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STRENGTHENING IAEA SAFEGUARDS FOR RESEARCH REACTORS

September 2016

Bruce Reid
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U.S. DEPARTMENT OF ENERGY

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Summary

During their December 10-11, 2013, workshop in Grenoble France, which focused on the history and future of safeguarding research reactors, the United States, France and the United Kingdom (UK) agreed to conduct a joint study exploring ways to strengthen the IAEA's safeguards approach for declared research reactors. This decision was prompted by concerns about: 1) historical cases of non-compliance involving misuse (including the use of non-nuclear materials for production of neutron generators for weapons) and diversion that were discovered, in many cases, long after the violations took place and as part of broader pattern of undeclared activities in half a dozen countries; 2) the fact that, under the Safeguards Criteria, the IAEA inspects some reactors (e.g., those with power levels under 25 MWt) less than once per year; 3) the long-standing precedent of States using heavy water research reactors (HWRR) to produce plutonium for weapons programs; 4) the use of HEU fuel in some research reactors; and 5) various technical characteristics common to some types of research reactors that could provide an opportunity for potential proliferators to misuse the facility or divert material with low probability of detection by the IAEA. In some research reactors, for example, such characteristics include rapid on-line refueling, and a core design with room for such a large number of assemblies or targets that it is difficult to detect diversion or undeclared irradiation. In addition, infrastructure associated with research reactors, such as hot cells, where plutonium could be separated, could pose a safeguards challenge because, in some cases, they are not declared (because they are not located in the facility or because nuclear materials are not foreseen to be processed inside) and may not be accessible to inspectors in States without an Additional Protocol in force.

Research reactors by their nature have many irradiation locations where undeclared target materials could be irradiated. These locations may be frequently in use and therefore cannot be sealed by the IAEA with tamper indicating devices (TID). Some of these paths provide potential proliferators with easy access for the irradiation of target materials for both the development of fissile material (plutonium, ^{233}U) production, separations, technology development and training. Research reactors, by design and routine legitimate usage, may be operated in a variable manner, making IAEA monitoring of declared operations very difficult. In addition, research reactors may provide the host state with some level of justification for having hot cell facilities capable of reprocessing spent fuel, or of conducting laboratory-scale research and development activities that could advance a non-civilian or undeclared reprocessing program.

To strengthen the effectiveness of safeguards at the State level, this paper advocates that the IAEA consider ways to focus additional attention and broaden its safeguards toolbox for research reactors. This increase in focus on the research reactors could begin with the recognition that the research reactor (of any size) could be a common path element on a large number of technically plausible pathways that must be considered when performing acquisition pathway analysis (APA) for developing a State Level Approach (SLA) and Annual Implementation Plan (AIP). This early recognition of the importance of research reactors in this process will go a long way toward applying the appropriate level of safeguards attention and intensity to the challenge posed by research reactors misuse or diversion of irradiated fuels.

To broaden the IAEA safeguards toolbox, the study recommends that the Agency consider closing potential gaps in safeguards coverage by, among other things: 1) adapting its safeguards measures based on a case-by-case assessment; 2) using more frequent and expanded/enhanced mailbox declarations (ideally with remote transmission of the data to IAEA Headquarters in Vienna) coupled with short-notice or unannounced inspections; 3) putting more emphasis on the collection and analysis of environmental samples at hot cells and waste storage tanks; 4) taking Safeguards by Design into account for the construction of new research reactors and best practices for existing research reactors; 5) utilizing fully all legal authorities to enhance inspection access (including a strengthened and continuing DIV process); and 6) utilizing new approaches to improve auditing activities, verify reactor operating data history, and track/monitor the movement and storage of spent fuel.

Contents

1.0 INTRODUCTION

The objective of this paper is, in cases where the International Atomic Energy Agency (IAEA) concludes that increased attention should be given to safeguarding declared research reactors, to make recommendations and propose measures that would strengthen the effectiveness and improve the efficiency of IAEA safeguards at such facilities, while keeping in mind that undue burden should not be imposed to the operators.

Specific safeguards concerns for research reactors fall into two main categories: (1) detecting the diversion of the declared fuel (fresh and irradiated); and (2) detecting any undeclared irradiation, either of fertile targets (to produce special fissionable material) or of other materials, which when irradiated, could be of significance for proliferation. A third category reflects the importance of understanding the full breadth of activities at research reactors. Research Reactor sites conduct a wide range of scientific and fuel cycle related activities and training, and they can provide a unique insight into a State’s broader nuclear program. This insight should be utilized as part of the State evaluation process and when developing the annual State Level implementation plan.

Under the Safeguards Criteria, which were developed in the late 1980s, the IAEA has focused its research-reactor-related efforts on detecting diversion of declared material or irradiation of undeclared targets at research reactors with higher power levels [i.e., those reactors with more than 25Mwt]. The optimization of safeguards implementation through the development of State Level Approaches (SLA) allows the Agency, among other things, to have the flexibility to adjust its safeguards efforts in each State, using acquisition pathway analysis, all safeguards-relevant information, and State Specific Factors (SSF). In particular, the Agency may consider whether it should in some cases put more emphasis on detecting misuse of smaller facilities (i.e., those reactors with less than 25MWt).

1.1 History of Misuse

During the last quarter of a century, six states have been reported to the UN Security Council (UNSC) for noncompliance with IAEA safeguards agreements – Iraq (1991), Romania (1992), the DPRK (1993), Libya (2004), Iran (2006), and Syria (2010). Many of these cases involved misuse of research reactors, including the irradiation of undeclared targets for undeclared laboratory-scale plutonium separation experiments. It should be noted that at the time of these safeguards violations the Additional Protocol (AP) either did not exist or the States in question did not have an AP in force. Although these States’ research reactor-related violations usually were not the main basis for reporting noncompliance, safeguards violations at research reactors have been a frequent feature of, and thus a potential warning sign of, undeclared nuclear programs that had a broader scope. This history suggests a need for IAEA inspectors to be alert for, and vigorously investigate, indications of safeguards violations at research reactors, associated hot cells, and laboratories. (See Appendix C for more details on history of misuse.)

1.2 IAEA Priorities and Effort Based on Safeguards Criteria

The IAEA applies safeguards to over 150 research reactors and critical assemblies (RRCA). Besides these reactors, there are more than 125 other RRCAs in operation in the United States, Russia, China, France, India, Israel and the DPRK. Of these, eight are operational heavy water research reactors (HWRR), with one other under construction in Iran.

The IAEA Safeguards Criteria for RRCAs are derived from an objective of detecting diversion (whether abrupt or protracted) of one significant quantity (1SQ) of direct-use material and/or the undeclared production within a single year of 1SQ of irradiated direct-use material. For these types of facilities, there are opportunities for improvements in both the effectiveness and efficiency of safeguards. However, experience has shown that smaller facilities, with lower power and lesser inventories of nuclear material, can also present proliferation challenges.

If the Safeguards Criteria alone continues to drive the IAEA's safeguards planning for safeguards approaches for research reactors, then there would be opportunities for a State, with limited risk of detection, to undertake weapons-related activities at research reactors and functionally-related locations or facilities, such as hot cells, accelerators, chemistry laboratories and machine shops, especially if the State did not have an AP in force.

A more flexible approach that uses acquisition pathway analysis, all safeguards-relevant information, and State Specific Factors allows the IAEA to prioritize the allocation of its limited resources while maintaining or strengthening safeguards effectiveness.

A revised, more flexible safeguards approach for research reactors would require a better understanding of the irradiation potential in various designs and the ability of a State to harness chemical reprocessing skills, facilities, and transport to process irradiated fuel or targets. Analysis of the reactor facility capabilities, outlined below, could help result in more flexible safeguards efforts with greater ability to detect misuse of declared research reactors. Improved understanding (both through open source investigations and host state declarations) of the research activities performed or planned at such sites can improve the overall understanding of the State's nuclear program.

1.3 Research Reactor Characteristics of Safeguards Relevance

1.3.1 Wide Variation in Design and Operation

There is a wide variation in the design and operation of research and test reactors. Facilities are often designed to support a range of research and development uses and operations, with the reactor serving as the centerpiece. The specific mission of the facility dictates how any functionally-related locations or facilities are arranged and integrated with the reactor, where material is stored and introduced into the specific facility, and the operational characteristics of the facility. For example, reactors that have high availability for operation pose increased safeguards challenges. The type of reactor and choice of moderator are also relevant safeguards characteristics. The large volume, when associated with a heavy water or graphite moderated reactor, provides space for a significant number of experimental facilities and increased flexibility. Light water moderated tank-type reactors typically have more compact cores, limiting the number of experimental facilities and flexibility when compared to the heavy water moderated reactor. Open pool reactor designs typically have fewer experimental facilities than tank-type reactors, but an open pool design allows for easy access to the reactor core and flexibility for handling large experiments and performing bulk irradiations. The open pool reactor designs are well suited for educational roles since access to the core for irradiation and shuffling of fuel is easier than in tank type reactors.

1.3.2 Type of Fuel

Most nuclear research reactors use low-enriched (LEU) or high-enriched uranium (HEU) fuel, but there are a limited number of research reactor designs that make use of natural uranium, thorium, or plutonium. Natural uranium fueled reactors must use either graphite or heavy water as moderator materials, and require rather large core configurations to achieve criticality. Research reactor fuel geometry may consist of plates, rods, tubes, or other forms. Fuel plates are typically used for reactors with a large specific power for the necessity of heat removal.

