Case For The Adoption Of FPGA Technology In The Implementation And Replacement Of Equipment And Systems In Nuclear Power Plants

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Abstract: Approximately 40 percent of the world's 450 nuclear reactors have some digital I&C upgrades of safety related systems. The 60 reactors currently under construction will incorporate some form of digital instrumentation and control (I&C) technology. The paper recognizes that analog instrumentation is obsolete, equipment and parts are difficult to obtain in the market, are expensive and not necessarily more reliable than digital.

Main goals of regulators and industry are to achieve safe, reliable and cost-efficient operation of reactor fleets. Use of digital technology is essential to achieve improved equipment and plant reliability. Field programmable gate array (FPGA) digital technology also provides ways to minimize impact of obsolescence and reduce plant operating costs. Digital technology allows designers to create very reliable applications thus reducing initiating events and minimizing spurious reactor scrams/trips at a significantly lower cost than analog based applications.

The various concerns associated with the use of digital technology in nuclear power plants are identified. These concerns include difficulties in quantifying software reliability, lack of universally accepted methodologies to address reliability, cyber security issues, and the perception that digital I&C systems are more prone to adverse effects from common cause failures.

The case is made for the adoption of FPGA technology. Solutions to the concerns expressed by industry and regulators are identified and organized for each objective (i.e., reliability improvement, obsolescence management, and cost reduction). The benefits that FPGA technology provide to improve the solutions are also identified. Additional questions worth asking when pursuing FPGA solutions for nuclear power plant projects are also identified for further consideration.

Keyword: ISOFIC, I&C, HMI, FPGA, retrofit, upgrade, obsolescence

1 Introduction

Approximately 40 percent of the world's 450 nuclear reactors have some digital instrumentation and controls (I&C) upgrades of safety related systems. Most of the upgrades have occurred in Europe and Asia. The United States in an exception to this trend. It is also the case that the approximately 60 new reactors currently under construction will incorporate some form of digital I&C technology, including modern digital control rooms.

Another important trend is that a high degree of vendor maturity has been reached in the development of digital product designs and verification and validation methods, which facilitates solutions to plant performance and obsolescence issues. The trend is most evident in the large non-nuclear market for digital I&C equipment for use in safety-critical applications.

Analog instrumentation is obsolete, equipment and parts are difficult to obtain in the market, are expensive and not necessarily more reliable than digital. The concerns with counterfeit, fraudulent, and suspect items threaten to make reliance on secondary source suppliers risky and more expensive.[1]

2 A Case for Digital I&C

The nuclear industry and regulators have shared goals to achieve safe, reliable, and cost-efficient operation of reactor fleets. There are several ways to achieve these goals: improve equipment and plant reliability, minimize impact of obsolescence, and reduce operating costs. The actions to meet these goals can be supported through the adoption of I&C digital technology. Digital technology offers features that allow designers to create very reliable applications that can minimize spurious reactor scrams at a significantly lower cost than analog based applications. Digital technology offers features that allow plant operators to optimize system surveillance testing to achieve cost savings. Most importantly, analog technology may not be a viable option in the foreseeable future, likely as soon as during the first life extension period.

3 Improve Equipment and Plant Reliability

It is much simpler to implement redundancy in I&C architectures using digital technology than it is to do using analog technology. The added redundancy can be used to eliminate important single point failure vulnerabilities and improve both I&C system and overall plant reliability. The number of hardware components in I&C equipment is reduced by approximately 80 percent using digital technology. This reduction in electronic components leads to a reduction of the probability of random failures affecting I&C modules and chassis.

Digital technology provides extensive self-diagnostic and messaging capabilities that can simplify maintenance troubleshooting and repair times, which leads to a corresponding increase in I&C system availability. This also results in a reduction of direct maintenance efforts to be dedicated to I&C systems, thereby allowing technicians to focus on other issues and improving the utilization of plant personnel. Modern digital I&C systems can provide more performance data about the I&C system and other connected equipment (e.g., input sensors and output actuators) that support performance monitoring and trending. This data can be used to diagnose degrading equipment and take action prior to the occurrence of failures.

Digital technology allows implementation of advanced control strategies that could not be achieved using analog technology. Many modern digital I&C platforms incorporate and employ self-monitoring techniques to ensure that errors and failures are detected sufficiently early to maintain the required system availability, as required by International Electrotechnical Commission (IEC) 61513.[2] These systems provide timely diagnostic information about failures to the plant operators so that they can take appropriate corrective actions. These designs employ 'graceful degradation' strategies to ensure safe system response to detected failures. These features ensure operational safety of the I&C systems and minimize plant transients created by I&C system failures, which helps focus plant maintenance activities and minimize operational distractions caused by I&C equipment failures.

