The design and operation of protective systems is an essential engineering responsibility. Ensuring public safety, while essential, must be accomplished at a feasible cost and within government regulation. Hence, protective system design and operational decisions must be evaluated with respect to benefit (both enterprise profit and social benefit) and cost (both enterprise and social costs).

Analytical arguments are made that establish the economic relationship between protective system margins of safety, regulatory authority, and the calculus of negligence. Within this risk-based analytical framework, protection efficacy is explored. In particular, the risk-economics of margins of safety are examined by identifying the reference efficacy with respect to which margins of safety are measured. Engineering design and operations decisions intended to improve protection efficacy can, thus, be gauged as the degree to which they advance a risk-based margin of safety.

Finally, our analytical framework is exercised to show how risk-based margins of safety reveal the relationship between uncertain costs and regulatory activity focused on ensuring public welfare that is backstopped by liability in the event of catastrophe. How both prescriptive and performance based regulations influence margins of safety with respect to protective system innovation can be identified here.

KEYWORDS Risk, Nuclear, Safety Margin, Regulation, NEI Nuclear Promise, Protective System

I. TENETS of PROTECTIVE SYSTEM DESIGN

Protective measures are deployed almost without exception whenever technology operates in situations where its failure can cause significant financial and/or physical harm. Today, engineers are responsible for developing and operating sophisticated protective systems that integrate hardware, personnel, and information to ensure public safety. When protective systems fail to mitigate catastrophic events, liability must be determined through regulatory response, judicial inquiry, or both. It is every engineer’s nightmare that she could be the source responsible for an error in design or operations that causes a catastrophic protective system failure.

I.A. Profit, Design, and Hazard

Of particular interest are the design or operational errors made in the commercial nuclear power sector. Of course, commercial nuclear power utility engineers are responsible for developing economical and safe designs; a difficult task in the nuclear power sector. At this time, interest is focused on cost of production in the setting where there exists a social benefit (social welfare) and a level of hazard (such as catastrophic failure in commercial nuclear power); an important topic still lacking an academic basis has not been established. Their focus is narrow, on the commercial nuclear power setting where regulation is enforced on many aspects of design and operation. Renewal following catastrophic failure is not attempted. This topic is important because the utility engineer is faced with balancing cost against a level of safety (hazard rate) and, without better support, must proceed on a qualitative basis. We believe we can help her do better by moving to a more quantitative basis for support. That is, the framework in which the engineer must make design decisions normally lacks consideration of the ultimate goal to be achieved in the regulated setting. Absent a basic understanding of the elements required to quantify costs involved with design decisions, suboptimal designs are a likely outcome.

Quantitative support is especially important to for-profit enterprise where the engineer’s decisions are made in a very complex setting and many options are available. Some of the elements and interactions in Fig. 1 that come to mind are illustrated. When market conditions are unfavorable, the utility engineer experiences the tensions that arise in balancing the economic responsibility to the owners and investors (reducing operational and maintenance costs) and the need for safe design and operation (presumably coming at higher cost).

The regulator also must make decisions on “adequate protection”, perhaps less directly than an engineer engaged in design and operation decision-making, which is, to some extent, based on governmental and public feedback. For exam-
Shavel\textsuperscript{3} develops quantitative liability measures in a general setting. The examination examination of safety margin should be prefaced with observations about regulatory authority, moral hazard, liability and the calculus of negligence. Moral hazard occurs when one party decides how much risk to take and another party pays if things go badly. While tort law provides legal remedies for those who have been harmed through the negligence of another party, it does not ensure prior protections from that harm. The relationship between taking risks and negligence is codified in the so called Calculus of Negligence (sometimes called the Hand Rule\textsuperscript{b}). The Hand Rule provides an analytical definition of negligence and is often written as

\[ b < P \hat{L}, \]

where \( \hat{L} \) is value of loss (harm) caused, \( P \) is the probability of that loss, and \( b \) is the burden of protection (value of the protection effort applied by the enterprise for the purpose of preventing harm). The Hand Rule offers a litmus test to determine if adequate measures have been taken to prevent collateral harm. However, liability for collateral harm does not eliminate moral hazard. In fact, a profit maximizing enterprise that can potentially cause harm through negligence has no economic incentive to provide protections beyond that which would marginally improve profit.

The general purpose of the government’s regulatory authority is to mitigate moral hazard. The development, deployment, and operation of protective systems overlaying nuclear facilities is, in part, dictated by regulation. Regulations serve to provide prior protections for the interests of neighbors who are not profit claimants and who might be harmed should a given nuclear enterprise suffer a catastrophic event. In this way, regulations do not provide for the general public benefit, but are directed at protecting those who suffer moral hazard (for example neighbors).