Research reactors that use HEU fuel are of particular safeguards concern due to the potential for direct weapons use of HEU recovered from diverted fresh or irradiated fuel. However, the diversion of LEU fresh fuel is still of concern, especially in states with an enrichment capability, because this uranium can be introduced into an enrichment facility. The enrichment of LEU to a weapons-usable level is much quicker than when starting from natural uranium.

Natural uranium and LEU fueled research reactors both offer the potential for diversion of spent fuel for plutonium separation. Natural uranium fueled reactors have historically been the reactor design of choice for plutonium production going back to the Manhattan Project. (In addition, if a potential proliferator has a research reactor that uses natural uranium fuel, then such a country does not require an indigenous uranium enrichment capability in order to produce its own fuel for the research reactor.) Therefore, safeguarding spent fuel discharged from a natural or low enriched uranium fueled reactor may require more safeguards effort than is currently the case.

The use of enriched uranium fuel provides the option to design a smaller core with an excess core reactivity that can be used to support target irradiation. The availability of significant core excess reactivity significantly increases the ability to support irradiation of larger quantities of target material. In a core using LEU fuel, the safeguards concerns are the undeclared irradiation and diversion of targets and the potential diversion of spent fuel elements. A natural uranium fueled core has little excess reactivity to support target irradiation therefore the diversion of the spent fuel itself is the greatest safeguards concern.

The specific fuel management scheme has safeguards relevance because a reactor that requires frequent refueling and has large numbers of discharged fuel elements may present greater opportunities for material diversion.

1.3.3 Reactor Power and Cooling Capacity

Plutonium production capability increases with reactor power since the higher the power the more neutrons are available for capture by U-238 that will decay into Pu-239. Therefore, the potential for unreported plutonium production capacity for a research reactor is strongly related to the reactor power level.[1]

Note that many reactors have designs with a high margin for safety, allowing them to operate at higher power levels than their respective ratings without a significant increase of the risk of an accident. As a result, States intent on maximizing plutonium production could operate such reactors at higher power levels than the official power rating. Operation at higher power levels requires correspondingly higher coolant flow rates and heat rejection capabilities. An understanding of the coolant flows and heat exchanger capability can provide insight into the potential for operation above name-plate power levels. Furthermore, many research reactors do not normally run in a production mode “around the clock.” Undetected reactor operation at power levels well above name-plate rating or for more hours per week than declared while falsely declaring the actual operating history offers the potential to generate an undeclared inventory of irradiated direct use material. Monitoring the power level of relatively high powered research reactors therefore should be a safeguards emphasis, to ensure that the operator’s declarations of power levels over time are accurate and correct and an upper bound on Pu production can be drawn.

1.3.4 Potential for Target Irradiation

Plutonium or ^{233}U production in either fuel or fertile targets requires power levels commensurate with the amount of plutonium or ^{233}U produced, and hence, significant fissile material production requires cooling. While reactor designs specifically provide for substantial coolant flow to fuel elements, many target locations in the core do not provide for significant cooling capability. In addition to adequate cooling capacity, production of fissile material in targets requires core space for the targets. Core or reflector locations with both the space and the cooling capacity to support fissile material production in targets are of particular safeguards relevance and have been a subject for analysis for LWRs[2] and RRCAs[3,4,5] for decades.

The irradiation of targets containing fertile materials requires excess core reactivity. Core designs with ample excess reactivity are more suitable for irradiation of significant quantities of target materials. The presence of targets will shorten the achievable refueling cycle length due to the impact on core excess reactivity that otherwise would have been used to overcome fuel depletion. Some core designs use burnable absorbers so that an increased fissile loading can be accommodated to support extended cycle lengths. Insertion of certain target materials, rather than burnable absorbers could be used to achieve the same objective.[6] Research reactor core designs that have a large amount of excess reactivity and use

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[1] V.N. Bragin et al: "Unreported Plutonium Production at Large Research Reactors." IAEA, STR - 300, June 1994; F. T, Binford, “Diversion Assumptions for High-Powered Research Reactors,” Oak Ridge National Laboratory Report ORNL-6022 (ISPO-201), January 1984.
[2] LU, M.S., ZHU, R.B., TODOSOW, M., “Unreported Plutonium Production in Light Water Reactors,” Rep. ISPO-282, Brookhaven National Laboratory, Upton, NY (1988).
[3] Jared S. Dreicer and Debra A. Rutherford, “Global Estimation Of Potential Unreported Plutonium in Thermal Research Reactors,” Proceedings of the 37th Annual Meeting of the Institute of Nuclear Materials Management, July 28-31, 1996, Naples, FL.
[4] T. F. Moriarty, and V. N. Bragin, "Unreported Plutonium Production At Large Research Reactors," Proceedings of the 35th Annual Meeting of the Institute of Nuclear Materials Management,, 1173-1178 (1994).
[5]IAEA, STR - 300, *op. cit*.
[6] The insertion of target materials for materials production, instead of the normal burnable absorbers, is only relevant if the target material behaves somewhat like a burnable absorber. If the target material and its high cross section capture products do not burn away during the course of the fuel cycle then it is simply an absorber that has an adverse impact on core reactivity over the entire

burnable absorbers for extended cycle life offer a greater capability for potential proliferators to irradiate target material for use in weapons programs.

1.3.5 Irradiated Fuel and Target Material Transfer Mechanisms

Plutonium recovery requires the movement of irradiated fuel or targets to shielded processing facilities (hot cells). Therefore, the transfer mechanisms for movement of this material have significant safeguards relevance. There are a limited number of ways to access either fuel or targets in research reactor cores. These access pathways out of the core may include transfer chutes, shielded casks, pneumatic transfer tubes, and fuel handling machines or tools. The monitoring of all possible material transfer pathways provides key safeguards relevant information. The transfer of irradiated materials from the core and irradiation locations requires tools and equipment to facilitate the material movement. Monitoring of the equipment and tools used to support irradiated material movement represents an opportunity to strengthen the safeguards approach for research reactors.

Likewise, the monitoring of irradiated material receipt at the end point location can be used to check the absence of diversion. Placement of irradiated materials in the hot cell installation's spent fuel storage can be monitored as can the introduction of irradiated materials in a hot cell facility. Hot cells have a limited number of access points by which irradiated materials can be introduced, which offer opportunities for monitoring visual or radiation signatures.

1.3.6 Presence of and Ease of Access to Hot Cells

Access to hot cells can help inspectors to assess their potential for use in extracting weapons-usable nuclear material from irradiated material produced in, or diverted from, a research reactor. The processing of irradiated materials requires hot cell operations. The separation of plutonium from either spent fuel or targets requires heavily shielded chemical separations processes. A collocated hot cell facility may facilitate more rapid separation and simplify transport of the irradiated material from the reactor to the hot cell, but it is possible that diverted materials could be transported significant distances to an off-site location for processing, which could facilitate concealment. Due to the integral role that hot cell operations would play in material production, these facilities have great safeguards relevance and merit increased attention. The Additional protocol (AP) takes this concern into account by requiring declaration of the scale of operations for the construction of hot cells and also providing Complementary Access mechanisms variously applicable to hot cells within reactor facilities, at sites of nuclear facilities, and elsewhere in the State.

Environmental sampling, especially at associated hot cells, can be a powerful tool for detecting the processing of diverted or clandestinely irradiated material. Unfortunately, in States without an AP in force, the IAEA may not have routine inspection access or DIV access if the hot cell installation is not declared to store or process nuclear material and if the hot cells are not within the reactor facility boundary as defined in the facility's Design Information Questionnaire (DIQ). Possible initiatives to improve access to hot cells are discussed in detail in Appendix A.

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life cycle. A burnable absorber typically has a large neutron cross section and is consumed over the cycle life so that at end of life the majority of the burnable absorber is gone. The most popular burnable absorber is boron. However, lithium, which can be used for tritium production, is also a very suitable burnable absorber (^{6}Li). Uranium however, is a poor burnable absorber, and will not serve to extend cycle life.

2.0 State Level Safeguards Objectives and Technical Objectives for CSA States

In a state with a Comprehensive Safeguards Agreement (CSA), to fulfill its obligations, the IAEA identifies and conducts safeguards activities in accordance with the following three State-level safeguards objectives:

A. To detect any undeclared nuclear material or activities in the State as a whole;

B. To detect any undeclared production or processing of nuclear material in declared facilities or locations outside facilities (LOFs) where nuclear material is customarily used;

C. To detect any diversion of declared nuclear material in declared facilities or LOFs.

Technical objectives are established for each State to address the State-level objectives. These technical objectives: 1) are derived from acquisition path analysis, (i.e., analysis of paths that a State could potentially use, from a technical point of view, to acquire nuclear material for a nuclear weapon or other nuclear explosive device); 2) are focused on detecting specific steps along all technically plausible acquisition paths; and 3) form the basis for identifying applicable safeguards measures in the State-level approach.

3.0 Plausible Acquisition/Misuse Pathways

As discussed briefly above, the IAEA's Department of Safeguards is further developing the planning, implementation, and evaluation of safeguards activities at the State level. The integration of all safeguards-relevant information collected and the State evaluation process conducted at IAEA headquarters will result in an SLA for all states. The SLA informs the development of Annual Implementation Plans (AIP) that describe the specific safeguards activities in a given year. The specific safeguards measures and the manner and intensity with which they are applied in an individual state will differ based on Acquisition Path Analysis (APA), which is used to identify and prioritize State Specific Technical Objectives, better use of all safeguards-relevant information, and use of State Specific Factors.

