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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Evaluation of a Business Case for Safeguards by Design in Nuclear Power Reactors

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December 2012

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Richland, Washington 99352

Executive Summary

Safeguards by Design (SbD) is a well-known paradigm for consideration and incorporation of safeguards approaches and associated design features early in the nuclear facility development process. This paradigm has been developed as part of the Next Generation Safeguards Initiative (NGSI), and has been accepted as beneficial in many discussions and papers on NGSI or specific technologies under development within NGSI. The Office of Nuclear Safeguards and Security funded the Pacific Northwest National Laboratory to examine the business case justification of SbD for nuclear power reactors. Ultimately, the implementation of SbD will rely on the designers of nuclear facilities. Therefore, it is important to assess the incentives which will lead designers to adopt SbD as a standard practice for nuclear facility design. This report details the extent to which designers will have compelling economic incentives to adopt SbD.

Safeguards implementation costs are typically a very small fraction of total reactor costs, and thus provide little real economic incentive for SbD through lowered costs. Applying an economic model to a standard reactor design and construction sequence shows that high costs would result from delay in reactor startup due to safeguards implementation. However, International Atomic Energy Agency (IAEA) regulations specifically forbid reactor start up delays due to safeguards implementation.[1] Further, a questionnaire for IAEA staff confirmed that these factors resulted in limited incentive for designers to complicate facility design cycles by adopting SbD.

While SbD may not offer an economically compelling paradigm for the current generation of nuclear power reactors (which were often designed for deployment in weapons states), a newer generation of reactors, including small and modular reactors (SMRs), would present a better opportunity for economic application of SbD.

This report also presents an analysis of a comprehensive list of emerging reactor designs that are candidates for current and future new builds - from a SbD perspective. Reactor designs were individually assessed according to three factors likely to influence the economic feasibility of SbD implementation for each design: 1) the existence of design features posing safeguards issues, 2) current stage of design, and 3) market viability. The results indicate several emerging designs in which SbD could present an attractive business case for reactor designers.

[1] INFCIRC153, Part 1, Paragraph 4, IAEA, 1972.

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We gratefully acknowledge the contributions of Scott Demuth (Los Alamos National Laboratory) and Mark Schanfein (Idaho National Laboratory), who provided insight and analysis of the history of International Atomic Energy Agency safeguards implementation in power reactors, including several cases in which safeguards systems installations had been retrofitted in operating reactors. We also acknowledge Casey Durst of Durst Nuclear Engineering and Consulting Inc. for his insight on economic incentives for SbD over several different classes of facilities. Karyn Durbin (NNSA NA-24) provided valuable guidance throughout the project. Finally, we acknowledge the use of reactor design economic assessments conducted under funding from Rich Goorevich and Sean Oehlbert (NNSA NA-24), and their kind permission to use this material here prior to formal publication.

Acronyms and Abbreviations

BWR	Boiling Water Reactor
C/S	Containment and Surveillance
CoK	Continuity of Knowledge
EPA	Evolutionary Power Reactor
FSA	Facility Safeguardability Assessment
Gen IV	Generation IV (reactor design)
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LWR	Light Water Reactor
NGSI	Next Generation Safeguards Initiative
NNSA	National Nuclear Safety Administration
NSSS	Nuclear Steam Supply System
PHWR	Pressurized Heavy Water Reactor
PIT	Physical Inventory Taking
PIV	Physical Inventory Verification
PNNL	Pacific Northwest National Laboratory
PWR	Pressurized Water Reactor
SbD	Safeguards by Design
SMR	Small and Modular Reactor

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1.0 Introduction

The Next Generation Safeguards Initiative (NGSI) Safeguards Policy Team at the National Nuclear Security Administration (NNSA) funded a study to explore the business case justification for Safeguards by Design (SbD). The study was initiated in FY 2012 by an inter-laboratory team from Pacific Northwest National Laboratory (PNNL), Idaho National Laboratory (INL), and Los Alamos National Laboratory (LANL) and completed in FY 2012 by PNNL with assistance from Durst Nuclear Engineering and Consulting Inc. An earlier draft of Section 2.0 of this report was previously published as an International Nuclear Materials Management (INMM) conference paper in the proceedings of the 9th International Conference on Facility Operations – Safeguards Interface.

The concept of SbD has been a strong focus of the nuclear industry. While some industry representatives have shown a preliminary interest in SbD, it has not yet been widely used or adopted by designers, investors, or regulators. As designers of nuclear facilities are the ones who must bear the costs of SbD efforts, they are the ultimate decision-makers who will determine whether SbD becomes an industry standard practice or not. The economic advantages of SbD are thus of particular interest.

One possible way to motivate designers in the nuclear industry to use SbD is to develop and communicate a clear business case for the process. This report documents incentives that might present a compelling motivation for designers to pursue SbD and includes recommendations on which emerging reactor designs might be the best candidates for SbD application on economic grounds in the next decade.

1.1 Types of Facilities and Scope of Study

The facilities of interest for this study were deliberately selected for greatest relevance to the nuclear industry. While it is clear that nuclear fuel cycle facilities (enrichment, fabrication, and reprocessing plants) pose much more daunting safeguards challenges than nuclear power reactors, they are also built much less frequently. For this reason, the study focused on nuclear power reactors.

The assessment was conducted in two stages: the first focused on specific historic cases of safeguards implementation at the International Atomic Energy Agency (IAEA), and the second on a review of emerging reactor designs.

Stage I (reported in Section 2.0) used a survey of five IAEA staff knowledgeable about the specifics of many safeguards installations. This phase of work was guided by our initial assessment of the costs of safeguards implementation relative to overall reactor costs, and a conclusion that simply gaining greater *efficiency* (lower costs) in safeguards implementation would not typically provide a large incentive to designers in the context of overall reactor costs. Thus, this phase sought to find and document cases in which the use of “traditional” (late in the construction cycle) safeguards implementation resulted in very large negative consequences – sufficient to pose unacceptable risks to owners and designers and thus serve as a powerful motivation to implement SbD.

