Enhanced Fundamental Nuclear Safety Principles: Dealing with ignorance concerning radioactive risks

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1. The IAEA's account on how to achieve nuclear safety.

The International Atomic Energy Agency (IAEA) conceptualises nuclear safety as

> "the achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks."[1]

Protecting the workers, the public, and the environment from undue radioactive risks are thus the aim of achieving nuclear safety. To achieve this aim, the IAEA provides ten safety principles as guides for nuclear practice around the world. These principles are responsibility for safety, role of government, leadership and management for safety, justification of facilities and activities, optimisation of protection, limitation or risks to individuals, protection of present and future generations, prevention of accidents, emergency preparedness and response, and protective actions to reduce existing or unregulated radiation risks[2]. The ten principles lay out what needs to be done in building nuclear facilities from the technical, management, and regulatory levels, as well as the responsible actors to achieve nuclear safety.

That said for new reactor technologies such as Small Modular Reactors (SMRs), things leading to radioactive accident could very well be unknown. Experience in operating nuclear power plants (NPPs) from previous generation does not guarantee that SMRs will face precisely the same challenge. Such is the reason why it is important to adjust existing fundamental nuclear safety principles to better deal with the unknown in Evolutionary and Innovative Design (EID) of NPPs. This work will therefore lay out how the unknown or ignorance could be addressed for a better application of safety principles in building NPP.

Generally, 'risk' applies to events with estimable probabilities, 'uncertainty' applies to events with inestimable probability, and 'great uncertainty' or 'ignorance' refers to unknown events and, consequently, unknown probability[4], [5]. Meanwhile, regarding ignorance or great uncertainty, Hansson states,

> "*Great uncertainty* is a general term for lack of knowledge that goes beyond lack of probabilities for a well-defined set of outcomes. Great uncertainty includes unknown possibilities, uncertain values, and uncertain demarcation. These different forms of great uncertainty all have in common that they are difficult if not impossible to express in probabilistic terms."[4]

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This work addresses how fundamental safety principles could better address ignorance in guiding the commercialisation of evolutionary and innovative designs (EID) of NPPs with SMRs as the key example.

2. Proposal to address ignorance in the context of achieving nuclear safety

2.1. Why is addressing ignorance important?

In the context of NPP, Hansson proposes that due to this field requiring highly specialised knowledge, there is a knowledge discrepancy about its risk[6]. This knowledge discrepancy is not necessarily a result of concealing information, but rather the highly technical knowledge required to understand the technology. This knowledge discrepancy could lead to low public acceptance in NPPs despite the long operational experience – such as water-cooled reactors – and despite all engineering effort at laboratory level to ensure the safety of new reactors – such as SMRs.

Knowledge discrepancy related to NPPs could also be a result of different perception on technological risks. For engineers, electricity generation via NPPs could be seen as an efficiency matter, but it could be seen as a safety issue by the general public. In this situation, following Vries and Hansson, moral questions need to be integrated into efficiency questions[7]. An example of this is consideration on justice for future generations in building a commercial-ready design of a molten salt SMRs.

That there are different degrees of uncertainty between engineers, policymakers, and the public is relevant in explaining the importance of addressing ignorance. Addressing ignorance could shorten the knowledge gap between engineers, policymakers, and the public.

2.2. How ethical risk analysis addresses ignorance.

This subsection examines how ethical risk analysis (eRA) address ignorance by 1) introducing Hermansson and Hansson’s three-party model of ethical risk analysis (eRA); and 2) explaining how eRA address the problem of ignorance.

Note that there are many ethical approaches to assess a technology such as anticipatory approach which focuses on development stages of technologies[8]. We choose to focus on eRA because of its focus on risks and further detailing on potentially involved parties.

