Advancement in Instrumentation and Control Systems of Nuclear power Plants and Reactor safety

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Introduction

- Instrumentation and Control (I&C) systems play a key role in nuclear power plants.

- Main functions of I&C systems of nuclear power plants are
  - Provide information about the plant to the plant operation staff
    to operate the plant safely and efficiently in all its operational states,
  - Process commands from the plant operators
    to maintain the plant in a safe state or to bring it back into such a state after the onset of either accident conditions or design basis events,
  - Run open-loop and close-loop control systems.

Introduction (2/6)

- **Major components of nuclear power plant I&C systems:**
  - **Sensors and actuators**
  - **Instrumentation racks**
  - **Open-loop and close-loop control systems**
  - **Control consoles, supervision desks and HSI**
- **Majority of I&C equipment and systems was designed at least 30 to 50 years ago based on analog electronics, low-level integration digital circuits, and microcontrollers. Many of which are obsolete.**
- **The obsolete equipment and systems are**
  - **Costly to operate and maintain**
  - **Degrading in performance**
  - **Lead to decreased reliability, availability, and accuracy**
  - **Lead to increased safety challenges.**

Introduction (3/6)

Capabilities of I&C systems affect all areas of reactor operation and impact reactor reliability, efficiency, and operating costs.

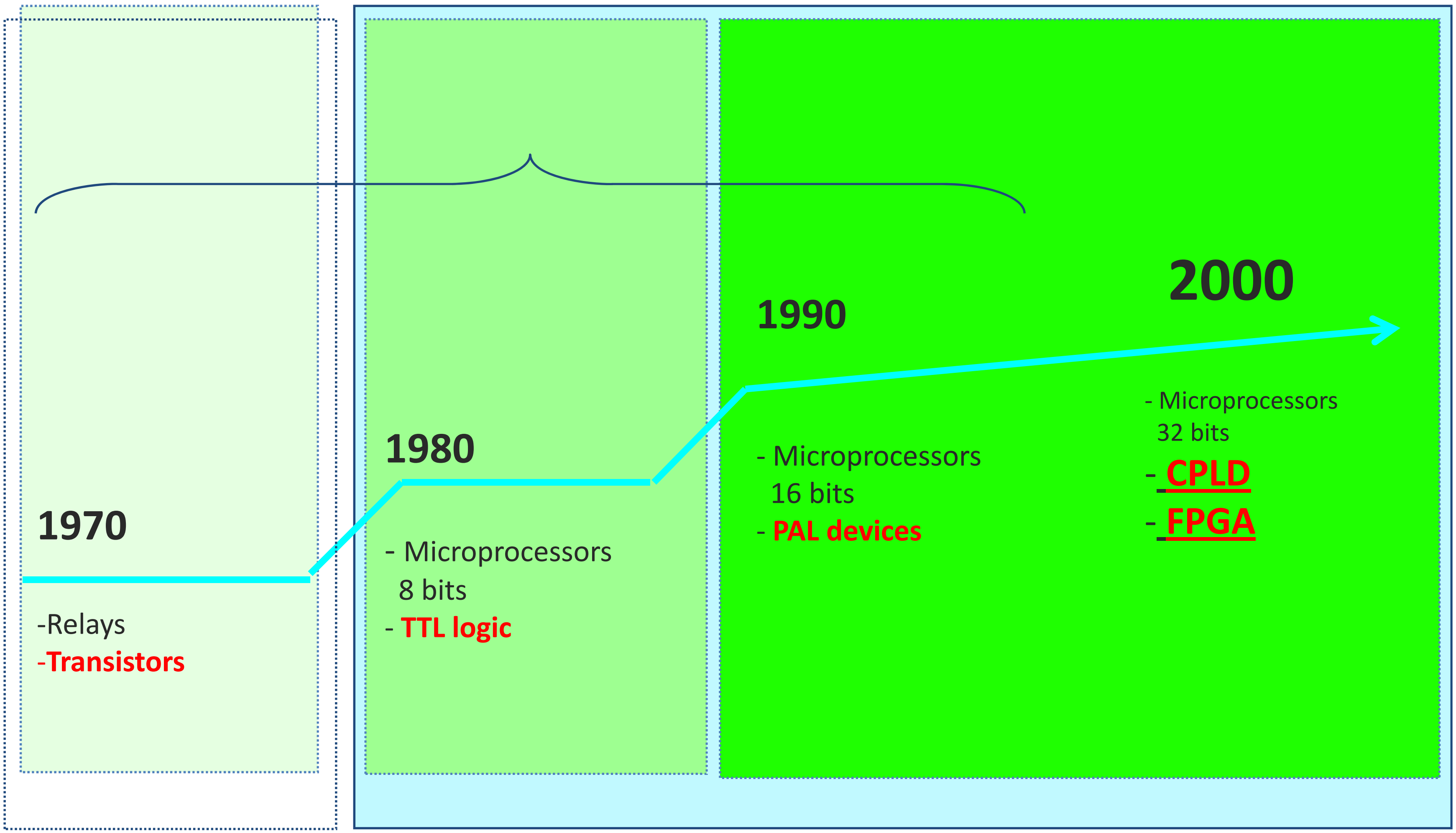
New nuclear power plants are using different approaches to achieve a higher level of safety than the old reactors. One approach is the use of the technological developments in computation and electronics in the form of digital instrumentation and control.

