Using PRA Insights to Inform Public-Facing Nuclear Safety Communication: Implications for Singapore's SMR Deployment Considerations

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Abstract:

Probabilistic Risk Assessment (PRA) serves as a cornerstone of nuclear reactor safety analysis, providing systematic insights into the risk triplet: scenarios, likelihoods, and consequences. As the global nuclear landscape evolves with new reactor technologies such as Small Modular Reactors (SMRs) and the entry of newcomer states pursuing nuclear energy programs, the role of PRA could expand beyond plant operations, maintenance support, and regulatory decision-making. Specifically, risk insights from PRA could facilitate risk communication with public audiences. The connection between PRA outputs and public risk communication remains underexplored, with limited work on the translation of those outputs into public-facing communication.

This paper presents the initial efforts to address this research gap. The paper first reviews representative public-facing NRC programs to establish a baseline understanding of current practice. The paper then proposes criteria for selecting PRA outputs suitable for translation into public-facing communication. Selection is guided by two dimensions: the public concerns addressed by PRA outputs and the types of scientific uncertainty those outputs entail. The practical implications of the proposed framework are illustrated through the Singapore case study, a context in which dense urban geography, constraints on offsite emergency response, and an early-stage regulatory infrastructure make the translation challenges distinct from those in countries with established nuclear programs. Building on this analysis, this paper proposes a nuclear safety guidebook as a possible implementation pathway for newcomer states.

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1. INTRODUCTION

Probabilistic Risk Assessment (PRA) has been serving as a key methodology for evaluating the safety of nuclear reactors. PRA breaks complex systems into critical functions and smaller components, assigns probabilities to event sequences leading to undesired consequences, and produces quantitative estimates of risk metrics such as Core Damage Frequency (CDF) and Large Early Release Frequency (LERF). The methodology is embedded within risk-informed regulation, which is widely adopted by most countries with nuclear energy programs [1].

This paper presents an initial attempt to address an underexplored research question: On top of utilizing PRA for supporting plant operations and maintenance, and for making regulatory decisions, could risk information generated by PRA also be used to inform public-facing communication about nuclear safety? Recent work has begun to investigate this direction. For instance, a review of PRA developments has found that the literature has not yet investigated the use of PRA methods for public outreach efforts, and risk communication was identified as a future research direction [2]. This paper seeks to explore that direction, proposing a set of criteria for selecting which PRA outputs are translatable for general audiences.

The paper is organized as follows. Section 2 introduces a theoretical basis for the review and discussion presented in the subsequent sections. Section 3 reviews how PRA insights currently flow into NRC engagement with the public, focusing on two representative NRC programs: the Reactor Oversight Process (ROP) and the State-of-the-Art Reactor Consequence Analyses (SOARCA). Section 4 develops the selection criteria for translatable PRA outputs, drawing on the theoretical basis provided in Section 2 and the key insights from the review of the NRC programs in Section 3. Then, Section 5 applies the selection criteria to Singapore's nuclear energy program development context and discusses a possible implementation pathway.

2. THEORETICAL BASIS

This paper draws on two strands of risk research by Fischhoff: (i) public risk perceptions (Section 2.1) and (ii) development phases of risk communication (Section 2.2).

2.1. Public Risk Perception and the Six Concerns

Risk-perception literature has established that lay audiences do not respond to nominally equivalent probabilities the same way across contexts. Slovic [3] and his later works showed that perceived risk is shaped by features beyond the probability and magnitude of harm, namely, familiarity with the hazard, comprehension of its mechanism, equity in the distribution of exposure, the dread it evokes, the audience's sense of control over it, and trust in the institutions managing it.

Building on this psychometric paradigm, the HM Treasury operationalizes six dimensions of public concern, asking, for each risk, whether it scores high or low on familiarity, understanding, equity, dread, control, and trust, and separating these judgment-based concerns from the quantitative risk assessment outputs for policymakers to better address risks that the public faces [4]. Fischhoff presents a similar framework of six concern factors, generalizing across hazard domains [5].

The framework's bearing on nuclear risk is clearest in the perception gap that Slovic documents [6]. The general public consistently perceives nuclear power and nuclear waste as high risk while perceiving other sources of radioactivity, such as medical X-rays and naturally occurring radon, as lower risk. This perception can be explained by the six concerns introduced above. For example, in terms of trust, it shows that risk acceptance is conditioned by trust in the operators of the technology and by its perceived personal benefit, both of which differ between medical and energy contexts.