The objective of APA is to identify and assess all plausible routes by which the States could, from a technical point of view, acquire weapons-usable nuclear material. Acquisition paths could involve the diversion of declared nuclear material, the unreported production or processing of nuclear material at declared nuclear facilities, undeclared nuclear material and activities, or any combination of these.

Acquisition pathways that are the easiest and fastest to achieve, based on the State's past and present technical capabilities, would be of the highest safeguards significance. An assessment of the speed of an acquisition path could be determined in part by taking into account: the available amounts of different types of nuclear material; the throughput of existing nuclear facilities; the level of difficulty for the State to fill capability gaps; the ability to acquire necessary equipment and non-nuclear materials; and the number and difficulty of steps in a path.

Developing State level approaches in states with RRCAs requires examining the role of such facilities in the State's broader nuclear program. As part of the State evaluation process, the degree of congruity of the facility and its operations with other nuclear activities in the State will be assessed. The possible role of such a facility in a range of possible acquisition paths must also be considered as well as its role in developing new capabilities and training. This is conducted as part of a broader assessment of all plausible acquisition paths in the State.

In defining paths, the Agency must consider a range of possible facility misuse scenarios and the irradiation or processing of undeclared material, as well as the diversion of declared material. The paths must be defined at a level of detail sufficient to support the design of an effective safeguards system. They also demonstrate the interplay between declared and possible undeclared facilities in the state.

For the purposes of this paper, we consider the following subset of generic acquisition paths:

1. Diversion of 1SQ of fresh HEU fuel (abrupt or protracted) with conversion to metal at an undeclared facility not on a declared site.
2. Diversion of 1SQ of irradiated HEU fuel (abrupt or protracted), HEU recovery at a hot cell on-site, and conversion to metal at an undeclared facility not on a declared site.
3. Diversion of 1SQ of irradiated HEU fuel (abrupt or protracted), HEU recovery at an undeclared hot cell off-site, and conversion to metal at an undeclared facility not on a declared site.
4. Uranium (from undeclared natural or depleted U) or thorium target fabrication at an undeclared site, undeclared irradiation at declared RRCA (>25MW), Pu recovery at a hot cell on-site, and conversion to metal at an undeclared facility not on a declared site.

5. Uranium (from undeclared natural or depleted U) or thorium target fabrication at an undeclared site, undeclared irradiation at declared RRCA (>25MW), Pu recovery at an undeclared hot cell off-site, and conversion to metal at an undeclared facility not on a declared site.

For safeguards purposes, an acquisition path terminates at the production of separated metallic fissile material, Pu or HEU. Each of these paths would, by necessity, require further steps in order to produce a nuclear explosive device. As noted previously, possible activities of interest include, *inter alia*, the production of neutron sources. Such activities could be performed at a RRCA site and should factor into inspection plans.

The acquisition paths above include a specification for the location of undeclared activities/facilities. Such undeclared activities could occur at either a declared or undeclared site or facility. As IAEA access rights differ from facility to facility and for undeclared activities and facilities, understanding the effectiveness of safeguards measures available to the Secretariat for each scenario is important. Acquisition path analysis helps focus the inspector's attention on the range of possibilities available to a potential proliferator, and thus provides the Secretariat with the opportunity to address plausible paths using an array of detection strategies.

Clearly, the small set of paths listed above cover only a limited number of possible RRCA designs and possible proliferation scenarios. Specific facility designs and operations will drive the definition of paths on a case by case basis. The plausibility of undeclared production depends on the power level and other technical characteristics (e.g., excess reactivity, cooling capabilities) of a specific facility. A comprehensive acquisition path analysis would also require greater detail including a specification of the mode of operation and location when proliferation activities occur (e.g., the schedule for insertion and removal of targets into the core or reflector area) as well as the quantities of material involved (e.g., either abrupt or protracted diversion). In developing a safeguards approach for the RRCA, a range of measures must be considered to address a range of plausible proliferation scenarios.

While the Agency has been aware of and focused on covering diversion and misuse at RRCAs for some time, the implementation of State Level Approaches, which put greater emphasis on the State as whole, provides the IAEA with an opportunity to leverage all relevant information to guide safeguards implementation and increase its understanding of the entirety of a State's nuclear program. The scope of inspections at RRCAs could change accordingly.

Given the historic challenges faced by the Secretariat in safeguarding RRCA, a wider array of acquisition paths should be considered. While of perhaps lower priority, scenarios involving smaller quantities of material and implemented over longer time periods should not be entirely ignored. The most attractive paths should receive greatest safeguards attention without leaving any plausible path uncovered to ensure adequate deterrence. While misuse has not been considered plausible for reactors with power levels below 25MW (see paths 4 and 5 above) and existing safeguards approaches at RRCAs have not addressed protracted misuse scenarios, past cases suggest this possibility should be taken into account (though requirements for timely detection could be relatively relaxed). With limited resources available, the Agency will need to analyze all safeguards relevant information to determine which research reactors and associated acquisition paths are priorities in terms of in-field safeguards effort.

In planning annual implementation activities, paths are examined individually and collectively to determine effective and efficient safeguards approaches. In examining the paths above, undeclared conversion facilities are difficult to detect (particularly since they often produce only small batches at a time), requiring continued emphasis on the technical objective of verification of un-irradiated HEU fuel (see path 1). The technical objectives of detecting the diversion of irradiated fuel assuming a variety of possible schedules will be important (see paths 2 and 3). A spectrum of safeguards measures will be needed to address these concerns. For example, it will be important for inspectors to have unannounced access to look for undeclared targets or other inconsistencies between declared and actual operations. Access to declared hot cells for environmental sampling will also provide important detection opportunities (as in path 4). Robust technical objectives for detecting RRCA misuse (of the type described in path 5) will be necessary, particularly in states where off-site detection opportunities are more limited.

The Agency must perform a State evaluation on all states that have safeguards agreements in force. For states with only a CSA in force the Agency has a more limited ability to understand and gain confidence regarding the totality of its nuclear program. This can necessitate a different focus and intensity at declared facilities such as RRCAs. For example, without confidence in the absence of undeclared reprocessing facilities (or target production for that matter), more safeguards emphasis must be placed on possible undeclared production. Searching for a wider array of indicators of undeclared irradiation at a declared research reactor can be a surrogate for measures aimed at detecting undeclared reprocessing.

Information regarding the research and experimental activities at RRCAs can play an important role in assessing a nuclear program as well. Such research and experimental activities at RRCAs could play an important education or training role in a proliferator's weapons program, and experimental or lab scale results could support the construction and operation of clandestine facilities. For purposes of both path coverage and state evaluation, on-site observations of experimental activities, along with access to log books, during safeguards inspections at RRCAs are important. Depending on the results, such observations could provide early indicators of concern and influence path priorities in future AIPs.

It should be noted that these proposals are not a panacea. One can envision that future proliferators would be aware of evolving Agency interests along these lines and will take countermeasures. In many cases they can simply declare the R&D activities. Similarly, some weaponization work has dual use applications and would not be prohibited but should likely receive increased attention from the IAEA.

4.0 Current Standard Safeguards Measures/Approaches for Research Reactors

The IAEA plans its safeguards in States with a CSA and no AP to fulfill the three state level safeguards objectives described in section IV. As detection of undeclared research reactors and functionally-related locations are beyond the scope of this paper, the paper focuses instead on safeguards measures to detect misuse of declared facilities and diversion of declared nuclear material (i.e., State-level objectives B and C).

Although the detailed elements of safeguards approaches vary for different types of research reactors based on their design (power level, fuel, etc.) and operation, specific objectives for safeguards at such declared reactors include detecting the diversion of the declared fuel and detecting any undeclared irradiation, either of fertile targets (to produce fissile material) or of other materials that when irradiated could be of significance for proliferation.

4.1 Current IAEA On-Site Inspection Measures for Research Reactors

In order to fulfill State-level objectives B and C (above) for declared research reactor facilities, the IAEA has utilized standard safeguards measures, including containment and surveillance (C/S), and design information verification (DIV), interim inventory verification (IIV), physical inventory verification (PIV), non-destructive assay (NDA) measurements on fresh, in-core, and spent fuel, and environmental sampling. These measures, discussed in more detail below, are specified in the Facility Attachment that is agreed by the IAEA and the State.

- <u>Examination of the State's records and reports:</u> To verify operators' declarations, the Agency verifies declarations of the uranium mass and U235 enrichment, serial number, and location of fresh fuel elements, the facility records of refueling activities and fuel movements, spent fuel storage locations, and shipment and receipts of nuclear material, examines facility operating records, assesses the operator's nuclear material measurement systems and related uncertainties, and conducts the inspections necessary in order to perform all of the above activities.
- <u>Physical inventory verification (PIV) and interim inventory verification (IIV):</u> As part of its verification of nuclear material accountancy, the IAEA conducts an annual PIV to verify that reports are consistent with records, verify the location, identity, quantity, and composition of all nuclear material. PIV inspections of the reactor should coincide with the refueling when possible. However, many research reactors can and must refuel more often that annually, while others do not need to refuel for years. In some cases, research reactor operators will take spent fuel and reuse it in a core. Depending on the types and quantities of nuclear material present at a research reactor facility, the IAEA also may conduct interim inventory verification (IIV) inspections to achieve timeliness goals and to verify nuclear material receipts and shipments. Attaching, removing, replacing, and verifying seals, evaluating surveillance data, and servicing surveillance equipment also take place during PIV and IIV inspections. Larger research reactors may have thermal power monitors attached to verify that the power is as declared by the State and hence that there is limited potential for unreported fissile material production.

