Title: An expert elicitation of the proliferation resistance of using small modular reactors (SMR) for the expansion of civilian nuclear systems

Abstract: To facilitate the use of nuclear energy globally, small modular reactors (SMRs) may represent a viable alternative or complement to large reactor designs. One potential benefit is that SMRs could allow for more proliferation resistant designs, manufacturing arrangements and fuel cycle practices at widespread deployment. However, there is limited work evaluating the proliferation resistance of SMRs, and existing proliferation assessment approaches are not well suited for these novel arrangements. Here, we conduct an expert elicitation of the relative proliferation resistance of scenarios for future nuclear energy deployment driven by Generation III+ light water reactors, fast reactors, or SMRs. Specifically, we construct the scenarios to investigate relevant technical and institutional features that are postulated to enhance the proliferation resistance of SMRs. The experts do not consistently judge the scenario with SMRs to have greater overall proliferation resistance than scenarios that rely on conventional nuclear energy generation options. Further, the experts disagreed on whether incorporating a long-lifetime, sealed core into an SMR design would strengthen or weaken proliferation resistance. However, regardless of the type of reactor, the experts judged that proliferation resistance would be enhanced by improving international safeguards and operating several multinational fuel cycle facilities rather than supporting many more national facilities.

Key words: expert elicitation, nuclear energy, small modular reactors (SMR), proliferation resistance

1. INTRODUCTION

Nuclear energy has the potential to make a significant contribution to mitigating greenhouse gas (GHG) emissions that cause climate change.(1) At the same time, enhancing the proliferation resistance of civilian nuclear energy systems should be consistent with a global expansion. Here, we conduct an expert elicitation to assess how different reactor technologies, fuel cycles, and institutional arrangements may alter the proliferation resistance of potential future civilian nuclear systems. We focus on whether emerging nuclear technologies, namely small modular reactors (SMRs), can enhance the proliferation resistance of these systems at scale by mid-century (e.g. 2050). Specifically, experts are asked to assess whether a specific SMR design —a 100MWe light-water pebble-bed reactor with many of the features that have been suggested in the literature to enhance proliferation resistance – produces these benefits.

Structured expert elicitations are used to gain insight into situations where there is substantial uncertainty around relevant parameters that limit the application of existing methods of assessment. Here, existing approaches, such as the International Atomic Energy Agency's PRADA model or the Generation IV International Forum (GIF)'s Proliferation Resistance & Proliferation Prevention (PR&PP) model (2), are difficult to apply, as SMRs are in early stages of development and many design parameters are not yet sufficiently defined to populate these models. Additionally, existing methods are often more appropriate for assessing individual reactor designs or fuel-cycle facilities within the context of current institutional arrangements and proliferation pathways. By contrast, we are interested in investigating SMRs relative to other reactor technologies and fuel cycles when deployed at scale and as part of a larger system with alternative institutional arrangements. Specifically, deploying SMRs to meet global demand could entail a tenfold increase in the number of reactors, with substantial changes to the nuclear system. Elicitations can also produce important guidance for policy-makers when they cannot wait for the uncertainty to resolve before making critical decisions.(3, 4) For example, Abdulla et al. conducted an expert elicitation on the costs of different SMR designs and deployment configurations for research and development (R&D) goals and expected competitiveness with other technologies.(5) Our elicitation on proliferation resistance provides needed guidance on another important dimension of deploying SMRs at scale. Finally, despite the progress that has been made to develop and improve proliferation resistance models, a recent National Academy of Science study reports that policymakers believe "existing tools have limited utility to inform their nonproliferation decisions beyond what a case-by-case analysis would produce."(6) Thus, elicitations may produce information that is more persuasive for policy.

Expanding nuclear energy capacity worldwide based on large centralized facilities (e.g. reactor designs with generating capacity greater than 1 GWe) poses challenges and risks due to the large capital outlays, potential safety issues, negative public opinion, and persistent concerns about proliferation—that is, the intentional misuse of nuclear technology and material.(7) Small modular reactors (SMRs), defined as units with a generating capacity of less than 300 MWe, may represent a viable alternative to large reactors. They require smaller initial capitalization; the smaller capacity may better match existing demand for energy; and their smaller footprint may be easier to site. Additionally, some SMR designs may engender less public opposition from the viewpoint of safety.(8, 9) Importantly, these features also make SMRs more suited for the expansion of civilian nuclear energy use in developing countries where electricity demand is anticipated to increase over the coming decades.(10)

It has also been suggested that SMRs have the potential to enhance proliferation resistance compared to conventional reactors designs and deployment approaches. Yet there is limited work evaluating the proliferation resistance of proposed SMR designs, manufacturing arrangements, and likely fuel cycle practices.(11, 12) For instance, it has been postulated that an SMR design incorporating a long-lifetime sealed core could reduce opportunities for material diversion.(13) SMRs could also be produced in centralized, assembly-line production, and the fueling could be brought under multinational control.(8) This could increase proliferation resistance compared to the production of reactors and fuel at a larger number of facilities under national control.(14) By contrast, an SMR design could require higher-enrichment fresh fuel than Generation III+ light water reactors (LWRs) and increase overall global enrichment requirements.(15) A long-lifetime core might also affect proliferation concerns related to disposal and storage, as some SMR designs can increase the amount of plutonium in the spent reactor fuel when compared to the spent fuel of in-use LWRs.(11) SMR designs could also affect the ability of regulators to safeguard the materials in the reactor core. For example, if SMRs are deployed in great numbers and in remote locations, this could affect negatively affect the application of safeguards.(15)

