U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Operator Support Technologies for Fault Tolerance and Resilience

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Nuclear Energy Enabling Technology

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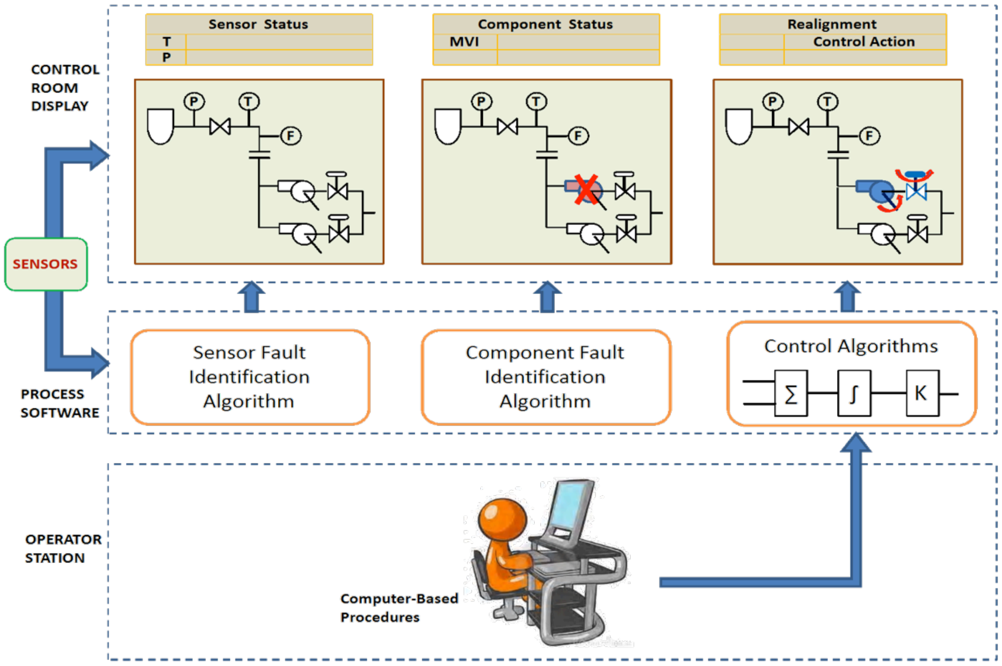
Project Overview

- **A nuclear plant operator presently takes a symptom-based approach to upsets**
  - Not necessarily expected to diagnose a fault
  - Fault diagnosis is time consuming, approximate, and prone to error
- **Situational awareness is limited by old technologies**

Project Overview

- **Objective - Develop and demonstrate technologies to significantly enhance nuclear plant operator response to time-critical component faults, resulting in fewer safety challenges and higher capacity factors**

- **Capitalize on performance, cost, and functionality improvements of software development tools, graphics hardware, and reasoning algorithms**



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Computerized Operator Support System - Definition

A Computerized Operator Support System (COSS) is a collection of capabilities to assist operators in monitoring overall plant performance and making timely, informed decisions on appropriate control actions for the projected plant condition. Features:

- **Monitoring plant states to detect off-normal conditions**
- **Diagnosis of plant faults**
- **Prediction of future plant states**
- **Recommendation of mitigation alternatives based on embedded expert knowledge**
- **Decision support in selecting appropriate mitigation actions**
- **Monitoring to verify mitigation is effective**

Goals of COSS

- **Provide information automation**
  - Display key information operators need in one place
- **Provide early detection system of faults**
  - Faults can be detected and validate before the normal plant alarms would be actuated
- **Help operators make decisions**
  - Provide intelligent prognostics system that informs operators of emerging problems and provides early decision support
- **Help operators perform actions**
  - Computerized procedure system (instead of reams of paper) that take operators directly to the control actions that will mitigate the particular fault

Fault Diagnosis in COSS

- **Conservation laws and sensor readings are used to infer the identity of a fault**
- **Reasoning process is not dependent on furnishing a list of candidate faults a priori to be processed by elimination**
- **Plant specific description is limited to process instrumentation diagram (P&ID) information**
- **The data is the model, hence does not require plant engineering parameter data or solving differential equations**
- **Diagnostic capability operates at the system level rather than being limited to the component level**
- **Diagnostic capability adapts to both life cycle changes and equipment realignment**

Fault Diagnosis in COSS

- **Sensor readings are mapped into conservation balances whose sign identifies fault. Mapping for generic valve shown here.**