2.2. The Developmental Stages of Risk Communication

Fischhoff set out a sequence of eight stages for the development of risk communication [7]:
1. All we have to do is get the numbers right
2. All we have to do is tell them the numbers
3. All we have to do is explain what we mean by the numbers
4. All we have to do is show them they’ve accepted similar risks in the past
5. All we have to do is show them that it’s a good deal for them
6. All we have to do is treat them nicely
7. All we have to do is make them partners
8. All of the above

Fischhoff offered these stages to indicate how the field's thinking had developed over time, and the successive attitudes practitioners had held about what good communication requires. Warren and Duckett [8] revisited Fischhoff's framework and argued that contemporary practice should place greater emphasis on early stakeholder engagement, reordering the stages to bring Stage 7 near the front and reflecting a shift from conveying risk to the public unidirectionally to communicating it with them interactively.

3. CASE STUDY: PRA INSIGHTS IN NRC'S PUBLIC COMMUNICATION

As representative examples of public-facing communication using PRA insights, this section reviews two programs by the U.S. NRC, namely, the Reactor Oversight Process (ROP) and the State-of-the-Art Reactor Consequence Analyses (SOARCA), positioning them within the theoretical basis introduced in Section 2.

3.1. The Reactor Oversight Process (ROP)

The ROP is a risk-informed framework for inspecting, measuring, and assessing the safety and security performance of operating nuclear power plants. The overall performance of facilities is evaluated using the ROP results, and this information is communicated to licensee management, members of the public, and other stakeholders [9].

The ROP has explicit public-facing elements. The NRC conducts annual public meetings in the vicinity of each operating reactor to discuss the results of its assessment of licensee performance. Plant-by-plant performance summaries, performance indicator data, inspection findings, and the action matrix are publicly accessible through the agency's website and linked to explanations of each metric. The action matrix uses a graded color scheme of green, white, yellow, and red to indicate increasing levels of regulatory engagement commensurate with declines in licensee performance, with explanations of the safety significance associated with each color.

To facilitate the communication of the ROP results with the public, the NRC has produced a dedicated public-facing brochure, published as NUREG/BR-0508 [10]. The brochure presents the ROP framework in compressed, plain-language form. It defines the three strategic performance areas of Reactor Safety, Radiation Safety, and Safeguards. It introduces the seven cornerstones, the four-color safety significance scheme, the cross-cutting areas, and the action matrix structure. The brochure demonstrates that the NRC recognizes that there is public interest in understanding these processes and hence sees value in making the framework digestible for a non-expert audience.

However, the ROP, while publicly accessible, was not initially designed for risk communication to a lay audience. Rather, ROP has served as a key mechanism for continuous monitoring of operating fleets. To fully understand and interpret the color-coded ROP findings, performance indicators, and the action matrix structure, substantial regulatory and technical literacy would be required. For the ROP findings, the four-color scheme is anchored to the ΔCDF and ΔLERF thresholds relative to the PRA outputs. And for other areas such as security and emergency preparedness, the same colors are assigned through largely deterministic evaluations. The brochure, however, does not explicitly provide details of these processes. It defines "very low safety significance" by its position in the color hierarchy, not by reference to the numerical thresholds or deterministic evaluation process that define safety significance. A member of the public reading the brochure receives a clear account of how the ROP is organized and what each color implies, but no account of what the underlying risk metrics mean or how the thresholds are set.

Within the developmental framework introduced in Section 2.2, the combination of the ROP website and the NUREG/BR-0508 [10] brochure corresponds to the first three stages, with a particular emphasis on the third stage, namely, explaining what the numbers mean. The later stages, which Warren and Duckett [8] argue should be foundational rather than terminal, remain present only in attenuated form through the annual public meetings, which have limited reach with the general public.