By assessing the potential impact of the deployment of an SMR with many of the features described above, this study provides decision makers with a clearer understanding of the potential for SMRs to alter the proliferation resistance of future nuclear energy systems. The expert elicitation approach also provides policy makers with information about the degree of agreement within the scientific community about which of the characteristics of the reactors, fuel cycle, or deployment scenario have the greatest effect on the proliferation resistance of the system.

2. METHOD

We employ a structured expert elicitation to assess the proliferation resistance of characteristics that could be a part of SMR designs and the energy systems that incorporate them. We focus on understanding the relative proliferation resistance of specific proposed designs and systems when compared against existing reactor designs and other possible future nuclear energy systems—not on developing an estimate of the absolute range of proliferation resistance of certain reactor designs and system features. Below, we outline the elicitation protocol. First, we describe the specific reactor designs and deployment scenarios. Second, we present the protocol and the selection of experts.

After a review of existing proliferation resistance models, we concluded that an expert elicitation was the appropriate method for this effort. Since many parts of SMR systems are not yet defined (e.g. advanced fuels, novel facility arrangements, deployment patterns, etc.), it is difficult to populate the parameters for many existing proliferation models. The existing literature also makes a number of divergent claims about the potential proliferation resistance of different features of SMRs as well as potential fuel cycle and institutional arrangements that SMRs may facilitate. An expert elicitation allows us to examine the differences in opinion amongst the experts on these features. Finally, expert elicitation allows us to explicitly address these factors by probing the rationale behind the experts' responses and isolate how the institutional structures interact with the reactors' technical characteristics.

2.1 The scenarios. We developed five scenarios, a baseline scenario and four alternative futures, for the use of nuclear energy from present to 2050. The scenarios were selected to span the expectations of future growth in nuclear energy and demand found in the literature, and to differentiate the primary dimensions that could influence the proliferation resistance of the energy system. As mentioned above, we are specifically interested in evaluating the potential benefits of an expansion scenario that includes advanced SMRs, centralized manufacturing and fueling facilities, and institutional arrangements to ensure the nondiversion of materials and technologies throughout the fuel cycle. Each scenario involves a description of a complete global nuclear energy system. This scenario approach is employed since the proliferation resistance of the reactors depends both on the reactor design as well as the deployment scenario.

In Table I, we describe the three different types of nuclear reactors that are included in the scenarios. The SMR is designed by scientists at Pacific Northwest National Laboratory and includes many of the characteristics that could provide SMRs with greater proliferation resistance.(16) It includes a long-lifetime core (18+ years) and does not require on-site fresh fuel storage. Its fresh fuel includes cermet particles enriched to between 12 and 14 percent U-235, and the fissile isotope Pu-239 comprises 8.6 percent of the plutonium in its spent fuel.(16) A gigawatt-scale Generation III+ LWR that resembles Westinghouse's AP1000 design, and a representative fast reactor design that resembles the 800-MWe Russian-designed BN-800) are the other two reactors.

In Table II, we outline the baseline scenario and the four alternative future scenarios. In selecting nuclear energy systems (including reactors, fuel cycle facilities, and other attendant systems and processes) that could be deployed by 2050 and about which experts could compare facets of proliferation resistance, we use baseline projections of global nuclear generating capacity and production developed by the Massachusetts Institute of Technology's "The Future of Nuclear Power" study group.(17) Three out of the five scenarios in the elicitation include global generating capacity and annual production estimates that correspond to the low-growth estimates for 2050 that were advanced in the initial 2003 study. We also developed an alternative scenario (Scenario A) that uses the global capacity and production from a more recently conducted estimate from the Global Change Assessment Model (GCAM).(18) GCAM is an integrated assessment model that incorporates the interactions of the economy, the energy system, and the earth and climate.(19)

We also made assumptions in our scenarios about the fuel cycles adopted in support of nuclear generation (e.g., whether they incorporate onsite refueling or spent fuel reprocessing); the global distribution of reactors and fuel cycle facilities; institutional arrangements, including the existence of multinational fuel cycle facilities and fuel take-back services; and safeguards requirements.

2.2 The protocol. This elicitation employs pairwise comparisons of future global nuclear energy scenarios, one of which includes SMRs. Experts are asked to rank the alternatives pairwise according to their relative proliferation resistance. Each item is compared with all others, following the approach developed by Goossens et al.(20) We offered experts two complementary options for characterizing their judgments on the paired scenarios: 1. a relative characterization of "more", "less" or the "same", and 2. a value (on a scale of 1 to 5) on the extent to which they judged one scenario to be more or less proliferation resistant than the other. More experts preferred the first options and thus, we focus on those results. This protocol does not provide a discrete measure of uncertainty. We explored experts' uncertainties through open-ended discussions in the protocol.