Introduction (4/6)

Advanced I&C systems for nuclear power plants are necessary due to various factors

- **Due to high cost long-term maintenance of obsolete equipment is not viable.**
- **Increasing need to improve reliability of reactor I&C systems and availability of nuclear power plants.**
- **Human factors concerns about systems contributing to potential human errors.**
- **There are difficulties with aged-analog technologies in complying with increased regulatory requirements and in attaining high availability of the plant.**

Development of Nuclear I&C technologies



History of Important I&C Systems

	1970's	1980's	1990's	2000's
H/W Technology				
Signal Processing	- Analog (Box type)	- Analog (Card type)	- Digital:Non-Safety - Analog:Safety	- Digital
Protection Logic	- Magnetic Relay	- Solid State	- Solid State	- Digital
Sequence Control （Open-Loop）	- Magnetic Relay	- Magnetic Relay	- Digital:Non-Safety - Solid State:Safety	- Digital

Advancements in I&C Technologies

Advancements in I&C technologies lead to the advanced I&C systems of nuclear power plants

- **Digital electronics: Microprocessors, ASIC/FPGA etc.**
- **Sensors technology: smart sensors, fiber-optic sensors, wireless sensors, etc.**
- **Communication technology: fiber-optic, fieldbus, wireless communication.**
- **Control devices and techniques: PLCs, DCS, digital control techniques, etc.**
- **Advanced monitoring techniques: monitoring, diagnostics and Prognostics techniques.**
- **Control room and HSI technologies: digital displays, soft controls, etc.**

Advanced I&C Systems of NPPs

Several existing and new nuclear power plants are now looking forward to make the transition into today's state-of-the-art digital I&C systems

- **Advanced sensors and transmitters**
- **Digital nuclear island**
- **Digital reactor protection and actuation systems**
- **Advanced control devices and techniques**
- **Digital display systems**
- **Intelligent alarming systems**
- **Advanced communication networks**
- **Modern control room and human system interface (HSI)**

Programmable Logic Controller (PLC)

I/O Modules (SW, PLD, FPGA)

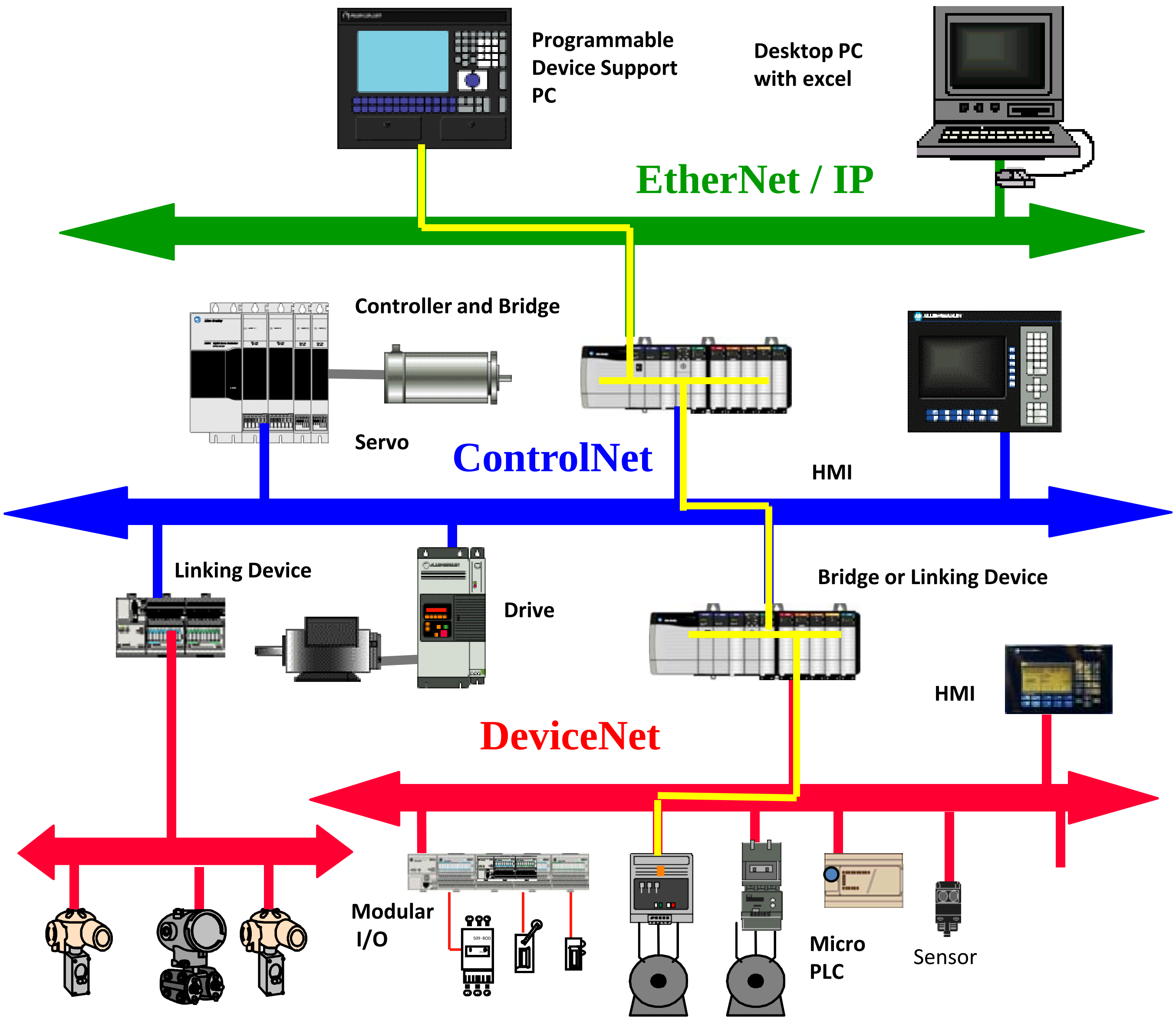
Communication Modules (SW, PLD)

Processor Module (SW, PLD)

Power Modules

- Includes:
  - Redundant Power Module
  - Processor Module
  - Communication Module
    - Safety Data Link
    - Information Network
  - I/O Modules
    - Analog I/O Modules
    - Digital I/O Modules
    - Special I/O Modules

Control System Architecture



Advanced I&C Systems of NPPs (4/4)

Examples:

- **Japan:** **advanced boiling water reactors Kashiwazaki-Kariwa-6, Kashiwazaki-Kariwa-7, Hamaoka-5 and Tomari-3 are fully digital I&C systems.**
- **China:** **Qinshan Phase III, with two 700 MW(e) CANDU reactors, high temperature gas cooled experimental reactor, the HTGR-10 and two 1000 MW(e) VVERs, Tianwan-1 and -2 are fully digital I&C systems.**
- **Russia:** **Kalinin-3, which was commissioned in 2004 is VVER-1000 with digital I&C safety and control systems.**
- **Republic of Korea:** **three 1000 MW(e) PWRs are under construction (Shin-Kori-1 and -2 and Shin-Wolsong-1), all with fully digital I&C safety and control systems.**

Safety and Licensing Issues

Safety, reliability , and regulatory issues are associated with advanced I&C for NPPs.

