10th International Workshop on the Application of FPGAs in Nuclear Power Plants

FPGA Applications in Life Extension Projects.

December 4-6, 2017, Gyeongju, Republic of Korea

Sergio Russomanno, COO, Projects and Business Development, SunPort S. A.

Sunport
Connecting Forward

www.sunport.ch

Sunport

Outline

Examples of 3 Modernization Projects.

1. ESFAS replacement at Kozloduy 5-6
2. Window Annunciator replacement in Safety Systems at Embalse NPPs
3. Addition of an SDS2 trip on low HTS pump RPMs

- Purpose
- Components, architecture and scope of work
- Details
- Equipment Qualification
- Key Factors in the success of the above projects.

Sunport

Kozloduy NPP. General Information

- Units 1-4 were older VVER units, built in the 70s (1-2) and 80s (3-4). Taken off service between 2004 and 2006

- Units 5 and 6 are VVER-1000. They were constructed 1987 and 1991 respectively.

Sunport

Purpose for the Refurbishment of Kozloduy 5-6 ESFAS

- Extend the plant life by 30 years and upgrade its generation capacity. ESFAS was implemented using FPGA technology.

- Achieve longer term operability by increasing safety and availability of the plant. The new ESFAS design incorporates self-test and on line diagnostics.

Sunport

Purpose for the Refurbishment of Kozloduy 5-6 ESFAS

- **Conformance with national and international regulations, standards and recommendations**
  - standards (IEC 60880, IEC 62138, IEC 61226, IEC 61513, IEC 61508)
  - IAEA standards (IAEA NS-G-1.3, NS-G-1.1, NS-R-1)

- **Addressing obsolescence**
  - The option chosen for Kozloduy was to adopt FPGA technology as a replacement for their obsolete ESFAS hardware. This would not only solve the immediate obsolescence problems but would also lower the burden posed by future obsolescence issues.

Sunport

Purpose for the Refurbishment of Kozloduy 5-6 ESFAS

- **Improve the efficiency and effectiveness of operation and maintenance activities. This reduces labour costs and frees plant personnel to execute other tasks.**
  - Improvements to the Human-Machine interface
  - Automation of periodic testing
  - Incorporation of on line diagnostics.

- **Compliance with regulatory requirements**
  - Improved the electrical and physical separation between safety divisions

Sunport

Adoption of FPGA-based Technology. Emphasis:

- **Safety**
  - Compliance with modern international standards to ensure a high degree of reliability
  - Excellent approach to defense-in-depth through diversity
- **Minimization of schedule risks.**
  - Simplicity of design and V&V processes
  - Modularity, standardization and minimization of parts to support Constructability
- **Catering to Obsolescence**
  - Portable applications (HDL) caters to obsolescence
- **Plant Availability**
  - Advanced on-line diagnostics supports Operability and Maintainability

Sunport

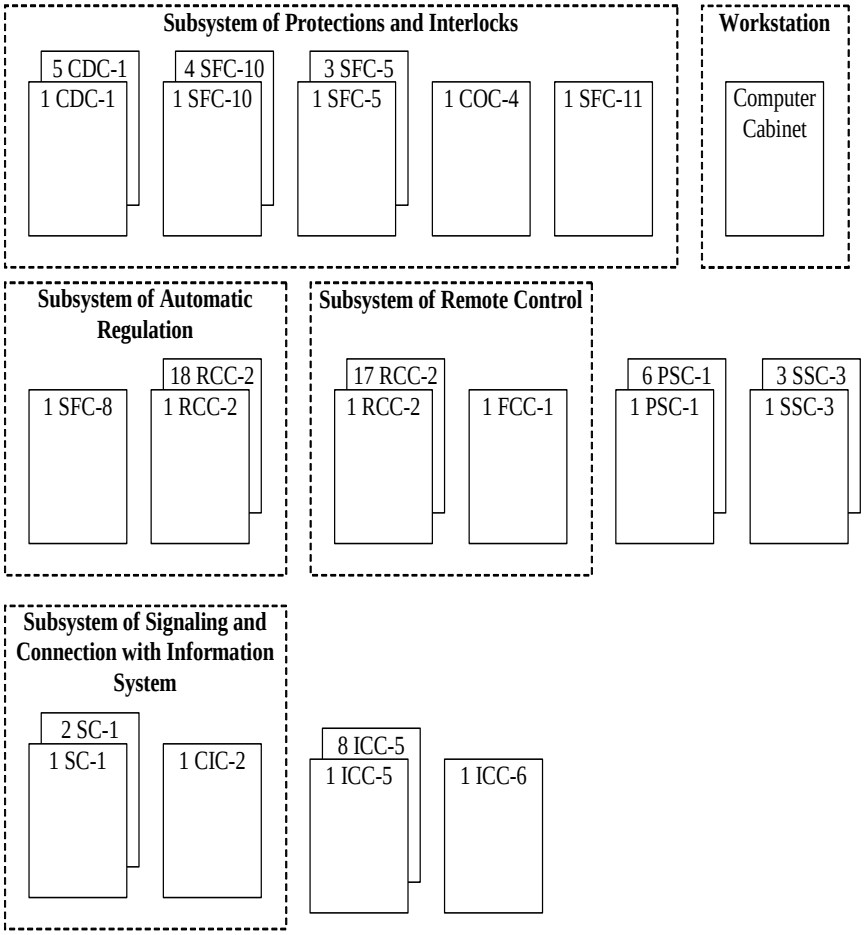
Kozloduy's ESFAS. Scope of Supply

- Logic Control Module;
- Analog Signals Input Module
  (0-5 VDC, 0-10 VDC, 0-5 mA, 4-20 mA);
- Normalizing Converter Module for Thermocouple Signals;
- Normalizing Converter Module for RTD Signals;
- Discrete Signals Input Module
  (Dry Contact > 10 KOhm, 24 VDC);
- Analog Signals Output Module
  (0-5 VDC, 0-10 VDC, 0-5 mA, 4-20 mA);
- Discrete Signals Output Module
  (Dry Contact; 0 – 450 VDC, 0 – 450 VAC);
- Actuators Control Module;
- Optic Communication Module;
- Power Supply Modules
  (AC/DC);
- Chassis and Backplanes;
- Terminal Block, Cable, Wire and Fiber Optic Sets;
- Cabinets.

Sunport

Kozloduy ESFAS. Equipment Composition

- Normalizing Converter Cabinets (NCC);
- Signal Forming Cabinets (SFC);
- Cross Output Cabinets (COC);
- Remote Control Cabinets (RCC);
- Signaling Cabinets (SC);
- Power Supply Cabinets (PSC);
- Sensor Supply Cabinets (SSC);
- Unified Current Signal Distribution Cabinets (CDC);
- Intermediate Clamp Cabinets (ICC)
- Remote Control Cabinet (RCC).