Since experts on proliferation are familiar with the International Atomic Energy Agency (IAEA)'s definition and typology of proliferation resistance, our protocol uses this definition to provide a common framework for experts when thinking about and assessing proliferation resistance.(21) The IAEA defines proliferation resistance as the "characteristic[s] of a nuclear system that impedes diversion or undeclared production of nuclear material, or misuse of technology" in order to acquire a nuclear weapon.(21) The protocol asks the experts to compare the scenarios along the IAEA's three distinct subcategories of proliferation resistance: material barriers, technical barriers, and institutional barriers. Material barriers are the inherent qualities of the nuclear materials used in a reactor and energy system that affect how attractive those materials are for use in a nuclear weapon. Technical barriers are the elements of an energy system's fuel cycle—its facilities, processes, and equipment—that make it difficult to gain access to materials and/or misuse facilities to obtain weapons-use materials. Institutional barriers are the arrangements and commitments that nations make to safeguard (and otherwise regulate) their nuclear systems from misuse. While proliferation resistance is often thought of in terms of state-level diversion of nuclear material and technologies, increasingly, sub-state actors may also pose a threat through material theft and sabotage. We restrict our scope to understanding the resistance of nuclear energy systems to state-level proliferation.

Following the best practices for elicitation as outlined in Cooke and Goossens and furthered by Roman et al. we first ran an initial pilot protocol with a small number (three) of experts.(4, 22) In the initial pilot elicitation, we found it difficult to identify how the experts' different conceptualizations of proliferation resistance and proliferation pathways were influencing their comparisons of the elicitation scenarios. For instance, some experts concluded that all reactors, fuel types, fuel cycle arrangements, etc. could be used to proliferate with enough time and expertise—an argument that arises in the academic literature as well.(23) To identify these constructs and aid our experts in explicitly identifying their mental map of potential proliferation pathways, we added a primer to the final protocol. In the primer, we provided an overview of the reactors and fuel cycle facilities that are part of the current global nuclear energy system; prompted participants to compare the importance of proliferation resistance barriers in general and to describe what specific factors they believed affected systems' proliferation resistance (see Appendix: Complete protocol); and asked them to identify what they believed were the most likely pathways for state-level proliferation. The protocol then introduced the IAEA's framework for defining proliferation resistance and the nuclear reactor designs that were included in the scenarios. We discuss the implications of the experts' divergence from the IAEA definition in their ranking of the scenarios in the discussion.

2.3 Identifying and selecting experts. Identifying and selecting experts is a crucial step in the elicitation process. Indeed, whether there are experts whose "knowledge can support informed judgement" is a main determinant of whether it is appropriate to use the elicitation process.(24) We define an expert as "a person whose present or past field contains the subject of the expert panel in question and who is regarded by others as being one of the more knowledgeable about the subject"(25) and included reputation, diversity in background, balance of views, and availability in our selection process. In this elicitation, we do not try to assess the performance of or combine expert opinions. Rather, we opt to show the diversity of opinions amongst the experts.

In identifying and selecting experts, this study roughly followed guidelines developed for the European Commission in 1999.(26) The first step in selecting experts involved a review of the academic literature, government reports, and studies by international organizations. Next, we identified the publications that included the research relevant to proliferation resistance and the sources of other frequently cited research on the topic. A list was created of the most frequently cited authors within these publications and of the researchers leading the relevant governmental and international organizations and projects. To diminish the influence of nationality on the elicitation outcome, a priority was put on including experts from different nationalities. Including experts with a range of professional training and backgrounds was also prioritized, including those with experience in reactor design and assessment, proliferation assessment, fuel cycle assessment, and the application of safeguards. According to these criteria, we chose approximately 20 experts from this list. Most of these experts were contacted. Three experts participated in a pilot elicitation during which the elicitation was refined.

Twelve experts in total agreed to participate in the elicitation; nine experts with eight different nationalities completed the elicitation protocol; two of the nine ended their interviews before they had worked through all of the pairwise comparisons; three of the initial twelve later decided that they didn't have time to participate. Of the completed interviews, six of the elicitation interviews were conducted in person—either in the experts' place of work or in a public setting; three were conducted via phone or skype video. The administrator of the protocol guided all experts through every question in the protocol. The experts were given ample opportunity to ask questions about the protocol and revisit their responses. In a few instances, experts were given a copy of the first several parts of the protocol in advance of their interview, so that they could have time to understand its objectives and structure. These experts completed and submitted these parts of the protocol prior to the interview. In these cases, the administrator still reviewed the first parts of the protocol with the experts to ensure that all questions were answered to the fullest extent possible and that the expert was satisfied with their responses. All of the experts were given the opportunity to follow up with the study administrators if they had additional thoughts or wanted to change their responses to protocol questions; none did so. Each of these interviews was completed in less than 115 minutes, and the average time of completion was 81 minutes.