Historically, the nuclear industry has been slower than others in implementing new technologies because nuclear reactors must perform a more thorough assessment than other industries before they can adopt a new technology because of the increased safety and licensing requirements.

Comparison of Safety Classifications

<table>
<tr><td>National or international</td><td colspan="12">Classification to the importance to safety
(excerpt from IAEA-TECDOC-780)</td></tr>
<tr><td rowspan="2">IAEA</td><td colspan="8">Systems important to safety</td><td colspan="4" rowspan="2">System not important to safety</td></tr>
<tr><td colspan="2">Safety systems</td><td colspan="6">Safety related systems</td></tr>
<tr><td>IEC 1226</td><td colspan="3">Category A</td><td colspan="4">Category B</td><td colspan="3">Category C</td><td colspan="2">Unclassified</td></tr>
<tr><td>France N4</td><td colspan="2">1E</td><td colspan="5">2E</td><td colspan="5">IFC/NC</td></tr>
<tr><td>European utility requirements</td><td>F1A
(auto)</td><td colspan="5">F1B
(auto & manual)</td><td colspan="5">F2</td><td>Not classified</td></tr>
<tr><td>UK</td><td colspan="5">Category 1</td><td colspan="4">Category 2</td><td colspan="3">Not classified</td></tr>
<tr><td>USA(IEEE)</td><td colspan="4">Class 1E</td><td colspan="8">Non-class 1E</td></tr>
</table>

Classification of Safety I&C Systems - IAEA

<table>
<tr><th colspan="2">Level</th><th>Description</th></tr>
<tr><td rowspan="2">Important to safety</td><td>Safety</td><td>I&C systems important to safety to implement following
- Ensure safe shutdown of reactor
- Ensure removal of residual heat in reactor core
- Mitigate the consequences of design bases event</td></tr>
<tr><td>Safety related</td><td>I&C systems important to safety which are not included in safety system</td></tr>
<tr><td colspan="2">Not important to safety</td><td>I&C systems which are not included in important to safety system</td></tr>
</table>

Classification of Safety I&C Systems - USNRC

Classification	Description
Class 1E	I&C systems or equipments perform the following functions - Reactor trip - Containment isolation - Emergency core cooling - Heat removal from reactor and containment - Protect radiation exposure to public
Non Class 1E	The other I&C systems which are not classified as Class 1E

Safety and Licensing Issues (5/8)

Digital systems have increased influence to the safety of nuclear power plants.
To ensure correct functionality and a high reliability the digital I&C systems should be thoroughly assessed before taken into use in nuclear power plants.

The assessment is most important if the digital systems are considered for safety functions.

Safety and Licensing Issues (6/8)

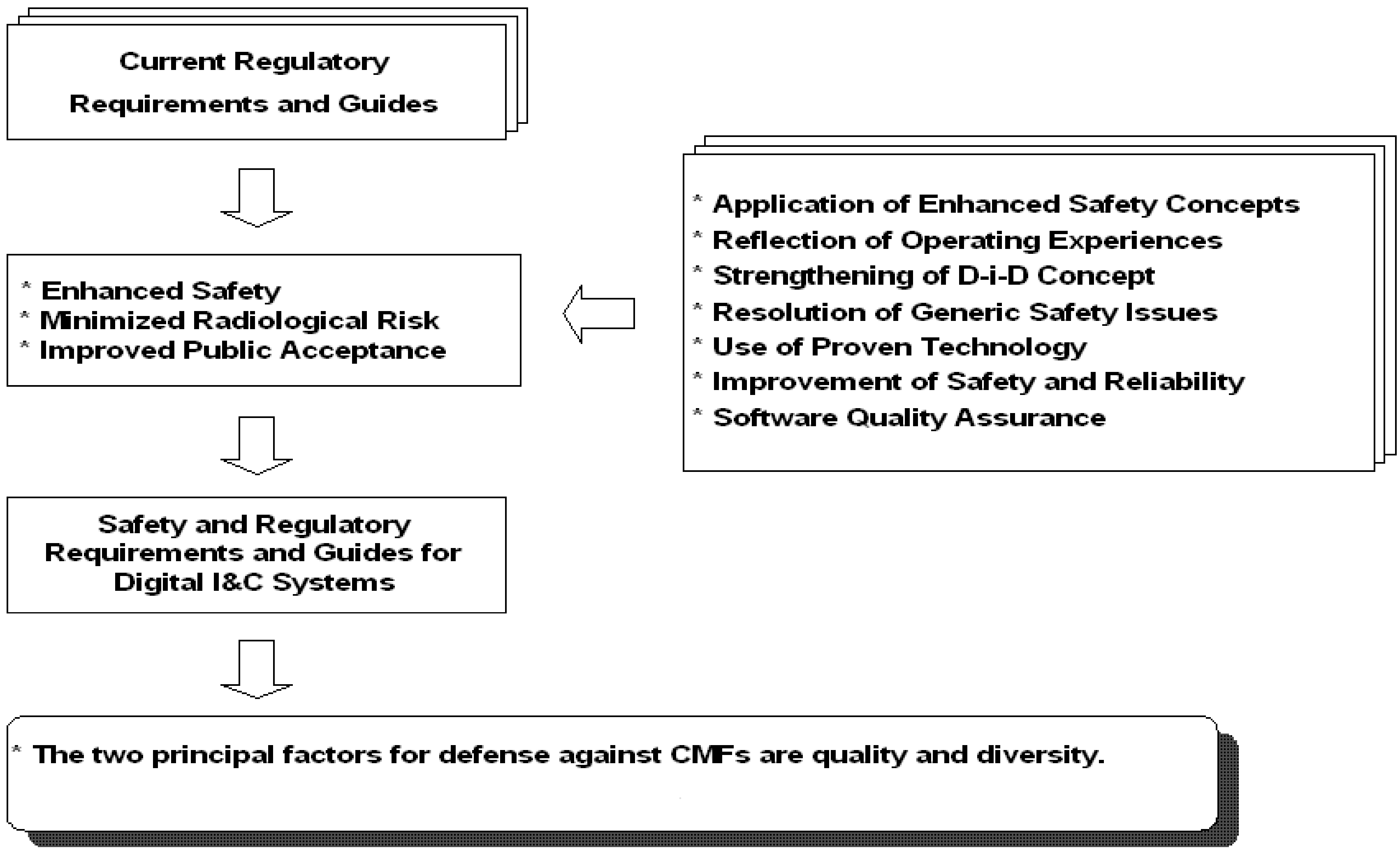
Safety standards and requirements change with time and technology, hence, need to enhance / improve safety and address new safety standards and requirements.