I/O Details:

AI – Qty 550

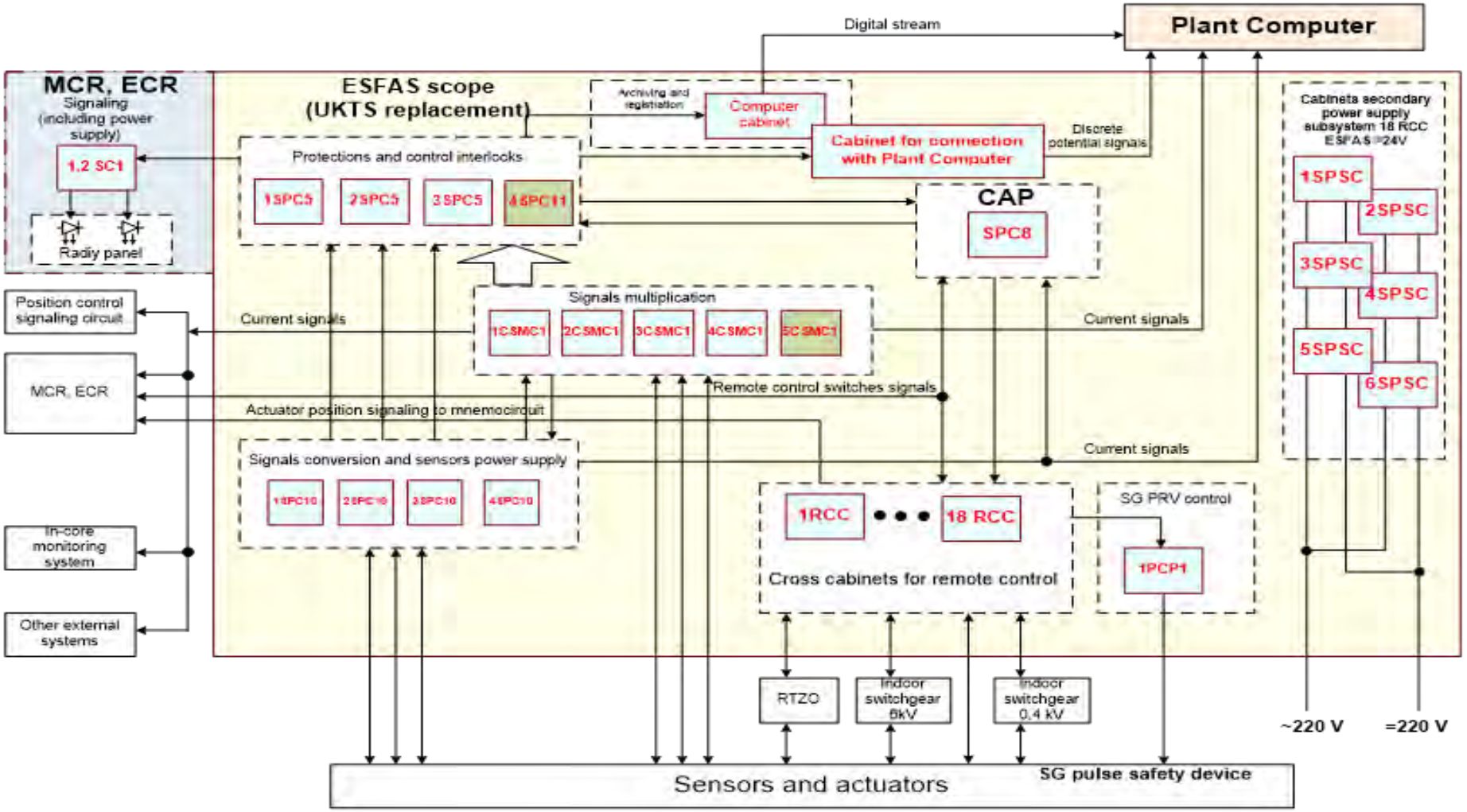
DI – Qty 1700

AO – Qty 100

DO – Qty 1000

Sunport

Kozloduy ESFAS Architecture



Designed by	Nurtsevytch			Safety system structure based on ESFAS produced by PC "RPC Radiy" for Kozloduy NPP
Revised by	Tokariev			
Approved by				

I&C Systems D
PC "RPC Radi

Sunport

Acronyms. ESFAS Architecture

ESFAS	Engineered Safety Features Actuation System
UKTS	Unified Software and Hardware System
PCP	Power control panel
RCC	Remote control cabinet
SPC	Signal Processing Cabinet
SPSC	Secondary power supply cabinet
PRV	Pressure relief valve
MC	Multiplication and current
SC	Signaling cabinet
ECR	Emergency Control Room
RTZO	Switchgears cabinets
CSMC	Current signals multiplication cabinet

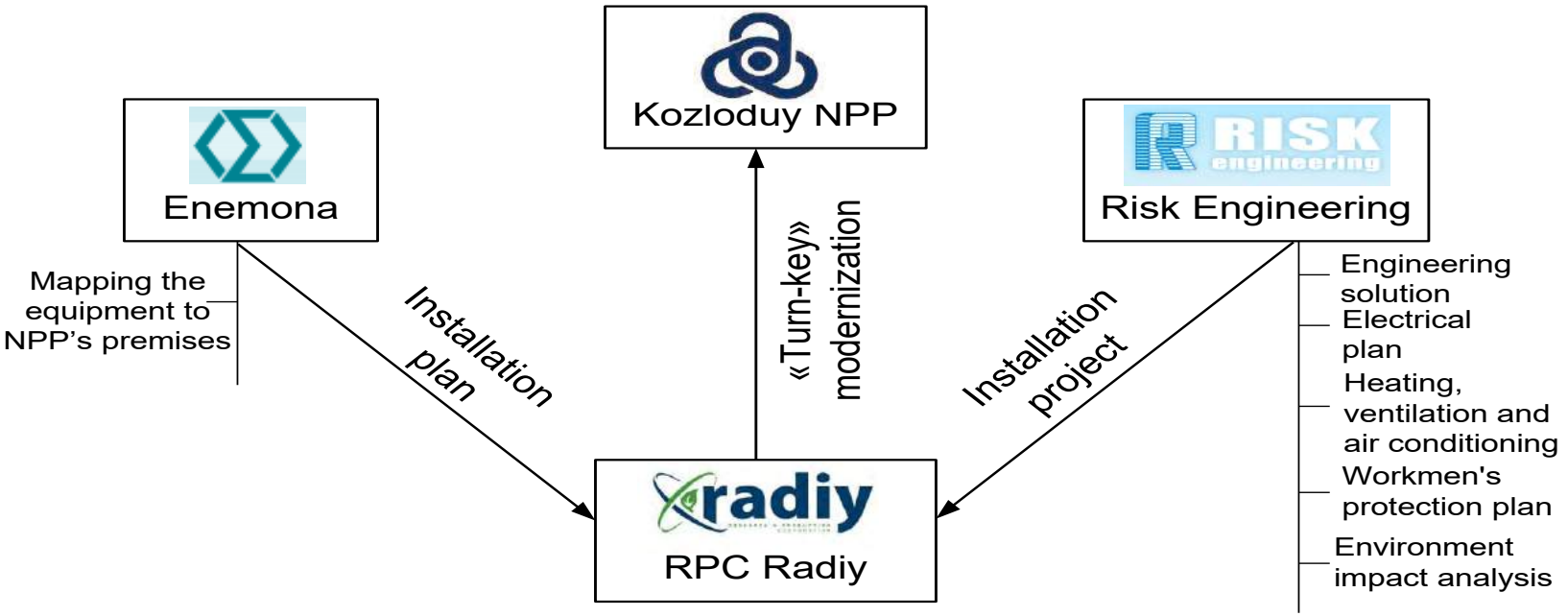
Sunport

Radiy's scope of work.