Stage II (reported in Section 3.0) focused on defining the set of design and market factors that would tend to favor a strong economic business case for SbD, and identifying which specific emerging reactor designs best exemplified these factors. While these criteria are explained in more detail in Section 3.0, there are three sets of factors which will affect the economic viability of SbD for emerging reactor designs: 1) the *relevance* of safeguards to a given design (i.e., the existence of significant safeguards technical issues); 2) the *opportunity* to fully implement SbD at an early design stage; and 3) the extent of *economic incentive* for successful application (as measured by the extent of prospective sales for each design).

The first two criteria were applied to 57 reactor designs [both traditionally sized reactors and small and medium sized reactors (SMRs)] that had previously been screened for likelihood of market success by a panel of PNNL reactor experts. As reported in Section 3.0, these combined assessments offer a technical/economic basis for consideration of SbD priorities for specific nuclear power reactor designs.

2.0 SbD Business Case Assessment for Existing Reactor Designs

Reactor designers have compelling incentives to maximize performance (i.e., reliability, efficiency, safety) and minimize costs of their designs. Thus, an economic or business case assessment must be framed in terms of costs and benefits relevant to overall reactor success in the market, and should be viewed relative to the “base case” or standard practice in the industry.

PNNL’s review of recent safeguards implementation in power reactors showed that the current standard practice is incorporation of safeguards features very late in reactor construction. It is typical for “design information” to be furnished to the IAEA 180 days before fuel loading at a reactor site. While this approach is compliant with IAEA requirements in INFCIRC 153, it clearly limits the opportunity for early incorporation of safeguards features in the design process. There are several reasons for this practice, including the fact that many reactor designs were originally developed for deployment in weapons states that typically have significantly fewer safeguards requirements and are simply adapted to deployment in non-weapons states during site-specific design. The market advantage of a regulatory pedigree associated with U.S. or European licensing, as well as the fact that IAEA agreements *preclude* safeguards interference with reactor operations, suggests that this practice is likely to continue.

PNNL found the overall cost of international safeguards design, installation, and application to be a very small percentage of the overall plant construction cost. Initial safeguards implementation costs are on the order of a few million dollars for most power reactors, therefore, any *prospective cost saving* achieved for these costs via SbD is of little consequence vis-à-vis reactor design and construction costs, which are three orders of magnitude larger.

On the principle that designers are attentive to the interests and concerns of reactor buyers and owners, we postulated that a principal financial motivation for SbD could be to prevent possible costly delays in plant startup. Delays in plant operation due to extended construction (including construction extended by re-design) are widely acknowledged as one of the main causes of high plant construction costs. PNNL demonstrated that avoiding delays in reactor start-up is a powerful incentive to minimize design-related construction delays of any type. The economic costs of delay are typically about $2 million per day for a one GWe reactor (see Appendix A). Accordingly, we sought examples where a failure to adequately consider international safeguards in a timely fashion had caused startup delays.

The initial approach consisted of questioning IAEA staff about their experience in the cause and cost of plant startup delays due to application of international safeguards. The results are described below. In addition, we present two case studies where SbD either added value or could have reduced construction costs.

2.1 Interaction with IAEA

Our team submitted a set of questions addressing safeguards costs and SbD to IAEA staff for comment and received comments back from five IAEA staff members. The questions, answers, and our interpretations are discussed below.

Our 20 questions (see Appendix B) sought to address the following questions:

1. Have any power plant startup delays occurred as a result of inadequate or inappropriate support for establishing the safeguards approach?
2. How does facility design affect safeguard costs? Have improvements/technical evolution of safeguards equipment/approach lowered overall costs?

Responses for each of these categories are analyzed in the following sections.

2.1.1 Costs Due to Startup Delays

The IAEA responses indicated that cost increases caused by startup delays due to international safeguards implementation for most designs in the past were rare, and when occurring, small in relation to reactor designs and construction costs. The concept of SbD was not an issue for most of these nuclear power plants because IAEA safeguards were applied primarily to existing or already designed facilities. Consequently, techniques and methods used to implement safeguards take this into account.

2.1.2 Safeguards Cost Variations

The responders indicated that safeguards costs in general are not uniform for a particular facility design, but depend on the facility location, impact of local labor costs, and the type of agreements and safeguards approaches decided between the State and the IAEA.

The cost of implementation of safeguards, while still a small part of the overall plant cost, can be impacted by several factors. For instance, responders indicated that delaying consideration of safeguards installation can result in more expensive installation costs. Waiting until the "last minute" to consider safeguards was estimated to potentially increase safeguards costs by a factor of 3 to 10.[1] In some cases, equipment-related costs dropped by 40% when equipment (e.g., containment and surveillance [C/S] equipment, cabling runs, safeguards related lighting) was installed during construction compared to a retro fit.

[1] This is a respondent's characterization and was offered without any specific examples.

The responders agreed that it was important for designers and owners considering SbD to recognize the cost/benefits of:

- Optimization of C/S measures
- Early provisions for cabling installation
- Optimization of the location for nuclear material verification instrumentation.

2.2 SbD Case Studies

Two specific examples of SbD implementation suggest a valid argument for SbD. In the first case, SbD has been adopted by a reactor designer with valuable results. In the second case, failure to consider several sets of design requirements (including safeguards) resulted in substantial added costs and delays.

2.2.1 The Canadian CANDU Experience

Some existing reactor designs have safeguards issues beyond those faced in typical LWRs, and thus have greater safeguards costs. A good example is the CANDU reactor fleet. While this fleet of pressurized heavy water reactors (PHWRs) initially required extensive onsite inspector presence, application of SbD to their facilities has resulted in significantly lower costs. Improvements included increased offsite monitoring systems, improved spent fuel storage inventory and monitoring, and enhanced containment and surveillance systems (Ellacott et al. 2010; Whitlock 2010).

2.2.2 The Finnish Experience

The construction experience of Olkiluoto 3 in Finland, a Generation III+ Evolutionary Power Reactor designed by AREVA, is an excellent example of the consequences of not considering SbD in the design of a new facility (Okko et al. 2010). There are a number of design issues with this facility that have caused significant delay and cost overruns, including those related to the facility safeguards approach.