It is now observed that government regulations cause an enterprise to depart from the profit maximization that might be achieved at an unregulated market equilibrium, and in doing cause that enterprise to operate in a manner that is not economically risk–neutral. Departure from risk–neutrality suggests that the risk preferences of

\textsuperscript{a}“Nuclear Energy Innovation and Modernization Act (S 2795)” US Senate.

\textsuperscript{b}The calculus of negligence, or “Hand Rule”, is a legal standard applied to establish liability for harm. If the harm could be avoided for less than the cost of the harm.
the enterprise now reflect a risk-averse social welfare responsibility. In principle, when the enterprise preferences are well-ordered (rational) their regulated risk preferences induce a social welfare function that is corollary to the Expected Utility Theorem. The induced (enterprise-specific) social welfare function will be appealed to in the following arguments.

II.A. Negligence in the Commercial Nuclear Power Setting

The regulatory framework in the nuclear industry is unique in the sense that the federal administrative agency has an absolute say in how liability should be assigned in a nuclear incident. Nuclear technology was largely a monopoly within the hands of the federal government until passage of the Atomic Energy Act of 1946 (McMahon Act) where the federal government allowed private production of nuclear energy via licensing and regulation. Nevertheless, despite a regulatory incentive for investment, the private sector was reluctant to be involved in the development of nuclear energy, largely due to the fear of incurring strict or unlimited liability in case of a nuclear incident, regardless of how insignificant the incident.

To address industry concerns and facilitate development of the then-fledgling commercial nuclear power industry, the Price–Anderson Act was enacted into law in 1957. This sets a limit on the monetary liability of private producers of nuclear power in case of a catastrophic nuclear accident, and defines the procedural mechanisms for insurance coverage in the nuclear industry. In the 1988 amendment to the Price–Anderson Act, the Congress established a sole and exclusive federal cause of action known as a Public Liability Action (PLA), for “any legal liability arising out of or resulting from a nuclear incident or precautionary evaluation” thereby preempting all state cause of actions for damages arising from nuclear incidents covered under the Act.

Whether or not implementation of protective systems can save private operators from being held liable for personal injury and property damage arising from the nuclear incidents might depend on the actual extent of the incident, that is, whether the event is an Extraordinary Nuclear Occurrence (ENO) or not. An ENO is defined as “any event causing a discharge or dispersal of source, special nuclear, or byproduct material from its intended place of confinement in amounts offsite, or causing radiation levels offsite, which the NRC or the Secretary of Energy, as appropriate, determines to be substantial, and which the NRC or the Secretary of Energy, as appropriate, determines has resulted or will probably result in substantial damages to persons offsite or property offsite.” This determination made by the NRC of the Secretary of Energy shall be final and conclusive, and is not reviewable by the judicial system.

The elements for establishing a PLA cause of action for an ENO case are essentially the same as the ones for negligence under state law, that is, the presence of a duty of care, breach of duty, proximate cause and damages. Nevertheless, if a nuclear incident is determined by NRC or Department of Energy (DOE) to qualify as an ENO, it can be almost certain that the PLA duty has already been breached (that is, the radiation released has exceeded the federal dose limits), which means the first two elements of PLA have been established to be adverse to the defendant (the operator). To speed up the litigation process, the NRC or DOE then may, but not necessarily, require the defendant in the PLA lawsuit to waive the defense of not being at fault (breach of duty

*Production of nuclear energy may be categorized as “abnormally dangerous activities” and is thus subject to strict liability. Restatement of Torts Second, section 519, provides: (1) One who carries on an abnormally dangerous activity is subject to liability for harm to the person, land or chattels of another resulting from the activity, although he has exercised the utmost care to prevent the harm. (2) This strict liability is limited to the kind of harm, the possibility of which makes the activity abnormally dangerous. To determine whether an activity is abnormally dangerous, see Restatement of Torts Second, section 520. See also WILLIAM L. PROSSER, THE LAW OF TORTS, §78 at 516 (4th Ed. 1971) (“In the field of strict liability, the first case raising the question as to the use of nuclear energy has yet to reach the courts. When it does, it may be predicted with a good deal of confidence that this is an area in which no court will, at last, refuse to recognize and apply the principle of strict liability.”)

*See Dubin, Jeffrey A., and Geoffrey S. Rothwell. “SUBSIDY TO NUCLEAR POWER THROUGH PRICE-ANDERSON LIABILITY LIMIT.” Contemporary Economic Policy 8.3 (1990): 73–79. Between 1959 and 1982, the Act set a limit of $560 million on the liability of civilian operators of nuclear power plants for accidental damages. After the 1988 amendment, this limit was increased to $7 billion.