- **System design**
  - Basic and detail design
  - S/W development
  - Documentation preparation
- **Equipment Manufacturing**
- Equipment Environmental Qualification and FAT, mostly in-house
- Site Acceptance Tests
- System installation in situ
- System Commissioning
- Operational acceptance tests
- Documentation update to reflect As Built and As Commissioned status
- Training of Engineering, Operation and Maintenance staff

Sunport

Project Execution

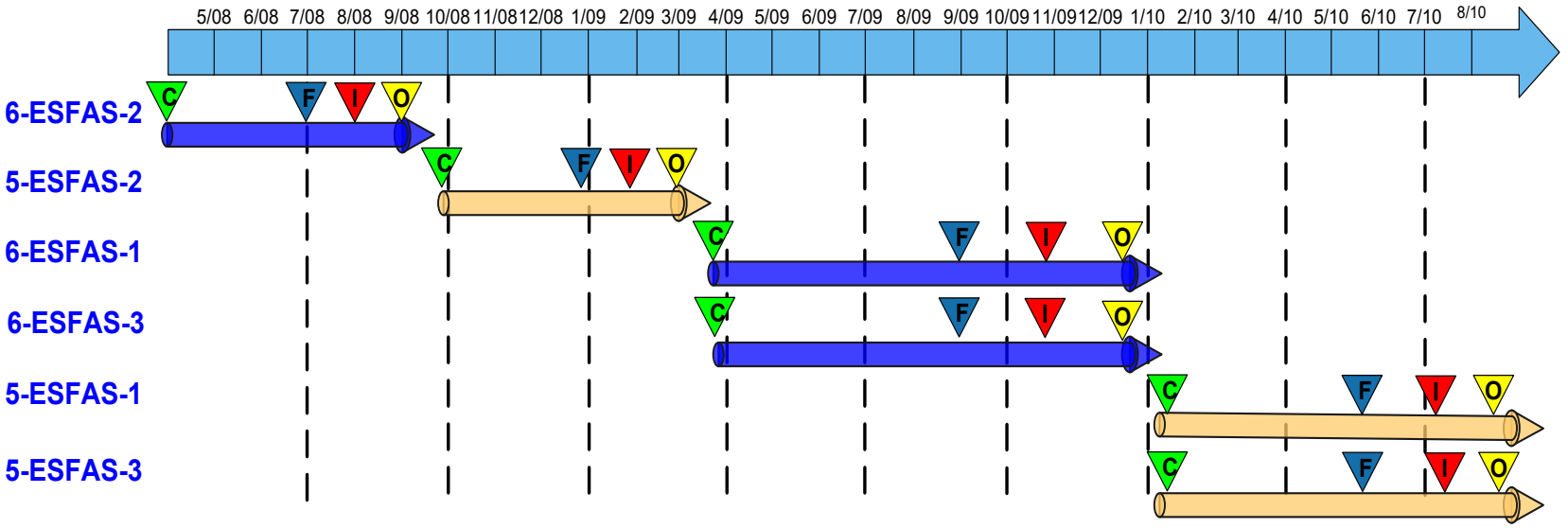


- Turnkey project. Therefore, Radiy was the Single Point of Contact with the utility for all activities associated with ESFAS refurbishment.

- Responsible for all pre-project and execution activities, from staff selection and qualification to installation and operational tests.

Sunport

Schedule of Turnkey Activities. Contract to Operation.



C - Contract with NPP

F - Factory Acceptance Testing

I - On-Site Installation

O - Operation

Sunport

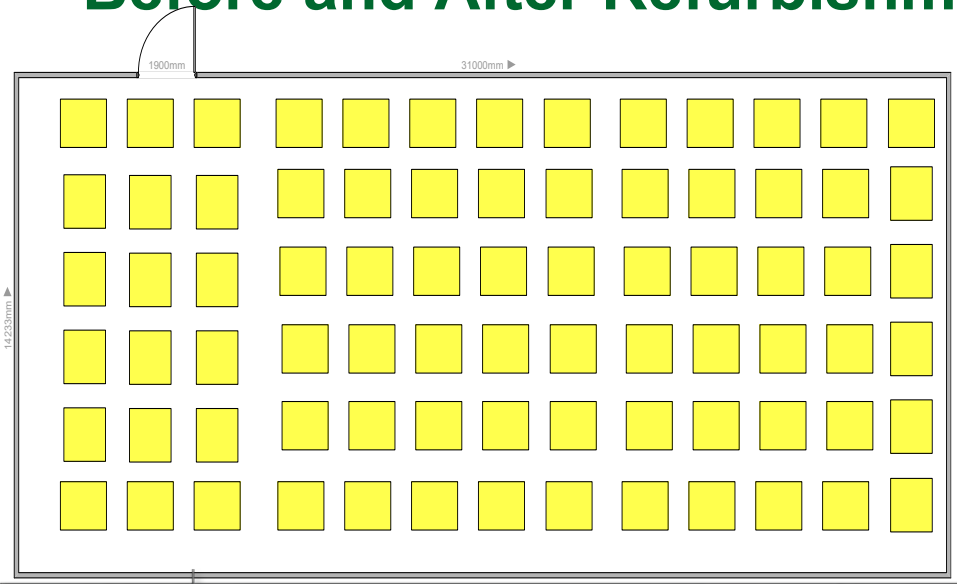
Installation Phase Day 1

Sunport

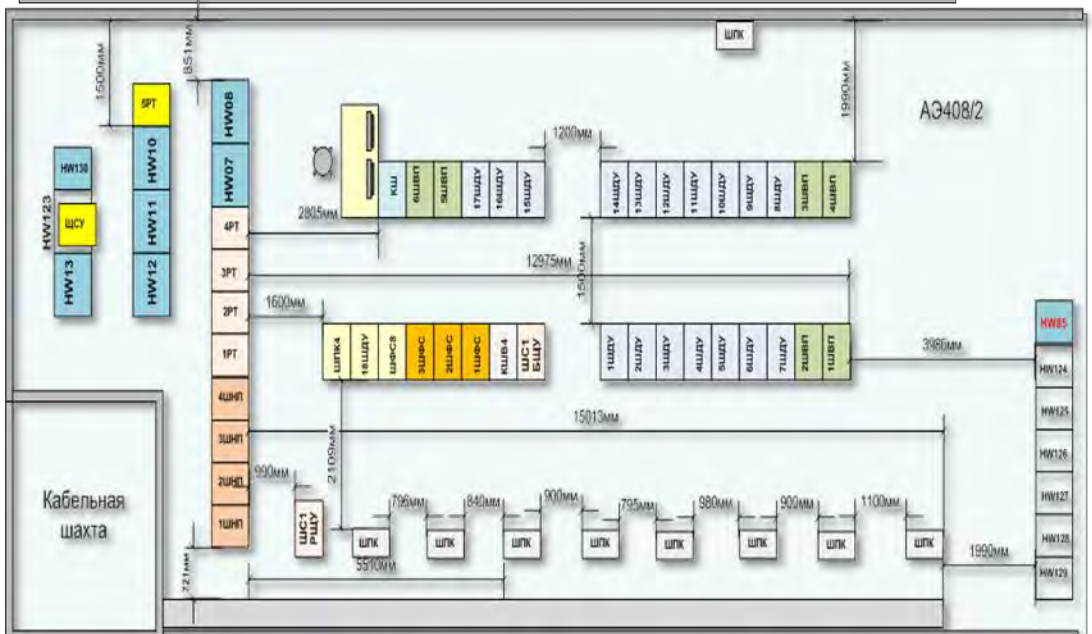
Finished (as installed) system cabinets

Sunport

Before and After Refurbishment



Before refurbishment. The ESFAS I&C system included 112 control panels.



ESFAS layout after refurbishment. All functionality implemented using 45 RadICS FPGA panels

Sunport

Embalse NPP

- Located in the province of Cordoba, approx. 700 Km NW of the city of Buenos Aires, Argentina
- CANDU (PHWR) began operation in 1983
- Presently in a Life Extension (30 additional years of operation) and power uprate (additional 40 MWe, up to 683 MWe).

Sunport

Purpose for the Refurbishment of Embalse NPP

30 years additional operation:

- Replacement of reactor components
- Cater to equipment obsolescence
- Trip Coverage
- Incorporation of changes resulting from PSA and DSA

Power Uprate. Additional 40 Mwe.

Sunport

RPC Radiy Projects for the Embalse NPP in Argentina

- Replacement of Main Control Room and Secondary Control Area Window Annunciators for critical safety systems.

- Shutdown System 2. Addition of Main Heat Transport Pump Motor Speed Measuring and Test Devices

Sunport

Purpose of the modifications

- **Replacement of Main Control Room and Secondary Control Area Window Annunciators for critical safety systems.**
  - The originally installed equipment (or a suitable substitute) was no longer offered by the manufacturer.

- **Shutdown System 2. Addition of Main Heat Transport Pump Motor Speed Measuring and Test Devices for**
  - The implementation of an additional trip parameter, i.e. a reactor trip on low speed of the Main Heat Transport Pumps.

