# Implementing Safeguards by Design for an Advanced Reactor

Thomas Wood
thomas.wood@westinghouse.com

Jo Anna Bredenkamp
joannabredenkamp@westinghouse.com

Thomas Grice
thomas.grice@westinghouse.com

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Abstract

Despite strong IAEA support for and increasing industry interest in Safeguards by Design (SbD), no definite model for its implementation in an advanced reactor program has yet been defined. Westinghouse Electric Corporation (WEC) is now pioneering SbD within the design and development program for its eVinci micro-reactor - and considering several important aspects of the implementation model in the process.  This initial application of SbD to the eVinci micro-reactor program will be the model for future SbD efforts at all WEC nuclear facilities. This paper describes some of the issues involved and how WEC is framing and addressing them.

The economic environment for advanced micro-reactor development demands technological innovation to meet demanding core lifetime, operational autonomy, and remote site deployment requirements.  This increases technical and economic risks for designers and introduces ambiguity about reactor systems design features.  In addition, these requirements must be met at costs competitive with conventional small power and process heat sources - in development, design, and licensing programs under challenging schedules.

In such a challenging development and deployment environment, several aspects of the SbD implementation program are critical, including [1] the economic costs of implementing SbD and their effects on the integrity of the business case for the reactor, [2] the appropriate stages of reactor systems development at which to explore design features and operating processes to support safeguards, and [3] definition of formal safeguards requirements which are integrable with the systems engineering process for reactor development.

Subsidiary to these core issues are many procedural questions – how to time SbD concept development and analysis to support the overall development schedule without risking delays in producing a licensable design, how to minimize the risk of compromising the licensing technical case in any manner, and how to estimate the incremental cost of a safeguards program which is “designed into” (integral with) the reactor design rather than “added on” to the design.

Among the findings from implementing SbD within the eVinci program to date are [1] a need to state SbD objectives in a technologically neutral context, allowing room for innovative approaches, [2] defining a definitive schedule window for the introduction of safeguards approaches in each major reactor subsystem, [3] the earliest possible definition and resolution of economic uncertainty regarding safeguards measures.

## I – eVinci Features and Challenges

eVinci is a 15 MWt, factory built, graphite moderated, HALEU-fueled reactor, passively cooled using heat pipe technology[1]. The reactor module is very compact and will be housed withing a standard CONEX container. It is designed for autonomous operation at remote sites over a core lifetime of up to 10 years. During this on-site operational period, there is no access to the reactor core except via an integrated sensor suite. At the conclusion of this on-site operational period, the reactor is returned to the factory for refurbishment and refueling. This design and fuel cycle poses significant safeguards challenges and *requires* an SbD approach. The WEC SbD program is being integrated into a structured reactor design process in which system and subsystem requirements are quantitatively defined and allocated to subsystems, and technical options for meeting requirements are formally evaluated for performance and cost.

The economic competitiveness of eVinci depends on t [1] minimizing capital cost by production at scale, [2] minimizing operations cost by limited on-site staffing, and [3] competitive licensing and deployment schedules. These aspects of the eVinci business case strongly influence both the design itself and the process through which the design is developed.