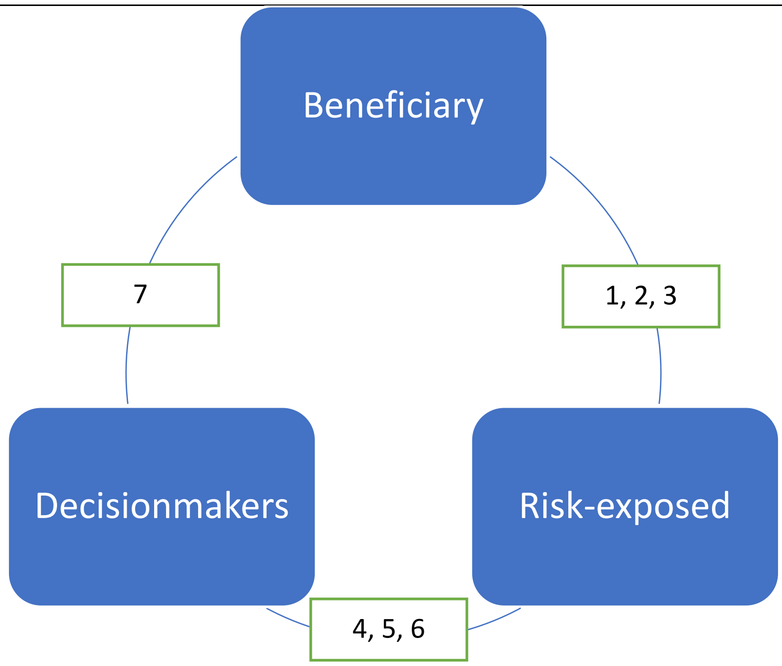
Hermansson and Hansson’s three-party model of an ethical risk analysis examines the relationship between the risk-exposed, the beneficiary, and the decision-maker in risk distribution[10], [11]. The three-party model analyses risk and responsibilities distribution tackles the problem of great uncertainty or ignorance by asking questions to elucidate how each party is exposed to risk and the extent of their responsibilities to such risk. They also state that six moral questions proposed here is open to modifications, and what constitutes fairness in risk-distribution also depends on our choice of moral account. These pointers allow some flexibilities in applying eRA.

According to Hermansson and Hansson, identifying ethical aspects of risk problem should be as self-evident as quantifying probabilities and consequences in risk analysis[10]. In this regard the three-party model of an ethical risk analysis does not replace various established probabilistic risk assessments. Rather it proposes two important elements to be integrated into

PRAs. *First*, the model proposes a map of those imposing and benefitting from risk at hand. *Second*, the model also suggests seven ethical questions to add on existing risk assessments.

The following Figure 1 is Hermansson and Hansson's three-party model of an ethical risk analysis:

Table 1. Hermansson and Hansson's three-party model for ethical risk analysis[8].



1. To what extent do the risk-exposed benefit from the risk exposure?
2. Is the distribution of risks and benefits fair?
3. Can the distribution of risks and benefits be made less unfair by redistribution or compensation?
4. To what extent is the risk exposure decided by those who run the risk?
5. Do the risk-exposed have access to all relevant information about the risk?
6. Are there risk-exposed persons who cannot be informed or included in the decision process?
7. Does the decision-maker benefit from other people's risk exposure?

The above figure inside Table 1 is Hermansson and Hansson's proposal to differentiate three different parties related to risk. In an event where risk is imposed, the ones included could be counted either as beneficiaries, decisionmakers, or risk-exposed. That said, the division of roles is not strict in the sense that one could be both a decisionmaker and beneficiary at the same time, a beneficiary and risk-exposed, a decisionmaker and risk-exposed, or three of them at the same time [11]. Therefore, in discussing risks, it is important to understand individuals involved in it and the role they have with regards to risk.

Instead of trying to estimate probabilities, this approach contains questions on to what extent each party is exposed to risks, whether or not it is fair, whether or not all have access to information about risk, and how could each party benefit on the risk exposition on others and himself. These moral questions address ignorance to a degree, and each of them could be implemented in assessing concrete SMRs issues.