Sensor Trend [a]	Status Indicators	Fault Diagnosis
$[dw_{in}]=-$ and $[dw_{out}]=-$ $[dw_{in}]=\uparrow$ and $[dw_{out}]=\uparrow$ $[dw_{in}]=\downarrow$ and $[dw_{out}]=\downarrow$	$\Rightarrow d[Q_{mom}]=-$ and $d[Q_{mass}]=-$ $\Rightarrow d[Q_{mom}]=-$ and $d[Q_{mass}]=-$ $\Rightarrow d[Q_{mom}]=-$ and $d[Q_{mass}]=-$	Normal Normal [b] Normal [b]
$[\Delta P]=/-$ and $[dw]=-$ $[\Delta P]=-$ and $[dw]=/-$	n/a n/a	Sensor Error Sensor Error
$[dw_{in}]=\downarrow$ and $[dw_{out}]=\uparrow$ and $[P]=\uparrow$ $[dw_{in}]=\uparrow$ and $[dw_{out}]=\downarrow$ and $[P]=\downarrow$	$\Rightarrow d[Q_{mass}]=\uparrow$ and $d[Q_{mass}]=\downarrow$ $\Rightarrow d[Q_{mass}]=\downarrow$ and $d[Q_{mass}]=\uparrow$	Leak Leak
$[\Delta P]=\uparrow$ and $[dw]=\downarrow$ $[\Delta P]=\downarrow$ and $[dw]=\uparrow$	$\Rightarrow d[Q_{mom}]=\downarrow$ and $d[Q_{mass}]=-$ $\Rightarrow d[Q_{mom}]=\uparrow$ and $d[Q_{mass}]=-$	Blockage Opposite of Blockage

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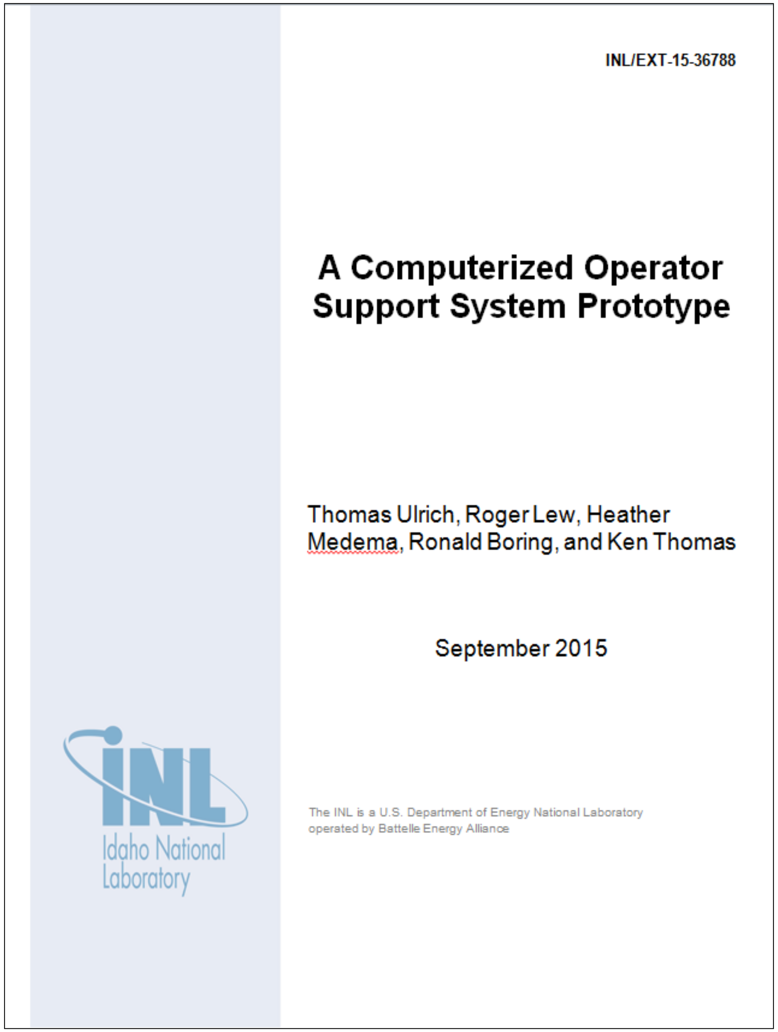
Accomplishments

- An earlier stand-alone COSS prototype has been integrated into the NPP Control Room Simulator (SIM) of the DOE Human Systems Simulation Laboratory (HSSL), providing dynamic interaction with changing plant conditions under fault conditions.
- Two fault scenarios have been developed for operator studies.

Accomplishments

- The COSS-SIM-PRODIAG Interface Protocol has been developed.
- Technical and Human Factors Requirements for a production COSS have been identified.
- Operator performance constructs and evaluation strategies for a COSS have been developed.
- A milestone report describing these results, *A Computerized Operator Support System Prototype (INL/EXT-15-36788)*, was published on September 30th.


