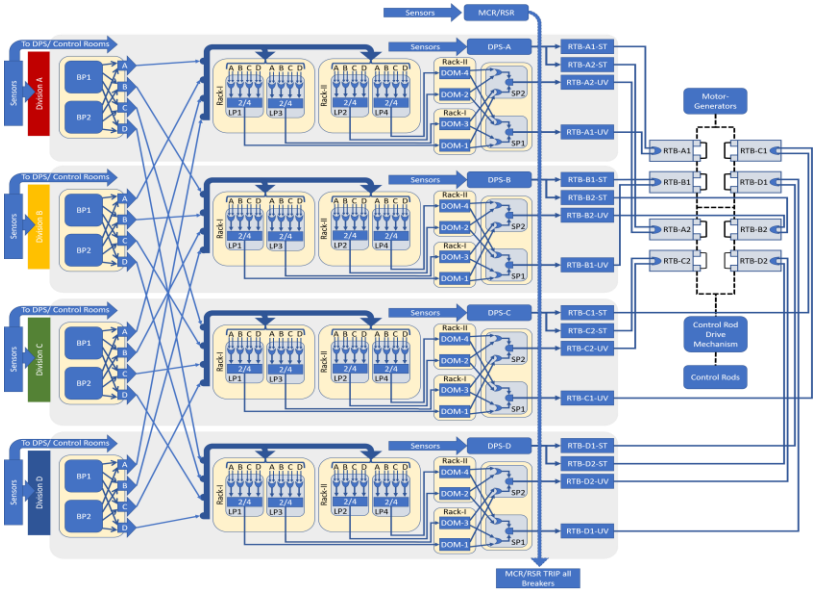
- Incorporates the concept of combining FTA and STPA from HAZCADS.
- Reframes STPA in a redundancy-guided way to address CCF concerns in highly redundant HSSSR DI&C systems.
- Identifies failures in Type II interactions (between different components of a DI&C system).





Workflow of the Redundant-guided System-theoretic Hazard Analysis (RESHA) in IRADIC

Determine Unsafe Control Actions (UCAs) Based on a Redundancy-guided Application of STPA



Redundancy of

- Reactor trip breakers
- LCL processors
  - *Division level*
  - *Unit level (two racks per division)*
  - *Module level (two processors per rack)*
- Bistable processors
  - *Division level*
  - *Unit level (two processors per division)*