One digital I&C platform vendor has successfully completed a Functional Safety Certification based on IEC 61508:2010[3] of their field programmable gate array (FPGA) based I&C platform designed for use in nuclear power plant safety systems.[4] The third-party certification company confirmed that the vendor processes and product complied with Safety Integrity Level (SIL) 3 requirements in single or multiple-channel configurations. The FPGA technology used by the vendor allowed the design to readily incorporate internal redundancy for critical functions, extensive self-testing of critical functions, and sufficient functional and technology diversity between key safety functions and associated diagnostic functions to achieve the SIL 3 rating in a single channel or division. Arranging these I&C platform chassis in redundant architectures typical of nuclear plant safety systems will achieve further reductions in system failure probabilities.

4 Reduced Exposure to Obsolescence

All electronic components will eventually become obsolete; therefore, managing obsolescence in the I&C system life cycle is critically important. A typical nuclear power plant contains approximately 17,000 I&C components. Up to 25 percent of those components are at or near the point of obsolescence. The ability to use proven digital I&C equipment can be an effective solution to the obsolescence of analog components. There are now many systems in use in nuclear power plants with a collective experience in the usage of digital technology amounting to thousands of "unit years."

A concern with microprocessor-based technology is its rapid obsolescence and short lifetime. It is not unusual for relay-based and analog components to be maintained in full operation for 30 years. It is unlikely this will be possible with microprocessor-based equipment (hardware and software); however, some vendors offer product lines for nuclear service that have longevity comparable to analog equipment. With the extended operating lifetimes of nuclear power units, one must consider the possibility that digital I&C systems may need multiple replacements over time; although, there are vendor products that are designed for a 30-year operating life.[5]

FPGA-based solutions can be designed to ease long-term support and allow for future replacements of aging and/or obsolete FPGA circuits without needing a major redesign. The FPGA-based design should be developed with long-term support and obsolescence protection in mind. A well-designed FPGA solution should be 'portable' to other circuits, even those from a different manufacturer, through use of standard languages and avoiding circuit-dependent features. Of course, if the new FPGA has a different footprint or pin-out, the circuit board will need some redesign.

The greater portability of FPGA designs and the degree of protection they offer against circuit obsolescence can be achieved by using available industry guidance in project planning, in designing the architecture of the circuit, choosing the particular blank circuit to be used along with the associated toolsets, and in the coding rules and practices followed in programming the circuit.[6] It is necessary to place requirements or constraints on how the design is developed, implemented and documented so that goals for long-term support, ease of modification, and design portability can be met. Project plans should specify what portions or levels of the design will be kept circuit-independent so that those portions can be re-used, even if a different blank circuit must be used for future replacements or upgrades. One should also consider requirements or constraints related to the use of third-party intellectual property cores or pre-developed blocks that are not circuit-independent.

When the I&C system design incorporates proper provisions for obsolescence management, only the final FPGA design steps (i.e., synthesis plus place and route) are dependent on the particular FPGA circuit chosen. As a result, if the FPGA circuit becomes obsolete it can be replaced by another one using the currently-available technology and the circuit-independent (i.e., register-transfer level) representation of the design.[7]

5 Reduced Cost

Digital technology offers features that allow designers to achieve cost savings through simpler designs that can lower operating costs.

5.1 Simpler Design

Digital technology makes it easier to implement applications with the desired redundancies and architectures, since many desirable features can be provided in the programmable digital portion of the design rather than in analog hardware. This capability is especially true of FPGA technology, where redundant circuits can be incorporated into the electronic designs.

Digital technology makes it easier to implement design changes. In most cases, changes to the system functionality will involve only software or (in the FPGA case) electronic design changes rather than hardware changes.

Digital technology makes it easier to incorporate advanced control strategies as part of I&C systems. These can be implemented as software-based algorithms that would be very difficult or impossible to implement in purely hardware-based environments.