IEEE 603: **Standard Criteria for Safety System in NPGSs**
IEC 880: **Software for Computers in the Safety Systems of NPS**
IEEE 323: **Qualifying Class 1E Equipment for NPGSs**
IEEE 420: **Standard for the Design and Qualification of Class 1E Control Board, Panels and Racks used in NPGSs.**
IEEE 344: **Recommended Practice for Seismic Qualification of Class 1E Equipment for NPGSs**
IEEE 1012: **Software Verification and Validation Plans.**
IEC 62566: **Complex Electronic Components**

Safety and Licensing Issues (7/8)

- **Licensing Issues on Digital I&C Systems**
  - **Safety classifications**
  - **Defense-in-depth and diversity**
  - **Computer system quality**
    - **Software QA, V&V, etc.**
    - **Software reliability and hazard analysis, etc.**
  - **Systems topics regarding digital technology**
    - **Real-time performance and timing analysis**
    - **Data communications**
    - **EMI/RFI qualification, etc.**
  - **Issues regarding human system interfaces**
    - **Advanced alarm, soft controls, computer-based procedures, etc.**

A Flow Diagram for Regulating Digital I&C Systems



1. Digital Electronics: ASIC/FPGA

- **Digital I&C systems are usually based on microprocessors, software based equipment and operating systems.**

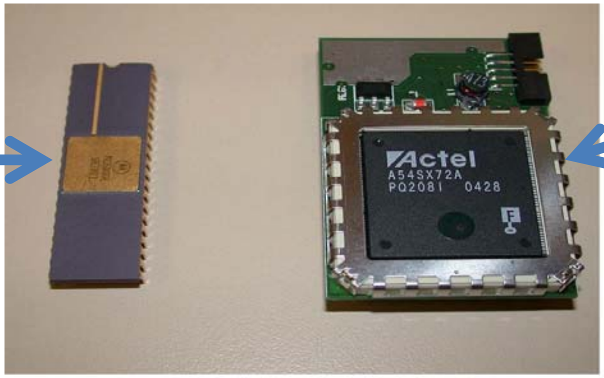
With all their advantages, these types of digital equipment have some drawbacks. In particular, the presence of micro-processors and operating systems creates licensing difficulties (for safety or safety-related applications), long-term maintenance and obsolescence issues.

Digital Electronics: ASIC/FPGA (2/7)

An alternative to software based systems is based on the use of application specific integrated circuits (ASICs) or field programmable gate arrays (FPGAs).

- **FPGA (Field Programmable Gate Array) is a semiconductor device that can be programmed after manufacturing.**
- **FPGA is alternative to microprocessor. FPGA with millions of cells can embed microprocessors and all kind of logic and mathematical processing capabilities.**