3. RESULTS AND DISCUSSION

In Tables III and IV, we show the experts' rankings of the relative proliferation pathways and selected results from experts' pairwise comparisons of scenarios, respectively. Each pair of scenarios is compared along 4 different categories: material, technical, and institutional barriers, and overall barriers. The main finding from this elicitation is that the experts do not consistently judge the scenario that incorporates SMRs (Scenario D) as enhancing the proliferation resistance of the system compared to the scenarios that relied exclusively on LWRs (scenarios Z, A and B). Importantly, four respondents (experts 2, 4, 5, and 8) concluded that the SMR scenario (scenario D) neither increased nor decreased the proliferation resistance of the overall global energy system compared to the LWR scenarios (Z, A, and B); two respondents (experts 7 and 9) judged scenario D to be less proliferation resistant than scenarios Z, A, and B; and one respondent (expert 6) judged scenario D to be more proliferation resistant.

Most of our experts did not conclude that the long-lifetime reactor core would influence the overall proliferation resistance of the SMR scenario. Experts who identified a difference diverged on whether this core would enhance or lessen the system-level proliferation resistance. The long-lifetime sealed reactor core is one of the key technical features that experts have postulated would affect the proliferation resistance of SMRs. The long-lifetime reactor core allows for 18 years or more of operation without refueling, limiting the need to access the core. A long-lived core, however, requires a higher-level of uranium enrichment (12%-14% U^{235}) compared to the LWR options. The cermet, pebble SMR fuel also presents novel physical and chemical forms of fuel compared to the LWR reactors which rely on traditional fuel bundles. The expert who judged the SMR scenario (Scenario D) to be more proliferation resistant than the business as usual scenario (Scenario Z) judged that the absence of fresh fuel storage at SMR reactor sites could potentially increase the overall proliferation resistance by reducing the amount of nuclear materials on site, reducing opportunities for the diversion of materials, and requiring fewer on-site inventories. Expert 5 explicitly noted that the long-lifetime core reduces opportunities for diversion and offsets concerns from an increase in fresh fuel enrichment levels. By contrast, other respondents judged that the higher enrichment level of the SMR fuel and the physical form of the fresh SMR fuel as increasing the attractiveness to proliferators and decreasing the ability to detect diversion. One expert also noted that the additional enrichment capacity required for the SMRs —rather than the fuel enrichment itself—could increase the likelihood of diversion.

Additionally, the large number of SMRs that would be needed to deliver comparable generation capacity to larger reactors did not affect experts' proliferation resistance judgements. Scenario D entails the deployment of 4,700 SMRs, some of which would be sited at locations with existing reactors, but many of which would be sited at new locations in countries with little or no existing nuclear energy infrastructure. The scenario also assumes that multiple SMRs would be colocated and operated by the same people. The experts do not judge the scale or geographic expansion as influencing the proliferation resistance of the scenarios. The lack of emphasis on the scale and location of the deployment of the SMR is in contrast to some experts' concern about the increase and geographic expansion of enrichment capacity necessary under scenario D. It also addresses potential concerns about the difference in the number of LWRs and SMRs that would be needed to develop equivalent nuclear generating capacities.

The fuel cycle arrangements that accompanied the SMR scenario (Scenario D) were judged to have same level of proliferation resistance as those that accompanied the LWR scenarios (Scenarios Z, A, and B). The SMR scenario proposes that global fuel requirements would be met by additional fuel cycle facilities, including uranium enrichment facilities, in countries that currently have fuel cycle facilities and in some countries that do not currently have these capacities. While most respondents judged that the technical barriers in the fuel cycle of the SMR scenario to be equal to the LWR scenarios, one judged that the technical barriers were less effective for scenario D based on the expansion of uranium enrichment capacity into states that are currently without nuclear weapons.

The development of additional types of fuel-cycle facilities also influenced experts' judgments about technical barriers. In the original scenarios, experts judged the scenarios that incorporate multi-national fuel cycle facilities to be more proliferation resistant than similar scenarios without these types of facilities. To probe these features, we introduced modified versions of a LWR expansion (Scenario B+) and SMR expansion (Scenario D+) with multinational fuel cycle arrangements. Rather than having the increased fresh fuel requirements met by additional national fuel cycle facilities, including enrichment facilities, the alternative scenarios—scenarios B+ and D+—included the establishment of regional or international fuel cycle facilities that would supply multiple countries with reactor services and fuel. This concept is promoted as a potential response to the proliferation of national uranium enrichment programs.(27) Under scenarios B+ and D+, most countries agree to limit their national fuel cycle operations and rely on these facilities, which would be owned and operated by stakeholders from multiple countries. These multinational facilities would all be under international safeguards, even if they involved or were located in nuclear weapons states.

The multinational fuel cycle facilities in scenarios B+ and D+ had the most significant and positive impact on how experts judged the institutional barriers to proliferation among all of the scenarios. Experts judged the institutional barriers in scenario D+ to enhance the proliferation resistance over scenario D, because of the ease of safeguarding fewer facilities, the increased transparency inherent in multinational operations, and the application of international, rather than national, safeguards at most fuel cycle facilities. Most of the experts judged that the technical barriers to proliferation in the SMR scenario with multinational facilities are equal or greater than the technical barriers in the SMR scenario without these facilities. However, only two of the experts (experts 7 and 8) judged the inclusion of multinational facilities in scenario D+ to affect their overall assessments when comparing it against business as usual, scenario Z. The experts drew the same conclusion for scenario B+ and B.