2.3. How could the eRA be applied to nuclear safety principles?

The three-party model bypasses the problem of uncertainty since it does not try to assign probability estimates. To a certain degree, the moral questions in eRA also address ignorance related to technological risk, mainly because addressing moral issues allows eRA to go beyond probability estimates of risk as well as the monetary measures to compensate with it. In this sub-section, I reflect on how eRA's way to address ignorance could help applying the IAEA's fundamental safety principles[2] to EIDs such as SMRs.

a. *Principle 1: responsibility for safety*

The IAEA states that the prime responsibility for safety must rest at the organisations or persons responsible for activities which rise radioactivity in the first place. Related to 'who is responsible for what', eRA's contribution lies in mapping parties included in the rise of radioactive risk and see that albeit each of beneficiaries, decisionmakers, and risk-exposed contribute to radioactive risk in a different amount, each party is still connected to one another in allowing activities which increase radioactive risk. However, decisionmakers and beneficiaries should bear more responsibility than the risk-exposed. If according to the IAEA the responsible ones are those whose activities and/or facilities raise radioactive risk, with an addition from eRA, the first principle is further detailed into the following: the prime responsibility for safety must rest with the person or organisation responsible *benefitting from and deciding to initiate* facilities and activities that give rise to radiation risks.

Applying eRA-enhanced responsibility for safety principle to SMRs context, one can be more specific in sharing responsibility mainly between policymakers and SMRs company. For example, in the development of molten salt SMRs in Indonesia, the ones to bear most responsibility should be the SMRs company (ThorCon), the local government, and the Indonesian National Energy Assembly. Various feasibility studies must be performed even from the moment to choose a siting for the SMRs. The studies then need to be publicly accessible, and in return, the general public needs to know about these in order to make an informed decision.

b. *Principle 2: role of government*

With this principle, the IAEA states that there has to be an effective legal and governmental framework for safety with an independent regulatory body. The government and regulatory bodies' task is to establish standards and regulatory framework to protect people and the environment from radiation risks with main responsibility held by the licensee. With addition from eRA, principle 2 could be thus formulated: there has to be an effective legal and governmental framework for safety with an independent regulatory body *assessing radioactive risk exposure, its distribution, and benefits related to it*.

In the SMRs case, applying eRA-enhanced principle 2 can be done by looking at the relation between the government and the SMRs company. For instance, in countries like Indonesia who not only are new to SMRs, but also new to NPPs, the radioactive risk could be higher due to unknown factors such as preparing the local engineers to operate and maintain this new technology for generations to come. With this higher radioactive risk, we need to ensure that both the government and SMRs company constantly involve local engineers and energy research centres as a form of responsibility in building sustainable SMRs.

c. *Principle 3: leadership and management for safety*

This principle concerns establishing and sustaining leadership and management for safety not only in facilities and activities that give rise to radioactive risks, but also in other organisations concerned with these risks. The leadership and management for nuclear facilities stipulated in this principle could benefit from eRA's questions about the risk-exposed. Working engineers are also exposed to radioactive risk as they build and maintain NPPs. With moral questions from eRA on knowledge accessibility for working engineers as the risk-exposed within nuclear facilities, eRA-enhanced principle 3 could be thus formulated: it is compulsory to establish and sustain leadership and management for safety in nuclear facilities which give rise to radioactive risks *by, among others, ensuring knowledge accessibility and knowledge distribution about radioactive risks*.

Addition of eRA into principle 3 is applicable to new reactors such as SMRs. Innovative features such as modularity, smaller and more compact reactor design, and the choice of nuclear fuel cycle should be understood by working engineers from SMRs companies as well as government and non-government experts assessing the feasibility of SMRs.

d. Principle 4: justification of facilities and activities

By this fourth principle, the IAEA seems to use a risk-benefit approach since it is stated that "facilities and activities which give rise to radiation risks must yield an overall benefit." What overall benefit means here are measured by consequences of nuclear facilities. In this regard, eRA could contribute in specifying what counts as benefits, for whom, and whether or not such benefits in exchange of radioactive risks could be considered fair. Additionally, eRA also gives room for compensation, either monetary or in-kind. With eRA, principle 4 could be formulated as the following: facilities and activities which give rise to radiation risks must yield an overall benefit *either monetarily or in-kind for the risk-exposed around the nuclear facilities.*