Sunport

Radiy's Scope of Work as Contracted by the System Designer, Candu Energy (SNC Lavalin).

- **Equipment design per CE's Technical Specifications, this included:**
  - Detail design
  - S/W development
  - Documentation preparation

- **Equipment Manufacturing and Testing, this included:**
  - PCB, modules and Panel wiring and assembly
  - Equipment Environmental Qualification and Factory Acceptance Tests

Sunport

General Approach to the Embalse NPP related projects

- **Replacement of Main Control Room and Secondary Control Area Window Annunciators for critical safety systems.**
  - o The standard FPGA based RadICS platform was used to implement this project.
  - o RadICS is a SIL3 certified platform under IEC 61508.
  - o FFF approach. Direct replacement of old modules with new ones.
  - o New modules replicate the functionality of the old ones per client's request + Diagnostics.
  - o No operator re-training was required
  - o No changes to the existing electrical mechanical interfaces
  - o No changes to the existing Human Machine Interface.

Sunport

General Approach to the two Embalse related projects Cont…

- **Addition of Main Heat Transport Pump Motor Speed Measuring and Test Devices for Shutdown System 2.**
  - Radiy custom designed the signal processing/test unit using FPGA technology.
  - Several of the documents and tests designed to SIL3 qualify Radiy's equipment were used as a basis for the qualification of the design and equipment
  - The SPU was qualified to IEC 61513 Class 1 and supports Category A safety functions

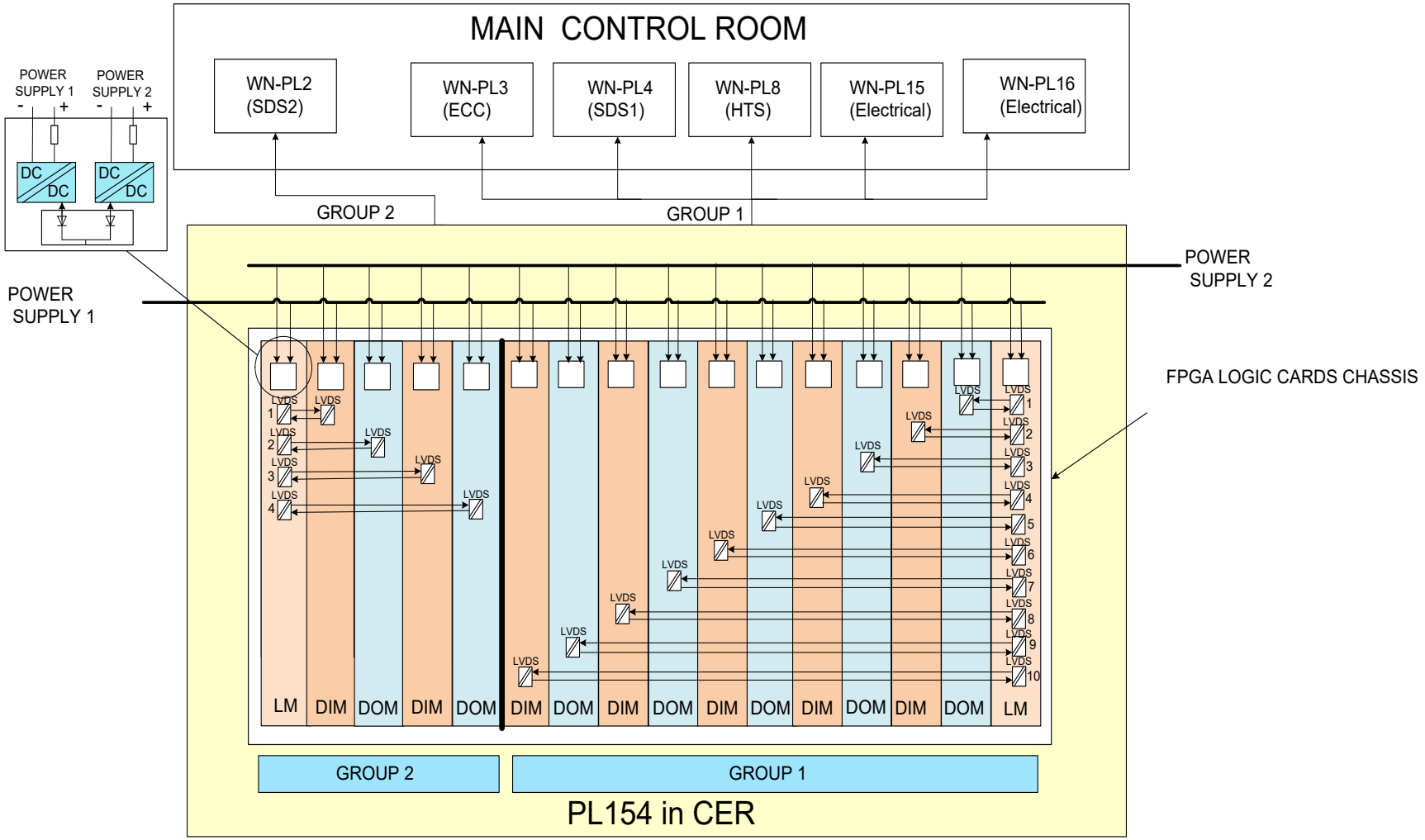
- **Both projects were implemented under a CSA Z299.1 quality standard as applicable to critical safety systems.**