INL/EXT-15-36788

A Computerized Operator Support System Prototype

Thomas Ulrich, Roger Lew, Heather Medema, Ronald Boring, and Ken Thomas

September 2015

INL Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

Accomplishments

- **Simulated twenty different faults in the Chemical and Volume Control System (CVCS) of a Pressurized Water Reactor (PWR)**
- **Verified and validated fault diagnosis algorithm using faulted-plant simulation data**

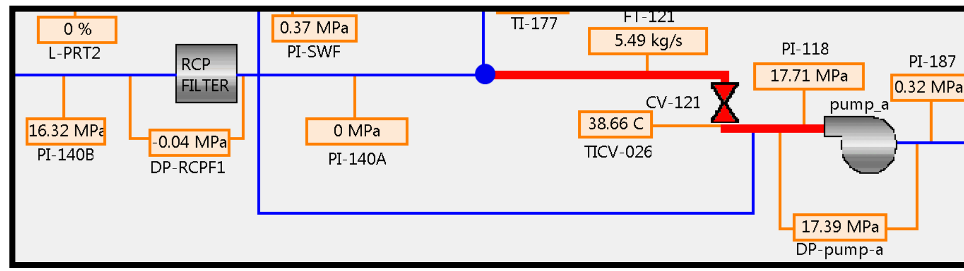
Fault	*Description*
CV01	Charging pump A trip
CVO2	Divert valve LCV-112A failure
CVO3	Pressure control valve PCV-131 failure
CVO4	RCS filter clogged
CVO5	RCP filter clogged
CVO6	Pressure transmitter PT-131 failure
CVO7	Temperature transmitter TE-130 failure
CVO8	Flow control valve CV-121 failure
CVO9	Letdown relief valve CV-8117 fails open
CV 10	Charging line leak outside containment

Fault	*Description*
CV 11	Regenerative heat exchanger tube leak
CV 12	VCT level malfunction
CV13	VCT pressure malfunction
CV 14	Charging header control failure
CV 15	Letdown line leak inside containment
CV 16	Letdown heat exchanger tube leak
CV 17	Letdown line leak outside containment
CV 18	Charging line leak inside containment
CV 19	Seal injection line leak
CV 20	Reactor coolant pump seal 1 failure

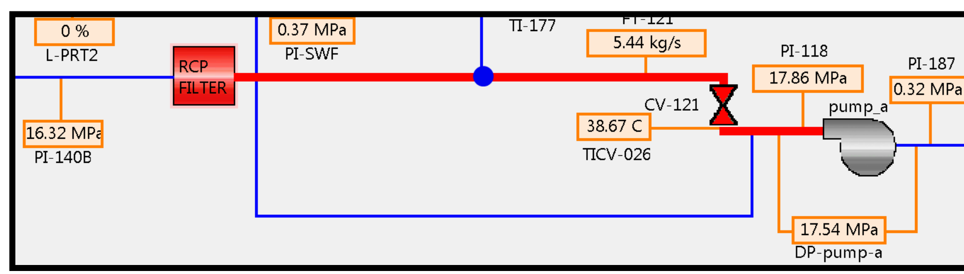
Accomplishments

- Characterized performance of fault diagnosis algorithm as a function of sensor set

Label	Default CVCS Sensor Set	Outcome with Rich Sensor Set
CV01	✔	✔
CV02	✘	✔
CV03	✔	✔
CV04	✘	✔
CV05	◯	✔
CV06	✔	✔
CV07	✔	✔
CV08	✔	✔
CV09	✘	✔
CV10	◯	✔
CV11	✔	✔
CV12	✔	✔
CV13	✔	✔
CV14	◯	✔
CV15	✘	✔
CV16	◯	✔
CV17	◯	✔
CV18	◯	✔
CV19	✔	✔
CV20	✔	✔