µP 6800



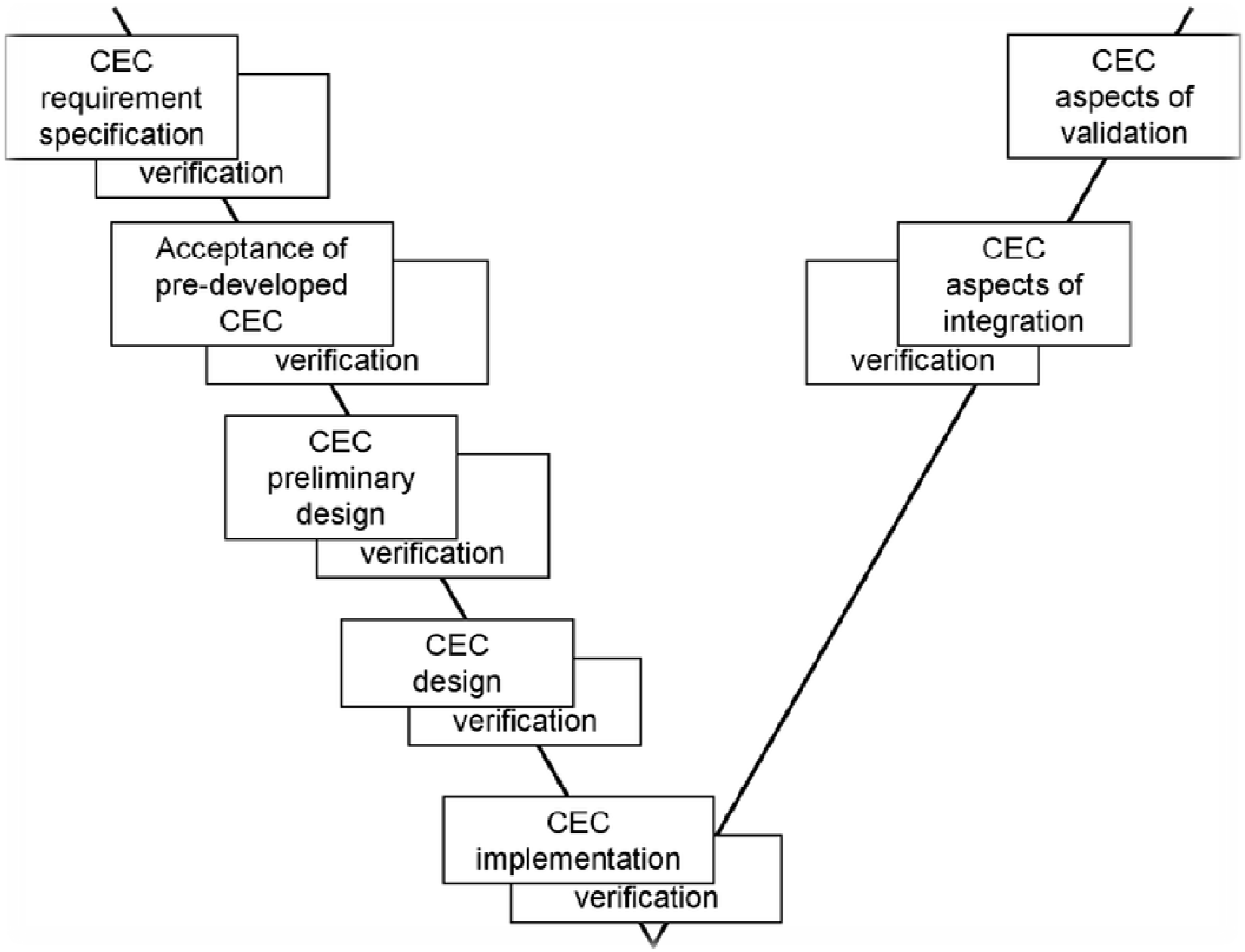
FPGA (A54SX72A)

Digital Electronics: ASIC/FPGA (3/7)

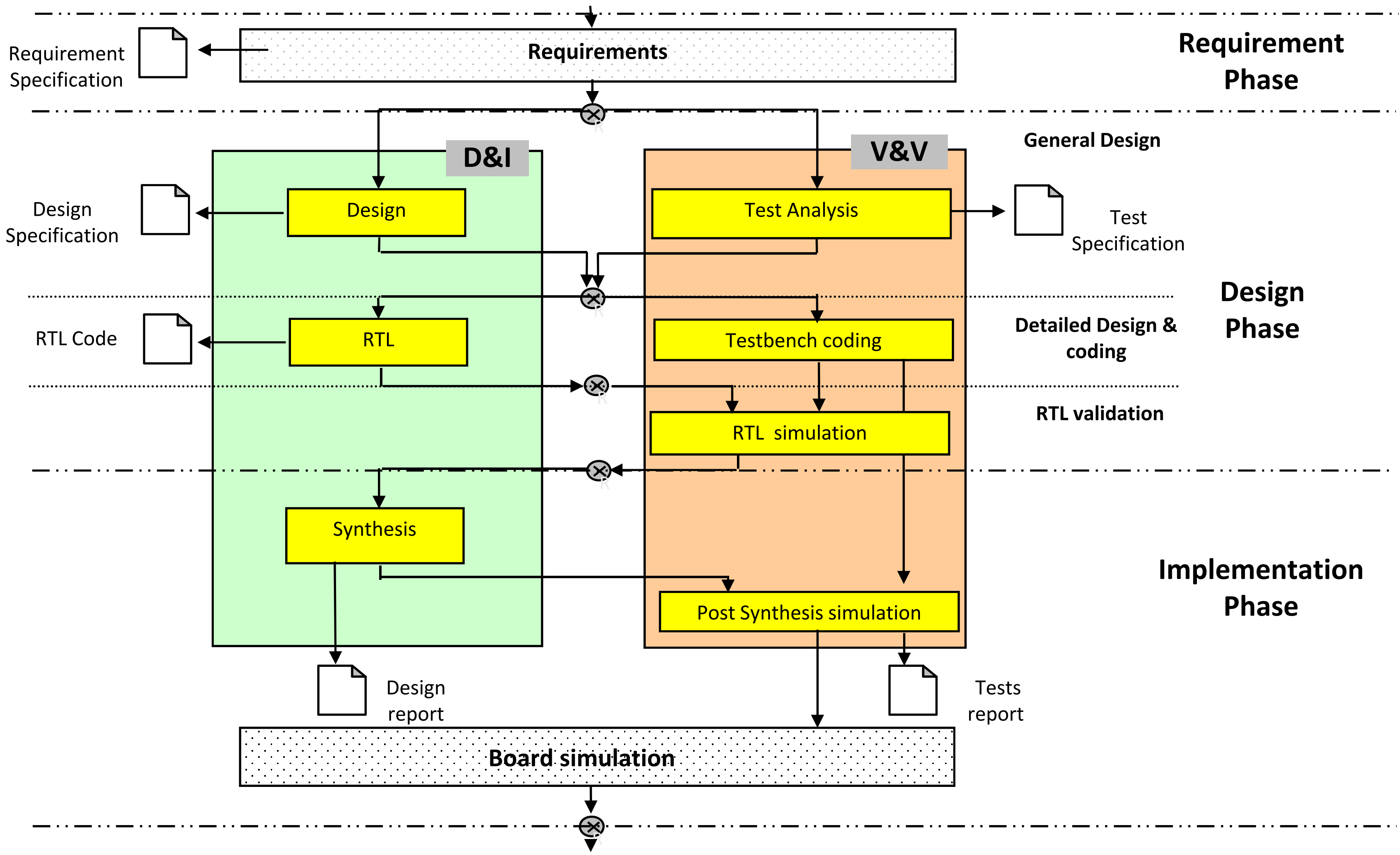
- **ASIC/FPGA based solutions provide component-level (circuit or module) replacements as opposed to I&C system-level replacements as in case of PLC and DCS, thus resolves long-term maintenance and obsolescence issues, and optimizing costs and efforts.**

In nuclear power plants safety-critical applications based on FPGAs already accepted by regulators in several countries (e.g. Japan, Ukraine, USA).