Safeguards implementation was not thoroughly considered in the early design stages, and there was a failure to coordinate safeguards requirements during the design of the containment structure. The identification of appropriate locations for instrumentation, surveillance cameras, and seals was not initiated until containment construction was underway. Thus, power and space requirements for safeguards instrumentation and cable penetrations were not considered during the design phase, making new cable penetrations difficult and expensive.

The fuel transfer routes between the fuel building and reactor were originally designed in such a way that continuity of knowledge for fuel identity could not be maintained during fuel transfer. If these requirements had been taken into account during the early design process, the transfer routes could have been designed to allow surveillance of the fuel assemblies in transit, while adding little or no extra cost for construction or operation of the plant. As it was, significant and expensive design changes were required to maintain continuity of knowledge during fuel transfers.

These and other problems were the result of a “just-in-time” engineering practice for safeguards, plus other design process issues. The Olkiluoto 3 experience demonstrates that the early introduction of safeguards during the design phase could reduce the impact of safeguards on the cost and facility operations and help to mitigate the risk of surprising, and possibly costly, changes required to fulfill the safeguards requirements.

We have shown (see Appendix A) that operational delays for new power reactors are a compelling financial incentive for reactor owners (and thus for reactor designers). While the operational delays likely to occur at Olkiluoto 3 are clearly of great consequence, there are multiple factors requiring these delays and safeguards issues alone cannot clearly be identified as the sole cause of delays.

3.0 SbD Business Case Assessment for Emerging Reactor Designs

To identify a set of emerging reactor designs for which the business case for SbD might be strongest, PNNL compiled a comprehensive list of reactor designs, which constitute potential candidates for new reactor construction (see Appendix C). This set of reactor designs was then assessed against three criteria; 1) existence of design features posing safeguards issues, 2) current stage of design, and 3) market viability. Together, this set of criteria addresses the technical incentive to employ SbD, the opportunity to insert SbD considerations at an early stage of design, and the extent of economic leverage that is gained in successful SbD application.

3.1 Reactor Design Features Posing Safeguards Issues

Safeguards equipment and procedures are well developed for evolving light water reactors (LWR); in particular, pressurized water reactor (PWR) designs. A new generation of reactors includes many with design features posing safeguards challenges, including those that are already known for certain reactor types. Therefore, conducting SbD in evolutionary facilities would not reveal surprising or unexpected safeguards issues within a facility. SbD will be most economically justified in reactor designs that are revolutionary or present new technological challenges to the international safeguards regime.

PNNL identified a set of reactor design features that might pose safeguards issues in the next generation of reactor designs. They are: 1) opacity of the coolant, 2) the presence of multiple cores, 3) unconventional fuel design, and 4) online refueling. For this report, multiple cores are defined as cores that share major plant components or that are seated in the same building and have multiple refueling schedules, not those that are located at the same site. Unconventional fuel design is any reactor fuel that cannot be thought of as a traditional assembly (or material inside hollow cladding). Online refueling is the capability to exchange fuel assemblies without reactor shutdown. Any reactor design with *any* of these design features will be more likely to profit from early consideration of safeguards technology and processes.

A full list of all reactor designs assessed against these four criteria can be viewed in Appendix D. Table 1 is our assessment of emerging reactor designs from this list that have one or more of these four safeguards issues.

Table 1. Design Features Posing Safeguards Issues

Reactor Design	Multiple Cores	Opaque Coolant	Unconventional Fuel Design	On-Line Refueling
4S (SMR)		x		
ACR-1000				x
AHWR				x
BREST (SMR)		x		
CEFR (SMR)		x		
China HTR-PM (SMR)			**x**	**x**
EC6				x
G4M (SMR)		x		
GT-MHR (SMR)			x	
GTHTR300C			x	
IPHWR-220				x
IPHWR-700				x
FBNR (SMR)			x	
KLT-40s – (SMR)	x			
KAMADO – FBR			x	
NuScale - (SMR)	x			
South Africa (PBMR)			**x**	**x**
PFBR-500 (SMR)		x		
PHWR-300 (SMR)				x
PRISM	**x**	**x**		
SVBR-100 (SMR)		x		
TP-1 (SMR)		x		

3.2 Design Phase

The essence of SbD is involving safeguards experts, techniques and solutions to a reactor design when there is a high degree of design flexibility. The stage of design therefore defines the degree of opportunity to fully implement SbD. There are several stages of design PNNL has identified to separate levels of completeness; they are: 1) conceptual design, 2) preliminary design, and 3) final design/ license submittal.

For the purposes of this report conceptual design was defined as the genesis of the facility concept, with qualitative discussion and analysis of the concept. The preliminary phase begins when quantitative design calculations are undertaken. The final design/license submittal phase occurs when a designer submits the design for licensing. Once a reactor design has been submitted for licensing consideration, there are powerful incentives not to perturb any features of the design lest regulatory review of an approval be delayed or precluded.

Taking a reactor design from the conceptual to the licensed phase is a long, expensive and arduous process. Any alterations to this process (including SbD during conceptual and preliminary design) will be considered in light of their impact on the schedule, costs and chances for successful licensing at the end of the process.

Ideally, SbD will be applied during the conceptual and preliminary design of the facility. During these phases the design is flexible and a designer can make significant changes, or consider creative solutions to critical safeguards issues with minimal impact to any stakeholder. Of the reactor designs analyzed for this report, several are currently in the conceptual or preliminary phase of design and therefore offer a high degree of opportunity for the designers to consider employing SbD. Facilities in the licensing, construction, or operation phase are not listed in Table 2. (A full list of reactor design phases can be viewed in Appendix E)

Table 2. Reactor Design Phase

Name[(a)]	Type	Design Phase(b)
4S	LMCFR	Preliminary
ABWR-II	BWR	Preliminary
AHWR	PHWR	Preliminary
APR-1000	PWR	Preliminary
BREST (SMR)	LMCFR	Preliminary
EM2 (SMR)	HTGCR	Conceptual
FBNR	iPWR	Conceptual
GTHTR20-300C	HTGCR	Conceptual
GT-MHR	HTGCR	Conceptual
HP-LWR	LWR	Conceptual
IMR (SMR)	iPWR	Conceptual
JSCWR	SCWR	Conceptual
KAMADO	FBR	Conceptual
KERENA	BWR	Preliminary
mPower	iPWR	Preliminary
NuScale - (SMR)	iPWR	Preliminary
PHWR-300 (SMR)	P-HWR	Preliminary
RMWR	BWR	Conceptual
SOUTH AFRICA PBMR	PBMR	Preliminary – complete
UNITHERM (SMR)	PWR	Conceptual
VBER-300	PWR	Conceptual
VK-300 (SMR)	BWR	Conceptual
VVER 640 (V 407)	PWR	Preliminary
VVER-600 (V-498)	PWR	Conceptual
Westinghouse SMR	iPWR	Preliminary

(a) Missing from the table above are the TP-1 and HI-SMUR reactors where the current status could not be identified.
(b) Design phases were determined from PNNL expert elicitation and from the IAEA-ARIS website.