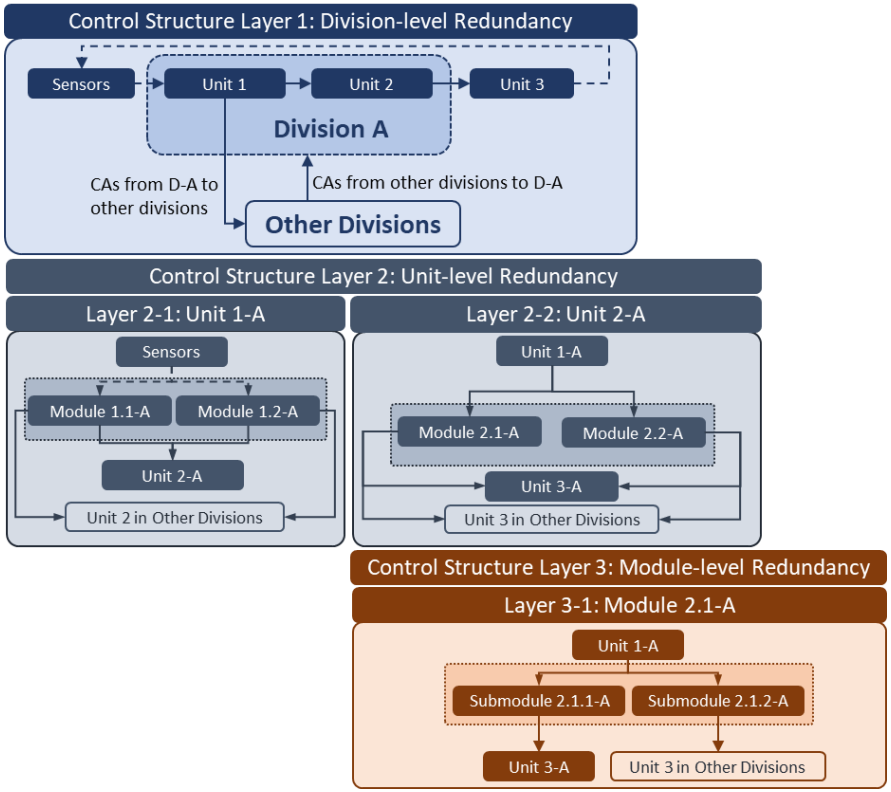


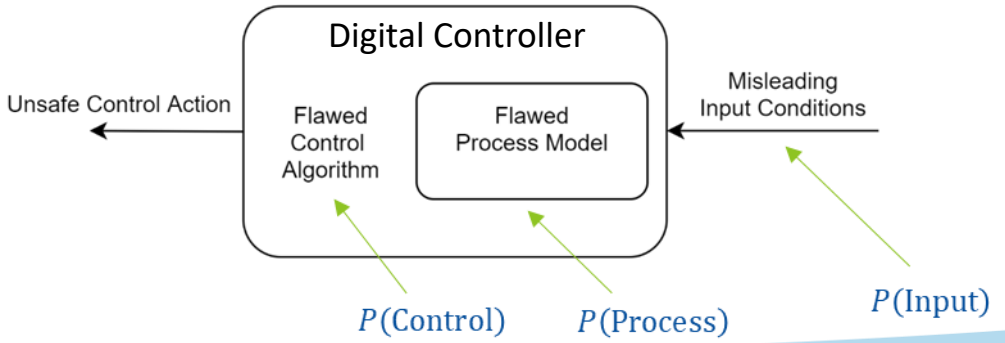
Illustration of a multilayer control structure that captures UCAs in different levels of redundancy

Key CCFs Leading to Potential Single Points of Failure (SPOFs) in the Design

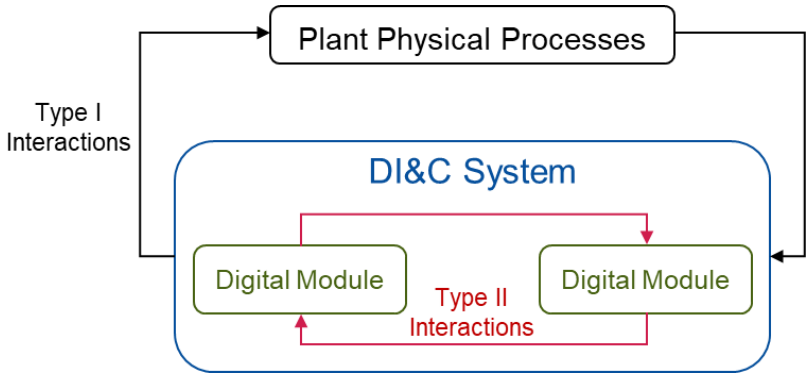
Table 5: First order cut sets for the RPS system.		
Number	Cut set	Description
1	SP-HD-CCF	Selective processor hardware CCF.
2	LC-DOM-HD-CCF	Logic cabinet digital output module hardware CCF.
3	RTB-UV-HD-CCF	Reactor trip breaker undervoltage hardware CCF.
4	LC-BP-HD-CCF	Logic bistable processor hardware CCF.
5	LC-LP-HD-CCF	Logic cabinet logic processor hardware CCF
6	LC-LP-SF-CCF-TA	Logic cabinet logic processor software CCF type A.
7	LC-LP-SF-CCF-TC	Logic cabinet logic processor software CCF type C.
8	LC-DOM-SF-CCF-TA	Logic cabinet digital output module software CCF type A.
9	LC-DOM-SF-CCF-TC	Logic cabinet digital output module software CCF type C.
10	SP-SF-CCF-TC	Selective processor software CCF type C.
11	SP-SF-CCF-TA	Selective processor software CCF type A.
12	LC-BP-SF-CCF-TA	Logic cabinet bistable processor software CCF type A.
13	LC-BP-SF-CCF-TC	Logic cabinet bistable processor software CCF type C.