V-shape CEC Life Cycle Processes (IEC 62566)



FPGA Development Process



Digital Electronics: ASIC/FPGA (6/7)

FPGA–based systems developed for nuclear reactors some examples

- **FPGA-based safety and non-safety radiation monitors, and power range neutron monitors in Japanese BWRs**
- **FPGA-based digital I/O module for safety PLC developed for nuclear power plants in Korea**
- **Toshiba has developed FPGA-Based Power Range Monitors (LPRM/APRM)**

Digital Electronics: ASIC/FPGA (7/7)

- Westinghouse has developed a FPGA-based Class 1E qualified system that has been approved by the U.S. Nuclear Regulatory Commission (NRC) for use specifically in safety-related, RPS/ESFAS applications.

- A number of FPGA–based I&C (including safety) systems has been commissioned in Ukraine and Bulgaria (15 NPPs at 4 sites in Ukraine (Zaporizhska, Rivne, Khmelnitsky, South-Ukraine) and 6 NPPs at the largest nuclear power generation facility in Bulgaria (Kozloduy)).

2. Sensors Technology

- **Today, a majority of measurements of nuclear and process parameters are made using conventional sensors such as neutron detectors, RTDs, thermocouples, and all of which have been in use since the inception of nuclear reactors.**

Although some of these conventional sensors suffer from long-standing and often inherent problems such as drift, they remain the best available technology for measurements with a long history of use in nuclear reactors.

Sensors Technology (2/4)

Smart Sensors

- Smart sensors are a fully developed and qualified technology used in nuclear power plants.
- Smart sensors are easier to calibrate and maintain than conventional sensors and contain self-diagnostic capabilities, memory, and digital equipment attributes.
- These sensors can produce digital output and contain memory to keep their calibration information, sensor identification (i.e., tag number), and so on.

Sensors Technology (3/4)

The nuclear industry is using conventional sensors, including smart sensors, and little is expected to change over the next decade.

The latest advances in sensors for the nuclear power industry in the next ten years are wireless sensors and fiber-optic sensors.

Wireless Sensors

- **Wireless sensors are becoming very popular in industrial processes for measurement and control, condition monitoring, predictive maintenance, and management of operational transients and accidents.**

Sensors Technology (4/4)

Fiber-optic sensors

- Fiber-optic sensors are a fully developed technology used in many industries to measure a variety of process parameters. However, qualification of fiber-optic sensors are required for use in nuclear power plants.

- They offer high bandwidth, no drift, ease of installation, light weight and small size, high sensitivity, and immunity to electromagnetic and radio frequency interference.

3. Software Based Digital Systems

- **Almost all digital systems are software-based systems:**
  - **microprocessor-based monitoring systems,**
  - **computerized systems (PLCs, DCS, PCs),**
  - **sensors and transmitters,**
  - **communication systems,**
  - **control room devices, etc.**

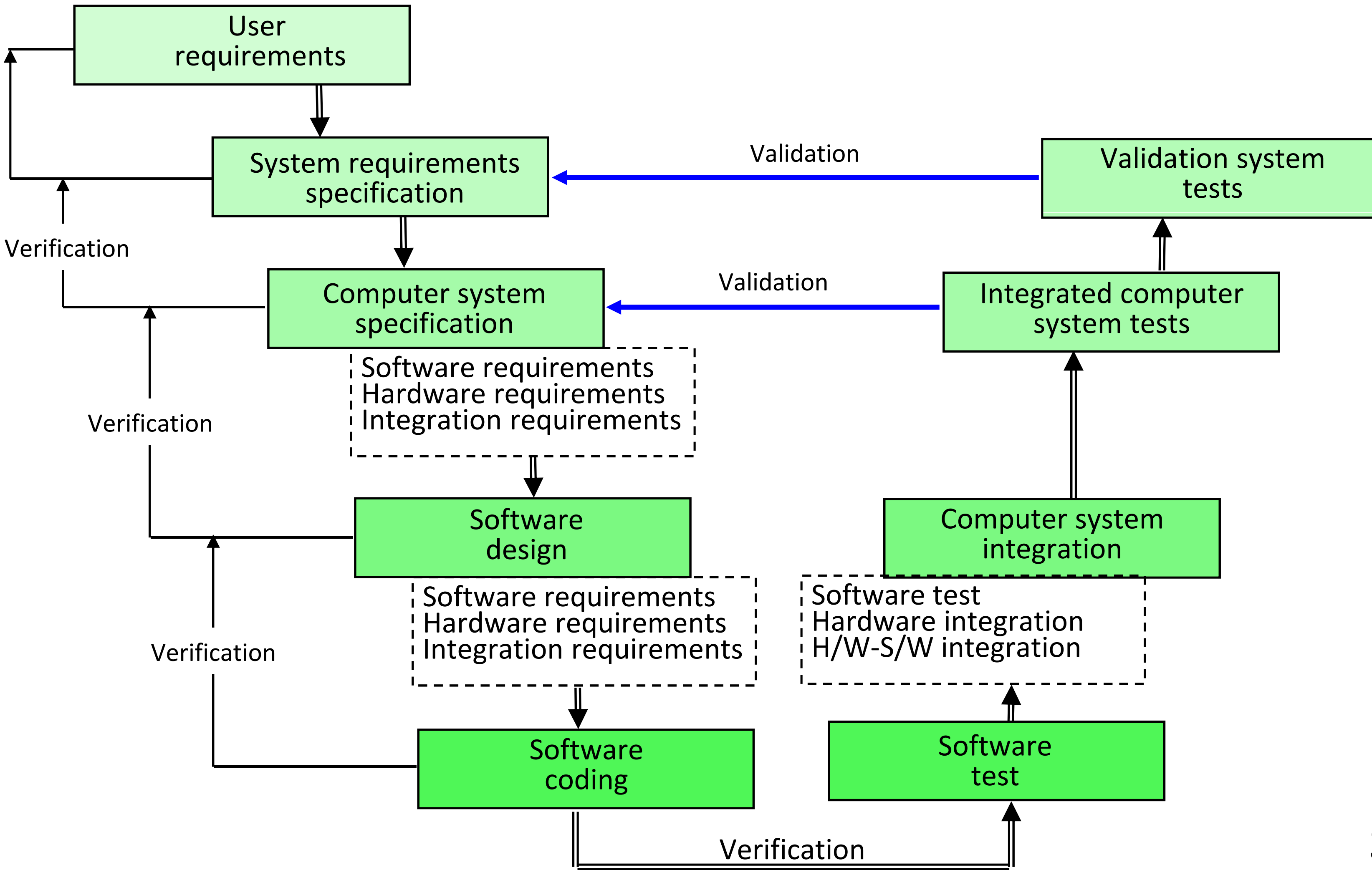
The risk of design faults in digital systems is greater since the implementation of diverse and complex functions is easier and the functionality of a system can be altered significantly just by making minor changes in the software.