3.3 Marketability

If many copies of a reactor design can be sold, the investment in SbD can be spread over a larger volume of revenue, thus greatly increasing the economic leverage involved for a designer. The application of SbD to a reactor with high market potential results in economies of scale – the initial input (time and effort) to employ SbD is justified or offset by the larger return on investments from each reactor that is sold. In contrast, it is difficult to build a SbD business case for reactor types where only one or two reactors are likely to be built. While all reactor designers aspire to sell many nuclear plants, it is clear that not all of the 57 emerging designs in our list will achieve this high market performance. While judging the likely market success of emerging designs is clearly the most subjective of our criteria, much of this work had already been accomplished by a panel of PNNL experts for another project, and was used as input for this assessment.

A number of new reactor technologies and designs, in various stages of technological development and deployment, constitute potential options to apply SbD. Previous PNNL analysis identified a set of reactor technologies and designs most likely to be constructed, per decade, through approximately 2050. A group of PNNL reactor experts evaluated each reactor technology currently under development and/or deployment according to a series of economic viability and market- potential criteria. These criteria included:

- Nuclear Steam Supply System (NSSS) Supplier
- Architect Engineer
- Site
- Interested Utility
- Fuel Supplier
- Licensing Basis
- Funding Source
- Fuel Material
- Cladding Material

Based on these criteria, the expert group was asked to assess market penetration of each reactor and in which decade they would be licensed.[1] Specifically, the group was asked to broadly determine whether ‘many,’ ‘some,’ or ‘a few” of each design would be built. The designs identified by the group as most likely to comprise future nuclear reactors consist primarily of advanced light water reactor (LWR) designs; specifically, PWRs.[2] The most popular designs (those which received the ‘many’ vote) were two advanced traditionally-sized PWRs (Westinghouse AP-1000 and Korean APR-1400). Three Russian VVER designs (VVER-1000, VVER-1200, and VVER-1500) and four SMR designs[3] (Holtec

[1] The group determined that ‘some’ of the following reactor designs would be built: CAREM, NuScale, mPower, Holtec HI-SMUR, VVER-1000, VVER-1200, VVER-1500.
[2] Including Russian VVERs.
[3] It should be noted that the set of SMRs evaluated in the assessment of marketability is notably smaller than that evaluated according to the other two criteria. This is a due to the fact that the preceding PNNL analysis of

HI-SMUR 140, mPower, CAREM, and NuScale) were identified as designs which would be built in fewer numbers (they received the ‘some’ vote) but would still be relatively successful.

The consensus of the group was that boiling water reactors (BWRs) and PHWRs will be built, but in smaller numbers than PWRs. The construction of other more unique reactor types, such as the molten salt and pebble bed reactor designs, will be limited and pursued by a small number of countries. Fast reactors are more likely to be built towards the end of the period of analysis, again by a limited number of countries seeking to close their fuel cycles.

Table 3 presents the reactor designs the PNNL expert group identified as the most commercially viable in the next decades. A full list can be viewed in Appendix F.

Table 3. Reactor Designs with High Marketability

Reactor Design	Reactor Type	Marketability (many/some/few)
AP-1000	PWR	Many
APR-1400	PWR	Many
CAREM – (SMR)	iPWR	Some
HI-SMUR 140 (Holtec) (SMR)	iPWR	Some
mPower – (SMR)	iPWR	Some
NuScale - (PWR?) (SMR)	iPWR	Some
VVER-1000	PWR	Some
VVER-1200	PWR	Some
VVER-1500	PWR	Some

3.4 SbD Priorities

The results of this assessment show three lists of next generation reactor designs that PNNL has identified as having the design and market factors that would favor a strong economic business case for SbD. When we compare these lists, we find a few reactor designs that fall on two or three lists.

anticipated reactors broke out SMRs as a separate case for analysis, and the base case includes only a subset of the many SMR concepts. The base case study did, however, include the most commonly discussed SMRs.

Table 4. Emerging Reactor Priorities for SbD

	Incentive	Opportunity	Emphasis	
Name	Safeguards Issues	Design Phase	Marketability	Total Score
ACR-1000	1			1
4S (SMR)	1	1		2
ABWR-II		1		1
AHWR	1	1		2
AP-1000			1	1
APR-1000		1		1
APR-1400			1	1
BREST (SMR)	1	1		2
CAREM – (SMR)			1	1
CEFR (SMR)	1			1
China HTR-PM (SMR)	2			2
EC6	1			1
EM2 (SMR)		1		1
FBNR	1	1		2
G4M	1			1
GTHTR20-300C	1	1		2
GT-MHR	1	1		2
HI-SMUR 140			1	1
HP-LWR		1		1
IMR (SMR)		1		1
IPHWR-220	1			1
IPHWR-700	1			1
JSCWR		1		1
KAMADO-FBR	1	1		2
KERENA		1		1
KLT-40S	1			1
mPower – (SMR)		1	1	2
NuScale - (SMR)	1	1	1	3
PFBR-500 (SMR)	1			1
PHWR-300 (SMR)	1	1		2
PRISM	2			2
RMWR		1		1
SOUTH AFRICA PBMR	2	1		3
SVBR-100	1			1
TP-1 (SMR)	1			1
UNITHERM (SMR)		1		1
VBER-300		1		1
VK-300 (SMR)		1		1
VVER 640 (V 407)		1		1
VVER-1000 (V-466 B)			1	1
VVER-1200 (V-392M)			1	1

Table 4. (contd)

Name	Incentive Safeguards Issues	Opportunity Design Phase	Emphasis Marketability	Total
VVER-1500 (V-448)			1	1
VVER-600 (V-498)		1		1
Westinghouse SMR		1		1

Although Table 4 shows a total score for each reactor, the effects of these various factors are not necessarily addable. Simple logic suggests that to have a reasonable chance of economically viable SbD implementation, a reactor should score for both incentive and opportunity. Ten reactors meet this condition. Further, the greater the marketability, the greater the revenue stream there will be with which to pay costs of design generally, and SbD in particular. It should be noted that each designer has already made a determination that his design has a good chance of selling, or he would not have invested in it.