The experience with digital I&C safety systems has shown that the treatment of digital common cause failure (CCF) and associated diversity strategies to address the 'beyond design basis' CCF regulatory criteria have had a significant impact on the complexity of I&C system architectures. International Atomic Energy Agency (IAEA) SSG-39 specifies that "I&C systems should fully meet the requirements of their design basis and unnecessary complexity should be avoided in the design."[8]

Multinational Design Evaluation Program (MDEP) Common Position DICWG-09 notes that modern digital I&C is more integrated and performs more functions (e.g. self–tests, enhanced data communication) than did the earlier generations of I&C systems. This increased integration and functionality can contribute to more complexity. A well designed overall I&C architecture will ensure a proper implementation of the relevant safety principles (e.g. defense-in- depth concept) in order to ensure safe operation, and to facilitate the safety demonstration.”[9]

A typical solution for a microprocessor-based I&C system is to augments the digital safety system with a small scope non-safety analog actuation system (See Fig. 1).[10] This example adds additional complexity using a non-safety diverse actuation system and the associated electrical isolation at the interfaces and requires additional design analysis to ensure proper coordination and priority of the non-safety actuation signals. This system also makes the operator tasks more complicated for the non-CCF failure case, since two systems must be reset to let the operator regain control of equipment necessary to support long-term event management or event recovery.

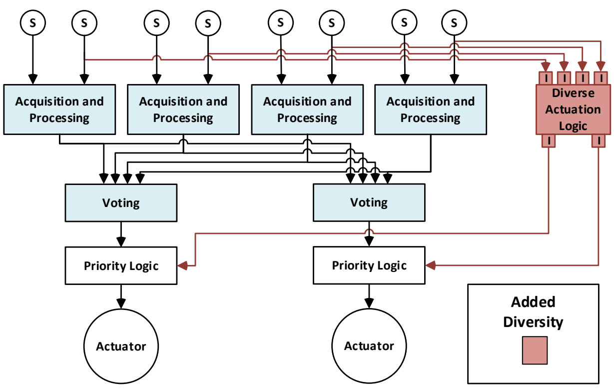

Fig. 1: Diverse Non-Safety Actuation System Concept

FPGA technology has led to other diversity strategies based on internal architecture features to address digital CCF vulnerabilities associated with the electronic design logic development. The solution shown in Fig. 2 utilizes two logic cores developed by diverse teams on a single FPGA.[11] The Diverse FPGA Core System concept relies on the application of adequate human and design diversity to the electronic design development process.

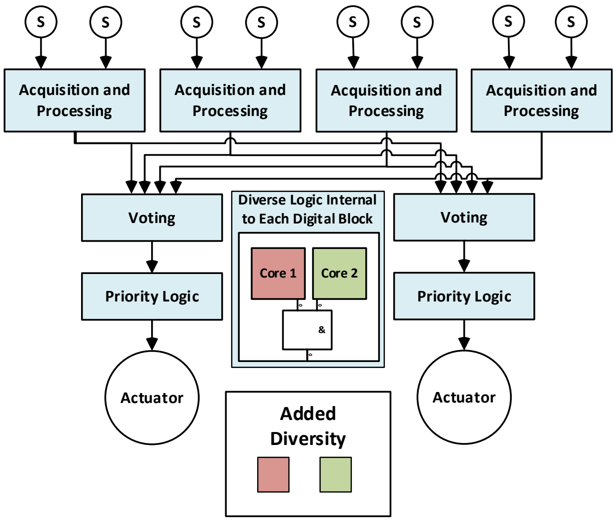

Fig. 2: Diverse FPGA Core System Concept

The Diverse FPGA System concept is another example of using FPGA technology to address CCF vulnerabilities (see Fig. 3).[12] This concept utilizes two subsystems designed with diverse FPGA technology.

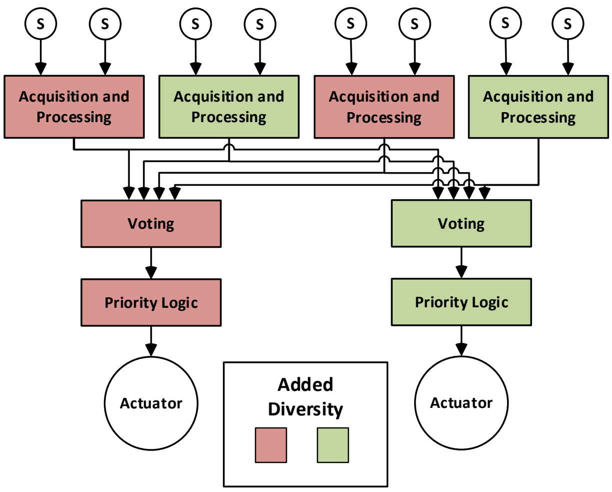

Fig. 3: Diverse FPGA System Concept

The SIL 3 FPGA-based platform employs several internal diversity features to provide sufficient protection to address CCFs that may be introduced using digital FPGA technology within the platform (See Fig. 4).[13] These defensive measures work to limit the effects of failures and ensures placement of the platform into safe states. These added features address CCF vulnerabilities associated with digital technology and add to the protection provided by the hardware qualification requirements. The FPGA-based electronic design and complex programmable logic device (CPLD) power supply monitor and watchdog provide diverse CCF protection for every module in that system. The functional diversity strategy between the application functions and self-diagnostics employed for the electronic designs has a greater degree of diversity than strategies that introduce functional diversity into FPGA electronic designs through the use of various degrees of development team diversity.