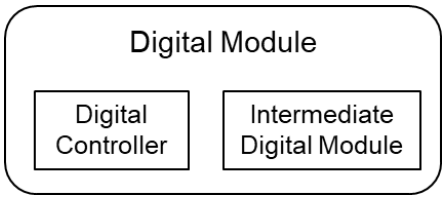
Causal factors of UCAs (e.g., software failures)

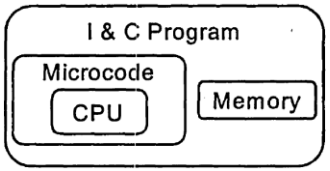
- Category 1: Inner software failure
  - Software design defect
  - Software implementation failure
- Category 2: Incorrect feedback or inputs
  - Failures in Type II interactions



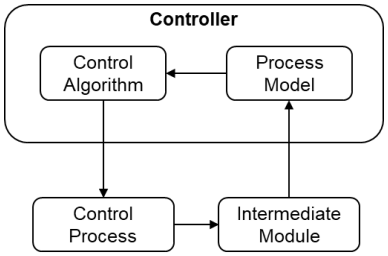
Identifying and Quantifying Failures in both Software and Type II Interactions





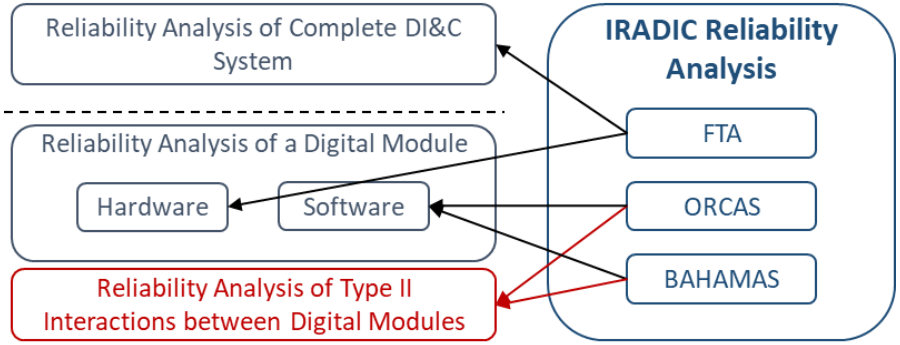


Architecture diagram of a DI&C controller [1]

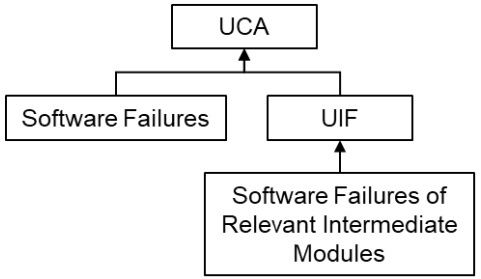


STPA handbook [2]

Large Scale



Small Scale



1. NUREG-6901: "Current State of Reliability Modeling Methodologies for Digital Systems and Their Acceptance Criteria for Nuclear Power Plant Assessments," 2006.
2. N. G. Leveson and J. P. Thomas, STPA Handbook, March 2018.

(II). Quantitative Software Reliability Analysis in IRADIC Technology

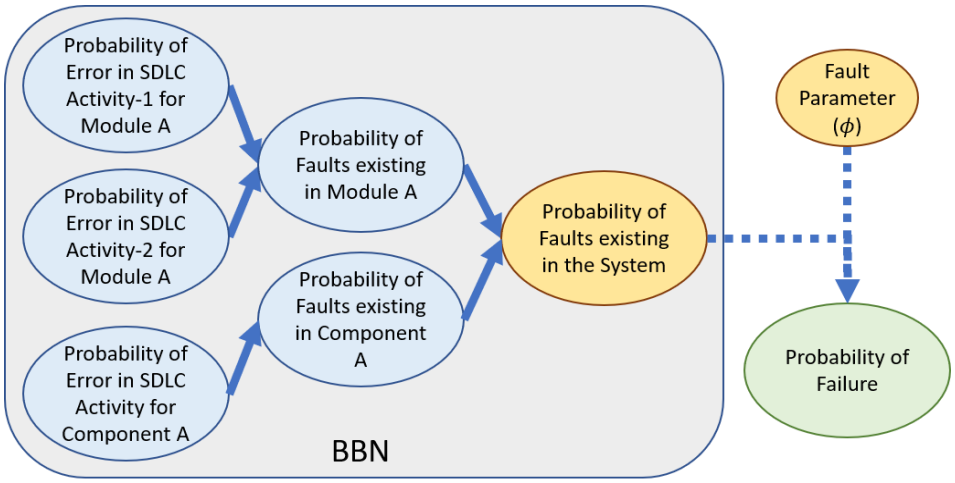
- **Methods developed within IRADIC:**
  - **BAHAMAS (**Bayesian and HRA-Aided Method for the Reliability Analysis of Software)
    - Developed for the conditions with limited testing/operational data or for reliability estimations of software in early development stage.
    - Provide a rough estimation of failure probabilities to support the design of software and target DI&C systems.
  - **ORCAS** (Orthogonal Defect Classification for Assessing Software Reliability)
    - Developed for the conditions with sufficient testing/operational data.
    - A relatively accurate estimation of software failure probabilities can be provided.