- Design Information Verification (DIV): To confirm that the construction and operation of the reactor facility is in accordance with the design information provided to the IAEA, the IAEA conducts DIV. Design information must be updated and verified whenever the facility is modified in ways that have safeguards implications. (Examples include increases in thermal power or heat removal capabilities, changes in the fuel design, e.g., conversion from HEU to LEU, significant changes to target irradiation zones, or changes to operations including spent fuel storage and fuel transfer paths).
- Containment and Surveillance (C/S) measures: At most research reactors C/S measures are limited to sealing of fresh fuel and instruments and cabinets such as the thermal power monitor. To ensure continuity of knowledge between inventory verifications and for shipments between facilities as well as to detect undeclared removal of or tampering with fuel elements, the IAEA uses tamper-indicating seals on material, equipment and reactor areas. Seals may be used, for example on fresh fuel areas and fuel transport containers, sealed reactor cores (where applicable), containment penetrations, fuel transfer channels, and spent fuel inspection ponds. In addition, surveillance of the irradiated fuel pathway and storage may use cameras, reactor power monitors, and radiation detectors (both neutron and gamma). Such measures may also be used to monitor the fresh and spent fuel pools, the reactor hall, core activities, and the entrance and access points to the reactor and fuel storage areas. The surveillance equipment itself is also sealed to detect any tampering. Research reactors by their nature have many beam paths (thus access ports) that are constantly in use and therefore cannot be sealed with tamper indicating devices (TID).
- Environmental Sampling: One of the key tools that IAEA has for safeguarding research reactors is the collection and analysis of environmental samples from hot cells associated with such reactors. (IAEA authority to collect and analyze environmental samples during inspections is discussed in detail in Appendix A. In general obtaining environmental samples is possible at locations to which inspectors have access.)

5.0 Candidate Safeguards Measures to Strengthen IAEA Detection Capabilities

5.1 Introduction and Problem Definition

This section will discuss potential methods and technologies to strengthen safeguards measures to detect: 1) diversion of nuclear material, 2) undeclared irradiation of nuclear material, 3) undeclared irradiation of non-nuclear material targets to produce materials in support of nuclear weapon-related activities, and 4) undeclared processing of irradiated nuclear material.

To detect and deter RRCA misuse, three categories of safeguards measures have been identified and are discussed in more detail below. The first is monitoring fuel throughout its time on site, from arrival of fresh fuel through irradiation and then storage or shipment of spent fuel. A second category involves means to authenticate and verify that a reactor was operated as declared. The third category involves implementing safeguards on associated facilities such as hot cells and analytical laboratories.

In addition to those potential enhancements the Agency could consider requiring frequent declaration of relevant activities via a mailbox, conducting additional unannounced or short notice interim inspections and more frequent and thorough physical inventory verifications (PIVs), along with more frequent updating and verification of design information. To support IAEA efforts regarding more frequent updating and verification of design information, it is essential that States provide more complete and updated Design Information Questionnaires (DIQs) than are often received. The safeguards importance of more frequent inventory verification and design information verification would be informed by the results of State evaluation and acquisition path analysis.

New measures and technologies to strengthen safeguards for research reactors are explored in more detail below. The IAEA would need to tailor its selection of safeguards measures to different circumstances, taking into account varying design, operational practices, and other factors.

5.2 Fuel Monitoring

An important concept in reactor safeguards is keeping track of the fuel as long as it is on site (continuity of knowledge), from fresh fuel arrivals to spent fuel put in storage casks and possibly shipped offsite. This is the most straightforward of the safeguards approaches because it is easier to maintain continuity of knowledge for large items than to detect misuse or undeclared processes. Much is currently being done to safeguard fuel inventories through tags, seals, and counting of fuel items, but additional measures could be taken. There are only a limited number of access points by which fresh fuel can be brought onto the reactor site and introduced into the core. These entrances could be monitored by cameras, unattended verification systems (neutron and/or gamma ray detectors), or unattended sensors that trigger video surveillance. Radiation measurements are preferable to simple item counting as a means to rule out possible substitution of fresh fuel with dummy fuel. Unattended sensors provide a practical means to assess every fuel assembly.

Specifically monitoring and verifying the fuel and targets moving in and out of the reactor itself is an important aspect of overall research reactor safeguards. More generally, monitoring and verifying fuel and target movement throughout the site is important. Therefore, fuel handling machines that move fuel around sites, in and out of reactors, and in and out of the spent fuel pools should in some cases be a key target of safeguards. This could be done with seals on the machines, unattended verification systems using radiation detectors, cameras, or a combination of those. Additionally, the contents of the spent fuel pool can be verified using video surveillance, seals on each assembly, and tools such as the spent fuel attribute tester (SFAT) specially designed for low burnup fuel typical of most RRCA spent fuel and is inserted into the spent fuel pool and take radiation measurements to characterize the contents of the assemblies.

Verification of fuel assembly inventories by counting and by matching serial numbers forms the basis of traditional safeguards on these items. While tags and seals are being used on spent fuel casks for safeguards, additional measures could also be taken to verify transport container contents and to detect diversion. An additional measure that could be implemented is environmental sampling of the outside of spent fuel casks or other containers. There may be other specific locations at the reactor site that represent promising locations for environmental sampling. Multiple projects at U.S. national laboratories and other member state research institutions have developed radiation detection capabilities to determine the contents of spent fuel casks while leaving them in placed unopened. These technologies are at various stages of completion, up to the field trial stage, but none have yet been fully implemented.

Finally, enhanced monitoring of spent fuel casks could be encouraged as a standard industry practice for diversion detection. Currently casks are physically counted during only some inspections, and a subset of seals and tags are randomly checked. Cask monitoring could be enhanced in some States (where it is not the current practice) by establishing and maintaining a registry of casks and using unique identifiers on them such as bar codes or radio-frequency identification tags (RFIDs) that are both authenticable and tamper resistant/tamper indicating.

5.3 Authentication of Declared Reactor Use

Keeping track of research reactor fuel throughout its lifetime is an important safeguards activity, but there are other potential new safeguards methods that could be implemented at research reactors. Authentication of the declared use of reactors has high safeguards value. A good first step toward this end would be to require that operators declare operations, including fuel operations and fuel management strategy, and those related to target irradiation and isotope production, with mailbox declarations as is done in the UF_6 industry. While examination of reactor operating records already is part of traditional safeguards, using the mailbox system would be more formal, more secure, and more comprehensive, and prevent falsification of records after the fact. The operator could input the above information, as well as information about fuel movement into an IAEA-owned system that only the IAEA can access. The input terminal and cables transferring the data could be sealed and monitored with video surveillance. The data could be stored on an IAEA hard drive in a closed, sealed, and video monitored room on site, or transmitted back to Vienna. These mailbox declarations of operations and material (both fuel and target) positions (both in and outside of the reactor core), could be authenticated through monitoring or auditing via regular and frequent, unannounced inspections and audits. The evolution of safeguards mailbox technology has progressed to the point where the operator can effectively submit a log report (similar to the operator’s shift logbook) on a daily basis, declaring the next days planned operations and declaring the previous day’s actual operations. The automatic transmission of these declarations (in encrypted and authenticated form) to IAEA headquarters in Vienna could be envisaged, subject to prior agreement with the State concerned. The IAEA can then determine the need for actual on the ground inspection activities. Even if full authentication was not possible, frequent mailbox declarations would contribute to the safeguards mosaic of relevant information available as part of an SLA.

There are technical means that can be employed for determining whether fuel burnup (including its spatial profile) is consistent with reported operations. This information can serve to authenticate declared reactor use. Means for accomplishing this include both thermal-hydraulic and neutronic methods. In the thermal-hydraulic method, reactor power is inferred from measurement of the amount of heat removal during reactor operations. This approach is currently utilized, for safeguards purposes, at a limited number of high power research reactors by using (independent IAEA equipment) thermocouples and acoustic flow rate meters to measure temperatures and cooling flow. Measuring temperatures and flow rates has been done with some success in the past, but the capability and practicality of such systems could be improved with additional investment. The Agency should consider extending power monitoring to lower power research reactors than now is the case. Monitoring research reactor operations using commercial overhead imagery could be used to evaluate consistency with declared reactor design or operations in high-priority cases, but it would be expensive, and its value may be limited to determining whether the reactor is at power or in shutdown at the times and dates when it is imaged.

Several novel tools for neutronic verification of reactor power history have been utilized or are currently being developed. These techniques include the strategic placement into the core of flux wires or coupons made of materials such as hafnium. These flux wires or coupons would provide a neutron "odometer" such that total fluence (cumulative neutron flux) can be determined upon examination after irradiation. The advantage of the wire is that if it extends throughout the entire length of the core, the average axial flux profile could be determined. Inserting the wires in multiple radial locations in the core would provide a measure of the average radial flux profile. There are a number of possible locations that such wires could be inserted in the core, including instrument tubes. Tamper indicating features and video surveillance of the flux wire locations would be desirable. A similar concept would be to attach hafnium buttons at different locations along the length of selected fuel assemblies; these buttons would function in similar ways as the flux wires or coupons and would provide a measure of fuel assembly burnup. Placing such indicator buttons on fuel assemblies would not require access to instrument tubes or other core locations. Placing them on reactor structural elements could be a useful element of safeguards by design (see below). The implementation and measurement of neutron flux wires, or neutron odometer buttons, would likely be a costly exercise but could be done in response to exceptional circumstances where additional safeguard measures were needed, or for reactors of special safeguards concern.