Sunport

Window Annunciation. MCR Panels

Sunport

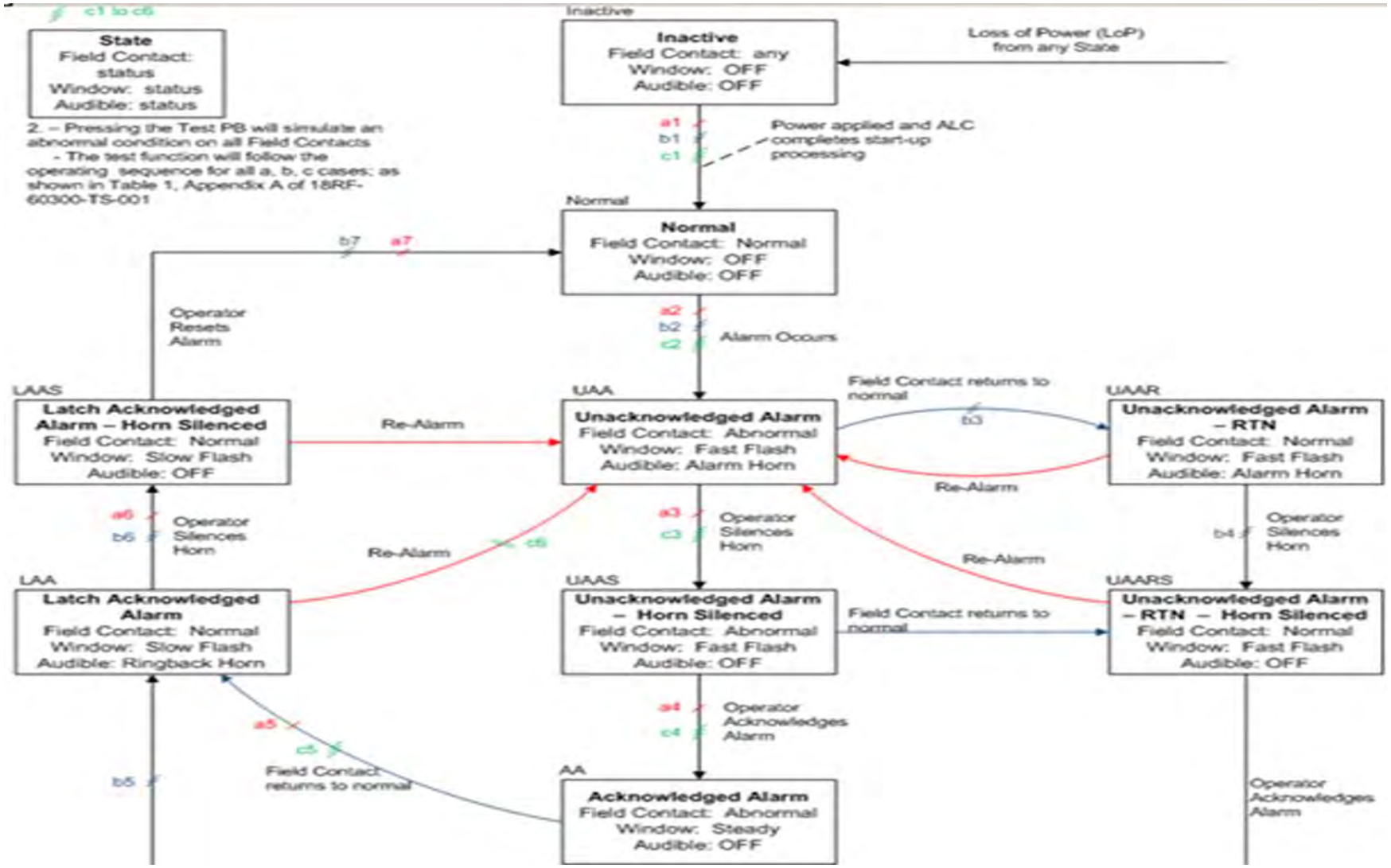
Window Annunciator Block Diagram



LVDS- LOW VOLTAGE DIFFERENTIAL SIGNALING

Sunport

State Transition Diagram. Window Annunciation.



Sunport

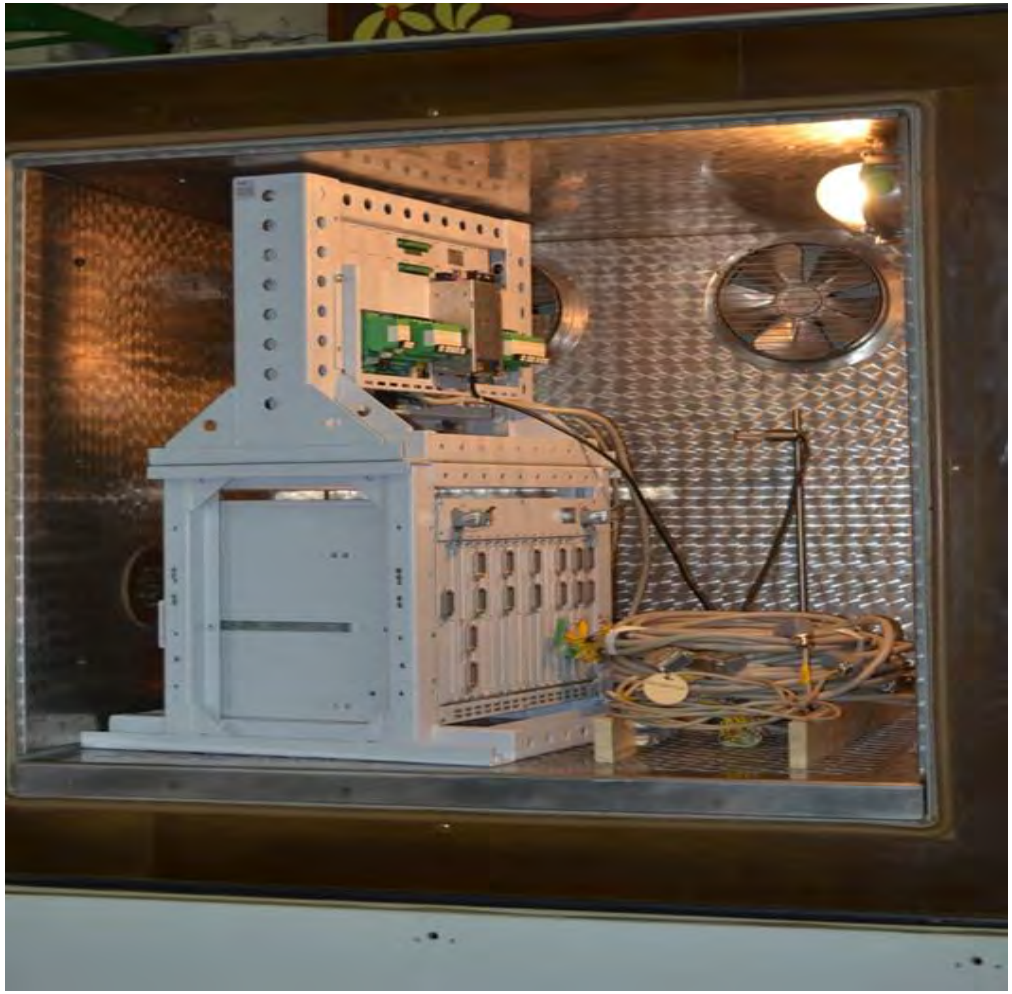
Qualification Tests

Test Type	Standard
Seismic and Thermal Aging	IEEE 344-2004
Environmental Qualification	IEC 60068-2-1 Test A IEC 60068-2-14 Test N
	IEC 60068-2-2 Test B IEC 60068-2-30 Test D
Electrostatic Discharge Immunity	IEC 61000-4-2:2008
Radio-frequency and Electromagnetic Field Immunity	IEC 61000-4-3:2006
Electrical Fast Transient/Burst Immunity	IEC 61000-4-4:2004
Surge Immunity	IEC 61000-4-5:2006
Immunity to Conducted Disturbances Induced by Radio-Frequency Fields	IEC 61000-4-6:2007

Sunport

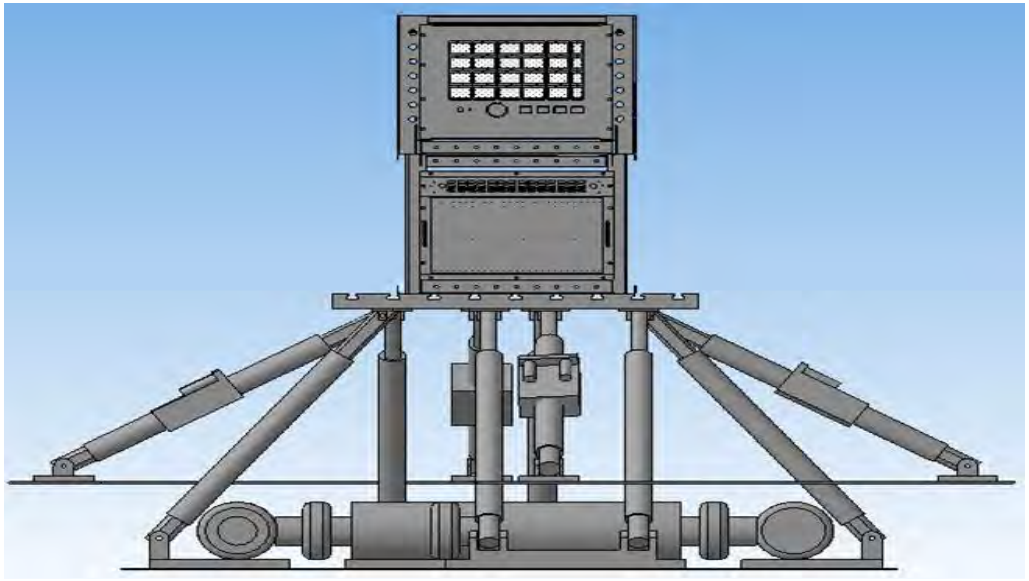
Qualification Tests. Cont..

