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Global Estimation of Potential Unreported Plutonium Production in Thermal Research Reactors

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ABSTRACT

As of November 1993, 303 research reactors (research, test, training, prototype, and electricity producing) were operational worldwide; 155 of these were in non-nuclear weapon states.[1] Of these 155 research reactors, 80 are thermal reactors that have a power rating of 1 MW(th) or greater and could be utilized to produce plutonium. A previously published study by T. F. Moriarty and V. N Bragin[2] on the unreported plutonium production at six research reactors indicates that a minimum reactor power of 40 MW(th) is required to make a significant quantity (SQ), 8 kg, of fissile plutonium per year by unreported irradiations. As part of the Global Nuclear Material Control Model effort, we determined an upper bound on the maximum possible quantity of plutonium that could be produced by the 80 thermal research reactors in the non-nuclear weapon states (NNWS). We estimate that in one year a maximum of roughly one quarter of a metric ton (250 kg) of plutonium could be produced in these 80 NNWS thermal research reactors based on their reported power output. We have calculated the quantity of plutonium and the number of years that would be required to produce an SQ of plutonium in the 80 thermal research reactors and aggregated by NNWS. A safeguards approach for multiple thermal research reactors that can produce less than 1 SQ per year should be re-visited and criteria adapted to ensure an appropriate degree of safeguards. This investigation should be conducted in association with further developing a safeguards and design information reverification approach for states that have multiple research reactors.

INTRODUCTION

As the U.S. and former Soviet Union (FSU) continue to advance and establish international agreements and treaties in the material protection, control, and accounting (MPC&A) and arms control and disarmament arenas, the potential of a nuclear-related military exchange is effectively nonexistent. Presently the predominant threat to U.S. national and international security appears to be the global proliferation of fissile material related to excess military weapons. This is true even though the total quantity of this excess and dismantled separated weapons plutonium is minor relative to the quantity of non-separated plutonium contained in stored commercial spent fuel and currently separated commercial plutonium. The non-separated plutonium in commercial spent fuel may continue to be separated if the closed fuel cycle (spent fuel is reprocessed and recycled) is more widely adopted. Whether or not the closed fuel cycle is pursued by more states, the plutonium contained in the spent fuel will constitute a great proliferation problem in the future, with projected growth rates of 60 to 70 MT of spent fuel per year.[3] Recent initiatives from the highest levels of the U.S. government, the National Security Science and Technology Strategy[4] (NSSTS), and the study by the National Academy of Sciences[5] (NAS) support measures and a system for global MPC&A as part of a disposition program to deal with this excess military and commercial fissile material. The NSSTS indicates that "the primary technical barrier limiting the spread of nuclear weapons is limits on access to the nuclear materials needed to make them."[4] This perspective is also propounded and expanded on by one of the primary recommendations of the NAS study, "that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and HEU worldwide."[5]

The combination of the military weapon and civilian energy fuel cycles has resulted in a significant quantity of plutonium being produced. This was estimated to be 1,095 MT by the end of 1994.[6] The breakdown of this military and civilian plutonium inventory is summarized in Table 1. The military related plutonium inventory represented about 24% of the total. The military inventory was roughly a third of the civilian inventory, but only about 17% of the civilian plutonium was separated. Several features distinguish the military plutonium inventory. All of the military inventory is separated and 91% of it is weapons-grade, some in weapon component form. Imminently resolving the proliferation concerns of this military inventory is critically important because the menacing implications of the military plutonium outweigh the numerical imbalance with respect to the total quantity of plutonium produced in both fuel cycles.

Table 1. Global Civilian and Military Plutonium Inventories

Global Inventory end of 1993	Total Pu (MT)	Total Pu Separated (MT)	Separated Pu Grade & Quantity (MT)
Civilian	845.0	144.0	Fuel/Reactor 144.0
Military	250.0	250.0	Weapon 228.0 Fuel/Reactor 22.0

*Source: derived from [5].