As an example from evolutionary and innovative design (EID)[13] of nuclear reactors such as SMRs, principle 4 could be applied by assessing whether or not there is a benefit beyond monetary ones when building SMRs. Countries like Indonesia which is dominated with fossil fuelled grid, particularly lignite, whose advantage is a cheap electricity, could see whether or not applying SMRs would not only maintain cheap electricity, but also a more stable, non-fluctuating supply while being emission-free. From this case, what counts as benefit could come from environmental and health aspects on top of economic one.

e. Principle 5: optimisation of protection

For this principle, the IAEA states that it is necessary to optimise protection "to provide the highest level of safety that can reasonably be achieved." To be as safe as reasonably achievable seems rather vague as to what 'reasonable' means. It could be interpreted as an implementation of all current available knowledge about nuclear energy to engineer facilities with next-to-none radioactive risks. That said, omitting 'reasonable' here could simply be removed and the idea of providing the possible highest safety would still be maintained.

In the context of NPPs, another interpretation for 'reasonable' part here could refer to economic viability which also explains why certain EIDs such as fusion reactors remain out of commercial use due to how expensive the technologies are. However, it does not change how principle 5 becomes ambiguous due to this word. Therefore, the eRA could contribute by adding elements of fairness of risk distributions by decisionmakers and nuclear companies as beneficiaries in order to optimise protection. The eRA enhanced principle 5 could thus be: *government and nuclear companies* must provide the highest level of safety *with fair radioactive risk distribution in mind*.

As an example, in building SMRs in Indonesia, the local and national government must first provide established regulations for nuclear energy applicable also to new reactors before construction even starts. This regulation is also based on continuous feasibility study involving not only the company's engineers, but also research centres. On the field, NPPs companies need to ensure that their licensed SMRs design is precisely constructed, such as the functioning of modularity feature, passive safety system, the choice of thorium as both coolant and moderator for the reactors, the adaptive construction to seismic activities, and so on.

f. Principle 6: limitation of risk to individuals

The sixth principle states that measures to control radiation risks must ensure that no individuals bear unacceptable risks of harm. As with the previous principle about the extent of 'reasonably achievable', ambiguity also lies with 'unacceptable risks of harm. Practically, the IAEA refers to a maximum threshold of radiation doses in order to remain within the desired level of safety. Towards this, eRA could contribute in precising how to keep radioactive risks for individuals to a minimum by empowering the risk-exposed with knowledge ensuring that protective measures remain in place. With eRA, principle 6 can thus be formulated: *engineering, policy, and educational* measures must ensure that no individuals bear unacceptable risks of harm.

In SMRs context, eRA-enhanced principle 6 can be implemented through, among others, compact reactors' design features such as the capability to keep radioactive material within the reactor in case of core-melting, thus preventing release of high-level radioactive material to the environment. Furthermore, scenarios such as core-melting accidents should also be covered within local and national regulations. Other SMRs-specific features such as the ability to partially shutdown reactors or and conditions to do so should also be made clear in the regulations and communicated to the general public.

g. Principle 7: protection of present and future generations

The seventh safety principle states that there has to be protection for present and future people and the environment against radiation risk. In NPPs context, this principle is relevant for intra and intergenerational justice issues. As for the compatibility with eRA, one of the focuses of the assessment concerns considerations on risk-exposed persons who cannot be included in the decision process. It is important to note that those who live now have no means to access either the interest of any parts of the environment or those who are not born yet. Therefore, it is important to ensure that a high standard of operation which is radioactive accident-resistant, or in case of accident, is ready to cope with it as quick as possible.