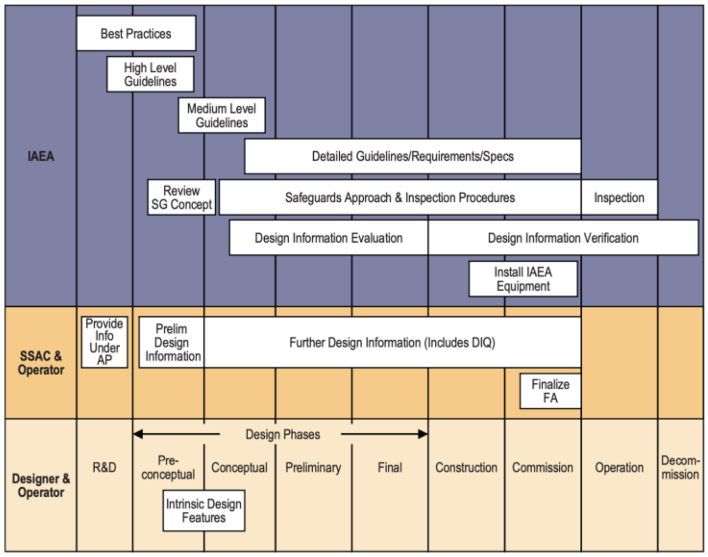
## II– Need for a New SbD Process

While there is broad support for the *concept* of SbD, there is yet no definite implementation process appropriate for advanced reactor developers. As early as 1992, the IAEA governing board had called for “preliminary” design information to be supplied for all planned nuclear facilities in non-weapons states but did not specify a form for this information or direct its submission at a certain point in design. By 2008, IAEA and industry interest in a new model for integration of safeguards with reactor design was widespread, and the IAEA sponsored a workshop on “Facility Design and Plant Operation Features that Facilitate the Implementation of IAEA Safeguards”. This workshop was attended by representatives from over 60 organizations from industry to national nuclear authorities and national laboratories and explored many concepts for both technical and procedural approaches to SbD.

Based on discussions at the IAEA workshop, participants from US DOE national laboratories published a description of a proposed implementation process for safeguards by design (Bjornard et al 2010). Figure 1 is from this report.

[1] Heat pipes utilize metal vapor transport and liquid recycle by capillary action within an enclosed tube. They provide passive cooling. See Grabaskas 2019.

Figure 1
IAEA Proposed Safeguards-by-Design Implementation Process




Source: INL/EXT-09-17085

The process shown in Figure 1 presents several problems for an advanced reactor design and development campaign. These are described briefly below.

Preliminary Design Information

Preliminary design information is shown as generated far too early in the design sequence. Preconceptual design is a phase in which multiple fundamental concepts are analyzed and the few core concepts for the reactor design are selected. [2] This stage of design does not provide any actionable information for safeguards. Additionally, the process in Figure 1 shows the preliminary design information being provided by the reactor owner and the State System of Accounting and Control (SSAC), rather than the designer. Given that an advanced reactor design undergoes significant evolution, the designer should be the source for this information.

Designer's role

The only process for which the designer is assigned responsibility in figure 1 is the generation of "Intrinsic Design Features" during preconceptual and conceptual design. These are the features inherent to a design concept that cannot be altered by refinements in the design – e.g., a liquid-sodium cooled reactor limits visual observation of the fuel. While this step may be helpful early on, the omission of further tasks for the designer is a serious shortcoming – it is the designer who must assess the costs of benefits of safeguards features and integrate them in the design. The proposed process has nothing to say about this essential step in SbD.

[2] For eVinci, this was the stage at which the decision to use heat-pipe technology was taken.

Review Safeguards Concepts

Concurrent with preliminary design information (and ending early in the conceptual design phase) is an IAEA review of the safeguards concept. While a prompt IAEA review of safeguards concepts will be desirable *once they are proposed,* the designer needs time to evaluate them in the context of other reactor requirements and design constraints. This is the WEC "optioneering" process now underway in the preliminary design phase for eVinci. This process is the essence of safeguards by design – the definition and integration of safeguards requirements within the overall requirements management and allocation ("flow-down") paradigm. It must be done by the reactor designer.

Detailed Guidelines/Requirements/ and Specs.

This IAEA task is depicted as beginning in the conceptual design phase - which is appropriate from a design management perspective. Early requirements definition serves to help in the early identification and resolution of design uncertainty. However, this task should not extend as late in the project (construction and commissioning phases) as shown in the figure. Definition of requirements during and after construction has been the root cause of cost escalation under traditional safeguards.