In light of these facts it is easy to understand why global proliferation concerns are currently focused on the accessibility and disposition of the excess and dismantled weapons-grade nuclear material resulting from past military production. Nevertheless, it is important that the alternative means of plutonium production (reprocessing commercial spent fuel and research reactor production) not be neglected. The recent proliferation experiences in Iraq and North Korea provide motivation for this continued vigilance. The premise of this report is that even though the risk and impact of illicit plutonium production in research reactors by non-nuclear weapon states appears quantitatively insignificant relative to the existing military and commercial-related plutonium (hundreds of kilograms versus hundreds of metric tons), it should be ensured. Indeed, the International Atomic Energy Agency (IAEA) has previously developed Safeguards Criteria,[4] which are "used for the planning of safeguards implementation activities in the field" and the "criteria cover safeguards performed with both INFCIRC/153-type and INFCIRC/66-type agreements."[4]

To better understand the quantity and distribution of plutonium that could result from unreported production in thermal research reactors, we calculated the estimated maximum plutonium with the Global Nuclear Material Control Model. This supported an immediate national level presentation of the potential plutonium distribution in the context of existing military and commercial plutonium inventories, nuclear facilities, and associated nuclear technical capabilities. The Safeguards Criteria address the synergistic effect of material production of less than 1 SQ at multiple facilities only during the evaluation of "Entire States" (Section 13[4]). The Entire States evaluation addresses facilities "with an inventory of any material type of 0.5 SQ or more,"[4] such facilities are to be inspected once during a year. It is not clear from the Safeguards Criteria that multiple facilities with less than 1 SQ are sufficiently addressed.

GLOBAL NUCLEAR MATERIAL CONTROL MODEL

The Global Nuclear Material Control Model[9] (GNMCM) characterizes site and facility information, nuclear material inventory data, and nuclear material production capabilities globally. There are three fundamental components to the GNMCM: physical process representation, model infrastructure design, and data and contextual information.

The physical process representation component has the primary functional computational capabilities of the GNMCM. These analytic computational capabilities are related to proliferation, disposition, safeguards and security, and graph* theory. The proliferation category provides analytical modeling and computational support for the following nuclear fuel cycle production processes and facilities: enrichment, fuel fabrication, reactor, reprocessing, metal fabrication, weapons assembly, weapons disassembly, and storage. The proliferation category permits the study of fuel cycle production, weapon dismantlement, storage, and material inventory issues. The safeguards and security category provides analytical modeling and computational support for studying, analyzing, and estimating future requirements and criteria for IAEA safeguards and security inspection and protection resources. The disposition options category provides analytical modeling and computational support for vitrification, geologic repository, and reactor-related research. The graph theoretic capability category provides the analytical modeling and computational functionality to conduct various graph theoretic and network optimization studies, including network (material) flow and shortest or constrained path analysis

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* A graph G = (V, E) is defined by a set V of vertices and a set E of edges. A graph may be either directed (each edge is an ordered pair of distinct vertices) or undirected (each edge is an unordered pair of distinct vertices).

There are four aspects to the model infrastructure: the graph-based data framework, the structural hierarchy, the nuclear fuel cycle visual representation, and the geographic illustration. The most fundamental design feature of this model is the graph theoretic framework. All facilities, sites, countries, and categories are represented as vertices, and every connection is represented as either a directed or an undirected edge. The structural hierarchy design decomposes the world into four designations: nuclear weapon states (NWS), threshold nuclear weapon states (TNWS), potential nuclear weapon states (PNWS), and non-nuclear weapon states (NNWS). These designations are further decomposed into their constituent states. The states are delineated by all of their respective nuclear sites. A site is determined by the facilities that exist at the site. The vertices are connected by unordered edges. Another feature of the model infrastructure is the geographic illustration; this provides an interactive map of the world that includes all of the modeled facilities and sites and some other geographic characteristics, such as rivers and lakes.