One key factor Table 4 highlights is that the majority of “marketable” reactor designs do not have any of the four priority safeguards issues. An economic business case model may want to assess if safeguards issues have a direct impact on the marketability of the reactor. If so, this could further build the case for SbD.

3.5 NuScale

The only reactor design from table 4 to score a one in each of the three categories is the new SMR design by NuScale Power, LLC. This does not necessarily mean that the NuScale design has the strongest economic business case for employing SbD, and it certainly does not mean that it is the only design that would benefit from SbD.

Perhaps (or perhaps not) coincidentally, in FY 2012, PNNL approached NuScale Power, LLC to conduct a Facility Safeguardability Assessment (FSA) on the current NuScale design. This is important not only because our team determined NuScale to be a good business case for SbD, but also because the designer has acknowledged there is some benefit to considering international safeguards requirements during design.

The NuScale design is currently in the preliminary design phase and is not expected to be submitted for licensing until 2014, giving the designer and technical safeguards experts time to assess the safeguardability of the NuScale design (Coles et al. 2012).

4.0 Conclusions

Although SbD is considered to be an important factor in the design, construction, and operation of new nuclear facilities, to date it has been difficult to build a business model that can be used to demonstrate this, in terms important to designers. In the past, most safeguards systems were added to existing designs where design modifications could not be implemented. The Canadian CANDU experience demonstrates that active consideration of safeguards requirements in design can effectively lower safeguards costs and improve safeguards practices. Considering the Olkiluoto 3 experience can be illuminating, as the failure to consider safeguards equipment locations and requirements caused expensive retrofits. As new reactor designs and construction processes are implemented, the economic efficacy of the SbD process has the opportunity to be tested.

Section 3.0 of this report highlights the reactor designs in the next generation of reactors where an economic business case for SbD is most likely to be viable. The reactors highlighted represent the designs that are in an opportune design phase, have priority safeguards issues and are marketable to the international community.

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Appendix A

Cost of Delays in Power Reactor Operations

Appendix A

Cost of Delays in Power Reactor Operations

A.1 A Cost Model of the Nuclear Construction Scheduling Problem

In order to examine the effects of schedule delay on overall project cost, it is useful to postulate a formal model of nuclear construction scheduling in economic terms, to describe its properties, and to exploit their implications for our problem.

The objective of our study is to define both a) the risk (likelihood) of overall delays in power plant operation (as a function of safeguards design/implementation model), and b) predict their economic consequences. This appendix deals only with sub-problem b).

First, we argue that the economic consequences of plant operational delay are independent of the nature of the delay. While this is not strictly valid for some causes of delay (e.g., an accident that damaged already installed equipment would be more consequential than one than simple halted equipment installation for a given resulting delay), it seems reasonable when applied to delays for administrative reasons. Failure to have an approved safeguards plan clearly falls in this category.

A.1.1 Types of Costs

Conceptually, there are several types of costs a power plant owner can incur as a result of safeguards approaches and implementation activities. Direct costs of implementing safeguards include the costs of design features incorporated in the plant to facilitate observations of materials flow and materials characterization measurements, plus the operating and maintenance costs of making these observations and measurements over the life of the plant. While these are significant costs, it is not straightforward to model variations in these cost streams.

In practice, this comprehensive cost modeling approach is difficult for a number of reasons:

1. Since a reactor is a complex system with many sets of design constraints and requirements, cost of specific design features are rarely “allocable” to specific functional requirements.
2. Even in cases where specific design features are allocable to single requirements drivers, construction cost estimates do not allow for facility costs to be functionally partitioned.
3. In general, the cost of safeguards at a modern reactor facility is small fraction of operation costs and is not separately tracked.
4. Capturing the various future cost streams involved with any fidelity is a very tedious and time-consuming undertaking, and ultimately subject to hundreds of detailed assumptions and judgments.

Another type of cost that is both more substantial and easier to measures as function of safeguards approach and implementation model is associated with the risk of plant operation delays. The traditional approach for safeguards definition and implementation occurs as late as 180 days prior to scheduled plant start-up. This approach risks delaying plant start-up, which can have serious cost impacts on a reactor owner.

A delay in scheduled reactor start up imposes at least two distinct and substantial cost penalties on the owner. The first is associated with Interest during Construction (IDC) charges. These are the "cost of capital" that a reactor owner pays to attract investment in construction, and are major component of total life-cycle costs for modern reactors (MIT 2011). The second cost of delay is that the revenue stream associated with power sales from the reactor is delayed, and is thus lowered in terms of present value.

The following section examines the context for these costs, and derives estimates for a typical 1 GWe reactor.

A.1.2 Interest During Construction

The overall management problem in setting and keeping to a schedule in nuclear construction is extraordinary complex. Its economic motivations, however, are very simple – to minimize construction overall costs, expressed in terms of present value.

We write this as:

$$\text{Min } [PV(C(t)] = \text{Min } [PV(C_{E,M,L}(t) + C_{IDC}(t)] \qquad \text{(A.1)}$$

where
$C(t)$ = total construction costs
$C_{E,M,L}$ = cost of equipment, materials and labor
C_{IDC} = interest during construction
$t = t_c - t_s$ = duration of construction, months.[1]

By convention, let $t = t^*$ denote the optimal schedule for a given plant design, factor prices, and interest rate.