Software Based Digital Systems (2/4)

Software qualification using codes and standards is necessary for all the software-based systems to ensure safety and to fulfill the licensing requirements.
Verification and Validation (V&V) process should be applied at each stage of development of the system.

- **Verification and Validation (V&V) stages**
  - **Concept V&V**
  - **Planning V&V**
  - **Software requirement specifications V&V**
  - **Software design specifications V&V**
  - **Implementation V&V**
  - **Test V&V**
  - **Installation and checkout V&V**

Life Cycle and Documentation for Development of Software Based Systems



Classified by Software Integrity Level (SIL)

(IEEE Std. 1012, "Software verification & validation" (1998))

Level	Criticality	Description
4	High	Selected function affects critical performance of the system
3	Major	Selected function affects important system performance
2	Moderate	Selected function affects system performance, but workaround strategies can be implemented to compensate for loss of performance
1	Low	Selected function has noticeable effect on system performance but only creates inconvenience to the user if the function does not perform in accordance with requirements

4. Communication Technology

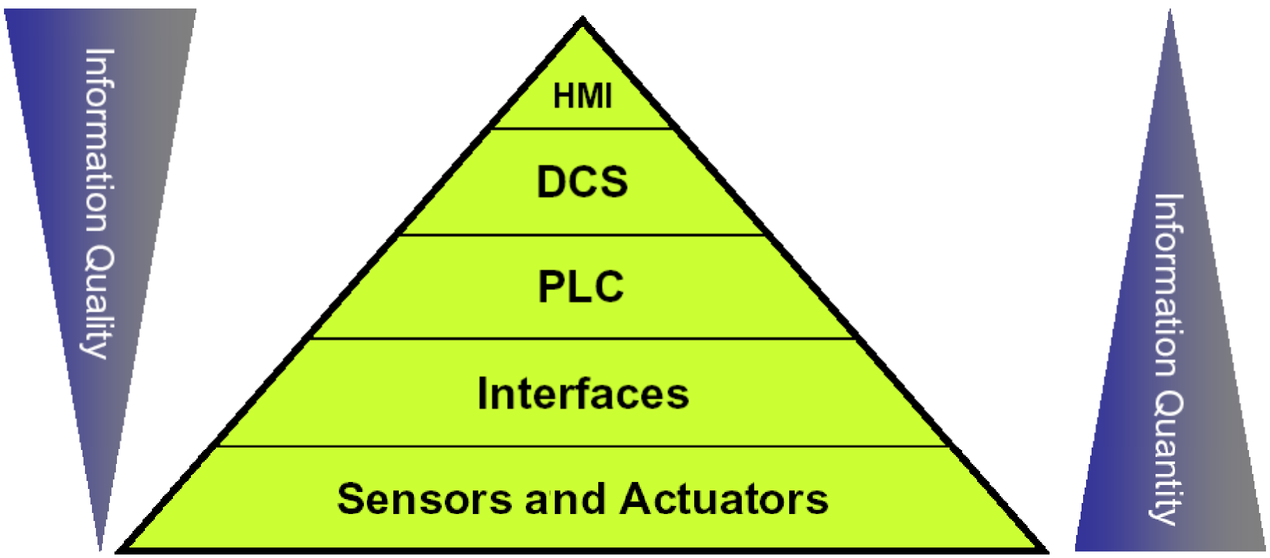
Fiber-optic lines for signal transmission and communication links are now common in nuclear power plants and are used for many applications including transmitting sensor signals.

Fieldbus

- **Fieldbus is a generic-term which describes a new digital communications network which is used for process automation applications and to replace the existing 4 - 20mA analogue signal, and it also replaces centralized control networks with distributed-control networks.**
- **Fieldbus is a digital, bi-directional, multi-drop, serial-bus, communications network used to link isolated field devices, such as controllers, transducers, actuators and sensors.**

Communication Technology (2/4)

Each field device has low cost computing power installed in it, making each device a 'smart' device. Each device will be able to execute simple functions on it's own such as diagnostic, control, and maintenance functions as well as providing bidirectional communication capabilities.



Communication Technology (3/4)

Wireless Technology

- The use of new wireless technologies in nuclear power plants is growing fast.
- The WLAN technology based on the IEEE 802.11 standard has a very promising future for its use in nuclear power plants due to features like mobility, reliability, security, scalability and compatibility with other communication networks technologies.

However, wireless technology may exhibit greater vulnerability to the nuclear power plant EMI/RFI environment.