*In re TMI Litigation Cases Consol. II, 940 F.2d 832 (3d Cir. 1991).

*See In re TMI Litig. Cases Consol. II, 940 F.2d 832, 855 (3d Cir. 1991) (“In explicitly providing that the ‘substantive rules for decision’ in public liability actions ‘shall be derived from’ the law of the state in which the nuclear incident occurred, . . . Congress expressed its intention that state law provides the content of and operates as federal law.”); O’Conner v. Commonwealth Edison Co., 13 F.3d 1090, 1099-1100 (7th Cir. 1994) (“Thus, a state cause of action is not merely transferred to federal court; instead, a new federal cause of action supplants the prior state finding.”)

*42 U.S.C. §2014.

*42 U.S.C. §2014(j).
under the category of non–
in reality, almost all nuclear accidents would fall
necessarily the focus of much mathematical and
safety and expense; hence, protective systems are
cause of cost; there always exist tradeoffs between
that the most reliable conceivable safety technolo-
will never actually occur. It is well-understood
circumstances for which the protection is deployed
operated, while ALL stakeholders hope that the
neering design in that they must be created and
protection are difficult to identity and (when iden-
The uncertainties associated with the efficacy of
protection are difficult to identity and (when iden-
ted) creating a circumstance that is similar to
the common law strict liability, except that such
waiver is controlled by the federal agency and cannot
be overruled by the court. By doing so, the
federal government can effectively prevent spend-
ing scarce judicial resources on litigation over the
elements of cause of action that are not question-
able and squandering the limited financial protec-
tion provided by Price–Anderson
Accordingly, in case of an ENO, whether a protective system has
been installed or not can hardly alter the facts
that the PLA duty has been breached, especially
when a waiver of defense is forced upon the
defendant. However, if the protective measures have
reduced the damages resulting from the nuclear
incident in practice, it could still be instrument-
tal to the operator since it can lower the amount
of compensation the insurance company/operator
needs to pay.

Summary How an ENO case would proceed in
court remains a scenario in theory since an ENO
has never occurred. According to the NRC, even
the Three Mile Island accident did not release
enough radiation to qualify as an ENO. Therefore,
in reality, almost all nuclear accidents would fall
under the category of non–ENO. The PLA for
non–ENO has the same four elements as ENO
cases. But here, adoption of protective measures may
be decisive if they keep release of radioactive
materials (exposures) under the federal radia-
tion safety standards. In such cases, the de-
defendant might be exempted from legal liability as
no duty has been breached. Generally speaking,
a non–ENO case may be litigated in court as a
typical negligence in court.

II.B. Information and Design
The uncertainties associated with the efficacy of
protection are difficult to identity and (when identi-
tified) extremely difficult to quantify. Protective
systems are exceptional in the endeavor of engi-
neering design in that they must be created and
operated, while ALL stakeholders hope that the
circumstances for which the protection is deployed
will never actually occur. It is well-understood
that the most reliable conceivable safety technolo-
gies and protective system are rarely deployed be-
cause of cost; there always exist tradeoffs between
safety and expense; hence, protective systems are
necessarily the focus of much mathematical and
empirical engineering analysis. Stress–testing pro-
tective systems with real–life catastrophes is ob-
osely not a desirable source of information in
engineering design (although some testing on sub-
systems may be done). Further, engineers cannot
avoid design decisions simply because operational
experience (for example catastrophic event data)
is limited. In the absence of rich operational data,
it is important to address uncertainty in a manner
consistent with the best available theory and ana-
lytics. When the stakes are truly high, there is no
room for ad hoc methods or anecdotal reasoning.

In the developments that follow, the authors
appeal to the well–accepted tenets of utility the-
ory and the Kolmorogov axiomization of probabil-
ity measure. This places the authors in the main-
stream of established economic theory, mathemat-
ics, and epistemology. Arguments will be built be-
ginning with the expected utility theorem and re-

dults developed that reveal the relationship be-
tween margin of safety, information, and prudent
engineering decisions in the design and operation
of protective systems.