Overall, the proliferation resistance of the SMR and LWR scenarios were judged to be largely equivalent. However, in open-ended discussion, some experts identified design, fuel, and fuel cycle characteristics in the SMR scenario that could alter both the specific and overall barriers for proliferation. One expert judged that the long life-time core and the absence of onsite fuel storage enhanced the proliferation resistance of the SMR scenario over the baseline scenario. Multiple experts (experts 2, 4, 6, 7, and 8) also found that the inclusion of multinational fuel cycle facilities increased the proliferation resistance of the SMR scenario. By contrast, two experts felt that the higher levels of enrichment of the SMR fuel, the increased enrichment capacity required to fuel these reactors, and the relative difficulty of detecting diversions of cermet fuel compared to traditional fuel elements (because it is more time consuming and laborious to control and account for cermet fuel pebbles), made the SMR scenario less proliferation resistant. Yet, these experts did not judge these features as having a decisive effect on specific barriers or the proliferation resistance of the overall SMR scenario compared to the LWR scenarios.

It is possible that our experts may be anchoring on the LWRs since they are more familiar with this generation of reactors, fuel cycle arrangements, and deployment patterns.(28) Alternatively, the SMR scenario (scenario D) includes a large number of LWRs since any expansion pathway for nuclear energy would include LWR generation at least for the foreseeable future. The LWRs would presumably have onsite fresh and spent fuel storage. This may have also contributed to the experts' judgment that the proliferation resistance of scenario D's system in its entirety is approximately equal to the LWR only scenarios. Finally, the two diversion pathways that the most experts judged as most likely—the use of an undeclared enrichment plant and the concealed reprocessing of spent nuclear fuel—are not directly affected by the introduction of SMRs to the energy system. That is, unless this occurs in the context of placing most or all enrichment and reprocessing facilities under multinational control, which most experts believed would increase the proliferation resistance of the entire system.

While the experts do not consistently conclude that the overall proliferation resistance of the SMR scenario differed from the strictly LWR nuclear generation options, they consistently judge the SMR scenario to be more proliferation resistant than the scenario that included fast reactors

(Scenario C). They also largely found the LWR scenarios advantageous compared to the fast reactor one. Five respondents (experts 4, 6, 7, 8, and 9) judged that the material barriers from the fuel in the SMR scenario presented more proliferation resistance than the barriers for the scenario with fast reactors. The experts found that both the fresh fuel requirements and spent fuel composition decreased the proliferation resistance of the fast reactor scenario. Specifically, the impact of the fast reactors' spent fuel composition—and the volume of plutonium that could be created in a fast reactor blanket—weighed heavier in respondents' judgments compared to the quantity of mixed-oxide (MOX) fresh fuel, which includes plutonium and natural or depleted uranium. Most experts judged the technical barriers to proliferation in Scenario D to be greater than those present in fast reactor scenario (Scenario C) based on the spent fuel reprocessing and MOX fabrication facilities that would be built to accommodate the fast reactors, in addition to the increased stockpiles of separated plutonium that would be created in the process. The spread of specialized technical skills associated with operating reprocessing and MOX fabrication facilities was also a concern. The greater time and expense of safeguarding reprocessing and MOX fabrication facilities, which introduce additional potential points of diversion, also played into experts' evaluation.

Two respondents (experts 2 and 5) judged the proliferation resistance of the fast reactors and the SMR scenarios to be equal in terms of material barriers, but differed on how they arrived at these conclusions. One expressed that the fissile materials in fresh MOX fuel present the same degree of proliferation resistance as the fuel used in the LWRs. This expert judged that the fuel from both types of reactors are unsuitable for use in nuclear weapons. By contrast, the other respondent argued that material barriers, in general, do not influence proliferation resistance; the fuel type and composition could only prolong the time it would take a state to divert and misuse nuclear materials, and not whether it was possible to do so.

A central challenge in conducting this elicitation was assuring that the scenarios included sufficient information for the experts to make the necessary judgements without bringing in additional information. To address this, during the pilot elicitation, we asked for feedback about the types of information that experts needed to complete the pairwise comparisons and added information to the final elicitation's scenarios accordingly. We also asked the experts included in the final elicitation to identify what information, other than that which was provided in the protocol, could have informed their assessments of the scenarios' proliferation resistance, they provided a range of responses: the number and training of operators at reactors and fuel cycle facilities that would be needed to support each of the scenarios; detailed information about the nuclear materials—their quantities, attractiveness, and barriers—present in an entire system; the operating state's industrial capacity and experience managing certain types of nuclear facilities; and "higher level" institutional arrangements within each scenario, including national commitments to peaceful use of nuclear energy, regional agreements, and technical cooperation agreements.