	BAHAMAS	ORCAS
Applicable conditions	• Limited testing/operational data • For reliability estimations of software in early development stage	• Sufficient testing/operational data • For reliability estimations of software in development or testing stage
Key assumption	Software failures can be traced to human errors in the software development life cycle	Sufficient data is available through testing (e.g., T-Way testing)
Ways to identify root causes	STPA + BBN + HRA in SDLC	STPA + ODC + Metric-based methods
Ways to quantify failure rate of root causes	HRA in SDLC	Software reliability growth modeling

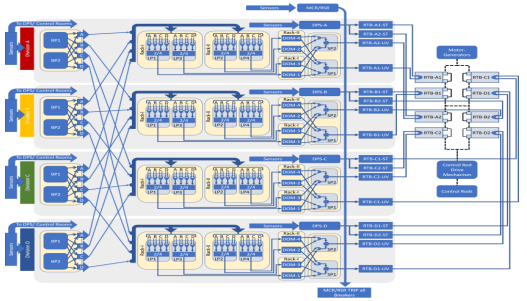
BNN	Bayesian Belief Network
ODC	Orthogonal Defect Classification
HRA	Human Reliability Analysis
SDLC	software development life cycle

Method 1. Bayesian and HRA-Aided Method for the Reliability Analysis of Software (BAHAMAS)

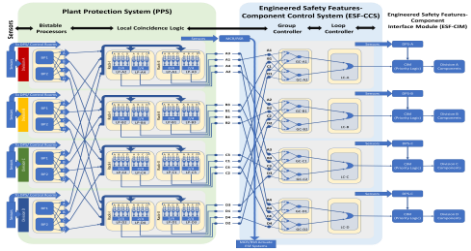
- **BAHAMAS quantifies fault tree basic events:**
  - **BBN** provides a means of combining disparate causal factors and sources of faults in the system.
  - **HRA** quantifies root human errors (i.e., causes of faults).
  - The fault parameter converts probability of faults into probability of failure.
  - **CCF modeling** parameter (Beta-factor method) accounts for single failure and CCFs.
- **Instead of relying on testing data,** BAHAMAS assumes **software failures can be traced to human errors in the SDLC** and modeled with HRA.