3.2. State-of-the-Art Reactor Consequence Analyses (SOARCA) Study

NUREG-1150, published in 1990, applied PRA methodology to five United States nuclear power plants and assessed severe accident risks [11]. The SOARCA study updated source-term and consequence estimates to address limitations in the NUREG-1150 analyses [12]. Its purpose was to provide the public and other stakeholders, including federal, state, and local authorities, with more realistic information about the potential consequences of a large release. SOARCA was accompanied by an information booklet, published as NUREG/BR-0359 [13], that incorporated risk communication techniques for presenting the results to internal and external stakeholders. Its qualitative findings, as seen below, together with three plain-language statements published on the NRC's SOARCA landing page [14], are most digestible to lay audiences.

SOARCA preliminary findings from the NRC website:

- *"Existing resources and procedures can stop an accident, slow it down or reduce its impact before it can affect public health."*
- *"Even if accidents proceed uncontrolled, they take much longer to happen and release much less radioactive material than earlier analyses suggested."*
- *"The analyzed accidents would cause essentially zero immediate deaths and only a very, very small increase in the risk of long-term cancer deaths."*

Key results laid out in the SOARCA brochure:

- *"When operators are successful in using onsite equipment during the accidents analyzed in SOARCA, they can prevent the reactor from melting, or delay or reduce releases of radioactive material to the environment."*
- *"SOARCA analyses indicate that all modeled accident scenarios, even if operators are unsuccessful in stopping the accident, progress more slowly and release smaller amounts of radioactive material than calculated in earlier studies."*
- *"As a result, public health consequences from severe nuclear power plant accidents modeled in SOARCA are smaller than previously calculated."*
- *"The delayed releases calculated provide more time for emergency response actions such as evacuating or sheltering for affected populations. For the scenarios analyzed, SOARCA shows that emergency response programs, if implemented as planned and practiced, reduce the risk of public health consequences."*
- *"Both mitigated (operator actions are successful) and unmitigated (operator actions are unsuccessful) cases of all modeled severe accident scenarios in SOARCA cause essentially no risk of death during or shortly after the accident."*
- *"SOARCA's calculated longer term cancer fatality risks for the accident scenarios analyzed are millions of times lower than the general U.S. cancer fatality risk."*

SOARCA represented a meaningful step toward public-facing translation of PRA-derived consequence information. As Reamer [15] documents, the accompanying brochure carried concrete translation techniques, rendering scientific-notation PRA values as 1 in X odds, supplying a glossary and shaded explanatory sidebars, and addressing the reader directly in the second person; hence, SOARCA covers broader stages within the developmental framework of Warren and Duckett [8] than ROP, including the first through fourth stages: get the numbers right, tell them the numbers, explain what the numbers mean, and partially show them the risk level is similar to what they have accepted.

3.3. Summary of Key Insights

These NRC's activities show that PRA outputs flow into public-facing materials, where the translation work has been performed on a project-by-project basis. The ROP program presents PRA-derived information in ways that require expert literacy to fully interpret. SOARCA came closest to deliberate public-facing translation. The position of these programs within the developmental sequence of Warren and Duckett [8], predominantly within the first four stages rather than the later stages, reflects the historical sequence in which technical work preceded communication work. One gap identified in our review is that no systematic, generic framework exists to facilitate the selection of risk information from PRA for translation into public-facing content. Section 4 addresses this research gap by proposing a set of criteria to support such a selection process.

4. SELECTION CRITERIA FOR TRANSLATABLE PRA OUTPUTS

This section proposes a set of criteria for selecting candidates among PRA outputs for public translation. The criteria have two dimensions: (i) how a lay audience receives a probabilistic risk output (Section 4.1) and (ii) the classes of scientific uncertainty to which the PRA output is exposed (Section 4.2).

4.1. Dimension 1: Public Reception of Probabilistic Risk Outputs

Table 1 evaluates each of the PRA-informed outputs reviewed in Section 3 against Fischhoff's six concerns introduced in Section 2.1. For each of the six public concerns, a rating of High indicates that the PRA-informed output directly engages that concern for a lay audience. Low indicates that the output engages the concern only weakly or indirectly, such that it would be unlikely to be recognized without additional explanation. Medium indicates an intermediate level of engagement, where the concern is partially engaged but requires some additional interpretation or supporting context to be communicated clearly. “Not directly engaged” indicates that the output contains no information relevant to that concern. The rating of each entry has been determined based on the authors’ expert judgment, as further described in the following paragraphs.