Consider a situation where a regulated enter-
prise will deploy a technology that has been se-
lected on the basis of public safety requirements,
revenue, and social costs; generally regulatory
constraints are enforced that cause the enterprise
to find the enhanced safety of the selection prefer-
able to all other candidate technologies that could
serve (the identical) future demand trajectories.
In what follows, the “margin of safety” associated
with the preferred selection will be explored and
the technology selection decision will be assumed
to follow all tenets of the von Neumann – Mor-
genstern Expected Utility Theorem. All candidate

technologies would face identical future demand,
generating identical revenue trajectories so long
as the technology does not suffer catastrophic fail-
ure, ending its useful life. While the lifecycle costs
can differ significantly among various technology
alternatives, lifecycle revenues are assumed to be
identical. The regulatory environment is captured
through social welfare function $u : \mathbb{R} \rightarrow \mathbb{R}$ on the
value of all alternative technologies.

II.C. Analytical Framework
In the arguments to follow, we have need to iden-
tify multiple probability spaces. In the interest of
manageable notation, the de Finetti notation is
adopted. Here, for a random variable $X$ defined
on the probability space $(\Omega, \mathcal{F}, P)$, the traditional
expectation integral $E[X]$ is replaced by $P(X)$.

Let all candidate technologies, available for pos-
sible selection by the enterprise, be indexed with

\begin{footnotesize}
\begin{itemize}
\item[\footnotemark] Under Price–Anderson Act, all defense costs are sub-
\item[\footnotemark]mitted from the available funds (“financial protection”) for compensation.
\end{itemize}
\end{footnotesize}
indices belonging to the set \( A \) where \( \alpha^* \in A \) is the preferred technology. Thus, there is a collection of probability spaces \( \{ (\Omega_\alpha, \mathcal{F}_\alpha, P_\alpha) ; \alpha \in A \} \). For each alternative \( \alpha \in A \), define on \( \{ (\Omega_\alpha, \mathcal{F}_\alpha, P_\alpha) \) the random variables:

\[ V_\alpha : \Omega_\alpha \to \mathbb{R}, \text{ the net present value of technology alternative } \alpha, \]

\[ C_\alpha : \Omega_\alpha \to \mathbb{R}_+, \text{ the lifecycle cost of alternative } \alpha, \]

\[ \chi_\alpha : \Omega_\alpha \to \{0,1\}, \text{ where } \chi_\alpha = 1 \text{ on the event that the lifetime of alternative } \alpha \text{ terminates in catastrophe.} \]

Inasmuch as the enterprise has rationally selected technology alternative \( \alpha^* \in A \), it follows from the expected utility theorem that

\[ \alpha^* = \arg \max_{\alpha \in A} E_\alpha [u \circ V_\alpha]. \tag{1} \]

Note that, since any selected technology must follow the same demand trajectory, \( V_\alpha = -C_\alpha \), \( \forall \alpha \in A \). Hence, it follows that (1) can be rewritten as

\[ \alpha^* = \arg \min_{\alpha \in A} E_\alpha [u \circ C_\alpha] \]

where, \( E_\alpha [u \circ V_\alpha] \) is the expected lifecycle social cost of technology alternative \( \alpha \in A \).

It is important to recall that technology \( \alpha^* \) is selected because regulation has imposed a value on public safety (implicitly represented by the social welfare mapping \( u \)), which reflects the high social cost associated with catastrophic failures that terminate a technology’s lifecycle. Thus, it is useful to explore lifecycle social costs on catastrophic events. In this way, the margin of safety that certain non-optimal alternatives might enjoy over \( \alpha^* \) can be investigated. To this end, note that the expected lifecycle social cost can be written as,

\[ E_\alpha [u \circ C_\alpha] = E_\alpha [E_\alpha [u \circ C_\alpha | \chi_\alpha]], \forall \alpha \in A, \]

or

\[ E_\alpha [u \circ C_\alpha] = E_\alpha [u \circ C_\alpha | \chi_\alpha = 0] P_\alpha (\chi_\alpha = 0) + E_\alpha [u \circ C_\alpha | \chi_\alpha = 1] P_\alpha (\chi_\alpha = 1). \tag{2} \]

As a matter of convenience, the following is defined:

\[ c^g_\alpha \triangleq E_\alpha (u \circ C_\alpha | \chi_\alpha = 0), \text{ the expected social cost of alternative } \alpha \text{ on the event that lifecycle terminates without catastrophe}, \]

\[ c^f_\alpha \triangleq E_\alpha (u \circ C_\alpha | \chi_\alpha = 1), \text{ the expected social cost of catastrophe–free lifecycle}, \]

and,

\[ p_\alpha \triangleq P_\alpha (\chi_\alpha = 1), \alpha \in A. \]

Hence, (2) is rewritten as

\[ E_\alpha (u \circ C_\alpha) = c^g_\alpha + (c^f_\alpha - c^g_\alpha) p_\alpha, \forall \alpha \in A. \tag{3} \]