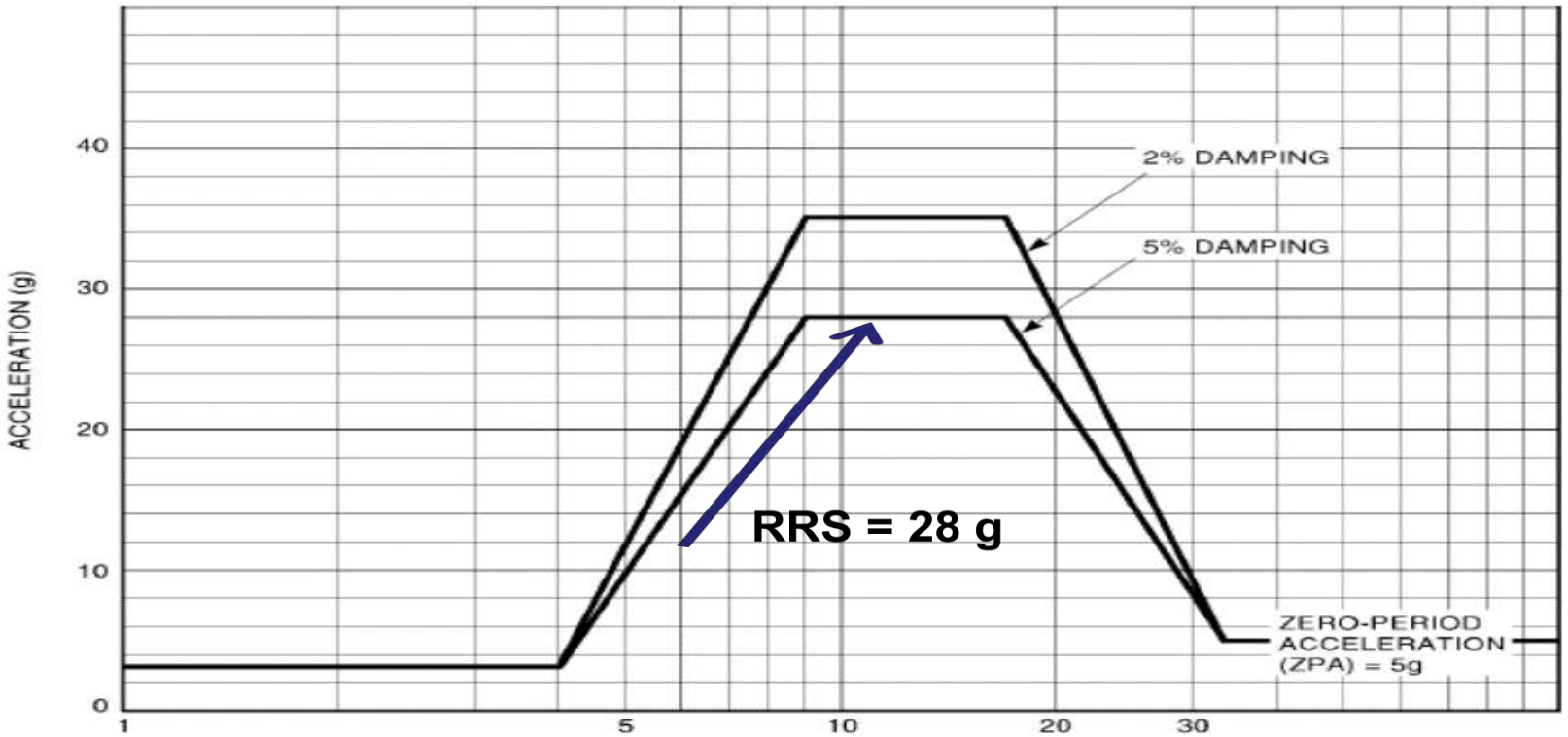
- Prior to seismic test, all components were thermally aged to an equivalent of 30 years of operation
- Thermal aging was achieved by exposing the equipment to a temperature of 116°C for 198 hours



Sunport

Seismic Qualification

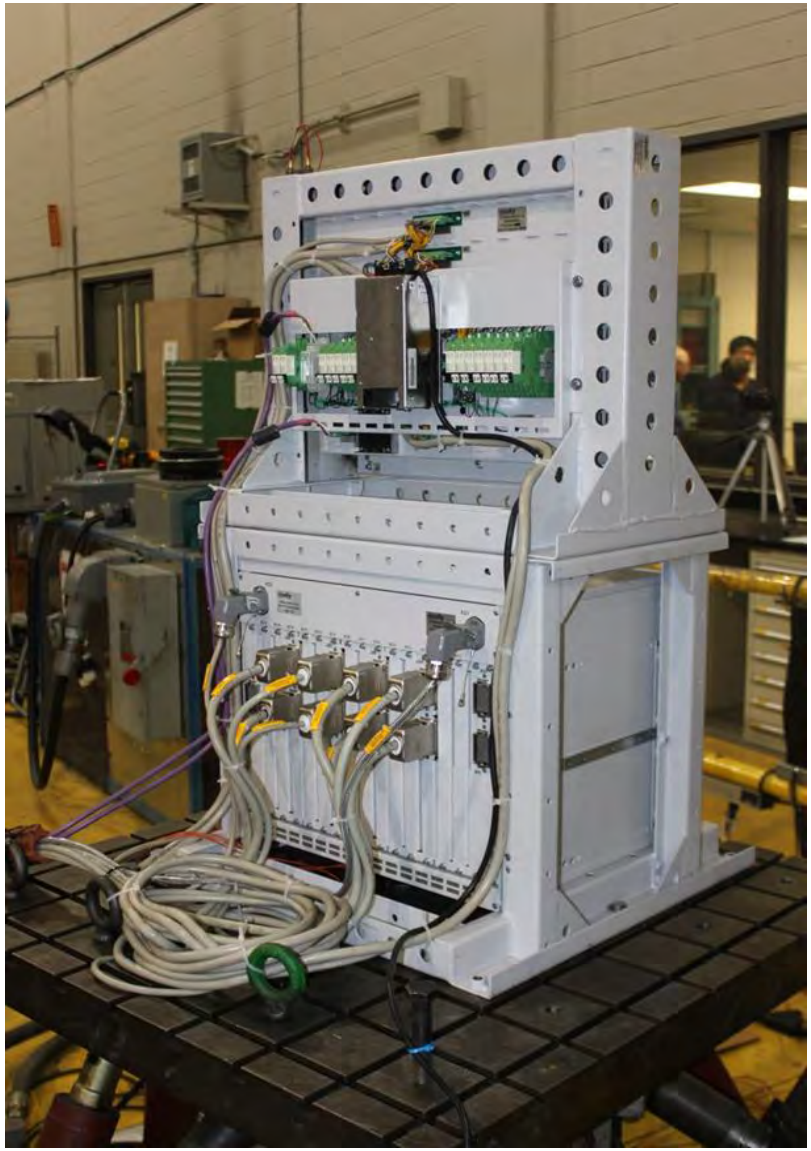




980917-1

Sunport

Annunciator. Seismic Qualification Cont…



Sunport

Annunciator. Environmental Qualification Tests

Name and unit of measurement	Testing value	Standard
Temperature, °C ➡lower, not more ➡upper, not less	 10 50	IEC 60068-2-2:1974 Environmental testing – Part 2: Tests – tests B: Dry heat
Speed of temperature change, °C/hour (not less)	5	
Relative humidity, % ➡lower, not more ➡upper, not less	 5 (at 15°C during 2 hours) 100 (at 50°C during 2 hours)	IEC 60068-2-3:1969 Environmental testing – Part 2: Tests – tests C: Damp heat, steady state
Barometric pressure, kPa ➡lower, not more ➡upper, not less	 84 108	

Sunport

Annunciator. Electromagnetic Compatibility Tests

Interference type	Interference parameters	Hardness degree	Standard
Electrostatic discharge	Contact discharge – 8 kV Air discharge – 15 kV	4	IEC 61000-4-2:2001. Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 2: Electrostatic discharge immunity test
Radiated, radio-frequency, electromagnetic field	Electrical field intensity – 10 V/m Frequency band – from 26 MHz to 1000 MHz Modulation frequency – 1 kHz Modulation depth (percentage) – 80%	3	IEC 61000-4-3:2001. Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 3: Radiated, radio-frequency, electromagnetic field immunity
Fast transient and burst (nanosecond noise spikes)	In power supply circuits – 4 kV In input-output circuits – 2 kV	4	IEC 61000-4-4:2001. Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 4: Electrical fast transient / burst immunity test
Surge (microsecond noise spikes)	In power supply circuits: Symmetrical interference – 2 kV Asymmetrical interference – 4 kV	4	IEC 61000-4-5:2001. Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 5: Surge immunity test

Sunport

SDS2. Main Heat Transport Pump Motor Speed Measuring and Test Devices.