We write all of these cost (C) functions with the argument t to emphasize our interest in the scheduling problem, that is to say the *choice and execution of* an optimal construction schedule. In general, and for a given plant design, the two components of C(t) move in different directions as functions of t. Thus

$$\delta(C_{E,M,L})/\delta t < 0, \qquad \text{(A.2)}$$

since sequencing construction for shorter construction times requires more productive and more sophisticated tools – larger and faster cranes, more or higher capacity welding gear, x-ray inspection equipment, etc., and requires either a larger labor force or overtime premia or both to achieve shorter construction times.

Also, since even at constant interest rate r, the function is monotonically increasing in t.

[1] As we formulate this as a continuous problem in t to simplify the math, we could make this days, hours, minutes, and so on without bound if we needed to satisfy math majors.

$$\delta(C_{IDC})/\delta > 0, \quad (A.3)$$

$$C_{IDC} (t) = \int c_{M,E,L(t)} * r^t dt \quad (A.4)$$

Note that the term $C_{E,M,L}$ – the sum of the equipment, materials and labor costs, is the so-called "overnight" construction cost – the cost which could be achieved if the plant were built instantaneously. Overnight capital costs of GW-scale nuclear plants are now in the range of $4000 to $5000 per kW, or about $4 to $5 billion for a one GWe plant. See for example (Hezir and Davis 2011). [1]

Thus, the first-order minimum condition for Equation (A.1) that

$$\delta C(t)/\delta t = 0, \text{ must require that} \quad (A.5)$$

$$\delta C_{E,M,L}/\delta = - \delta C_{IDC}/\delta t. \quad (A.6)$$

Equation (A.6) says that at the optimal construction duration t*, the upward (marginal) change in C_t due to the effects of compressing the construction schedule must exactly balance the downward change due to lower IDC charges.

Given $C_{E,M,L} (t^*)$ is about $5 billion, we can estimate C_{IDC} and $\delta C_{IDC}/\delta t$ for t near t* using a typical IDC interest rate. At 8% per year, interest on the entire overnight cost would amount to $400 million per year. For continuous compounding, this gives an approximation of $1.05 million per day of delay in plant completion.

A.2 Prospective and Realized Costs

It is important to distinguish between the estimates of future costs used in setting the plant construction schedule and actual realized costs of particular plant construction experience. The costs in Equation (A.1) through (A.6) above are *prospective* or ex-ante costs. The optimal total cost curve in Table A.1 reflects these costs. If, in fact for a particular plant, completion of construction is delayed beyond t^*, the curve in Table A.1 no longer applies, since the opportunity to adjust the schedule (and change $C_{E,M,L}$) has been foregone. The actual, realized $C_{E,M,L}$ is at this point a sunk cost, and the figure of $1.05 million per day of delay in plant completion applies to each and every day of completion delay.

A.2.1 Delayed Power Sales Revenue

In addition to cost incurred for increased IDC charges, a reactor owner facing a delay in plant operation incurs a cost associated with the delay in power sales revenue.

The annual revenue for a power plant can be estimated as

$$R_{y\,=}\, G_Y{*}P_{Y\,=}\, C{*}\gamma{*}P_Y, \quad (A.7)$$

[1] ANALYSIS OF GW-SCALE OVERNIGHT CAPITAL COSTS, Energy Policy Institute at Chicago, The Harris School of Public Policy Studies, Contributors Joseph S. Hezir, Principal, EOP Foundation, Inc. Edward M. Davis, Pegasus Group, LLC, November 2011.

where R_y = revenue in year y, dollars
G_Y = generation in year y, kWh
C = plant capacity, MWe
γ = a constant, the product (kW/MW)*(hours/year)*(average plant capacity factor)
P_Y = sales price of electricity, $/Kwh.

Using typical values for a one GWe plant (40 year life, 85% capacity factor, $0.06 per kWh), we estimated revenue stream with the following present values (Table A.1).

Table A.1. Present Value of Electricity Sales Revenue

Discount Rate	PV($R_{1,}$ …… $R_{40)}$
3%	1.03E10
4%	8.84E9
5%	7.67E9
6%	6.72E9
7%	5.96E9
8%	5.33E9
9%	4.81E9
10%	4.37E9

Since our typical plant is assumed to cost $4 to 5 billion plus an IDC of perhaps $1 billion, discount rates above about 8% are not applicable if the project is to be feasible. Using a discount rate of 6% gives a present value of $6.72 billion for the expected revenue stream from the one GWe plant.

The cost of a 1-day delay in obtaining this revenue stream (or a lump-sum payment of $6.72 billion) is approximated, using the same discount rate of 6%, at about $1.1 million.

Thus, both the incremental IDC on plant construction costs, and the incremental decrease in the present value of the plant revenues steam, are the vicinity of $1 million per day of plant operational delay. The total cost of a 1-day delay in plant operation is then on the order of $2 million.

Appendix B

Questions for the IAEA

Appendix B

Questions for the IAEA

1. Have any power plant startup delays occurred as a result of inadequate or inappropriate support for establishing the safeguards approach?
   a. If so, how many plant startups have been delayed?
   b. If safeguards related delays occur, how long do they typically last?
   c. Are startup delays a phenomenon of initial startup, or have delays occurred because of plant modifications?
   d. Is there a correlation between safeguards related startup delays and plant design?
   e. Is there a correlation between startup delay and the state in which the plants are located?
2. How does facility design affect safeguard costs?
   a. Are safeguards costs the same in all states for a particular design?
   b. As facility designs evolve, do safeguards costs come down?
   c. There is an estimate that safeguards costs are about 0.1% of facility cost. Is this a reasonable estimate?
   d. Is the IAEA seeing an increase in advanced notice from States of nuclear facility construction so safeguards can be cost effectively designed into these new facilities?
   e. What steps is the IAEA taking so States provide earlier notice of nuclear facility construction plans?
   f. Does the IAEA have the necessary resources to rapidly engage a State who gives advanced notice of nuclear facility construction
   g. Is there an existing State model of early nuclear facility construction notification that has assisted the IAEA in implementing safeguard by design? If so, what are the key attributes for this success?
3. Have improvements/technical evolution of safeguards equipment/approach lowered overall costs?
   a. If remote process monitoring equipment is used, does it decrease costs to both IAEA and facility?
   b. How would safeguards costs be affected if equipment is shared between IAEA and facility?
   c. Has the Agency evaluated the cost savings at any facility where Joint-Use equipment was used instead of independent IAEA systems? If so, what was the outcome?
   d. Are safeguards costs expected to be lower at Gen III/IV facilities?
   e. Does the IAEA see differences in safeguardability between nuclear facility designs to be constructed in Non-Nuclear Weapon States that are provided by Nuclear Weapon States versus Non-Nuclear Weapon States?