Fig. 2. The nature of alternative selections in relation to cost \( (C_\alpha) \) and catastrophic failure probability \( (p_\alpha) \) over the plant lifetime with relation to possible liability in light of failures.

\[ c^p_\alpha \triangleq (c^f_\alpha - c^g_\alpha) \]

will be referred to as the catastrophe–premium of technology \( \alpha \). Thus, (3) states that:

**For any technology alternative, its expected social cost is given by its expected social cost with catastrophe–free operation, plus its catastrophe–premium weighted by the probability of catastrophe.**

It now follows from (1) and (3) that for all \( \alpha \neq \alpha^* \)

\[ c^g_{\alpha^*} + (c^f_{\alpha^*} - c^g_{\alpha^*}) p_{\alpha^*} \leq c^g_\alpha + (c^f_\alpha - c^g_\alpha) p_\alpha \]

or,

\[ c^g_{\alpha^*} + c^p_{\alpha^*} p_{\alpha^*} \leq c^g_\alpha + c^p_\alpha p_\alpha. \tag{4} \]

Rearranging (4) into point–slope form gives

\[ p_{\alpha^*} \leq \frac{c^p_\alpha}{c^p_{\alpha^*}} p_\alpha - \frac{(c^g_{\alpha^*} - c^g_\alpha)}{c^p_{\alpha^*}}. \]

\[ c^p_{(\alpha^*, \alpha)} \triangleq (c^g_{\alpha^*} - c^g_\alpha), \] the expected difference in social cost between technology alternatives \( \alpha^* \) and \( \alpha \), is referred in here as the reliability premium of choosing \( \alpha^* \) over \( \alpha \in A \). Note that it may happen that the reliability premium takes a negative value (as would be the case of rejecting a more reliable alternative because of its cost). Thus, it now follows that for all technology alternatives \( \alpha \in A \),

\[ p_{\alpha^*} \leq \frac{c^p_\alpha}{c^p_{\alpha^*}} p_\alpha - \frac{c^p_{(\alpha^*, \alpha)}}{c^p_{\alpha^*}}. \tag{5} \]

To illustrate different aspects of (5) and complexity between socially and regulatory optima, Fig. 3 is created based on an ad hoc correlation between the probability of catastrophic
Fig. 3. Twenty-six hypothetical socially suboptimal alternatives plotted with the socially optimal alternative selected from a total of twenty-seven alternatives hypothesized.

failure and social costs for 27 hypothetical alternatives. In the assumed correlation, the tendency is to relate smaller social costs with smaller probabilities of catastrophic failures which would be desirable to industry and the regulator. The figure shows that a case which is socially optimum would not necessarily be the regulatory optimum ("super-optimal"), since there are two alternative technologies plotted to the "northwest" of it. In this figure, super–optimal technologies would relate to alternatives selected under regulation (their corresponding probabilities are less than the socially optimal one). Once the socially optimal alternative is known, none of the alternatives would lie to the south of it.

Engineers typically couch technology choices in terms of system reliability and cost. shows that $\alpha^*$ is the most preferred technology only when its life cycle unreliability $p_{\alpha^*}$ is at least as small as the life cycle unreliability $p_{\alpha}$, for all $\alpha \in A$, scaled by the quotient of catastrophe premiums less the quotient of the reliability premium to the un–preferred alternative’s catastrophe premium. Fig. illustrates the behaviors described by . Thus, the conditions set forth by the expected utility theorem can be understood in terms that are both analytically and intuitively specific to protective system design and operation. Of course, in practice, the particular values of elements that form are difficult to obtain since information (including event probabilities and the social welfare function) is typically vague or incomplete. Nonetheless, the decision design of selecting the most preferred technology alternative cannot be avoided.

III. CONCLUSION

The examination of protective systems offered establishes a decision–analytical framework capturing the relationship between margins of safety and regulatory authority. It is argued that because potential liability (as identified through the calculus of negligence and following from the well–known Coase Theorem) does not substantially influence profit maximizing decisions associated with the design and operation of safety–critical protective systems, regulatory authority necessarily arises so as to ensure mitigation of moral hazard for a certain element of the public (those having large potential for losses in the event of a catastrophe). Regulatory authority induces a unique (up to affine transformation as corollary to the Expected Utility Theorem) social welfare function that enforces unique socially optimal price–point for regulated protection that does not enhance revenues. Margins of safety are thus defined to be associated with protective system alternatives that exhibit a lower probability of catastrophe than a unique socially–optimal level of protection. The framework identifies reliability premiums and catastrophe premiums associated with safety margins in a manner that allows protective system design and operation decisions to be considered in the context of system lifecycle expects costs.

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