The type of information requested—with a focus on institutional arrangements, broader scientific and industrial capabilities, and specific national commitments—reinforces the elicitation's finding that technological changes to reactor designs are insufficient to significantly affect overall proliferation resistance. This also aligns with the experts' general agreement that the scenarios that significantly altered the spread of reprocessing and enrichment technologies (including the scenario that included fast reactors and those that included multinational fuel cycle and production facilities) and affected the process of safeguarding fuel cycle facilities were most likely to increase or decrease proliferation resistance.

We gained additional confidence that our scenarios provided sufficient information during the pilot elicitation. During the pilot elicitation, we also asked participants to use an ordinal scale (from 1 to 5) to specify the degree that one scenario was more or less proliferation resistant than the other and on the certainty with which they held their judgements. The three pilot participants willingly engaged in this exercise, giving us confidence in their ability to differentiate between the scenarios. When we employed this scale in the final elicitation, only some of the experts chose to quantify the degree of relative proliferation resistance of one scenario to another. Thus, we only compare the more general judgements of the experts in this paper.

We also note that two experts did not complete the protocol. One (expert 1) judged that there is insufficient uranium for the expansion assumed in the scenarios. The other (expert 3) wanted us to include more reactor designs, which the expert viewed as favorable. In principle, we could have extended our scenarios. However, all elicitations must make trade-offs on the scope of the proposed investigation. While we take these objections seriously, our results suggest that these trade-offs did not affect the overall findings.

6. CONCLUSION

The respondents who participated in this expert elicitation do not generally judge SMR expansion scenarios to be more proliferation resistant than those that rely exclusively on LWRs, but they do judge both the SMR and LWR scenarios to be more proliferation resistant than the fast reactor scenario. They also see the potential to increase the proliferation resistance of future nuclear energy systems, regardless of what reactor technologies are deployed, by incorporating multinational production facilities into the fuel cycle.

Several potential characteristics of SMR designs—the long-lived core, the lack of on-site fresh fuel, the lack of a requirement for reprocessing fuel—were consistently mentioned as potentially enhancing proliferation resistance. SMR designs are at a relatively early stage of development, with projected timelines of readiness for deployment ranging from the present to 2025–2030.[29] At some point, choices will have to be made as to which designs are worthy of the private and/or public development that will be necessary to bring the most promising ones to market. This study provides guidance into some of the important features—e.g. fuel, design, storage plans—that technicians and policy makers should consider when assessing the potential proliferation impact of SMR deployment. This study's findings also reinforce the general notion that while it is possible for a nuclear facility or a nuclear system to be made more proliferation resistant, it is not possible to make it entirely resistant to proliferation.

Our results do not suggest that the experts found the barriers present in the LWR or SMR scenarios (including the baseline scenario) as sufficient. In evaluating the present day nuclear system, the experts did express concern about multiple existing pathways to proliferation within current arrangements of reactors and fuel cycle facilities. Importantly, multiple experts specifically suggested that an uneven application of international safeguards in the five initial scenarios as lowering barriers to increased weapons capabilities in existing nuclear weapons states.

While the experts generally accepted the safeguards arrangements presented in each scenario, some questioned whether there would be adequate financial and material resources to safeguard the reactors and fuel cycle facilities that were part of the SMR scenarios. Indeed, this was a concern for all of the scenarios. As such, the ease of safeguarding facilities should be prioritized when designing and developing reactors and fuel cycle facilities, and steps should be taken to decrease the likely costs and workforce requirements of applying and maintaining safeguards within these systems. Similarly, the use of multinational fuel cycle facilities could limit the global number of these facilities, including enrichment and reprocessing facilities; potential points of diversion; and the spread of technical know-how. They could also provide greater transparency between countries, and ease the process of safeguarding fuel cycle facilities—both of which could increase the detectability of diversion.

This study does not examine whether deploying SMRs on a large scale would be more or less likely to be coupled with multinational fuel cycle facilities or services than a nuclear energy system that relies primarily on LWRs. Yet there has been discussion about the potential for off-site, assembly-line construction of SMRs to contribute to economic and proliferation advantages, and it is conceivable that such a set-up could more easily be paired with multinational nuclear fuel cycle facilities than large on-site LWR construction projects.(11, 30)

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Table II. Potential future global nuclear energy systems