Appendix C

PNNL List of Emerging Reactor Designs

Table C.1. PNNL List of Emerging Reactor Designs

Reactor Name	Type	Designer
4S (SMR)	LMCFR (liquid metal cooled fast reactor)	Toshiba
ABV-6M (SMR)	LWR	OKBM
ABWR	BWR	GE-Hitachi
ABWR-II	BWR	GE-Hitachi
ACR-1000	PHWR	Atomic Energy of Canada Limited (AECL)
AHWR	PHWR	BARC
AP-1000	PWR	Westinghouse
AP-600	PWR	Westinghouse
APR-1000	PWR	KEPCO/KHNP
APR-1400	PWR	KEPCO/KHNP
APWR	PWR	Mitsubishi Heavy Industries
ATMEA1	PWR	AREVA/Mitsubishi
BREST (SMR)	LMCFR (liquid metal cooled fast reactor)	RDIPE
CAREM – (SMR)	iPWR	CNEA
CEFR (SMR)	LMCFR (liquid metal cooled fast reactor)	CNEIC
China HTR-PM (SMR)	PBMR	Tsinghua University
CNP-300 (SMR)	PWR	CNNC
EC6	PHWR	Atomic Energy of Canada Limited (AECL)
EM2 (SMR)	HTGCR (high temp gas cooled)	General Atomics
EPR – PWR	PWR	AREVA
ESBWR – (Economic simplified)	BWR	GE-Hitachi
FBNR (SMR)	iPWR	Federal University of Rio Grande de Sul - Brazil
G4M (SMR)	LMCFR	Gen4 Energy
GTHTR20-300C	HTGCR	Japan Atomic Energy Agency
GT-MHR (SMR)	HTGCR (high temp gas cooled)	General Atomics
HI-SMUR 140 (SMR)	iPWR	Holtec International
HP-LWR	LWR	Karlsruhe Institute of Technology
IMR (SMR)	iPWR	Mitsubishi Heavy Industries
IPHWR-220	PHWR	Nuclear Power Cooperation of India Limited (NPCIL)
IPHWR-700	PHWR	Nuclear Power Cooperation of India Limited (NPCIL)
IRIS (SMR)	iPWR	Westinghouse-led Consortium
JSCWR	SCWR	Japan Atomic Energy Agency
KAMADO	FBR	Central Research Institute of Electric power Industry (CRIEPI)
KLT-40s – (SMR)	PWR	OKBM Afrikantov

Table C.1. (contd)

Reactor Name	Type	Designer
mPower – (SMR)	iPWR	Babcock & Wilcox Company
NuScale – (SMR)	iPWR	NuScale Power LLC and Fluor
PFBR-500 (SMR)	FBR (fast breeder reactor)	Indira Gandhi Centre for Atomic Research
PHWR-300 (SMR)	PHWR	Nuclear Power Cooperation of India Limited
PRISM	LMCFR (liquid metal cooled fast reactor)	GE-Hitachi
RITM-200 (SMR)	iPWR	OKBM
RMWR	BWR	Japan Atomic Energy Agency
SMART – (SMR)	iPWR	KAERI
South Africa PBMR	PBMR	PBMR (Pty) Ltd.
SVBR-100 (SMR)	LMCFR (liquid metal cooled fast reactor)	AKME
TP-1 (SMR)	Traveling Wave Reactor (TWR)	TerraPower
UNITHERM (SMR)	PWR	RDIPE
VBER-300	PWR	OKBM Afrikantov
VK-300 (SMR)	BWR	RDIPE
VVER-640 (V-407)	PWR	OKBM Gidropress
VVER-1000 (V-466 B)	PWR	OKBM Gidropress
VVER-1200 (V-392M)	PWR	OKBM Gidropress
VVER-1200 (V-491)	PWR	OKBM Gidropress
VVER-1500 (V-448)	PWR	OKBM Gidropress
VVER-300 (V-478) (SMR)	PWR	OKBM Gidropress
VVER-600 (V-498)	PWR	OKBM Gidropress
Westinghouse SMR	iPWR	Westinghouse
KERENA	BWR	AREVA

Appendix D

Full List of Reactors against Four Criteria Posing Safeguards Issues

Table D.1. Full List of Reactors against Four Criteria Posing Safeguards Issues

Name	Type	Multiple Cores	Opaque Coolant	Unconventional Fuel Design	On-Line Refueling
4S (SMR)	LMCFR		x (Na)		
ABV-6M (SMR)	PLWR				
ABWR	BWR				
ABWR-II	BWR				
ACR-1000	PHWR				x
AHWR	PHWR				x
AP-1000	PWR				
AP-600	PWR				
APR-1000	PWR				
APR-1400	PWR				
APWR	PWR				
ATMEA1	PWR				
BREST (SMR)	LMCFR		x (Pb)		
CAREM – (SMR)	iPWR				
CEFR (SMR)	LMCFR		x (Na)		
China HTR-PM (SMR)	PBMR			x (TRISO Pebble [Pu,U]O2)	x
CNP-300 (SMR)	PWR				
EC6	PHWR				x
EM2 (SMR)	HTGCR				
EPR	PWR				
ESBWR	BWR				
FBNR	iPWR			x (Spherical UO2)	
G4M	LMCFR		x (Pb-Bi)	UN (Pb filled)	
GT-MHR	HTGCR			x (TRISO Prismatic UCO)	
GTHTR20-300C	HTGCR			x (TRISO Prismatic [Pu,U]O2)	
HI-SMUR 140 (SMR)	iPWR				
HP-LWR	LWR				
IMR (SMR)	iPWR				
IPHWR-220	PHWR				x
IPHWR-700	PHWR				x
IRIS	iPWR				
JSCWR	SCWR				
KAMADO	FBR			x(UO2/MOX)	
KERENA	BWR				