Sunport

SDS2. Main Heat Transport Pump Motor Speed Measuring and Test Devices.

- Addition of a reactor trip on low HTS pump RPM
- Scope of supply includes sensing, signal processing, self diagnostics and test capabilities.
- Design based on the customer Technical Specifications
- Sensor and cable\connector were LOCA qualified
- The SPU was qualified to IEC 61513 Class 1 Category A safety functions

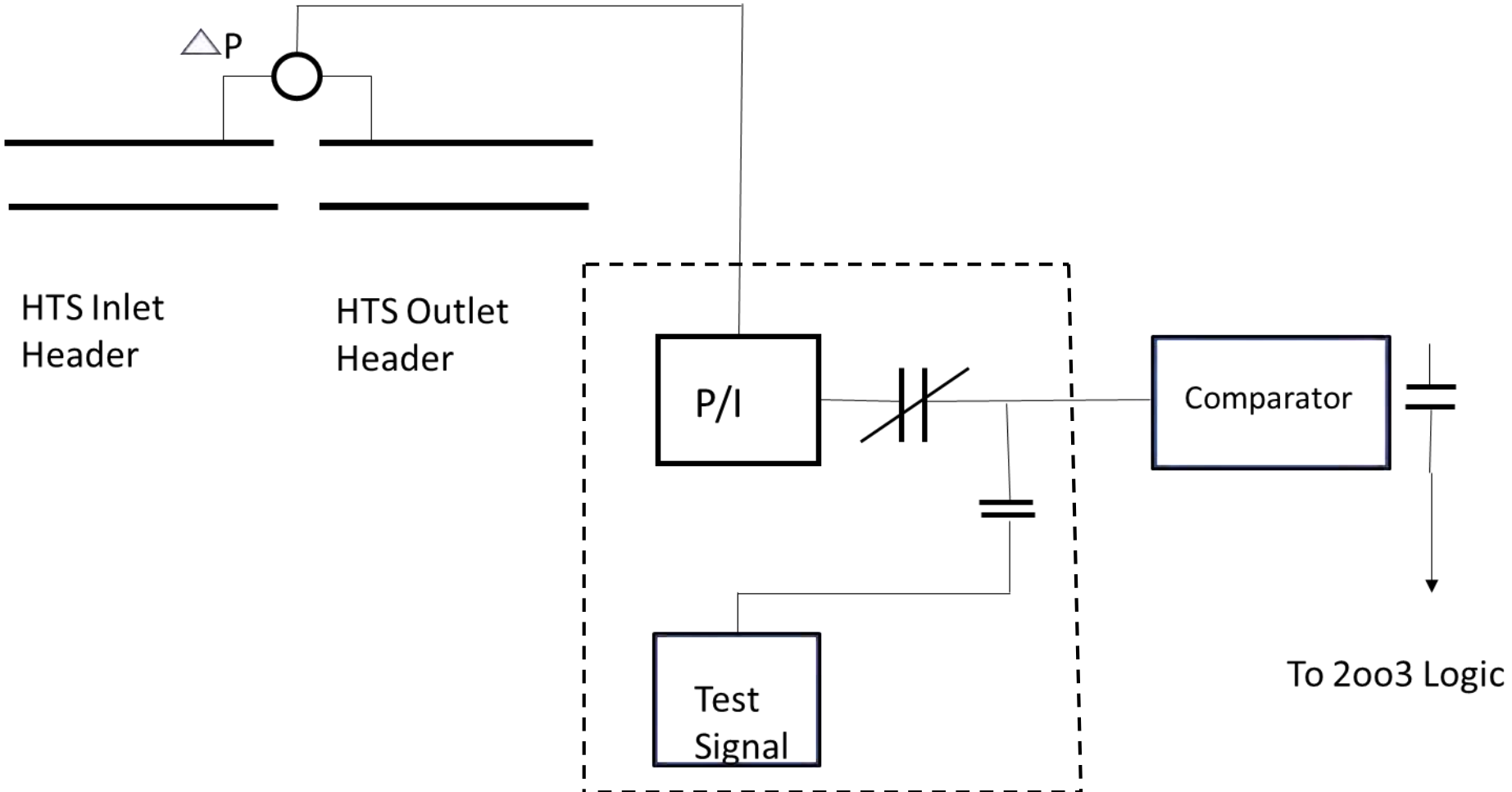
Sunport

SDS2. Main Heat Transport Pump Motor Speed Measuring and Test Devices. Main Functions.

- Converts pump RPMs to an electrical signal as input to the SPU
- The SPU outputs a current proportional to the input signal frequency
- The SPU simulates a pump run-down curve to test availability of the trip function on low RPM and captures the trip point as part of periodic automatic testing.
- Performs self-diagnostics and drives the SPU output to a safe state in case of critical failures

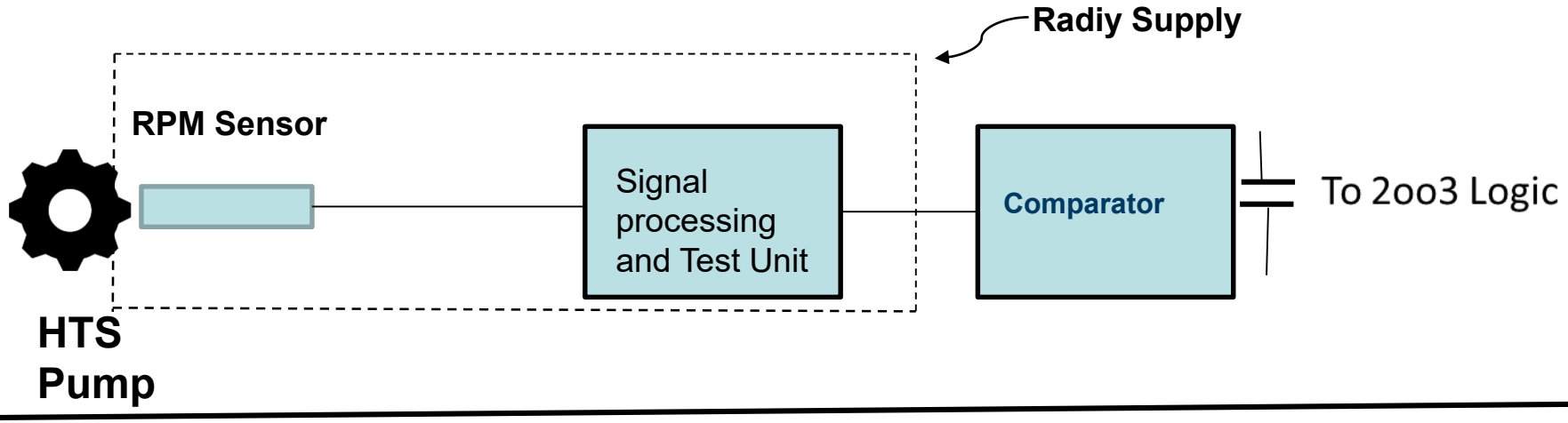
Sunport

Existing trip parameter to cover loss of HTS Flow at the Embalse NPP



Sunport

New trip parameter parameter to cover loss of HTS Flow at the Embalse NPP



Diverse

Direct measurement

Simpler design

Higher reliability

Hiigher resilience to obsolescence

Sunport

Equipment Qualification

Factor	Standard
Operation temperature and storage temperature	IEC 60068-2-1 Test A IEC 60068-2-14 Test N
Operation humidity and storage humidity	IEC 60068-2-2 Test B IEC 60068-2-30 Test D
Vibration	IEEE 344-2004
Electrostatic Discharge Immunity	IEC 61000-4-2:2008
Radio-frequency and Electromagnetic Field Immunity	IEC 61000-4-3:2006
Electrical Fast Transient/Burst Immunity	IEC 61000-4-4:2004
Surge Immunity	IEC 61000-4-5:2006
Immunity to Conducted Disturbances Induced by Radio-Frequency Fields	IEC 61000-4-6:2007
Thermal ageing	For 30 years of operation
*Radiation withstand	Requirement in TS
*LOCA withstand	Requirement in TS