Table 1: Evaluation of the translatability of PRA-informed outputs against Fischhoff's six public concerns

PRA output	Familiarity	Understanding	Equity	Dread	Control	Trust
Core damage frequency (CDF)	Low	Low	Not directly engaged	High	Low	Medium
Large early release frequency (LERF)	Low	Low	Low	High	Low	Medium
Four-color significance scheme (as presented in ROP)	Low	Medium	Low	Low	Low	High
Qualitative consequence findings (as presented in SOARCA)	Low	High	Medium	Medium	Low	Medium

All outputs score Low on familiarity and on control. This is because PRA-informed outputs are not part of everyday experience, and the public has no direct means of affecting reactor performance.

On understanding, the CDF and LERF values are rated as Low. A frequency in scientific notation per reactor year is not accessible to a lay audience in terms of statistical meaning and quantitative magnitude. A reader who encounters 1E-6 and another who encounters 1E-7 would have difficulty, without further explanation, telling how these numbers could affect nuclear safety. The four-color significance scheme used in ROP scores Medium, because encoding safety significance into a four-color scale draws on familiar everyday devices such as traffic lights and weather alerts and can be grasped without quantitative literacy once learned. The supporting brochure, NUREG/BR-0508 [10], is the learning artifact, and the score increases with exposure to it. The qualitative findings used in the SOARCA score higher, at High, because they are written for a lay audience in comprehensible English. Phrases such as “essentially zero immediate deaths” and “a very, very small increase in the risk of long-term cancer deaths” are translated outputs, and they earn the highest understanding score in the table. But it should be noted that, as will be discussed in Section 4.2, this translation is achieved by omission of uncertainty rather than by communicating it explicitly.

On equity, CDF is a plant-level frequency and says nothing on its own about who is exposed if core damage occurs, so its equity score is listed as not directly engaged. LERF, by contrast, is explicitly about release to the surrounding population; however, it only provides the frequency of large releases at the plant level and does not evaluate the distribution of offsite consequences. Hence, LERF is rated as Low on equity. The four-color scheme in ROP carries Low equity loading because the colors describe plant performance rather than population exposure, and the qualitative findings in the SOARCA score Medium because they do mention public health consequences, though without distributional detail.

Perhaps the most consequential concern is trust. The four-color scheme scores High because the colors are the most public-facing point at which institutional credibility is loaded. A green finding communicates the NRC's decision that the plant is performing safely, and the audience's response depends almost entirely on whether they trust the agency that assigned it. Visschers and Siegrist [16] found that social trust operated as a key upstream determinant of how the public perceived the risks and benefits of nuclear power, and therefore of its acceptance, and that trust in nuclear-related institutions fell significantly after an accident. This makes the four-color scheme a double-edged sword. Where trust is intact, a green finding reassures, but where trust has eroded, the same finding inherits that erosion, conveying little reassurance and perhaps even suspicion. Because a finding is reduced to a single color, the audience has little to fall back on other than the credibility of the issuing institution, whereas other outputs that pair quantitative content with the institutional framing give readers additional material to evaluate.

Overall, Table 1 shows that each type of PRA output can be translatable along some dimensions and not others. The aspects of public concern rated as “Low” would require careful attention when designing public-facing materials for each type of PRA output, for instance, by supplementing them with other types of PRA outputs.

4.2. Dimension 2: Classes of Scientific Uncertainty

The second dimension of the selection criteria concerns the uncertainty associated with each PRA output. While there are multiple uncertainty taxonomies depending on their purposes, this section adopts the classification introduced by Schuster and Scheu [17] from the field of science communication, which examines how communicating these types of uncertainty affects public trust. They set out three classes of uncertainty. ‘Epistemic uncertainty,’ in their usage, arises from known or unknown research gaps. ‘Methodological uncertainty’ arises from limitations in data collection, modeling, or analysis. ‘Consensus uncertainty’ arises from inconsistent or contradictory findings or expert interpretations. Their scheme is oriented toward explaining whether the disclosure of uncertainty strengthens or erodes trust in science. It should be noted that this taxonomy differs from the one commonly used in PRA, for instance, NUREG-1855 [18]. The uncertainties addressed in NUREG-1855 largely correspond to the ‘methodological uncertainty’ in the taxonomy by Schuster and Scheu [17]. It should be noted that, in Schuster and Scheu's [17] study, the evidence is drawn mainly from climate and public health communication in Western Europe and North America rather than nuclear. As this paper extends their study to nuclear risk communication, the analysis in this section should be considered as suggestive rather than conclusive.