Rich sensor sets



Incomplete sensor sets

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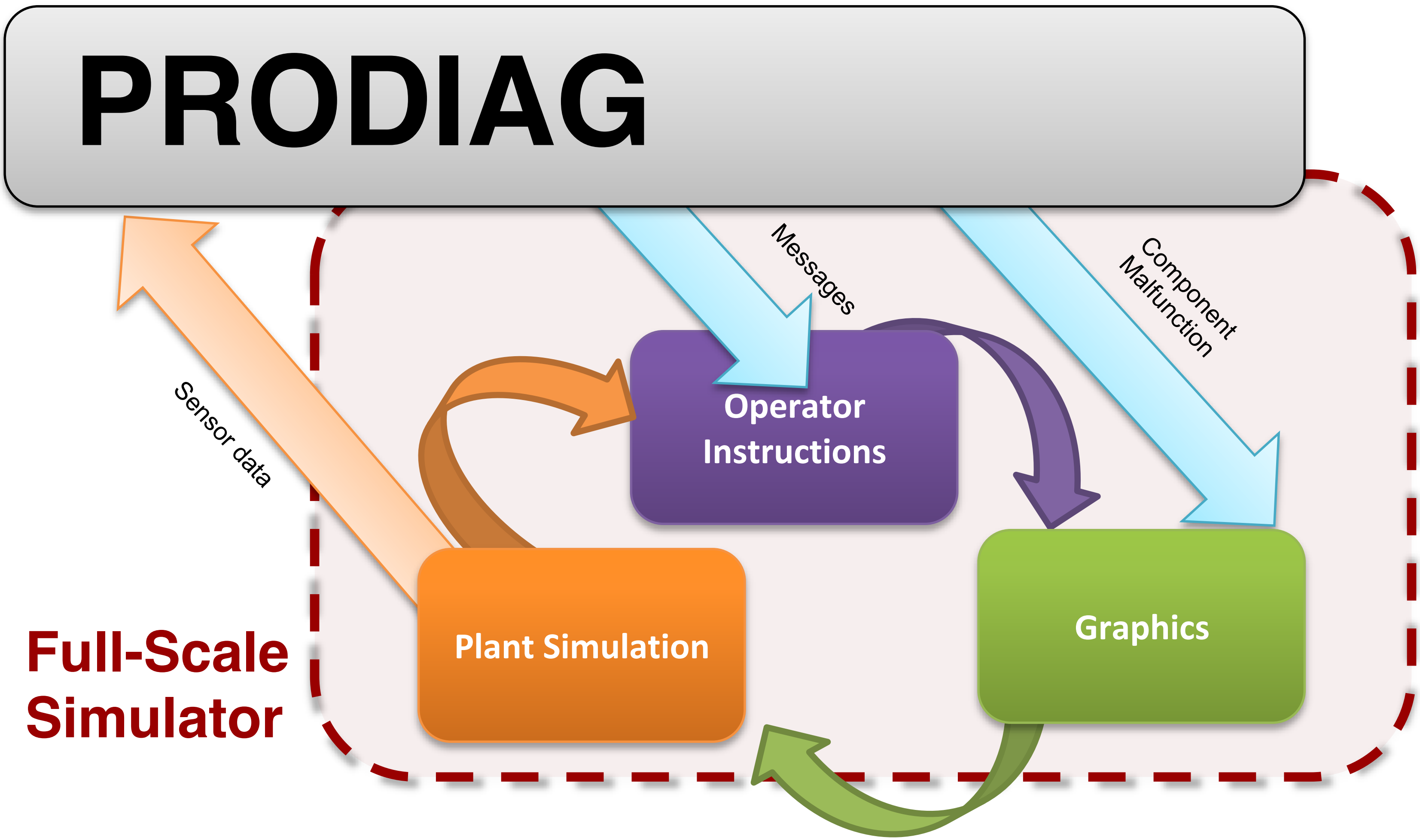
Overview of Integration



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COSS Integrated with HSSL Simulator

COSS has been integrated into the full scope simulator for a 3-Loop PWR. The COSS display to the left is the Operator Interface panel. The COSS display to the right is the Plant Systems Overview. The COSS displays reflect the real-time plant parameters for normal and fault conditions.