These three FPGA diversity approaches offer benefits by simplifying the overall I&C systems designs, since a separate diverse actuation system is not required to mitigate digital CCFsCHFs.

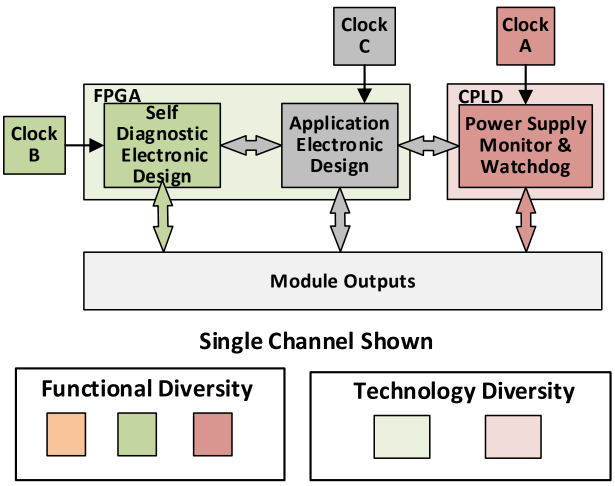

Fig. 4: SIL 3 Diverse Defensive Measure Concept

5.2 Lower Maintenance and Operating Costs

Modern digital platforms employ robust self-testing features that offer several operational benefits to plant operators and maintainers, including: reduced troubleshooting efforts, less overall maintenance work, and reduced surveillance test requirements. Digital technology offers extensive self-diagnostic and messaging capabilities that can simplify maintenance, troubleshooting, and repair times, which leads to a corresponding decrease in I&C maintenance costs.

The higher reliability of modern digital I&C components and the ability to allocate functionality to software result in lower part costs and reduced spare parts inventory. The improved reliability achieved through added redundancy and the elimination of single point vulnerabilities will improve plant capacity factors and reduce generation costs.

The 'graceful degradation' features used in some I&C platform designs can lead to optimized response to detected failures, which can allow corrective maintenance to be performed at regularly scheduled times.

The self-testing and self-monitoring features available in modern digital I&C platforms can be used to optimize system surveillance testing. Input channel data can be exported to the plant process computer for automated comparison and an alarm in online monitoring system can replace existing analog channel checks. Self-testing features can replace standard analog channel functional tests used to verify setpoints and protection systems trip actuation capability (e.g., continuously checking integrity of module software or electronic design). Auto-calibration features in input modules can simplify the standard channel calibration surveillance requirement for an entire instrument loop. Automated test carts can be used to shorten the time to perform end-to-end testing during refueling outage periods.

One digital retrofit project achieved substantial cost savings from the implementation of a digital I&C system replacement of an obsolete analog system. The new design enabled the plant operators to eliminate the individual input channel checks they performed every shift. Instead, these parameters were continuously monitored by the plant process computer, which sent alarms messages to the operators when deviations were detected. The platform self-testing features were used to eliminate all online surveillance testing of the system. The high reliability of the placement system eliminated plant transients caused by I&C component failures. The ‘graceful degradation’ features eliminated the need for any rapid response maintenance support, since failures were detected early and safe system operation was maintained in the interim period.

6 Experience with FPGA Technology and Methods

Most regulators expect that FPGA safety and safety-related applications should be treated similarly to microprocessor-based systems. This approach has introduced difficulties in demonstrating development process quality due the lack of a universally accepted FPGA development methodology. This situation is most pronounced in the United States, since the regulator only has endorsed software-oriented standards issued by the Institute of Electrical and Electronics Engineers (IEEE).

The perception in the industry that there is an unstable or insufficiently clear regulatory framework for the application of digital technology in safety systems should be dispelled based on the recent experience with FPGA technology in the United States and the developments of FPGA-oriented guidance documents and international standards.