Another demonstrated method for neutronic verification of cumulative reactor operating history is the isotope ratio method (IRM). In the IRM, small samples of the reactor vessel or other core structure are taken and analyzed. The transmutation of the impurity elements in the core structural samples can be used to determine the overall reactor power history up to that point. Taking multiple samples in different locations would also yield information on average flux profiles. The implementation of IRM is relatively costly, but could be a useful tool in specific cases, where it is desired to verify declarations. To verify burnup on specific assemblies after they have been removed from the core, the IRM method could be applied to structural components of the assembly itself.

While the techniques mentioned above are not all well proven or easy to implement and would likely require a high level of cooperation from the operator, the technology should be considered and further developed both for utilization in new Research reactors and for the possible deterrence benefit in existing research reactors.

Research reactors often incorporate unique features to support their design-specific mission or capability. Therefore, the consideration of reactor-specific safeguards approaches could offer benefits. However this approach would require updated, complete DlQs, which have sometimes been problematic to obtain. The incorporation of an enhanced DlV, when developing the annual implementation plan, would allow the inclusion and verification of specific design features related to potential misuse (such as target areas or excess cooling). The Safeguards AIP could be tailored taking into consideration parameters such as available excess reactivity, available core locations for target irradiation, and heat removal capacity.

There is currently no IAEA requirement for the declaration of plutonium production in research reactors due to the assumption that the quantities have traditionally not been significant. However, that is not always the case, and such declarations could be required and verified. While not traditionally done, neutronic and thermo-hydraulically modeling of the specific core could provide insight to the consistency of declarations on reactor operations. That modelling would permit improved estimation of both the quantity and quality of plutonium being (or that could be) produced.

5.4 Monitoring Additional Associated Infrastructure

Another key class of advancement in research reactors safeguards would be to monitor associated infrastructure such as hot cells, analytical laboratories, and waste tanks. Co-located infrastructure represents the most immediate risk, but hot cells at other locations in the State also represent misuse potential. One potential obstacle is the common historical practice of States providing insufficient design information to the IAEA. Some DIQs have not mentioned hot cells or analytic laboratories on the site of a declared research reactor facility, as they were claimed not to be intended to process nuclear material. Therefore, these safeguards measures would require access to these facilities through careful definition of the facility or site declarations. There is precedent for IAEA access to these installations, because CSA and AP authorities have been used as the legal basis for environmental sampling at associated infrastructure in the past. (See Appendix A.) In addition to physical access to hot cells, analytical laboratories, and waste tanks, this approach would also require access to associated documentation, such as sample analysis result libraries and analytical logbooks from the hot cell installations and analytical laboratories. Finally, this approach would require means for authenticating the documented and declared uses of these associated infrastructures.

The most effective way to safeguard hot cells is to monitor their entrances. Hot cells have only a limited number (one or two each) of entrances that are large enough to accommodate insertion of spent fuel or targets.[7] These entrances could be monitored on the outside of the hot cells themselves by cameras, unattended verification systems (neutron and/or gamma ray detectors), or unattended sensors that trigger video surveillance.

[7] Targets for research on reprocessing and etc. do not have to be large they could be inserted thru a pipe-sized port or a manipulator port during routine maintenance (these ports are nominally a foot in diameter and are very radioactive so that plastic houses and glove port sand etc. to mask any undeclared activity would be completely normal

Additional safeguards measures for authenticating declared use of associated infrastructure would involve targeted environmental sampling. Swipe samples could be taken in analytical laboratories and hot cells to verify declarations (e.g., that no fuel was reprocessed in the hot cells). This approach has some promise, but also limitations in some cases since it cannot determine quantities or purpose, only presence of material. For example, if hot cell swipes determined that fuel had been cut up and possibly even dissolved, the operator could declare it was done for post-irradiation examination of a single fuel rod, and that activity would be indistinguishable from reprocessing relatively large quantities of fuel. Nevertheless, the ability to detect that irradiated nuclear material has been present in the hot cell or that processing has taken place can in some instances be a good indicator of misuse and could be used to trigger additional follow-up investigation. Also, indications of specific undeclared target processing, such as separation of polonium-210 from irradiated bismuth, possibly could be discovered with this method.

A more costly and intrusive safeguards measure would be sampling of hot cell waste tanks. This would likely be done only for specific cases when it is determined to be warranted, such as when swipes taken in the hot cells showed the presence of irradiated nuclear material or evidence of its processing. Work has been done to develop technology for accessing and sampling waste tank inventories. While hot cells can be cleaned to remove obvious traces of undeclared material processing, the associated waste tanks would nevertheless retain clear signatures of such operations. Waste tanks are normally accessed through piping underneath the hot cells, but detailed understanding of the piping, along with accurate and complete as-built blueprints may be needed to ensure the appropriate sampling locations are reached. Waste tank ventilation pipes offer the most promising access point. Further, technology has been developed to estimate plutonium content in the waste tanks by acquiring a simple gas sample from the headspace of the waste tank. The measurement of volatile fission products, resulting from the spontaneous fission of Pu-240, combined with information on Pu isotopics, provides the ability to obtain a rough estimation of the quantity of plutonium that is contributing to the signature in the waste tank.

5.5 Safeguards by Design for Research Reactors

The IAEA defines safeguards by design (SBD) as an approach whereby international safeguards requirements and objectives are fully integrated into the design process of a nuclear facility, from initial planning through design, construction, operation and decommissioning[8]. SBD has two main objectives: (1) avoid costly and time-consuming redesign work or retrofits of new nuclear facilities and (2) make the implementation of international safeguards more effective and efficient at such facilities. In the long term, the attainment of these goals would save operators and the IAEA time, money, and resources—a mutually beneficial, win-win endeavor.

Research reactors have certain design and operational features that impact how the IAEA chooses to implement safeguards at those facilities. These features include the potential for plutonium and uranium-233 production and on-load refueling. Some best practices for considering safeguards during the design of research reactors are listed in Appendix D.

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Facility Design and Plant Operation Features that Facilitate the Implementation of IAEA Safeguards, IAEA-STR-360, IAEA, Vienna (2009);

To ensure the success of the SBD process, active dialog and interactions must occur among the designers, operators, Safeguards Regulatory Authority, and IAEA as early as practical to allow safeguards features to be effectively integrated into the design of research reactors, eventually minimizing safeguards intrusiveness at the facility.

6.0 Key Recommendations

As we look for ways to improve safeguards for research reactors, it is important to note that the IAEA will need to tailor safeguards measures to individual States and individual reactor characteristics, establishing performance targets and utilizing all safeguards-relevant information, and State Specific Factors to optimize State Level Approaches (SLA). Given limited safeguards resources, it would not be cost-effective or appropriate to seek uniformly rigorous standards for all research reactors. The Agency will need to conduct acquisition pathway analysis to determine its priorities when developing annual implementation plans. Tailored safeguards measures will have to be defined and implemented taking into account, as foreseen in IAEA safeguards agreements, the need to avoid undue interference in the operation of facilities, and in particular the economic and safe conduct of nuclear activities, and the protection of commercial and industrial secrets and other confidential information. With these considerations, and the discussion above, in mind, we offer the following observations and proposals to strengthen international safeguards for research reactors.

7.0 Findings and Observations

- Note that natural uranium heavy water research reactors (HWRR) have been used to produce plutonium for nuclear weapons programs since the 1940s.
- Recognize that a State's misuse of research reactors (as has happened several times in the past) may be an early indicator of a broader undeclared nuclear program, requiring the need to remain extra vigilant in a specific situation.
- Take advantage of the flexibility and opportunities afforded by the development of State Level Approaches (SLA), and consider ways to focus additional attention and broaden the safeguards toolbox for research reactors, recognizing that a research reactor can be a common path element on a large number of technically plausible pathways that must be considered when performing acquisition pathway analysis (APA) for developing a State Level Approach (SLA) and Annual Implementation Plan (AIP).
- Note that the safeguards approach for individual research reactors will vary.
- Take into account the possibility of misuse of declared research reactors with power levels below 25MW, focusing more on high priority paths to the acquisition of fissile material (including protracted misuse involving production of less than 1 SQ per year) and early indications of proliferation related experiments. Recognize that detecting diversion of declared material or detecting undeclared activities will not require the development of new technologies and is more a function of determining the right frequency and intensity of inspections.
- Encourage the development of new tools and strengthened safeguards approaches to detect misuse, using existing safeguards technologies to strengthen and supplement the new approaches.

8.0 Recommendations and Proposals

1. Tailor Safeguards Approaches at State level

   - Develop holistic SLAs that take into account research reactors' relationship to associated fuel cycle facilities (i.e., acquisition path analysis), or peculiarities of a particular design for misuse. For example, recognize that undeclared irradiation at a declared research reactor could be an indicator of undeclared reprocessing activities.