In SMRs context, commercialising this new technology, particularly for new nuclear adopting countries, the government, nuclear companies and general public need to be well-informed about the type of SMRs used, its functioning, down to the use of the nuclear fuel, coolant and moderator. If one is using molten salt as coolant and moderator with thorium as its fuel, for instance, there has to be detailed information and measures on how much HLW is produced by the reactors, whether or not these will be recycled back into the reactor, how to acquire them, as well as how to transport them before and after the fission process inside the reactors.

h. *Principle 8: prevention of accidents*

The eighth principle states that it is a must to employ all practical efforts in order to prevent and mitigate nuclear or radiation accidents. In this principle, both preventive and mitigative actions are equally important and both must be treated. The question then is about the one with the most responsibility to employ all practical efforts. While policymakers are responsible to issue NPPs license, practical efforts in terms of engineering NPPs should mainly fall to the licensee. Towards this principle, eRA can further define those who should bear responsibility for preventing and mitigating nuclear accidents. The eRA's addition to principle 8 could thus be formulated: all practical efforts must be made *mainly by business entities in cooperation with the government* to prevent and mitigate nuclear or radiation accidents.

Taking an example from SMRs, as new reactors due to its smaller size and possibly new use of materials as its fuel, moderator, and coolant – such as using thorium as its fuel with molten salt as its moderator and coolant – nuclear companies must exercise cautions in building, operating, and maintaining it. It can be done, for example, by taking full responsibilities for the safety of the reactor design and providing policymakers with transparent data on the safety status on the NPPs.

i. *Principle 9: emergency preparedness and response*

The ninth principle states that arrangements must be made for emergency preparedness and response for nuclear and radiation incidents. The eRA could develop this principle further by specifying parties responsible to ensure emergency preparedness and response of NPPs in case of nuclear incidents. Although the public receives benefits in exchange of being exposed to radioactive risk – mainly abundant, clean, and in many cases, affordable electricity – NPPs companies still enjoy the most benefit, particularly monetarily. With that in mind, using eRA, principle 9 can be formulated as thus: *nuclear companies bear the most responsibility* to ensure emergency preparedness and response for nuclear or radiation incidents.

As an example, in SMRs, companies in charge of building, operating, and maintaining SMRs along its decades of NPPs lifecycle bears the most responsibility in accounting for radiation accident scenarios, even for the ones from natural disasters such as earthquakes. It is true that SMRs companies are not in control of geological activities, but they are responsible for preventing highly radioactive materials to spill to the environment in case of events such as tsunamis or earthquakes.

j. *Principle 10: protective actions to reduce existing or unregulated radiation risks*

The tenth principle states that protective actions to reduce existing or unregulated radiation risks must be justified and optimised. The scope of justified protective actions here could benefit from eRA due to the assessment's reliance on fairness in risk distribution. While the assessment is open to other criteria of fairness, not exposing minority groups to risks is still regarded as important. With that in mind, eRA-enhanced principle 10 could be formulated in the following: protective actions to reduce existing or unregulated radiation risks must be optimised *without further exposing minority groups to risks.*

In SMRs context, applying principle 10 can be done in, among others, deciding where to build the NPPs. The small size and modularity feature allow SMRs to be built near inhabited area and make SMRs ideal to supply electricity to nearby cities. That said, it is necessary that given the existing radioactive risk, the siting of the NPPs is close to regions with intermittent, or even devoid of electricity. That said, it is also important that nuclear accident scenario for the site are well-planned, along with building infrastructure to support nuclear safety such as the route to transport nuclear fuels, reactor modules, and so on.

3. Future research: Despite the eRA's capability to address ignorance, ignorance will still remain.

Despite eRA's capability to enhance fundamental safety principles, ignorance is essentially that which one has very little or even no idea about. As shown above, eRA can indeed enhance fundamental nuclear safety principles by specifying each of its points. That said, ignorance will always remain despite our best effort to reduce it.

Therefore, this work is but an invitation to scholars interested in nuclear energy ethics in particular or philosophy of technology in general to engage with ignorance issues related to policy to tackle radioactive risk. One can, for instance, address virtues that policymakers need to possess when benefits from EIDs are clear, but not the risks. Virtues such as courage in the form of risk-taking without being rash, or even *poiesis* or practical wisdom in commercialising EIDs, could potentially be an interesting topic in applying fundamental nuclear safety principles.

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