*Only for sensor, cable and connector

Sunport

RPC Radiy FPGA Product Experience

- **Reactor Trip Systems since 2003**

- **RPCLS since 2004**
- **ESFAS since 2007**

- Cumulative systems > 40
- Cumulative system years > 260
- Cumulative module years > 23000

Sunport

Key Factors in the success of the projects.

- Meticulously planning of every activity. “Planned the work and worked the plan”
- The adoption of formal process in line with industry standards
- Clearly defined responsibilities and accountability
- Project personnel highly qualified for the tasks assigned to them. Strong team dedication
- Customer involvement throughout project execution
- Reduction in the quantity of equipment, standardization and modularization compressed manufacturing and installation time
- Adoption of FPGA technology simplified design and test processes, kept costs under control and reduced duration of associated activities.

Sunport

Thanks for your Attention.

Questions?

Sunport

Safe Failure Fraction. Definition

$$SFF = \frac{\lambda^{SD} + \lambda^{SU} + \lambda^{DD}}{\lambda^{SD} + \lambda^{SU} + \lambda^{DD} + \lambda^{DU}}$$

Where:

λSD/λSU: Safe Detected and Safe Undetected trip rates

λDD/λDU: Dangerous Detected and Dangerous Undetected trip rates

SFF is defined as the ratio of the average rate of safe failures plus dangerous detected failures of the subsystem to the total average failure rate of the subsystem. It is defined for a single channel (no redundancy, 1oo1).

Sunport

Probability of Failure on Demand. Definition.

PFD = λDU * PTI /2 + (λT) * MTTR

PFD: Probability of Failure on Demand

λT: Total trip rate

MTTR: Mean Time to Restore (detect, repair and restart)

PTI: Proof Test Interval (period between tests)

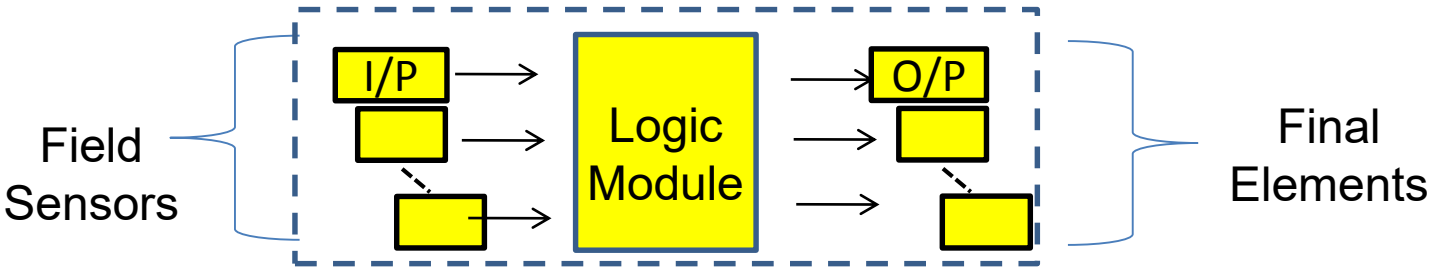
FMEDA Results for the FSC*

	FSC results	61508 Requirements SIL 2	SIL 3
SFF	99.5%	90%	99%
PFD_{AVG} (test interval – 3 y)	9.0 E-4	1 E-2	1 E-3

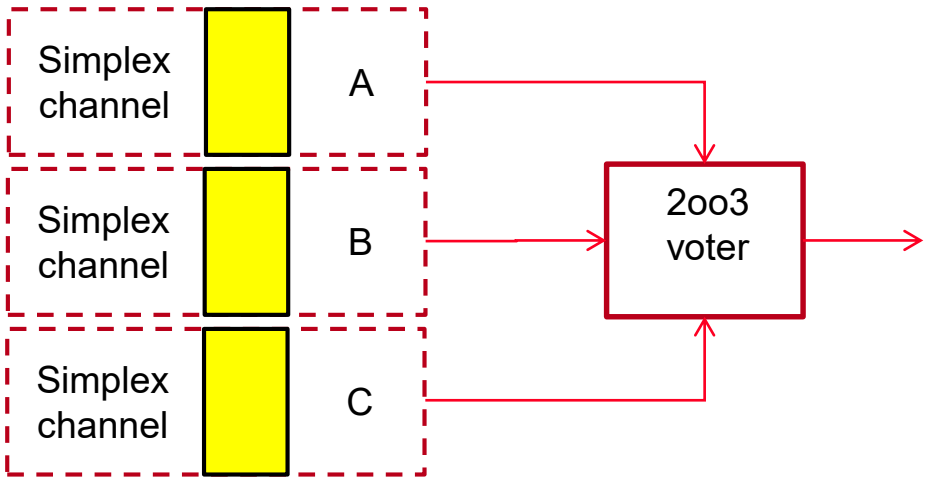
* Conservative values wrt altittude

Sunport

The RadICS platform meets SIL3 requirements in a single (simplex) channel configuration



The RadICS platform in a multi-channel arrangement would far exceed SIL3 requirements



Sunport

Factors contributing to the high reliability of the RadICS platform.

Redundancy coupled with self-testing features. Achieved at three levels, in compliance with Single Failure Criteria (IEEE Std 379-2000):

- **Architecture-level. Separate, independent divisions/channels feeding a 2oo3 or 3oo4 voting logic.**
- **Redundancy built into the hardware for inputs, outputs, and power supplies.**
  - For inputs, signals are transmitted to redundant units.
  - For outputs, 1-out-of-2 to de-energize to a safe state, plus testing of individual switches. Once an unsafe condition is detected all outputs are de-energized.
  - Redundant Power supplies for all RadICS Modules
- **Redundant processing units.**

Sunport

Diversity to cater to CCF

The RadICS Platform addresses the following CCF related vulnerabilities:

- Electronic Design execution failure, e.g. platform potential failures
- H/W failure, e.g. failure of an FPGA circuit segment
- Corruption of the FPGA Netlist, e.g. failures affecting FPGA loading or EEPROM storage

Sunport

Diversity to Avoid CCF Cont…

Electronic design failures. Addressed via diversity in technology between the Watchdog (WD) and the modules FPGA

- The system includes a CPLD-based watchdog, separate and technologically diverse from the Module FPGA.

Hardware failures. Addressed by independent and functionally diverse self-test methods.

- Self-tests and diagnostics are executed in independent circuits from the FPGA control logic. Thus no failure propagation between these two.
- The self-test and diagnostics are implemented using a functionally diverse method than the FPGA control logic
- Upon detection of a h/w failure, the module outputs are set to the safe state.

Sunport

Diversity to Avoid CCF Cont…

Corruption of the FPGA Netlist, during loading or operation may affect both the control logic and the self-test diagnostics.

- Addressed by self testing on initial loading and on a periodic basis during operation.
- The Netlist is checked against a 64-bit CRC independently calculated and stored alongside the FPGA Netlist.
- The Netlist self-test and diagnostics is functionally diverse from the other diagnostics.