2. Establish mailbox declaration protocols, similar to those used at uranium conversion and enrichment plants, requiring operators to declare reactor operations at agreed regular intervals, including fuel operations and fuel management strategy, isotope production, and related to target irradiation. The required declarations would be identified during the development of the safeguards approach agreed with the State, and codified in the facility attachment. Such declarations would be accompanied by (or trigger) unannounced or short notice inspections with randomized target selection and verification goals. The declarations might include, among other things:

   - Declaration of fresh/spent fuel transport container (identity – serial number, dimensions, capacity) locations , planned and actual movements;
   - Annual/quarterly declaration of programmed or planned activities (level of detail to be determined during Facility Attachment negotiations), average number of planned shipments;
   - Specific to each reactor facility–
     - Daily log requirements – power, temperatures, neutron flux, anomalies
     - Modification or removal of reactor system components in reactor or pond, beam tubes etc.;
     - Information on irradiated targets (e.g. capacity, load factor);
     - List of on-going and planned experiments, including purpose, type of materials involved;
     - All planned experiments should be permanently logged – who, how, what, when etc., with an experiment number;
     - All experiments should include, among other things, a mailbox log of specimen in/out of reactors, what ports, seals removed, unusual events etc. Where specimen was taken to for post irradiation examination, etc.
   - All possible access points and ports to the reactor should be sealed by the IAEA with the IAEA acknowledging that some seals may have to be removed by the operator for unique unusual experiments or maintenance etc. The removal of these seals should be mailbox-logged – date time, seal number, person removing etc.
   - Any changes/deviations to the facility or to the previously declared planned activities be declared via mailbox declaration to the IAEA in a timely manner (FA negotiated time).

3. Increase the Frequency of Environmental Sampling at Hot Cells, While Improving Advanced Sampling Techniques

- Encourage States to include hot cells and all other associated infrastructure within the facility boundary of the DIQ and promote/seek periodic environmental sampling.
- Exercise fully all legal authorities to conduct environmental sampling at hot cells (see Appendix A).

4. Consider Enhancing Existing Safeguards Approaches[9]

On a case-by-case basis, the IAEA could strengthen its detection capabilities by selecting safeguards measures among the following:

For Fuel Monitoring:

- Conduct PIV and DIV and unannounced inspections more frequently
    - Monitor access points for fresh fuel with surveillance cameras
    - Apply seals to fuel handling machines
    - Collect environmental samples from the outside of spent fuel casks & other containers.

For Authenticating Declared Reactor Use:

- Determine whether core burnup is consistent with declarations using thermal hydraulic and neutronic methods.
- Monitor research reactor operations using commercial satellite imagery in high priority cases.
- Place flux wires or coupons made of materials such as hafnium into the core (see below).

For Monitoring Additional Associated Infrastructure:

- Monitor the entrances of hot cells and other associated infrastructure with surveillance cameras
- Target environmental sampling in hot cells
- Collect environmental samples from hot cell waste storage tanks.

5. Develop New Safeguards Measures to Detect Misuse

- Employ fluence monitors (e.g., hafnium) to get a better understanding of flux distribution on an average basis to augment power monitor approaches, taking cost-effectiveness into account. For example, if possible, very small hafnium "buttons" (i.e., small pieces of hafnium metal) could be inserted into convenient locations in the reactor's core, and would be removed for analysis on a random basis, or if there were indications of misuse. Analysis of the data from a couple of Hf monitors could help determine whether the cumulative reactor power operation (and core power shape) was consistent with the State's declarations. Given cost/benefit considerations, the removal and analysis of core fluence monitors would be infrequent, but could serve to deter the State from conducting undeclared operations.[10]

[9] See, for example, "Safeguards Considerations for Research Reactors and Critical Assemblies" by B.W Smith, T.E. Shea, April 15, 2007, PNNL Contract DE-AC05-76RL01830

[10] A fluence measurement gives only, for a given position in the reactor, integration of a part of the neutron spectrum flux; it is not a direct power measurement; a measure of validation for each specific reactor or neutron calculations are required

- Employ modern unattended and remote monitoring measures (e.g., radiation detectors and cameras to track the movement of spent fuel from the reactor to the spent fuel pool, unique identifiers to track the locations and movement of transport containers).

6. Seek Enhanced Access

- Increase frequency of unannounced inspections, if called for by the state-level approach, to detect undeclared irradiation and processing of nuclear and non-nuclear materials in hot cells.

7. Promote Safeguards by Design

- Encourage facility designers and operators to take Safeguards by Design into account for the construction of new research reactors. For example, include the installation of a wire or coupon in the core that could be sampled and analyzed to determine the reactor's historical neutron flux levels. Some "best practices" identified by Safeguards by Design guidance documents (see Appendix D) could also be applied to *existing* reactors, when technically and economically feasible, as well as the construction of *new r*eactors. For example: 1) Minimize, when operationally possible, the number of access points in the reactor containment, nuclear material storage areas, and other shielding structures through which any fresh or spent fuel movement could occur; 2) Plan the fuel transport routes so that if a surveillance system is deemed necessary, it can help inspectors distinguish clearly between routine and non-routine fuel transfers and other fuel pond activities. Radiation detectors and the monitoring of transport containers and/or cranes can also be used as to alert the IAEA to any movement of material.; 3) Enable inspectors to view the tops of the fuel assemblies in the fuel handling area and a provision for monitoring the canal gate (when applicable) to indicate to the inspectors when it is open; 4) Provide a mechanism for the IAEA to track movement of the crane and fuel handling equipment to verify the movements and positions of fuel elements in the core; 5) Use a sealing system on the reactor core to provide a tamper indication for the nuclear material contained in the reactor core if physically possible (such a system should be accessible for inspection, easy to install, and protected against damage); 6) Incorporate underwater illumination in the reactor pool/tank and sufficient water clarity so that the inspector can count the fuel assemblies and read their identifiers; 7) Make use of tamper-resistant surveillance cameras, radiation detectors to monitor operational activities in the core, peripheral piping, and to monitor target movements in all irradiation channels, including ducts and beam tubes, or seal biological shield and transfer channels; and 8) Incorporate power monitors at reactor and experimental areas.
- Enhance design information verification (DIV) to gain a better understanding of and strengthen safeguards for potential target irradiation. For example, look for design features related to misuse, such as target areas or excess cooling.

8. Improve Auditing of Records

- Improve auditing activities (e.g., include fissile material production and burn-up of discharged spent fuel in states' nuclear material reports); develop requirements for reporting reactor fissile material production.
- Spot check operating log books to supplement other measures to provide a minimum detection capability to detect undeclared irradiation of nuclear material.

9. Work with Member States

    - Identify research reactors where some of these new safeguards approaches could be developed and tested.
    - Encourage and assist Member States with research reactors to further strengthen the State System of Accounting for and Control of Nuclear Material (SSAC), in particular to ensure adequate resources and capabilities of the Safeguards Regulatory Authority (SRA).

Appendix A

The IAEA’s Legal Authority to take Environment Samples at Hot Cells

Appendix A.

The IAEA's Legal Authority to take Environment Samples at Hot Cells

One of the key tools the IAEA has for safeguarding research reactors is the collection and analysis of environmental samples from hot cells associated with such reactors. This Section reviews the Agency's relevant legal authorities under various safeguards agreements.

A.1 INFCIRC/153 Routine Inspections and DIV

In February 1995, as part of the Programme 93+2 process for strengthening safeguards, the Director General submitted a report to the Board of Governors in which he noted that pursuant to paragraphs 74(d) and (e) of INFCIRC/153, the Agency was authorized to apply and use surveillance measures and use other objective methods which have been demonstrated to be technically feasible for the purposes of carrying out ad hoc, routine and/or special inspections. He noted that both paragraphs provided justification for the use of the then relatively new technology of environmental sampling. He also noted that, in connection with design information verification (DIV), INFCIRC/153 did not specify the methods which were to be employed by the Agency, and that environmental monitoring could contribute significantly to DIVs.

In June 1995, the Board took note of the Director General's plan to implement at an early date the measures described in "Part I", i.e. measures for which the Agency had existing legal authority. As indicated in the Director General's follow up report to the Board in May 1995, those measures included the Agency's right to carry out environmental sampling at any location to which the Agency had the right of access for purposes of inspections (ad hoc, routine or special) or DIV.

Within a facility:

- Pursuant to paragraph 76(a) of INFCIRC/153, until such time as "strategic points" have been specified in the Subsidiary Arrangements, the Agency has access to carry out ad hoc inspections at "any location where the initial report or any inspections carried out in connection with it indicate that nuclear material is present". Thus, if the State declared there to be nuclear material at a hot cell within a facility, or inspections carried out before agreement on strategic points indicated nuclear material was present, the Agency could request access to the hot cell and take environmental samples during an ad hoc inspection.
- Paragraph 76(c) of INFCIRC/153 limits the Agency's routine inspections to a facility's "strategic points" as specified in the Subsidiary Arrangements and defined in paragraph 116 as "a location selected during examination of design information where, under normal conditions and when combined with the information from all 'strategic points' taken together, the information necessary and sufficient for the implementation of safeguards measures is obtained and verified; a 'strategic point' may include any location where key measurements related to material balance accountancy are made and where containment and surveillance measures are executed." The most straightforward way

for the IAEA to be in a position to collect environment samples on a regular basis at hot cells in facilities is to designate the hot cells as strategic points.

- INFCIRC/153 also provides for access within a facility to other locations beyond strategic points for the purpose of DIV. Thus, if a hot cell were not agreed to as a strategic point, DIV access authority would provide an alternative basis for environmental sampling at the hot cell, provided it was declared as within the boundary of the facility layout as described in the DIQ for the research reactor. It would be desirable for DIV to be extended to include associated hot and lead-shielded cells capable of handling irradiated nuclear material, which should also be included to be part of the facility, even if located in another building.
- Ideally and logically, if there is a hot cell co-located with a research reactor, it should be defined as constituting a part of the facility, and not a separate facility.