Communication Technology (4/4)

Benefits of Wireless Technology

- Using wireless technology cost-effective way to get more plant data for applications without having to run expensive cable
- It can support the "wired" worker for tasks such as operator rounds and maintenance
- It can support multi-media including voice, data, and video
- Ability to successfully manage multiple nuclear reactor applications over a single wireless network

5. Control Room and HSI Technologies

Emerging control room and HSI technologies

- **Display functions (e.g., task-based displays, function-based displays, overview displays)**
- **Automation**
- **Computer-based procedures**
- **Soft controls**
- **Intelligent alarming**
- **Computerized operator support systems**

Control Room and HSI Technologies (2/5)

Questions must be addressed for modernization of control room and HSI

- **What are the new operating concepts?**
- **What should be the functional and HSI capabilities in the control room?**
- **How do you incorporate human factors engineering concepts?**
- **How do you reduce the likelihood of human errors?**
- **How do you design for operating under degraded conditions?**
- **How do you achieve the potential benefits from the new technology?**
- **How do you train operators during the changes?**

Control Room and HSI Technologies (3/5)

Functions of Dynamic Large Screen Displays in Reactor Control Room

- **Safety systems actuations**
- **Overall process overview**
- **Status of all important safety systems**
- **Indications of all alarming systems**
- **Mini trends of important parameters**
- **Key process parameters**
- **Status of key components**

Large Screen Displays

Control Room and HSI Technologies (5/5)

During the first few minutes of the accident at Three Mile Island, more than 100 alarms went off, and no system was in place to filter out the important signals from the insignificant ones. "Overall, little attention had been paid to the interaction between human beings and machines under the rapidly changing and confusing circumstances of an accident".

By contrast the level of computerization and information transfer available today could give Japanese officials much more insight to what happens in the four troubled reactors at Fukushima—at least in theory. "Japanese have got so much more going on in terms of the earthquake and the tsunami than the information got at TMI".

Technology Transformation

There are certain issues that should be understood in adopting advanced technologies

- **High development costs:** **The development costs of new systems may be high due to Verification and Validation (V&V) and licensing processes.**

- **Software common mode failure risk:** **Without suitable architectures and proper development processes in the development of the new systems, there are risks involved that can be reduced through proper use of V&V.**

Technology Transformation (2/4)

- **Quantified assessment of reliability:** **A quantified assessment is very difficult to come up with defendable reliability estimates for software based systems.**
- **Retraining of operating and maintenance staff:** **Need for new training and skills both in the operating and maintenance staff.**
- **Absence of standards:** **Standards are still emerging**
- **Acceptance by regulatory bodies:** **Experience has shown that national safety committees sometimes are reluctant about acceptance.**

Technology Transformation (3/4)

- **Verification and Validation:** A considerable amount of effort for verification and validation is required.

- **Difficulty of identifying all possible defects:** Due to the complexity of system, a complete proof is not possible that they exhibit all intended and not any other functionality in the operational modes.

- **Short technological lifetimes:** Digital systems often exhibit faster release of revisions. It may make configuration management and obsolescence issues harder.

Technology Transformation (4/4)

- **Qualification of tools:** There are many computer based tools available for the design and V&V of digital systems. The benefit of these tools may, however, be reduced due to difficulty of proving that they are producing correct results.

- **Problems with staff acceptance and retraining:** The change of technology is sometimes opposed by the staff for the new systems.

Benefits of Advanced Technologies

Advantages of Advanced I&C Systems of NPPs

- Addresses equipment aging and obsolescence issues.
- Allows approaches to address faster obsolescence cycles of some modern technologies
- Provides reliable and cost-effective approaches for design, development, qualification, implementation, operation, and maintenance.
- Increased accuracy to reduce uncertainty margins allows increased power output

Benefits of Advanced Technologies (2/6)

- **Flexibility, increased functionality (improved controls, self checking / diagnostics, on-line monitoring, etc.) and improved performance advantages are the basis for modernizing I&C systems**

- **Integrated information and controls**

- **Reduced unnecessary duplication of equipment, functionality, and information**

- **Modern, efficient systems offer increased reliability, availability, accuracy, and functionality as well as decreased costs and safety challenges.**

Benefits of Advanced Technologies (3/6)

Advanced systems support enhanced accuracy, higher reliability, and more complex calculations

Examples:

- **More accurate feed water flow measurements can allow increased power output by reducing measurement uncertainty margins.**
- **Smart core monitoring systems can achieve a flatter power distribution minimizing local peaks**
- **More accurate safety system calculations can reduce margin uncertainties and could lead to increased power output**
- **Intelligent closed loop controllers can be used to reduce power losses during transients.**

Benefits of Advanced Technologies (4/6)

Advanced technology allows better utilization of resources

Examples:

- **Sophisticated monitoring of fuel burn-up could reduce fuel costs.**
- **Fast, on-line water chemistry control could reduce corrosion damage.**
- **Fatigue monitoring system could allow corrective actions before failure**
- **Improved controllers could protect components from rapid changes, thus slowing down fatigue.**

Benefits of Advanced Technologies (5/6)

Advanced technology allows the development of systems for improvement of performance and availability of NPPs

- **Self-testing systems**
- **Self-calibrating systems**
- **Trending and early fault detection warning systems**
- **Diagnostic systems**
- **Condition-based predictive maintenance programs using on-line monitoring**

Benefits of Advanced Technologies (6/6)

Modern technology allows improvements in monitoring and display systems

- **Safety parameter display systems**
- **More accurate representation of plant and equipment conditions**
- **Improved access to information**
- **Improved human-system interfaces (HSI)**
  - **VDU and large screen overview displays**
  - **Improved presentation of complex relationships**
- **Reduced likelihood of human error**

Challenges of Digital I&C Systems

- Discontinuous and sequential machines performing many functions are to some degree of difficulty in achieving real time performance.
- Increased complexity and high sensitivity to any error.
- Design failures, rather than operational failures, predominate.
- Especially, vulnerability of a common mode or cause failure.
- Difficulties of channel separation and testability, and in addition of reliability quantification.
- In the long run, licensing problems still remain.

Last

Thank You