Table D.1. (contd)

Name	Type	Multiple Cores	Opaque Coolant	Unconventional Fuel Design	On-Line Refueling
KLT-40S	PWR	x (2 cores/ ship)			
mPower – (SMR)	iPWR				
NuScale - (SMR)	iPWR	x			
PFBR-500 (SMR)	FBR		x (Na)		
PHWR-300 (SMR)	PHWR				x
PRISM	LMCFR	x (3 share single generator)	x (Na)		
RITM-200	iPWR				
RMWR					
SMART	iPWR				
SOUTH AFRICA PBMR	PBMR			x	x
SVBR-100	LMCFR		x (Pb-Bi)		
TP-1 (SMR)	Traveling Wave Reactor (TWR)		x (Na)		
UNITHERM (SMR)	PWR				
VBER-300	PWR				
VK-300 (SMR)	BWR				
VVER 640 (V 407)	PWR				
VVER-1000 (V-466 B)	PWR				
VVER-1200 (V-392M)	PWR				
VVER-1200 (V-491)	PWR				
VVER-1500 (V-448)	PWR				
VVER-300 (V-478)	PWR				
VVER-600 (V-498)	PWR				
Westinghouse SMR	iPWR				

Appendix E

Full List Reactor Design Phases

Table E.1. Full List Reactor Design Phases

Name	Type	Design Phase
4S (SMR)	LMCFR	Preliminary Design
ABV-6M (SMR)	PLWR	Final Design/Licensing
ABWR	BWR	In Operation
ABWR-II	BWR	Preliminary Design
ACR-1000	PHWR	Final Design/Licensing
AHWR	PHWR	Preliminary Design
AP-1000	PWR	Under Construction
AP-600	PWR	Final Design/Licensing
APR-1000	PWR	Preliminary Design
APR-1400	PWR	Under Construction
APWR	PWR	Final Design/Licensing
ATMEA1	PWR	Final Design/Licensing
BREST (SMR)	LMCFR	Preliminary Design
CAREM – (SMR)	iPWR	Under Construction
CEFR (SMR)	LMCFR	In Operation
China HTR-PM (SMR)	PBMR	Under Construction
CNP-300 (SMR)	PWR	In Operation
EC6 (SMR)	PHWR	Final Design/Licensing
EM2 (SMR)	HTGCR	Conceptual Design
EPR	PWR	Under Construction
ESBWR	BWR	Final Design/Licensing
FBNR	iPWR	Conceptual Design
G4M	LMCFR	Final Design/Licensing
GTHTR20-300C	HTGCR	Conceptual Design
GT-MHR	HTGCR	Conceptual Design
HP-LWR	LWR	Conceptual Design
IMR (SMR)	iPWR	Conceptual Design
IPHWR-220	PHWR	In Operation
IPHWR-700	PHWR	Under Construction
IRIS	iPWR	Final Design/Licensing
JSCWR	SCWR	Conceptual Design
KAMADO	FBR	Conceptual Design
KERENA	BWR	Preliminary Design
KLT-40S	PWR	Under Construction
mPower – (SMR)	iPWR	Preliminary Design
NuScale - (SMR)	iPWR	Preliminary Design
PFBR-500	FBR	Under Construction
PHWR-300 (SMR)	PHWR	Preliminary Design
PRISM	LMCFR	Final Design/Licensing
RITM-200	iPWR	Final Design/Licensing
RMWR	BWR	Conceptual Design
SMART	iPWR	Final Design/Licensing
SOUTH AFRICA PBMR	PBMR	Preliminary Design

Table E.1. (contd)

Name	Type	Design Phase
SVBR-100	LMCFR	Final Design/Licensing
UNITHERM (SMR)	PWR	Conceptual Design
VBER-300	PWR	Conceptual Design
VK-300 (SMR)	BWR	Conceptual Design
VVER 640 (V 407)	PWR	Preliminary Design
VVER-1000 (V-466 B)	PWR	Under Construction
VVER-1200 (V-392M)	PWR	Under Construction
VVER-1200 (V-491)	PWR	Under Construction
VVER-1500 (V-448)	PWR	Final Design/Licensing
VVER-300 (V-478)	PWR	Final Design/Licensing
VVER-600 (V-498)	PWR	Conceptual Design
Westinghouse SMR	iPWR	Preliminary Design

Appendix F

Full List Reactor Design Marketability

Table F.1. Full List Reactor Design Marketability

Name	Type	Marketability
4S (SMR)	LMCFR	Few
ABWR	BWR	Few
ABWR-II	BWR	Few
ACR-1000	PHWR	Few
AHWR	PHWR	Few
AP-1000	PWR	Many
AP-600	PWR	Few
APR-1000	PWR	Few
APR-1400	PWR	Many
APWR	PWR	Few
ATMEA1	PWR	Few
CAREM – (SMR)	iPWR	Some
China HTR-PM (SMR)	PBMR	Few
EC6 (SMR)	PHWR	Few
EPR	PWR	Few
ESBWR	BWR	Few
FBNR	iPWR	Few
G4M	LMCFR	Few
GT-MHR	HTGCR	Few
GTHTR20-300C	HTGCR	Few
HI-SMUR 140	iPWR	Some
HP-LWR	LWR	Few
IMR (SMR)	iPWR	Few
IPHWR-220	PHWR	Few
IPHWR-700	PHWR	Few
IRIS	iPWR	Few
JSCWR	SCWR	Few
KAMADO	FBR	Few
KERENA	BWR	Few
KLT-40S	PWR	Few
mPower – (SMR)	iPWR	Some
NuScale - (SMR)	iPWR	Some
PRISM	LMCFR	Few
RMWR	BWR	Few
SMART	iPWR	Few
SOUTH AFRICA PBMR	PBMR	Few
VBER-300	PWR	Few
VVER 640 (V 407)	PWR	Few
VVER-1000 (V-466 B)	PWR	Some
VVER-1200 (V-392M)	PWR	Some
VVER-1200 (V-491)	PWR	Few
VVER-1500 (V-448)	PWR	Some

Table F.1. (contd)

Name	Type	Marketability
VVER-300 (V-478)	PWR	Few
VVER-600 (V-498)	PWR	Few

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