	Scenario Z	**Scenario A**	**Scenario B***	**Scenario C**	**Scenario D***
Nuclear generating capacity (GWe)	370	507	1,023	1,053	985
Annual nuclear production (BkWh)	2,351	4,000	8,000	8,000	8,000
No. of reactors	430 LWRs	500 LWRs	1,000 LWRs	Approximately 500 1-GWe LWRs and 800 880-MWe FRs.	Approximately 500 1-GWe LWRs and 4,700 100-MWe SMRs.
Fuel requirements	7,000 tonnes of LEU annually	12,000 tonnes of LEU annually	24,000 tonnes of LEU annually	12,000 tonnes of LEU annually; 7,650 tonnes of MOX; depleted uranium for FR blanket.	12,000 tonnes of LEU annually; 6,370 tonnes of cermet fuel
Global distribution of generating capacity	Most nuclear generating capacity is in U.S., Canada, Europe, Russia, South Korea, and Japan. In total, approximately 30 countries have power reactors.	A lower capacity than present in “legacy” countries; a larger capacity than present in Asia. In general, global distribution will remain concentrated in countries with current nuclear capacity.	A higher capacity in all countries, particularly in markets in Asia, including China, India, and South Korea, etc. Approximately 20 states that don’t currently operate power reactors will begin to do so under this scenario.	FRs would be developed in markets in Asia (particularly China and India), while LWRs would be located in other “legacy” countries and in new entrants.	LWRs would be concentrated in “legacy” countries, while SMRs would be distributed within countries with little or no existing nuclear infrastructure.
Fuel cycle facilities	9 countries (China, France, Germany, Japan, Netherlands, Pakistan, Russia, UK, US) house 14 commercial uranium enrichment facilities, all but one of which employs uranium centrifuges. 14 countries house 21 LWR fuel fabrication facilities.	Some new fuel cycle facilities (including enrichment and fuel fabrication facilities) will be built in China, South Korea, and India to support regional generating capacity.	To meet demand for LEU fuel, fuel cycle facilities (including enrichment and fuel fabrication facilities) will be added in China, Korea, India, and in some non-nuclear weapon states that don’t currently have these types of facilities (e.g., Taiwan, Australia, Mexico, South Africa, Indonesia).	Countries with FRs would have to expand fuel cycle capacities (to include reprocessing facilities) to meet demand. Some new fuel cycle facilities (including enrichment and fuel fabrication facilities) will be built in China, South Korea, and India to support expanded regional generating capacity.	To meet demand for LEU fuel, fuel cycle facilities (including conversion, enrichment, and fuel fabrication facilities) will be added in China, Korea, India, and in some non-nuclear weapon states that don’t currently have these types of facilities (e.g., Taiwan, Australia, Mexico, South Africa, Indonesia).
Back-end plans	4 countries house 6 commercial-scale operational spent fuel reprocessing facilities. Limited reprocessing of LWR fuel and use of MOX	There will be limited reprocessing of LWR fuel and use of MOX globally. States engaged in these activities will include nuclear weapons states and Japan.	There will be limited reprocessing of LWR fuel and use of MOX globally. States engaged in these activities will include nuclear weapons states and Japan.	There will be significant reprocessing of LWR and FR spent fuel and use of MOX, including in markets that don’t currently have commercial-scale reprocessing facilities.	There will be limited reprocessing of LWR fuel and use of MOX globally. States engaged in these activities to include current nuclear weapons states and Japan.
	All reactors and fuel cycle facilities in NPT non-nuclear	All reactors and fuel cycle facilities in NPT non-nuclear	All reactors and fuel cycle facilities in NPT non-nuclear	All reactors and fuel cycle facilities in NPT non-nuclear	All reactors and fuel cycle facilities in NPT non-nuclear

	weapon states are subject to international safeguards. Power reactors and fuel cycle facilities in weapons states are only subject to national safeguards.	weapon states are subject to international safeguards. Power reactors and fuel cycle facilities in weapons states are only subject to national safeguards.	weapon states are subject to international safeguards. Power reactors and fuel cycle facilities in weapons states are only subject to national safeguards.	weapon states are subject to international safeguards. Power reactors and fuel cycle facilities in weapons states are only subject to national safeguards.	weapon states are subject to international safeguards. Power reactors and fuel cycle facilities in weapons states are only subject to national safeguards.

*The elicitation protocol included variations of scenarios B and D, referred to as scenarios B+ and D+, in which states would rely significantly on multi-national fuel cycle facilities to supply fresh fuel and other fuel services to their nuclear reactors.

Table I: Reactor types[*]

	Representative LWR	Representative FR[**]	Illustrative SMR
Electric output	1090 MWe	864 MWe	100 MWe
Fuel type	UO_2 core	PuO_2/depleted UO_2 (core/blanket)	UO_2 Cermet
Fresh fuel composition	4.5% U^{235}, 95.5% U^{238}	93% Pu^{239}, 0.01% U^{235}, 7% U^{238} (core); 0.2% U^{235}, 99.8% U^{238} (blanket)	12% and 14% U^{235}
Number of fuel assemblies	157	229	4 fuel zones in which fuel spheres circulate in a sealed core.
Full load operation between refueling periods	18 months	140 days (~4.5 months)	18+ years
Maximum average burnup	65 GWd/tHM	56.1 GWd/tHM (core); core breeding ratio of .73	80 GWd/tHM
Spent fuel composition	.3% U^{235}, 91% U^{238}, .5% PU^{239}, and other actinides	84.6% Pu^{239}, 14.2 % Pu^{240}, .96% Pu^{241} (core); 2% Pu^{239} (blanket)	10.6% U^{235}; 8.6% Pu^{239}
Onsite fresh fuel storage?	Yes	Yes	No
Onsite spent fuel storage (pool or cask)?	Yes	Yes	No
Estimated capacity factor	90%	80%	95%
Front-end fuel cycle requirements	Uranium mining, milling, conversion, enrichment and traditional fuel fabrication	UO_2 and MOX fuel fabrication	Uranium mining, milling, conversion, enrichment and cermet fuel fabrication
Does this reactor require spent fuel reprocessing?	No	Yes	No