The general BAHAMAS structure



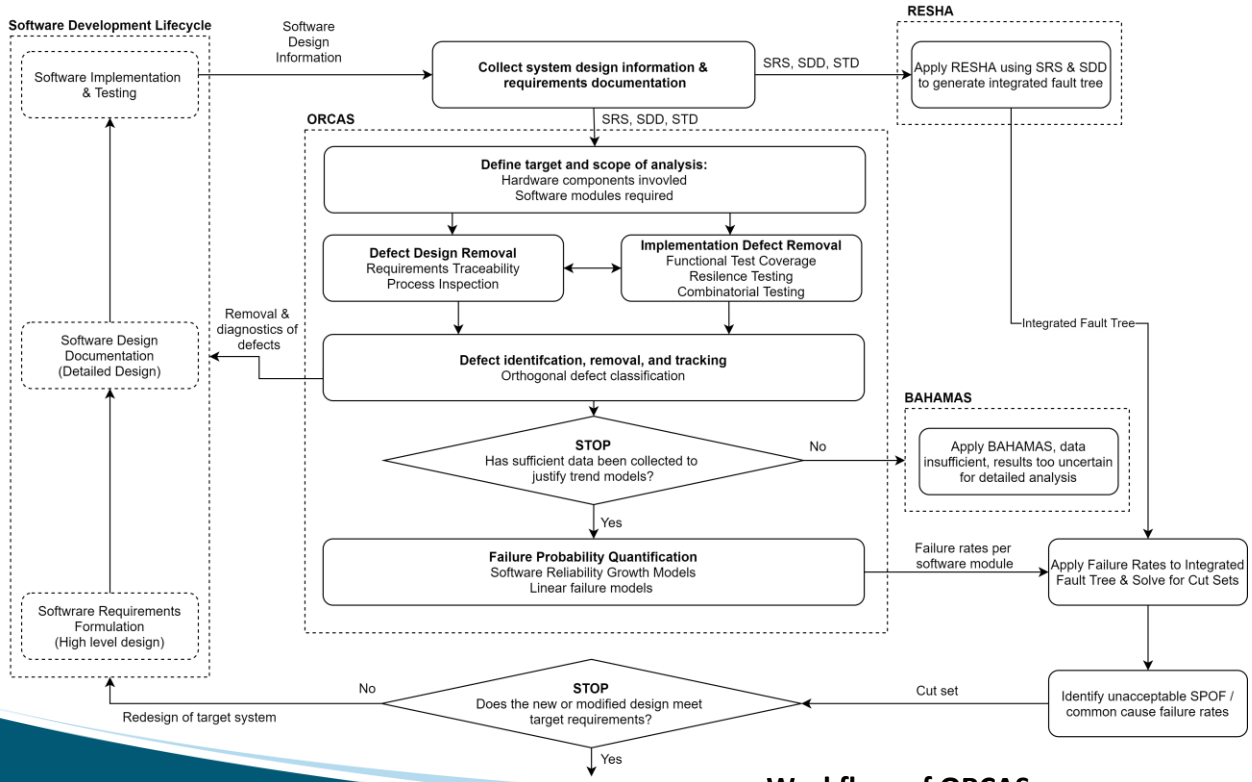
A 4-division digital Reactor Trip System based on APR 1400 design



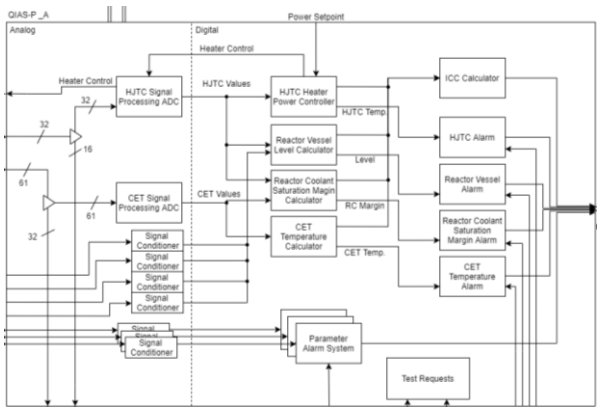
A 4-division digital Engineered Safety Feature Actuation System based on APR 1400 design

Method 2. Orthogonal Defect Classification for Assessing Software Reliability (ORCAS)

- Compared with BAHAMAS, **ORCAS quantifies FT basic events:**
  - Using sufficient operational and testing data when available.
  - Using metric-based and test-based methods to identify software defects.
  - Using ODC systematically to link identified defects with potential failure modes.