6.1 Recent Experience in the United States

The United Stated Nuclear Regulatory Commission (USNRC) has gained experience with FPGA technology through a number of licensing actions they have approved. The Wolf Creek Generating Station modified their license to allow the use of a FPGA-based replacement system for a limited functionality subsystem. USNRC approval for the Wolf Creek system was issued in March 2009.[14] The Diablo Canyon Power Plant modified their license to incorporate a FPGA-based subsystem into the plant protection system. USNRC approval for the system was issued in December 2016.[15]

The USNRC has also approved a number of FPGA-based vendor platforms through the review and approval of topical reports. USNRC approval for the Westinghouse Advanced Logic System platform topical report was issued in January 2014.[11] USNRC approval for the Westinghouse Pressurized Water Reactor Owners Group Solid State Protection System (SSPS) Board Replacement Board topical report was issued in September 2014.[16] USNRC approval for the Lockheed Martin NμPAC topical report was issued in March 2017. USNRC approval for the NuScale Highly Integrated Protection System Platform Design Concepts topical report was issued in June 2017.[17]

The USNRC has two FPGA-based vendor topical reports under review. The Toshiba Non-Read/Write FPGA platform topical report was submitted to the USNRC in October 2012.[18] Radiy RadICS platform topical report was submitted to the USNRC in September 2016.[13]

6.2 FPGA-Oriented Guidance Developments

There has been a steady trend for the development of FPGA-oriented guidance, industry standards, and regulatory criteria.

EPRI 1019181 provides tutorial information, perspectives and suggestions on the use of FPGA technology in nuclear safety applications.[5] It has been augmented with EPRI 1022983, which provides comprehensive and integrated guidance for FPGA technology on the use of FPGA technology in nuclear safety applications.[6]

IEC 62566 is a comprehensive and integrated standard for the application of FPGA technology in nuclear safety applications.[19]

MDEP DICWG-05 provides a common regulatory position on the expectations for the use of FPGA technology in nuclear safety applications. It mirrors the high-level guidance in IEC 62566.[20]

IAEA NP-T-3.17 provides tutorial information and general guidance on the use of FPGA technology in nuclear safety applications.[21]

7 Concerns about Embedded Digital Technology

Embedded digital devices (also called Smart Devices) contain a microprocessor(s) or other form of complex programmable electronic components that provide specific forms of functionality. Typical examples of smart devices for use in electrical applications can include: protective relays, emergency diesel generator controllers, and controllers associated with uninterruptible power supplies.

IAEA No. NP-T-1.13 addresses the use of Smart Devices and discusses options, associated benefits, challenges, precedent decisions, country experience, and recommendations.[22] Smart devices should be considered where they provide nuclear safety benefits. Smart devices are complex with a range of potential failure modes, and qualification should include an assessment of potential consequences of these failure modes, and adequacy of measures to protect against them.

IEC 62671 is a standard that addresses the selection and use of industrial digital devices of limited functionality in nuclear safety applications.[23] It provides criteria for functional and performance suitability, dependability (i.e., evidence of correctness), integration into the application (i.e., limits and conditions of use) and considerations for preservingacceptability.

MDEP DICWG-07 provides a common regulatory position on the use of industrial digital devices of limited functionality in nuclear safety applications.[24] It mirrors the high-level guidance in IEC 62671.

These guidance documents address the embedded digital devices selected by the user; however, it is also important to recognize that there may be embedded digital devices in industrial I&C provided for use in safety systems that are not known to the user. The USNRC recently notified the nuclear industry of a problem where a vendor of industrial time delay relays made a change to the design and introduced an embedded digital device.[25] The change was not identified with a new part number and was not reported to customers purchasing the devices. The change replaces a solid-state integrated circuit logic chip with a CPLD. This design change introduced the potential for new failure mechanisms such as greater susceptibility to electrical noise.

The non-nuclear sectors using digital devices for safety-critical applications have had a strong influence on the supply chain. More vendors are now providing digital components (from small devices like sensors up through processing platforms) with an IEC 61508 SIL certification. This certification specifically addresses several points of interest that are shared with the nuclear sector. The certification process assesses the management of functional safety (i.e., project organization and responsibilities, personnel competence, development lifecycle, tools, and documentation). The technical evaluation assesses design features intended to avoid systematic failures (i.e., design of system architecture, hardware and software modules, including techniques and measures). The technical assessment also looks at the control of operational failures (i.e., techniques and measures for control of random hardware, environmental, or operational failures). The product design is subject to a Failure Modes, Effects, and Diagnostic Analysis (FMEDA) to calculate a Safe Failure Fraction (SFF) and Probability of Failure on Demand (PFD_{AVG}). This analysis often identifies additional requirements for the software to provide increased diagnostic coverage.