Further Design Information

This task is shown extending from the beginning of conceptual design to the end of facility commissioning. This phase has been described as a "dialog" with IAEA. As such, its duration and cost are inherently unpredictable and pose schedule risks for an advanced reactor developer. Additionally, this task is shown as a responsibility of the owner and SSAC. Design information should flow from the designer.

Summary of IAEA Proposed SbD Process

The issues described above make implementation of the proposed IAEA process as depicted in Figure 1 unadvisable and reflect some fundamental biases or assumptions that are inappropriate for advanced reactor design. These include a desire to begin SbD as early as possible in the process, a traditional (site-built) reactor design and construction sequence, and the constraint that IAEA has formal relations only with host states. The SbD program now being planned for eVinci seeks to address these issues and define a process that is effective and efficient within the context of planned design and development tasks.

## III – the Economic Environment and the eVinci Business case

### The Economic Environment and "Design"

The economic environment now facing developers of advanced reactors is fundamentally different from that in which current generation reactors have been built, and the "design" required in advanced reactor development is fundamentally different from that utilized for the current generation of site-built reactors. Micro-reactors such as eVinci are the most challenging from an economic perspective since they must overcome the most extreme disadvantages due to dis-economies of plant scale.

The last 50 to 60 years of reactor and fuel design has been an *evolutionary* process, in which several fundamentally different design concepts were refined and tested in the market. Proven design features were inherited by successive generations of designs. (Rothwell 2021). The commercial environment facing developers of advanced small reactor designs today demands a *revolutionary* process – more challenging than the recent historical economic environment for nuclear power in in several ways: [1] greater performance risk due to introduction of commercially unproven technologies, [2] greater market (competitive) risk due to the introduction of many designs in the same era, [3] greater schedule risk due to the urgency of nuclear as a climate mitigation technology, and [4] the need to increase reactor production to an unprecedented scale to capture economies of factory production. These features of the design/development environment demand both new safeguards and security technical approaches and a new paradigm for incorporation of safeguards and security in the design, development, and construction cycle. The facts that many new reactor concepts *can* be factory-built due to small unit scale and *must* be factory-built to achieve economies of large production scale, mean that safeguards and security systems cannot be added to an almost completed installation. To this extent, some form of safeguards and security by design is a necessity for many new designs.

For these reasons, the "design" connoted in the original IAEA use of SbD is not the "design" required for a new advanced reactor. The former was the process of adapting a well-proven and previously licensed reactor design to the specific requirements of a customer on a specific site. The latter deals with a much broader span of phenomenology – beginning with the fundamental physics of an unproven reactor concept, the integrity of new materials in a radiation environment, the technology of component manufacture, and a new model to frame and capture imagined transient event sequences. These additional degrees of freedom add greatly to technical uncertainty and economic risk.

### Business Case

A core principle in the WEC approach to SbD is accounting for and minimizing any adverse effects on the business case for the reactor. A business case is a rationale which shows how a design, design feature, design practice or a design investment effects the economic feasibility of an engineered system. A successful business case must demonstrate both acceptably low costs for reactor buyers and sufficient rate of return on design and development investment.

The business case is framed in the context of a business model, which defines markets, financial and non-financial objectives of the producer, and the transactions in which the system is offered to market. For a new reactor design, the business case is based on the design and modeled operational characteristics rather than experience in past reactor builds. For advanced reactors, it involves extending the physics which define technical feasibility to include consideration of materials selection and cost, manufacturability, time to market, fuel cycle/economic performance of a system, and the extent of market demand for the product. To be sound, it must account for the risks created by the uncertainties in all these domains.

The possible economic effects of SbD were first evaluated by Pacific Northwest National Laboratory (PNNL). (Wood et al, 2012). Among the types of possible effects of SbD on the business case for any advanced reactor design are [1] direct capital and operating cost increases, [2] additional design effort and schedule delays imposed by additional requirements on reactor systems, [3] increased uncertainty regarding the cost and time-to-market for the approved design, and [4] expansion of markets due to ability to deploy in counties requiring international safeguards.