Workflow of ORCAS

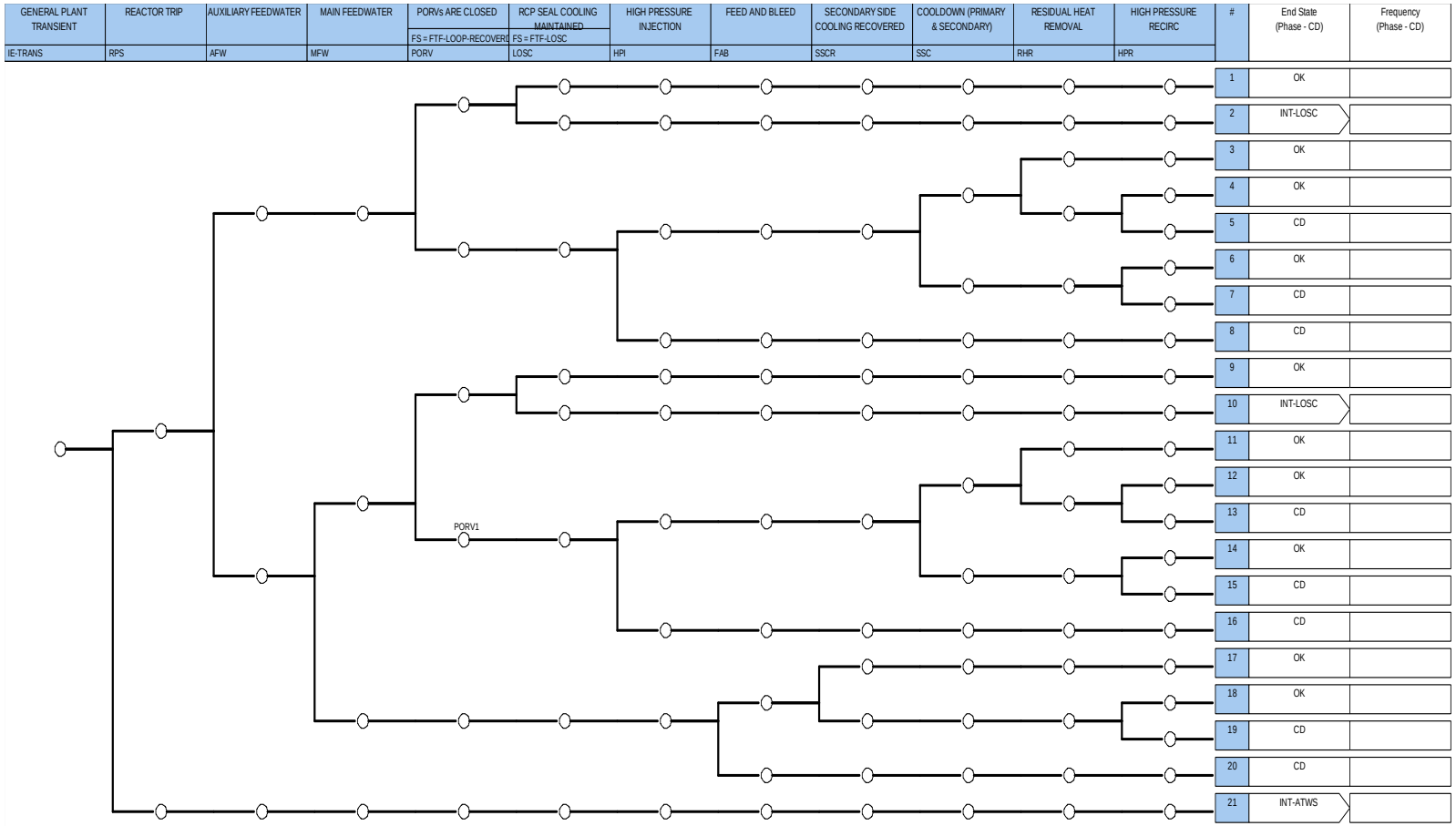


QIAS-P reconstructed architecture based on APR 1400 design

QIAS-P	qualified indication and alarm system – safety
SDD	software design description
SRS	software requirements specifications
STD	systems test document

(III). Consequence Analysis

- In FY-21, consequence analysis has been performed **by comparing the changes of CDF after adding integrated FTs of digital RTS and ESFAS** to the generic PWR event tree model.



A General PWR Transient Event Tree

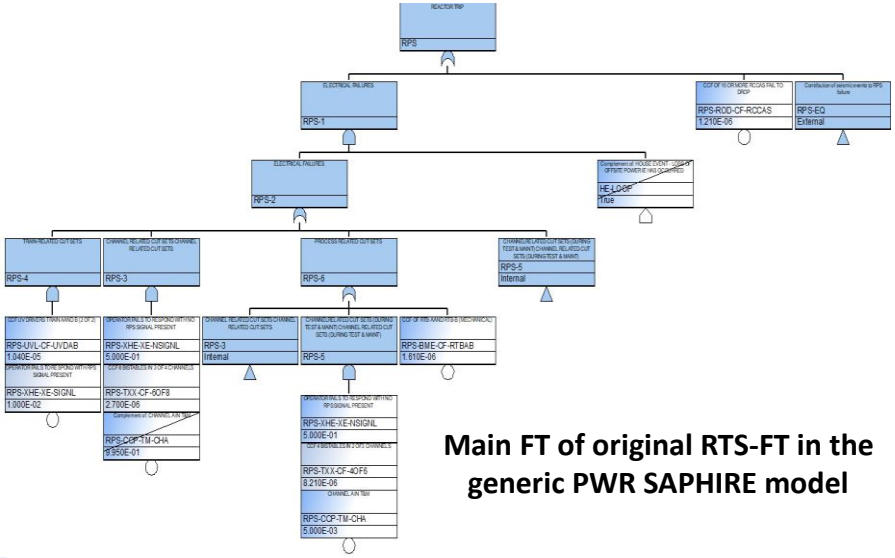
Original and New Fault Trees for Reactor Trip System