*Most reactor information is drawn from design specifications. **Fuel calculations for this reactor assume that its fresh fuel incorporates weapon-grade plutonium. Key – LWR:light water reactor; FR:fast reactor; SMR:small modular reactor; MWe: megawatt-electric; GWd/tHM: gigawatt-days/metric ton of heavy metal; U:uranium; Pu:plutonium; MOX:mixed-oxide

Table IV. Selected results of pairwise comparisons of scenarios

	Type of barrier	Expert 1	2	3	4	5	6	7	8	9
Is scenario Z more or less proliferation resistant than scenario A?	Material	MORE	EQUAL	MORE	EQUAL	EQUAL	EQUAL	MORE	EQUAL	EQUAL
	Technical	EQUAL	EQUAL	MORE	EQUAL	EQUAL	MORE	EQUAL	EQUAL	EQUAL
	Institutional	LESS	EQUAL	EQUAL	EQUAL	EQUAL	EQUAL	EQUAL	EQUAL	EQUAL
	All barriers	MORE	EQUAL	MORE	EQUAL	EQUAL	MORE	MORE	EQUAL	EQUAL
Is scenario Z more or less proliferation resistant than scenario D?	Material	NA	EQUAL	NA	EQUAL	EQUAL	LESS	MORE	EQUAL	MORE
	Technical	NA	EQUAL	NA	EQUAL	EQUAL	MORE	EQUAL	EQUAL	MORE
	Institutional	NA	EQUAL	NA	EQUAL	EQUAL	LESS	EQUAL	EQUAL	EQUAL
	All barriers	NA	EQUAL	NA	EQUAL	EQUAL	LESS	MORE	EQUAL	MORE
Is scenario C more or less proliferation resistant than scenario D?	Material	NA	EQUAL	NA	LESS	EQUAL	LESS	LESS	LESS	LESS
	Technical	NA	EQUAL	NA	LESS	EQUAL	LESS	LESS	LESS	LESS
	Institutional	NA	EQUAL	NA	EQUAL	EQUAL	LESS	LESS	LESS	EQUAL
	All barriers	NA	EQUAL	NA	LESS	EQUAL	LESS	LESS	LESS	LESS
Is scenario D more or less proliferation resistant than scenario D+?	Material	NA	EQUAL	NA	EQUAL	EQUAL	EQUAL	LESS	EQUAL	EQUAL
	Technical	NA	EQUAL	NA	EQUAL	EQUAL	LESS	LESS	EQUAL	EQUAL
	Institutional	NA	LESS	NA	LESS	EQUAL	LESS	LESS	EQUAL	LESS
	All barriers	NA	LESS	NA	LESS	EQUAL	LESS	LESS	EQUAL	LESS

NA = No answer.

Table III. Respondent rankings of potential pathways of state-level diversion (1=most likely, 7=least likely)[1]

EXPERT	1	2	3	4	5	6	7*	8	9
Diversion of natural uranium from a refinement or conversion plant.	7	NA	7	7	7	7	High	7	7
Misuse of declared enrichment plant.	1	NA	6	2	3	5	Low	4	2
Use of undeclared enrichment plant.	6	NA	2	5	2	3	High	2	1
Misuse of fuel fabrication plant for production of undeclared materials for irradiation.	4	NA	5	4	5	6	Low	3	6
Misuse of reactor for production of undeclared nuclear material.	5	NA	3	6	1	1	Low	5	5
Concealed reprocessing of spent nuclear fuel.	2	NA	1	1	4	4	High	1	4
Diversion of materials resulting from reprocessing (e.g. plutonium or U233) from storage facilities prior to fuel fabrication.	3	NA	4	3	6	2	Med	6	3

NA = No answer.

*Expert 7 did not want to rank the potential diversion pathways but did assign a general probability to each pathway.

[1] This list of potential diversion pathways was drawn from the IAEA, "Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems," a volume from the final report of phase 1 of INPRO, November 2008. As part of this ranking process, respondents were asked to identify other potential pathways of note. The only addition to the above list was the possibility of using a research reactor as a radiation source to manufacture weapons-usable materials.

Table V. Participating experts

Affiliation	Years working on nuclear energy	Years working on nuclear nonproliferation	Highest level of education	Age
Sandia National Laboratories	44	10	MA Physics	65
Chinese Institute for Atomic Energy	13	0	PhD Nuclear Physics	48
Japanese Atomic Energy Agency	35	35	PhD Radio Chemistry	59
Oak Ridge National Laboratory	21	5	MA Reactor Physics	45
Korea Institute of Nuclear Nonproliferation and Control	13	8	PhD Nuclear Engineering	42
Institute for Physics and Power Engineering	50	30	PhD Nuclear Technology	72
Electronuclear	28	28	PhD Engineering	54
Nuclear Regulatory Commission	30	30	PhD	59
Independent Consultant	33	10	MA Physics	67