Table 2 shows the results of evaluating the three classes of uncertainty proposed by Schuster and Scheu [17] for the PRA-informed outputs listed in Table 1. Unlike Table 1, where the ratings describe the degree to which an output engages a public concern, the ratings in Table 2 describe the degree to which each class of scientific uncertainty is reflected in the output. Each entry's rating in Table 2 has been determined by the authors’ expert judgment. The results in this table should, hence, be considered preliminary and subject to further evaluation.

For each uncertainty class, Low, Medium, and High indicate the extent to which the interpretation of the PRA-informed output is affected by that class of uncertainty. Low indicates that the impact of each uncertainty type is comparatively limited or well characterized; Medium indicates that it has a noticeable influence on the output; and High indicates that it plays a substantial role and should be explicitly considered when translating the output for lay audiences.

Table 2: Evaluation of PRA-informed outputs against uncertainty classes by Schuster and Scheu

PRA output	Epistemic uncertainty	Methodological uncertainty	Consensus uncertainty
CDF	Low to Medium	Low to Medium	Low
LERF	Low to Medium	Medium	Low
Four-color scheme (ROP)	Low	Medium	Low
Qualitative consequence findings (SOARCA)	Medium	High	Medium

The typical PRA outputs, i.e., CDF and LERF, are rated as "Low" or "Medium" for epistemic uncertainty and methodological uncertainty, while they are rated as "Low" for consensus uncertainty. This is because, generally, the component failure databases are available, the modeling assumptions are well-established in most areas, and consensus within the PRA community is relatively high, so all three classes are comparatively low.

The qualitative findings translate the underlying analyses into plain language, resulting in the omission of uncertainty from those findings. For instance, the "zero immediate deaths" statement in the SOARCA study reads as definitive, though the underlying calculations carry substantial methodological and consensus uncertainty about source-term assumptions, evacuation effectiveness, and emergency response. Hence, from the viewpoint of recipients of this type of information, all classes of uncertainty are rated higher compared to other PRA-informed outputs.

It is worth noting that across Tables 1 and 2, translatability and uncertainty disclosure are in a trade-off. The output with the highest understanding score in Table 1, the qualitative findings, is the one that most thoroughly suppresses its uncertainty in Table 2. The outputs with the lowest understanding scores, i.e., CDF and LERF values, do not fully disclose their uncertainty either, since a bare frequency in scientific notation reveals a probability rather than the distribution around it, but their explicit probability framing at least does not conceal that uncertainty exists. Hence, the two dimensions (Sections 4.1 and 4.2) are intended to be considered together. A translation of PRA outputs must account for both requirements simultaneously rather than trade one off for the other.

5. APPLICATION TO SINGAPORE'S SMR CONSIDERATIONS

This section applies the selection criteria from Section 4 to the context of newcomers in nuclear energy, using Singapore as a case study. Two features of Singapore's context make the translation question particularly interesting. First, the country's small and densely populated land area constrains emergency response options (e.g., evacuation), which raises the importance of the equity dimension of Table 1. Second, Singapore's nuclear regulatory communication is in its early stages of development, which can create the flexibility needed to implement the engagement-first reordering of risk communication stages proposed by Warren and Duckett [8].

5.1. The Singapore Context

Singapore's engagement with civil nuclear power has shifted in recent years. The 2012 pre-feasibility study concluded that the reactor technologies then available, predominantly large light water designs requiring substantial evacuation planning zones, were not suitable for the country [19]. In 2025, Singapore embarked on a feasibility study examining the safety and technical feasibility of advanced nuclear energy technologies [20]. The signing of the Agreement for Cooperation Concerning Peaceful Uses of Nuclear Energy, (also called the 123 Agreement), with the United States in 2024, and the launch of Singapore Nuclear Research and Safety Institute (SNRSI) in 2025, mark institutional steps toward more active engagement with the question of whether emerging designs, particularly SMRs, warrant reconsideration [19]. The announcement on 19 May 2026 that Singapore will undertake the first phase of the IAEA Integrated Nuclear Infrastructure Review further signals that the question is being taken up within an established international assessment framework [21].