Cut sets for the original RTS-FT

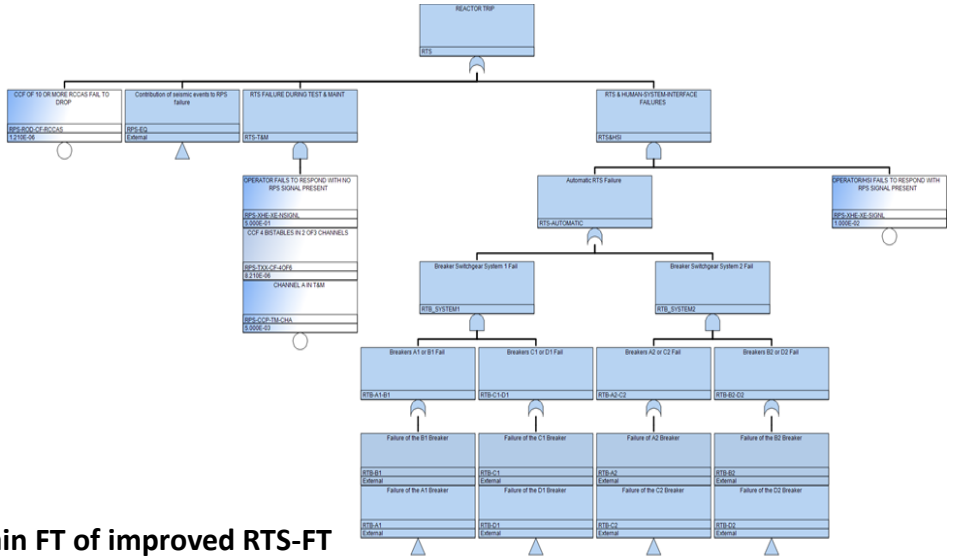
#	Prob.	Total %	Cut Sets
1	1.610E-6	37.55	RPS-BME-CF-RTBAB
2	1.343E-6	31.33	RPS-CCP-TM-CHA, RPS-TXX-CF-6OF8, RPS-XHE-XE-NSIGNL
3	1.210E-6	28.22	RPS-ROD-CF-RCCAS
4	1.040E-7	2.43	RPS-UVL-CF-UVDAB, RPS-XHE-XE-SIGNL
5	2.052E-8	0.48	RPS-CCP-TM-CHA, RPS-TXX-CF-4OF6, RPS-XHE-XE-NSIGNL
Total	4.288E-6	100	-

Cut sets for the new RTS-FT

#	Prob.	Total %	Cut Sets
1	1.210E-6	95.25	RPS-ROD-CF-RCCAS
2	2.052E-8	1.62	RPS-CCP-TM-CHA, RPS-TXX-CF-4OF6, RPS-XHE-XE-NSIGNL
3	1.976E-8	1.56	RPS-XHE-XE-SIGNL, RTB-SYS-2-HD-CCF
4	1.976E-8	1.56	RPS-XHE-XE-SIGNL, RTB-SYS-1-HD-CCF
Total	1.270E-6	100	-



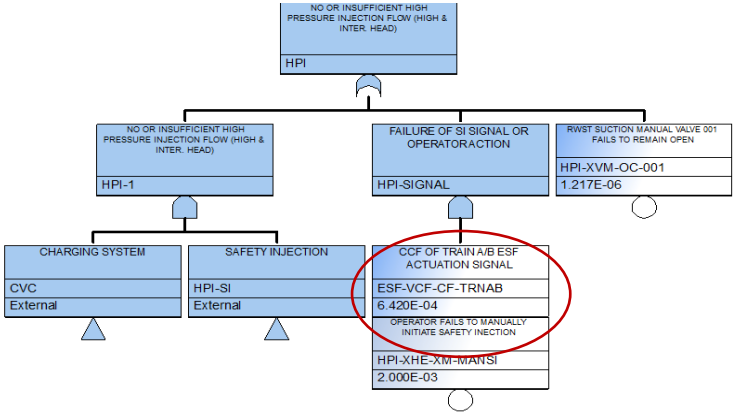
Main FT of original RTS-FT in the generic PWR SAPHIRE model