At this preliminary stage, WEC assesses the net effects of SbD to be positive for the eVinci business case. This assessment is contingent on an SbD implementation process that minimizes adverse effects, and strongly driven by the large potential markets for microreactors in non-nuclear weapons states. This assessment will be updated as the design and safeguards measures become better defined.

## IV - Implementing SbD for eVinci – Core Principles and Possible Effects

While it is too soon in the eVinci SbD program to propose a definite alternative to the IAEA process described in section I, some of the risks posed by the IAEA process, along with the WEC design management paradigm and philosophy, suggest a conceptual model for SbD implementation. This model should be appliable to all nuclear facility or equipment designs in which safeguards or security requirements are anticipated. This conceptual model should seek to minimize the incremental schedule and economic risk and ensure that the market expansion potential of SbD is fully realized. Such a model is being developed and pioneered within the WEC eVinci program, applying three guiding principles:

[1] SbD should not interfere substantially with the design, development, licensing, or commercialization schedules, or the design of safety-critical systems, for new products.

[2] SbD processes should allow the design organization to pursue innovative, non-traditional safeguards concepts that complement the physical designs and business models for new products.

[3] SbD processes should see to minimize incremental schedule and economic risk by identifying, clarifying, and resolving uncertainty early in the design and commercialization sequence.

As applied to the eVinci design, these principles suggest that there is an optimal *phase* of design at which each of the major reactor systems are well-enough defined to allow safeguards features to be conceptualized and yet flexible enough to allow joint optimization to meet both reactor functional and safeguards requirements. The structured requirements definition and allocation process employed at WEC also implies that there is an optimal process for describing and introducing safeguards *requirements* rather specific design features. Such an approach should allow implementation of SBD with design flexibility and minimal incremental economic risk.

## Direct Cost Effects

Direct costs of safeguards infrastructure are typically a small fraction of nuclear facility costs. These include sensors (cameras, radiation measurement systems) and other instrumentation to observe and record nuclear material measurement, seals or Tamper Indicating Devices (TIDs), and the cost of staff time to prepare declarations and other reports to IAEA. Two considerations are especially relevant in assessing these costs for eVinci. First, the very demanding space constraints within the eVinci reactor module make it highly problematic and likely infeasible to incorporate a new suite of dedicated safeguards instrumentation in the design. Thus, the strategy for meeting material monitoring requirements is to use information from the set of instruments in the reference Instrumentation and Control (I&C) design. This set of information is extensive to support the autonomous control requirements already in the design basis and will be evaluated to ensure that it can meet safeguards requirements.

A similar strategy will be followed to minimize the incremental costs of physical barriers used to control access to the reactor. To the extent possible, new structures will be minimized and existing structures modified to control unauthorized access to the reactor.

Given the nature of the eVinci fuel cycle, there should be no requirement for reactor site staff dedicated to safeguards. There are no nuclear material transfers at the reactor site. Estimates of $U_{235}$ depletion and Pu accumulation in the core can be made directly based on power monitoring inputs in the reference I&C system. Verification of these estimates may be required based on fuel Non-destructive Examination (NDE) – but this will occur at the refueling facility.

## Schedule Delay

As noted in section I, previous IAEA proposals for implementing safeguards-by-design in power reactors show an extended period of “dialog” between the designer and the IAEA. This interaction is depicted as extending through several phases of reactor design and could thus take several years. In such a process, there is a clear risk that the overall development or deployment schedule for a new reactor design could be extended.

There are three types of costs that such a delay could impose on WEC: [1] increased direct design or testing costs for extended activity schedules, [2] increased carrying charges for capital investment in an extended design and development cycle, and [3] loss of market share to competitors due to late market entry. Preliminary analysis of the cost of schedule delay for eVinci shows significant cost impact from deployment delays in range of months beyond the reference schedule.