8 Cyber Security

Cyber security is a concern with FPGA-based systems as it is with computer-based systems; however, FPGA-based solutions have characteristics that tend to increase the level of difficulty that would be faced by a would-be attacker as compared to conventional microprocessor-based systems. FPGA-based systems that directly implement the required I&C functions do not contain high-level, general-purpose components that can be easily diverted or hijacked for malicious purposes; malicious functions must be introduced as complete designs, using technology-specific engineering tools. This aspect of FPGA designs raises the level of difficulty a would-be attacker would face in attempting to make malicious modifications. Some of the FPGA technologies now used for safety or critical applications can be used in such ways as to require physical access to, and disabling of, the I&C equipment in order to alter the current programming.

9 Plan for Success

There are clear reasons to replace analog with programmable/configurable equipment in nuclear power plants. The main reasons are listed below:

- Address obsolescence
- Improve reliability
- Fix existing maintenance problems
- Improve maintainability
- Reduce workload
- Shorten outage time or simplify plant start-ups
- Provide better control leading to fewer plant upsets
- Use common digital platforms
- Support workforce plans

Modernization projects are most successful when there are clear reasons for doing the project and that define the proper scope.

In addition to obsolescence driven replacements of analog with programmable digital technology, consideration should be given to potential enhancements made possible by the adoption of digital technology. Typical enhancements include the following:

- Elimination of single point failures
- Ease of maintenance
- Reduction or elimination of testing
- Automation of testing
- Additional information available to operations and maintenance through enhanced Human Machine Interfaces
- Improved diagnostics of the control system resulting in simplified trouble shooting activities
- Instrumentation upgrades
  - Change switches to transmitters (e.g., pressure, flow, etc.)
  - Introduction of redundancy in I&C architectures
  - Smart transmitters for ease of calibration

It is helpful to educate oneself and understand what is possible by upgrading. Based on this information, the next step should be to define and specify the required functionality. It is best to choose your I&C system supplier up front and work with them to develop a Functional Requirement Specification rather than a bid specification.

It is critical to provide enough time to write a good specification and have it reviewed. This helps to avoid a common scenario: the specification is issued late, but the supplier is expected to meet the original schedule.

It is important to have clear supplier selection criteria that considers experience with a variety of nuclear plant digital I&C projects. It is also important to understand the supplier’s history of product support and a platform migration path in order to lessen obsolescence impact.

It is beneficial to have a comprehensive set of platform selection criteria. Typical elements of a platform selection criteria may include the following:

- Platform operating experience in similar applications
- Platform technology is appropriate for system requirements
- Platform technology is consistent with utility digital strategic plan
- Requisite fault tolerant and self-testing and diagnostic features are available
- Demonstrated high availability and reliability
- Complexity of the licensing process
- Platform technology has requisite third-party certification (if required)
- Longer term support offered from vendor
- Expandability
- Maintainability

Internalize the old mantra: proper prior planning prevents poor project performance.

10 Summary

Digital technology is a mature and reliable option, as demonstrated by the thousands of reactor-years of operation in safety and control applications.

There are costs and risks associated with postponing adoption of digital technology and clinging instead to analog products that are difficult and expensive to find in today's market.

Recognize that there are many positive actions (e.g., regulatory approvals) occurring throughout the nuclear industry that are changing the perception that there is an unstable or insufficiently clear regulatory framework for the application of digital technology.

There are benefits that come from the use of digital technology that need to be quantified and communicated to utility decision makers.

FPGA technology can be used to successfully address a number of digital concerns, among them common cause failures, cyber threats, obsolescence, and failure modes.

There is a mature set of FPGA-oriented guidance and international standards that can be used to ensure successful project implementation.

Nomenclature

CCF	common cause failure
CPLD	complex programmable logic device
DICWG	Digital I&C Working Group
FPGA	field programmable gate array
HDL	hardware descriptive language
IEEE	Institute of Electrical and Electronics Engineers
I&C	instrumentation and control
IAEA	International Atomic Energy Agency,
IEC	International Electrotechnical Commission
MDEP	Multinational Design Evaluation Program
SIL	Safety Integrity Level (as defined in IEC 61508)
SSPS	Solid State Protection System
USNRC	United Stated Nuclear Regulatory Commission

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