A.2 INFCIRC/153 Special Inspections

If a hot cell is not declared as being located within a facility, the Agency could seek access to the hot cell in accordance with the provisions for special inspections. Pursuant to paragraph 73(b) of INFCIRC/153 special inspections may be requested “if the Agency considers that information made available by the State, including explanations from the State and information obtained from routine inspections, is not adequate for the Agency to fulfill its responsibilities under the Agreement.” If the IAEA obtained information about a hot cell not located within a facility, it could seek additional information about, and access to, that location as provided for in paragraph 73(b). A case could be made for this because the IAEA’s responsibility is to apply safeguards to all nuclear material, a responsibility that it would not be able to fulfill in the case of a hot cell processing undeclared nuclear material. However, it should be noted that paragraph 77 of INFCIRC/153 requires consultation with the State, and that the Agency may only obtain such access “in agreement with the State”.

Should the State reject the Agency’s request for access, the Board could determine that such action is essential and urgent to verify non-diversion and call upon the State to provide the requested access (paragraph 18), in which case, the State would be legally obliged to provide it.

A.3 INFCIRC/540 Complementary Access

The focus of INFCIRC/540 (the Model Additional Protocol, or MAP) is to provide the Agency with increased information and access, inter alia, to help the Agency to more effectively detect and deter undeclared activities. Depending on the circumstances, various MAP provisions would provide complementary access authority to conduct environmental sampling at hot cells.

- Article 5.a.(i) provides Agency access to any place on a site, and Article 5.c. provides Agency access to any location specified by the Agency (other than locations referred to in Article 5.a. and b.) to carry out location-specific environmental sampling. If a hot cell is co-located with a facility, a State is obligated under Article 18.b. to include it as part of the site of a facility, and the IAEA would be able to collect environmental samples at such a hot cell.
- Under Article 2.b. (ii), the State is obligated to “make every reasonable effort” to provide the Agency with a “general description of activities…at locations identified by the Agency outside a site which the Agency considers might be functionally related to the activities of that site.” The case might arise

where the State has not included a hot cell within a site boundary. In this case, upon specific request by the IAEA, the State is obligated to consult with the IAEA and provide the information in a timely fashion. If the IAEA still had a question about the location, then it could seek access under Article 5.b, and it could collect environmental samples if it obtained access. The State must provide access or, if the State “is unable to provide such access, the State shall make every reasonable effort to satisfy Agency requirements, without delay, through other means.”

- If the IAEA obtained knowledge of a hot cell not co-located with a facility and depending on the situation, the IAEA could potentially seek to invoke INFCIRC/153, paragraph 73(b), special inspection authority or seek access under INFCIRC/540, Article 5.c.

A.4 INFCIRC/66 Inspections and DIV

The IAEA currently implements INFCIRC/66-type agreements in three states that have never been parties to the NPT: India, Pakistan, and Israel. While INFCIRC/66/Rev.2 does not specifically prescribe all of the inspection activities that may or may not be carried out under such agreements, it is reasonable to conclude that environmental sampling could be carried out during inspections (under INFCIRC/66-type agreements, the provision corresponding to “DIVs” refers to “initial inspections”). This would provide assurance that there is no misuse, i.e., undeclared production or separation of direct-use material at declared facilities.

A.5 Voluntary Offer Agreements

The IAEA does not need to collect environmental samples to verify that no declared nuclear material has been withdrawn under Voluntary Offer Agreements.

Appendix B

Research Reactor Types and Characteristics of Safeguards Relevance

Appendix B

Research Reactor Types and Characteristics of Safeguards Relevance

B.1 Types of Research Reactors

B.1.1 Pool- and Tank-Type Light Water Moderated Reactors

The pool-type reactor is a relatively simple and the most common research reactor design where fuel elements are arranged in an open pool. The pool's light water serves to moderate and cool the reactor. Graphite or beryllium can be used as reflector materials. Most pool type reactors operate up to a few megawatts of thermal power, at most, and therefore cooling is accomplished by natural convection. Nonetheless, coolant pumps and heat exchangers may be used to allow operation at higher powers (e.g., > 1 MWt) and some reactors use a diffuser pump to diffuse the convective flow to the pool surface to mitigate radiation from Nitrogen-16 produced from the reactor operation.[11] There are a limited number of pool-type reactors that operate with a power as high as 10 MWt and up to 100MWt (Russian MIR M1). Research reactors are typically used for material testing irradiation, reactor fuel development and qualification, radio isotope production for medical or industrial use, neutron activation and neutron transmutation doping, and therefore contain empty channels within fuel elements and/or reflector positions for experimental materials that are easily accessible. Apertures to accommodate neutron beams are typically set in the wall of the pool and allow for a wide variety of neutron irradiation and scattering experiments to be performed. Hence, an IAEA inspector's understanding of the operating parameters of a research reactor combined with insights from DIV can provide key data needed to evaluate the scenarios in which this facility could be misused.

The tank-type reactor design is similar to the pool-type reactor, except that the core is contained within a tank sealed at the top. In some cases, the tank containing the core may be a full pressure vessel. With a pressure vessel, the light water coolant can be pumped through the core at elevated pressure compared with an open pool. This forced draft provides enhanced cooling capability. The higher powered tank-type reactors are often referred to as test reactors as a result of their enhanced irradiation capability compared to the average research reactor. Test reactors are typically used to expose materials to intense neutron irradiation conditions to study changes in material properties that can advance the development of advanced fuels. The enclosed tank-type reactor configuration makes it more difficult to access fuel and targets in the core compared to pool-type reactors and would be more amenable to C/S measures, such as surveillance of the opening of the tank.

B.1.2 High Performance Heavy Water Reactor, High Power

The use of heavy water as the moderator in nuclear reactors permits the use of a wide range of fuel cycle materials and fuel management schemes. Uranium enrichment requirements for heavy water

[11] Safety Analysis Report for Renewal Of License R-2 For the Breazeale Nuclear Reactor, Penn State University, December 2005.

systems may range from natural enrichment to high enriched. Low neutron parasitic absorption characteristic of heavy water compared to light water provides these reactors with a neutron economy that is advantageous for plutonium production when a large quantity of natural uranium can be irradiated. Heavy water moderated reactors can use either light water or heavy water for coolant. Heavy water tank-type reactors typically provide a large thermal flux volume with a high thermal neutron flux. Heavy water reactors capable of operation at powers greater than 25 MWt are of particular safeguards concern due to their capability for producing a SQ or more of plutonium per year. Many large designs for heavy water reactors allow for on-load refueling, and therefore offer the ability to maintain a high level of reactor availability while accommodating short irradiation times for fuel and/or targets. Similar to the light water research reactors, numerous irradiation positions for experimental materials are typically located throughout the reactor core as well as outside the core in a ring around it in the heavy water reflector and at the end of beam tubes. Plutonium production can be optimized by arranging driver fuel in a configuration to maintain criticality while surrounding the core with a blanket containing target material in such versatile reactors. Heavy water reactors with HEU fuel, such as Brookhaven National Laboratory's High Flux Beam Reactor (HFBR) and the Laue-Langevin Institute (ILL) High Flux Reactor (HFR), are designed to generate neutrons at various energies for experiments and could be adapted to breed small quantities of fissile material.

B.1.3 One-of-a-Kind Reactors

Most test reactors, and a few research reactors, are one-of-a-kind reactors by virtue of their design, and are often designed around a specific mission and capability. Reactors that offer a wide range of flexibility in both fuel usage and operational envelope can certainly be classified as one-of-a-kind. Most reactors are flexible in their operational envelope. In particular, high power heavy water reactors and fast reactors allow for the use of a wide range of fuel cycle materials and fuel management schemes without significant alterations to the reactor design or operational characteristics.

There are a number of one-of-a-kind reactors that have been designed, and even built, that employ an innovative set of materials and configurations. These unique reactor designs have some attractive qualities because they exhibit potential for inherently greater safety or offer the potential for greater economic efficiency. A few of the more unique designs includes the following:

- A High Temperature Gas Reactor (also pebble bed reactor) consists of a large reactor vessel containing a matrix of graphite encapsulated pebbles that are cooled by flowing helium. The pebbles, which are approximately the size of a tennis ball, encapsulate a population of smaller silicon-carbide and pyrolytic carbon coated fuel particles. The robust encapsulation of the fuel, and the large heat capacity and very high temperature capabilities of the materials used in this design provide significant inherent safety.
- A Sodium Cooled Fast Reactor consists of a core with a traditional configuration of fuel pins bundled into a number of fuel assemblies. The core is located in a tank or pool of low pressure liquid metal sodium which provides the cooling. The use of liquid sodium allows high power density due to the heat rejection capability and the potential for greater thermal efficiency due to higher temperature operation. Though sodium is highly reactive with water, its high thermal conductivity provides inherent safety benefits by offering the potential for natural circulation cooling of the core following an off-normal event. The "inherent safety benefits" are referring to the high thermal conductivity of the sodium, not the sodium itself. The sodium is also a hazard in air, due to its reactivity. The high

level of the neutron flux and external core neutron leakage offer possibilities of breeding fissile material in specific axial and radial blankets or irradiation channels in the metal reflector.