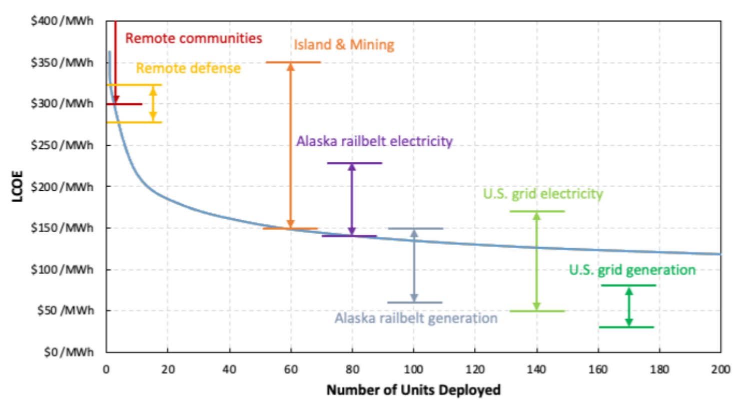
Market Expansion

Among the features of eVinci markets, the size of the end-use market is the most important to the business case.  This is so because it is essential to achieve a large scale of production (on the order of several hundred units ) to achieve unit electricity costs competitive with conventional power sources.  Market demand gains are also the only realistic source of business case benefits from SSeBD to offset the potential costs described in previous sections.

Figure 2, taken from (Shropshire et al, 2021) illustrates both the ranges of electricity prices currently prevalent in a series of market sectors, and a typical "learning curve" for microreactor production. This learning curve defines the expected average cost of production (expressed in LCOE units) as a function of the scale of production.    An important aspect of the market price ranges in figure 2 is that they are set by well-known and well-developed technology, and by the economics of fuel transport and electrical grid interconnection.  There is little uncertainty about the lower limits of for these ranges. The upper limits are subject to much greater uncertainty due to secular trends and volatility in oil and natural gas prices.

Given that the mining sector market is large compared to the remote community and defense markets, and is largely located in states requiring international safeguards, an eVinci design incorporating safeguards capabilities will find a much larger market than one without, which could be sold only in NPT weapons states.  Data on the mining sector was evaluated to assess of the importance of non-weapons states markets to the eVinci business case.   This analysis showed that mining sector markets will be significantly expanded for an eVinci design and fuel cycle incorporating adequate safeguards.

Figure 2
Costs of Electrical Energy in Microreactor Markets and
Typical Production Learning Curve



Summary

Decisions on whether and how to implement SbD for eVinci are highly consequential for the reactor business case. SbD could entail both significant costs - direct costs of technology and staff, and possible delays in reaching eVinci marketability, and important benefits - a significantly larger market and greater customer acceptance.  Minimizing costs and maximizing benefits will depend on the details of SbD implementation – both in terms of the technology employed and the processes for [1] introducing safeguards and security concepts at the appropriate points in the design sequence, [2] accounting for the direct costs and potential schedule risks of the approaches developed, and [3] managing the interactions with IAEA and other regulatory agencies to ensure approval of SbD approaches and features.

An early proposed International Atomic Energy Agency (IAEA) implementation model for SbD, if utilized as described, would create several business risks for an advanced reactor project – a protracted interaction with IAEA beginning very early in design and extending throughout all phases of design, definition of requirements late in the design process, and a very limited role for the designer (as opposed to the reactor owner).  It is clear this process was set forth in the context of traditional site-built reactors, in which a mature design was adapted to a specific site and its requirements. As a result, there is not yet have a well-defined implementation model for SbD in advanced reactors. This allows WEC the freedom to implement SbD in a manner consistent with its design-management process and the constraints imposed by a feasible eVinci business case. Analysis of prior proposals for SbD implementation and the safeguards literature have defined the important business risks to be mitigated in implementing SbD – including increased direct (capital and operating) costs and the potential indirect costs of delayed deployment to the market. Analysis of a key market sector (mining) has shown that expansion of the market to states requiring international safeguards is essential to producing eVinci at economic scale.

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