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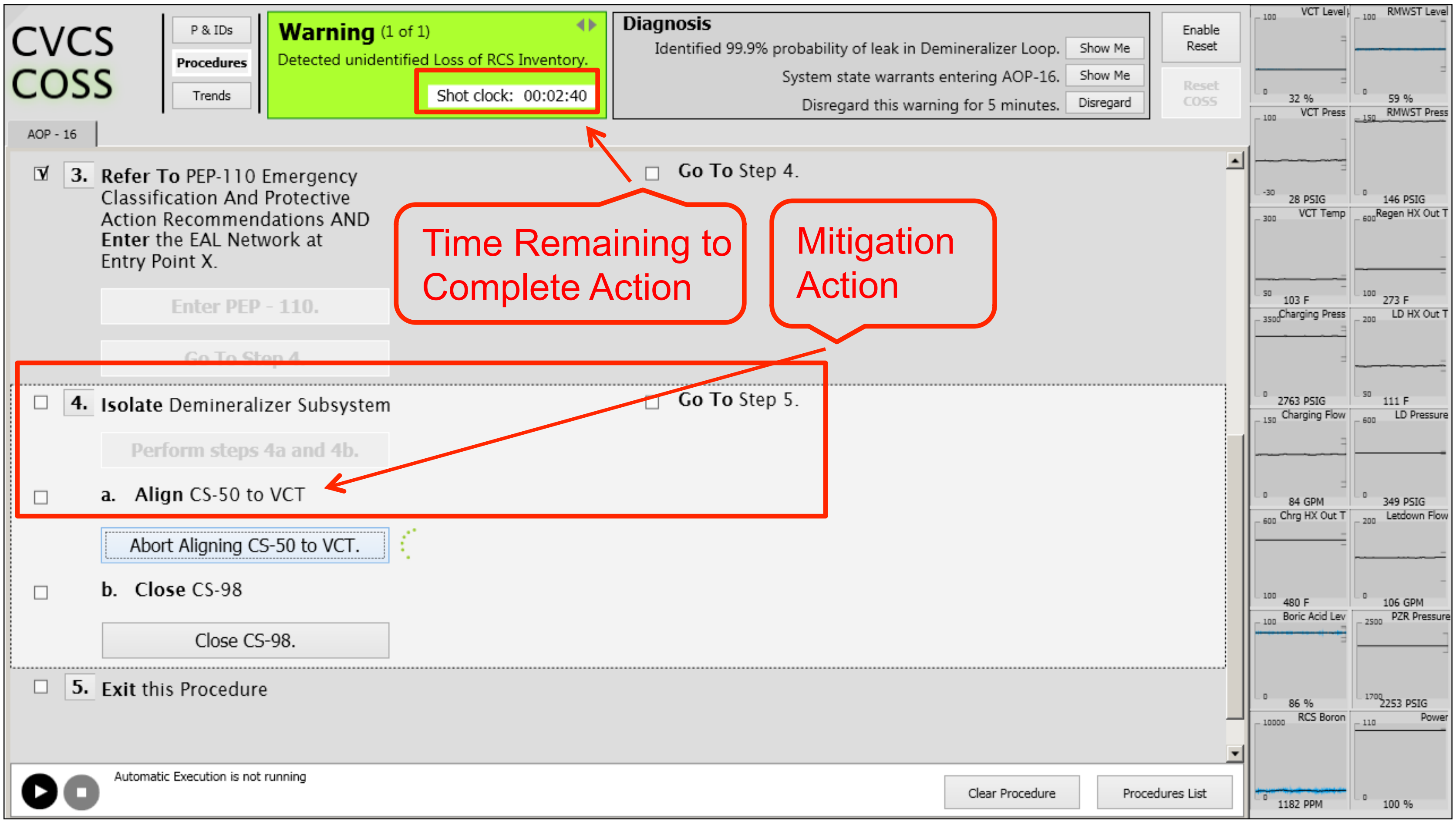
COSS Transitions to Computer-Based Procedures for Fault Mitigation



Initial Operator Feedback

- **Walked four licensed reactor operators through two scenarios**
  - Conducted think-aloud protocol paired with semi-structured interviews
- **Findings (open-ended feedback)**
  - The system responded accurately to the plant upset
  - Warning system deemed effective in alerting operators to problems
  - Integration of information in the computer-based procedures greatly reduced operator movement across the control boards
  - Multiuse of alarm tiles to both trend and alarm was considered extremely helpful to the operators

Technology Impact

- NPP control room operator performance remains a significant factor in nuclear safety for operating plants, in spite of two decades of emphasis on various human performance techniques. While partially successful, these techniques have added substantial operator burden.
- There has been very little innovation to assist control room operators with plant system monitoring, fault detection and diagnosis, and decision support for fault mitigation.
- COSS is a highly promising technology to reduce operator burden while improving operator performance and thereby increasing nuclear safety margins. It assists operators without encroaching on licensed operator responsibilities and authority.
- COSS builds on concepts that have been proven in other industry sectors, notably aviation.

Conclusion

- **Implemented, tested, and demonstrated main technologies**
  - The respective Labs have completed their first year tasks and as we enter the second year integration will take place
  - Method for fault diagnosis requires only P&ID input and so unlike other approaches it is tenable from a business model perspective – does not require a subject matter expert either during initial deployment or during operational life
  - Operators are looking for structure and organization in the way data is displayed – good feedback so far
- **Ready for full-scale simulator link-up**
  - Integration of validation, detection, diagnosis, control, and monitoring steps
  - On path to demonstrate that an operator advisory system – for the longest time an unrealized concept – is now achievable given the current state of supporting technology infrastructure (hardware, software, development tools)