Main FT of improved RTS-FT using IRADIC

Original and New Fault Trees for ESFAS

- In the original generic PWR SAPHIRE model, ESFAS failure is presented using a CCF of the ESF actuation signals in both Train A and B (a 2-division ESFAS).
- Compared with the original ESFAS-FT, the new ESFAS-FT has:
  - A complicated logic to match the 4-division digital ESFAS structure deployed in APR-1400.
  - A significantly reduced failure probability.
- **Software CCFs in the new ESFAS-FT do not significantly affect the reliability of digital ESFAS** because of the high-redundant design and high reliability of PLC-based digital systems.
- All the **failure probabilities of these safety features have been reduced** due to the decrease of ESFAS failure probability.



Main FT of HPI failure in the generic PWR SAPHIRE model where CCF of analog ESFAS is considered.

Cut sets for the new ESFAS-FT

FT Name	Prob.	# of Cut Sets
New ESFAS-FT	2.600E-5	13
Original ESFAS-FT	6.420E-4	1

Comparison of the top events with original ESFAS-CCF basic event and improved ESFAS-FT

Top Event	Probability		# of Cut Sets	
	Original	New	Original	New
Failure of AFW	1.487E-5	1.240E-5	1539	1551
Failure of AFW-ATWS	2.367E-4	2.343E-4	906	918
Failure of HPI	1.104E-5	9.803E-6	1163	1172
Failure of LPI	8.416E-4	2.258E-4	1567	1579

CDF Reduction by Adding Digital RTS and ESFAS Fault Trees into Event Trees

- Results show the **CDFs have been greatly reduced**.

Event Trees	Original CDF	New CDF	Δ CDF	Δ CDF/ Original CDF
INT-TRANS	**1.073E-6**	**5.795E-7**	**- 4.935E-7**	**- 46%**
INT-SLOCA	7.784E-8	7.512E-8	- 2.720E-9	- 3.4%
INT-MLOCA	6.279E-7	5.032E-7	- 1.247E-7	- 20%

- By adding the integrated FTs of the 4-division digital RTS and ESFAS into the PRA models, the safety margin increased by the digitalization of HSSSR I&C systems are quantitatively estimated.
  - RTS failure probability is half-reduced from 4.288E-6 to 1.270E-6.
  - LPI (low-pressure injection) failure probability greatly decreases from 8.416E-4 to 2.258E-4 due to the improvement of ESFAS fault tree.

Using **IRADIC technology** shows **deploying advanced digital RTS and ESFAS** provides great benefits to plant safety **through an increased safety margin** to accident management

Summary

- **INL-IRADIC Technology aims to:**
  - Develop a best-estimate, risk-informed capability to estimate quantitatively and accurately the safety margin obtained from plant digitalization, especially for the high safety-significant safety-related (HSSSR) DI&C systems.
  - Construct a modularized platform for I&C designers, software developers, plant engineers, and risk analysts to efficiently estimate and prevent the risk introduced by CCFs, especially software CCFs.
  - Provide technical basis and risk-informed insights to assist NRC and industry in formalizing licensing processes relevant to addressing CCF issues in HSSSR DI&C systems.
  - Be an integrated risk-informed tool for vendors and utilities to meet the regulatory requirements and optimize the D3 applications in the design stage of HSSSR DI&C systems.
- Demonstration results show **digitalization of HSSSR I&C systems** (e.g., digital RTS and ESFAS) **provides great benefits to plant safety** through an increased safety margin to accident management.
- Future work in FY-22 includes:
  - Building up the capability of software CCF modeling and embeding it into the IRADIC technology.
  - Improving the methodology and demonstration of IRADIC-ORCAS method.
  - Performing uncertainty quantification and validation to better support the best-estimate prediction of safety margins (e.g., ΔCDF) obtained by the deployment of DI&C systems.

Sustaining National Nuclear Assets

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