- Lead, or a lead-bismuth eutectic, may also be used as an alternative liquid metal coolant.
- A Molten Salt reactor consists of a design in which the fuel is dissolved in the primary coolant and which achieves criticality only when it's pumped into the reactor vessel where it attains the proper geometry and moderation. The fuel is dissolved in a molten fluoride salt often with other metals. The low pressure, but high temperature operation, offer potential for improved safety while providing higher thermal efficiency.
- A Very High Temperature Reactor consists of a helium-cooled, graphite-moderated core, with graphite encapsulated fuel molded into prismatic blocks. This reactor design can operate at elevated temperatures that offer enhanced thermal efficiencies for electricity production and can also support the production of hydrogen as a by-product. The graphite core has a large heat capacity and the inert helium coolant provides inherent safety characteristics.

The overall conclusion is that all unique, one-of-a-kind reactors should be carefully evaluated for reactor design characteristics and safeguards approaches.

Appendix C

Historical Cases of Research Reactor Misuse

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Historical Cases of Research Reactor Misuse

LWRRs. Past experience in the implementation of IAEA safeguards includes several cases in which States have failed to meet safeguards requirements related to research reactors and associated facilities. Instances where the Secretariat has reported such failures to the Board of Governors include cases involving research reactors in Iraq (1991), Romania (1992), Iran (2003), Libya (2004), South Korea (2004), Egypt (2005), and Syria (2010).[12] (It should be noted, however, that not all of these failures resulted in a Board finding of non-compliance.)[13]

HWRRs. While none of the cases brought to the Board's attention have involved a misuse of *heavy-water* research reactor, concerns about the nature and direction of nuclear activities in Taiwan in the 1970s and 1980s have been widely reported in the press and literature, and in 1988 Taiwan reportedly agreed shut down it 40-MWt HWRR in response to such concerns.[14] [15]

Collectively, these cases illustrate several different types of misuse:

- Introduction of diverted or undeclared nuclear material for reactor irradiation and subsequent undeclared chemical processing
  - *Iraq:* Irradiation and reprocessing of undeclared natural uranium fuel elements
  - *Iran, Libya:* Undeclared irradiation of uranium targets for plutonium extraction R&D
  - *Iran, Egypt:* Undeclared irradiation of uranium targets for radioisotope production
- Diversion of declared fresh or irradiated fuel for subsequent recovery of fissile material
  - *Iraq:* Preparations to divert HEU fuel from research reactors for extraction
  - *Romania:* Declared material irradiated (possibly clandestinely) and secretly reprocessed in hot cells
  - *South Korea:* Undeclared reprocessing and misreporting of declared irradiated fuel
- Irradiation of non-nuclear material targets to produce materials in support of nuclear weaponization research (a non-peaceful use, but not a safeguards compliance matter)
  - *Iraq:* Irradiation of non-nuclear materials for nuclear weapons initiators
  - *Iran:* Irradiation of bismuth metal samples for polonium-210 production

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[12] The dates in parentheses indicate the year in which the misuse first was reported to the Board. In many cases, the actual misuse occurred earlier, sometimes much earlier than the year shown. And findings of noncompliance by the BOG, if any, may have occurred later.

[13] Although the Secretariat reported Egypt's and South Korea's activities to the Board of Governors, the Board did not deem them to be of sufficient proliferation concern to report these matters to the UNSC.

[14] See for example "Taipei Halts Work on Secret Plant to Make Nuclear Bomb Ingredient," *New York Times*, 23 March 1988, Associated Press; "Taiwan Conducted Plutonium Experiments," Associated Press, 13 October 2004; and "ROC/IAEA Safeguards," excised U.S. State Department cable TOKYO 3212, 8 March 1977, available at the Georgetown University National Security Archive, http://www2.gwu.edu/~nsarchiv/nukevault/ebb221/T-12.pdf.

[15] Despite those earlier concerns, Taiwan's more recent safeguards performance has been fully consistent with its obligations. Taiwan's was the first large nuclear program to accept application of AP measures, and Safeguards Implementation Reports have repeatedly stated that the Secretariat found no indications of diversion or of undeclared nuclear material or activities.

Details of these cases can be found in corresponding reports by the Director General to the Board of Governors. While the cases vary in many particulars, some cross-cutting observations can be drawn:

- Safeguards violations at research reactors have been a frequent feature of—and thus a potential warning sign of—undeclared nuclear programs that had broader scope. This suggests that the IAEA should be alert for, and vigorously investigate, indications of even relatively minor safeguards violations at research reactors and at associated hot cells and laboratories.
- Research reactors under IAEA safeguards have not, at least to date, been successfully misused to acquire kilogram quantities of weapons fissile material for nuclear weapons.[16] The quantities of material clandestinely produced or diverted at safeguarded research reactors in these seven cases were quite small, orders of magnitude below the quantity goals for detection by IAEA safeguards. Nevertheless, early detection of research reactor misuse might have provided necessary focus and leverage to expose or deter other elements of the States' undeclared activities.
- Most cases of misuse occurred in the 1980s or early 1990s, prior to the implementation of new safeguards-strengthening measures, although some cases involve activities that occurred more recently, in the 2000s. None of the known instances of misuse occurred in a State with an Additional Protocol (AP) in force at the time of the misuse, however.
- The cases varied widely with respect to method of discovery of the misuse:
  - Discovery through the State's voluntary disclosure (Libya, ROK, Romania)
  - Discovery through information provided by the State in the context of IAEA investigation of third-party leads (Iran, Syria)
  - Discovery through information provided by the State in the context of Security-Council mandated inspections (Iraq)
  - Discovery through environmental sampling (ROK, Syria)
  - Discovery through open-source analysis (Egypt)

[16] The risk of overt breakout remains a potential nonproliferation concern, of course. Iraq's 1990-1991 "Crash Program," initiated in anticipation of military intervention by Coalition forces following Iraq's invasion of Kuwait, had as its objective to rapidly prepare to divert fuel from the IRT-5000 and Tammuz-2 reactors and extract HEU for use in a nuclear explosive. [GOV/2816/Add. 1]

Appendix D

Safeguards by Design for Research Reactors

Appendix D

Safeguards by Design for Research Reactors [17]

The following issues related to IAEA safeguards implementation should be considered during the design of research reactors:

- Provide inspector access to the reactor and spent fuel ponds to enable verification of the core fuel and spent fuel. The inspectors must have an unobstructed and overhead view of irradiated core and spent fuels. Access to the spent fuel pond should allow NDA equipment to be inserted to verify spent fuel qualitatively (verifying that the fuel rods were irradiated) and in the future possibly quantitatively to measure plutonium content.
- Minimize the effect of safeguards on plant operation by selecting locations for safeguards equipment that are accessible for inspection, monitoring, and maintenance and that do not obstruct or impede plant operations.
- Minimize, when operationally possible, the number of access points in the reactor containment, nuclear material storage areas, and other shielding structures through which any fresh or spent fuel movement could occur.
- Design for adequate and reliable illumination at the containment access, the fuel dry & wet storage areas, reactor bay, and fueling mechanism areas.
- Plan the fuel transport routes so that if a surveillance system is deemed necessary, it can help inspectors distinguish clearly between routine and non-routine fuel transfers and other fuel pond activities. Radiation detectors and sealing transport containers and/or cranes can also be used as to alert the IAEA to any movement of material.
- Design a mounting for surveillance equipment suitable for inspectors to view the tops of the fuel assemblies in the fuel handling area and a provision for sealing the canal gate (when applicable) to indicate to the inspectors when it is open.
- Provide a mechanism for the IAEA to track movement of the crane and fuel handling equipment to verify the movements and positions of fuel elements in the core.
- Design a sealing system on the reactor core to provide a tamper indication for the nuclear material contained in the reactor core if physically possible (such a system should be accessible for inspection, easy to install, and protected against damage).
- Incorporate underwater illumination in the reactor pool/tank and sufficient water clarity so that the inspector can count the fuel assemblies and read their identifiers.

[17] Most of the information in this section is drawn from a safeguards by design guidance document sponsored by the U.S. National Nuclear Security Administration (NNSA), see www.nnsa.energy.gov/safeguardsbydesign. In addition, see: Safeguards by Design (SBD): “Safeguards Guidance for Research Reactors and Critical Assemblies” by Paul Pan, Brian Boyer and Chantell Murphy, LANL, LA-UR-12-26349; see also IAEA Nuclear Energy Series No. NP-T-2.8, “International Safeguards in Nuclear Facility Design and Construction”

- Incorporate tamper-resistant surveillance cameras, radiation detectors to monitor operational activities in the core, peripheral piping, and to monitor target movements in all irradiation channels, including ducts and beam tubes, or seal biological shield and transfer channels.
- Incorporate power monitors at reactor and experimental areas.
- Incorporate tamper resistant fluence tags in key reactor locations that can be used to verify cumulative core power and power distribution.
  - Store fuel in the pool in a single layer to permit viewing, directly from above, on the top of each fuel assembly with its identifier showing (e.g., no overhang over fuel storage locations should exist). Alternately, include provisions (i.e., adequate pitch) for verifying and sealing the fuel in a lower layer(s) if fuel storage is in more than one layer (as in CANDU spent fuel storage);
  - Provide a single dedicated space for the IAEA safeguards equipment with the provision for sealing the equipment, if needed.
  - Support an IAEA tamper-resistant local area network connection at each safeguards measurement point and make allowances for analysis and digital data storage equipment at the measurement sites
  - Consider working with the IAEA to employ joint-use equipment (e.g., used by both the operator and IAEA) with adequate authentication of IAEA data feeds that measure critical parameters, including temperature, flow, radiation level and fluxes, and core inventories, to allow verification of operations (including fuel loadings and thermal power levels) with sufficient authentication of the data for the IAEA to draw independent conclusions.
  - Enable automatic transfer of agreed data to an IAEA mailbox.

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