This posture raises the question of how PRA insights might inform public perception. Lye et al. [2] identify risk communication as one of six future research directions for the Singapore community, observing that the literature has not yet examined the use of PRA methods as educational tools for risk communication. This section addresses a related question, namely, the translation of PRA outputs for lay audiences.

5.2. Lessons for Singapore's Case

Among the representative PRA outputs reviewed in Sections 3 and 4, CDF and LERF directly engage dread and trust. In contrast, they score Low on understanding, and CDF does not directly engage with equity, while LERF scores Low on equity. In dense urban contexts such as Singapore, equity considerations can be more complicated and nuanced than in larger countries, such as the United States, because the consequences of accidents are geographically compressed. The lesson a newcomer can take away is that risk communication should not rely solely on CDF or LERF. In the meantime, as Table 2 suggests, a general tendency is that as the scope of PRA extends from the plant-level outcome to the offsite consequences, the associated uncertainty increases. Further investigation is required to advance the plant risk metrics so that the equity and consequence-pathway information can be explicitly embedded, while improving the translation of significant uncertainty in offsite consequence analysis.

The four-color scheme can raise a different question in Singapore. As discussed in Section 4, its communicative power rests on trust, namely, institutional credibility, which, in the United States, is inherited from decades of NRC operations. Singapore has no nuclear regulator with a comparable history, so a similar scheme could not inherit that trust and would have to build it from scratch. The lesson is that trust-building cannot be left to the technical or research community alone and cannot be assumed as a starting point. It has to be a foundational consideration from the outset of public-facing communication, which is precisely the engagement-first sequence Warren and Duckett [8] advocated.

Presenting qualitative findings can help the lay audience better understand risk insights, which matters where lay understanding is especially load-bearing, as with a newcomer public. However, as discussed in Section 4.2, that understanding is achieved by suppressing uncertainty. In the context of a still-developing institutional trust environment, that suppression poses a possible failure mode of reduced long-term trust, as identified by Schuster and Scheu [17]. The lesson is that further research is required to develop a qualitative, plain-language scheme to translate risk information that can alleviate the suppression of uncertainty.

One potential way to implement the implications discussed above is to develop a nuclear safety guidebook. At a high level, such a guidebook could incorporate four kinds of content from this paper. First, plain-language explanations of the key PRA-informed outputs, each carrying supplementary information on equity, consequence pathway, and uncertainty. Second, a section on the structural constraints of dense urban geography, including emergency-planning constraints, is framed as an honest acknowledgment rather than as reassurance. Third, a section introducing the institutional architecture being established for nuclear safety in Singapore, with explicit attention to the trust-building that institutional credibility requires when it cannot be inherited from operating history. Fourth, mechanisms for ongoing public engagement with the guidebook's content, including iterative revision in response to feedback, consistent with the engagement-first principle.

6. CONCLUSION

This paper addresses an underexplored connection between PRA and public-facing risk communication. While PRA has been used to anchor nuclear safety analysis in support of risk-informed decision-making by regulators and the nuclear industry, its translation into public-facing communication has not been formally investigated. Bridging this gap requires not only technical translation but also careful attention to public risk perception and the types of scientific uncertainty to which different PRA outputs are subject.

This paper has first reviewed risk communication in representative NRC programs, ROP and SOARCA, to establish a baseline understanding of current practice. This review informs the development of two-dimensional selection criteria for identifying PRA outputs suitable for translation into public-facing communication, organized around the public concerns the PRA outputs address and the types of scientific uncertainty they entail. The practical implications of these criteria are then illustrated through the Singapore case study, where dense urban geography, constraints in emergency response, and an early-stage regulatory infrastructure create translation challenges that differ from those in countries with established nuclear programs.

Looking ahead, and as a closing remark, Fischhoff [22] identifies four types of expertise required for effective public risk communication: subject-matter specialists, risk and decision analysts, behavioral scientists, and system specialists. These are the competencies that the PSAM community can directly support. The authors hope that this work will plant a seed for a new research pathway within the PSAM communities, aimed at strengthening the use of PRA-derived outputs to enhance risk communication with lay audiences.

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