The last component of the GNMCM is the data and contextual information specific to each level of the hierarchy of the model. This ranges from facility-specific physical process data to more general world information and data. Examples of some of the data are geographic location of facilities; type of facility; physical process data; the Nonproliferation Treaty signatory status of a country; and fissile material inventory data for each facility, site, country, category, and world.

POTENTIAL PLUTONIUM PRODUCTION IN THERMAL RESEARCH REACTORS GLOBALLY

As of the beginning of 1994 there were 303 operational research reactors (research, test, training, prototype, and electricity producing) worldwide listed in the IAEA research reactor database. As part of the GNMCM effort we recently estimated that at most one-half metric ton (500 kg) of plutonium could be produced in thermal research reactors worldwide (excluding those in the U.S.). This estimate was based on the following assumptions: a one-year period, a reactor load factor of 0.90, fertile targets (^{238}U), a thermal power for the research reactors of 1MW or more, and the application of the reported maximum operating power. Of the 303 research reactors worldwide, 155 of these were in non-nuclear weapon states.[3] We believe that 80 of these 155 research reactors are thermal reactors that have a power rating of 1MW(th) or greater (see Table 2) and are capable of producing plutonium. During this analysis we estimated that in one year about a quarter metric ton (250 kg) of plutonium could be produced in these 80 thermal research reactors combined. We have calculated the quantity of plutonium and the number of years that would be required to produce a significant quantity (SQ), 8 kg of plutonium, in the respective research reactors. Table 2 summarizes this data by providing values based on the declared operating power level. For example a research reactor operated at 10 MW(th) power with a load factor of 0.90 is estimated to be capable of producing plutonium at a rate of 2.24 kg/yr and it would take roughly 3.6 years to obtain 1 SQ. The quantity of plutonium and the number of years that would be required to produce an SQ of plutonium aggregated by NNWS based on the 80 research reactors is summarized in Table 3.

Moriarty and Bragin[2] published a study on the unreported plutonium production at six research reactors confirming the "Binford line." For these calculations we utilized the function that represents an upper bound on the Binford line. This expression is based on the analysis of the results from the study of these six large thermal research reactors, it is not applicable to fast reactors. The Binford line is based on the "estimate that a minimum reactor power of 40 MW(th) is required to make 8 kg of fissile plutonium per year by unreported irradiations with a load factor (LF) of 0.85."[1] By assuming a 0.90 load factor for the Binford estimate, Moriarty and Bragin have established an upper bound on the maximum possible quantity of plutonium that can be produced by a thermal research reactor, as described in Ref. 2. The minimum reactor power to produce an SQ drops to 36 MW(th) with the assumed load factor of 0.90. After modifying Moriarty and Bragin's expression, we obtained the following expression for our estimated maximum plutonium production (EMPu) calculations:

EMPu [kg/yr] = 0.224 [kg/MW(th) yr] •
Operating Power Level [MW(th)]

A number of factors ultimately influence the actual rate of plutonium production in a reactor, including reactor operation (load factor, irradiation time, and power level), the fluence (product of irradiation time and flux magnitude), the reactivity, and target material (type, quantity, design, location, and heat dissipation). For an in depth discussion of these production factors see Binford's report[1] and for a briefer discussion see Moriarty and Bragin's report.[2]

Table 2. Number of Thermal Research Reactors Within Power Range and the Estimated Maximum Plutonium Production (EMPu)

Operating Power Level (MW(th))	Number of Reactors	EMPu @ LF = 0.90 (kg/yr)	Years to Produce 1 SQ (yr/SQ)	Aggregated EMPu for Power Level (kg/yr)
1 - 5	42	0.22 - 1.12	36.36 - 7.14	26.768
6 - 10	18	1.34 - 2.24	5.97 - 3.57	38.976
11 - 15	3	2.46 - 3.36	3.25 - 2.38	9.856
16 - 20	2	3.58 - 4.48	2.23 - 1.79	8.960
21 - 25	2	4.70 - 5.60	1.70 - 1.43	10.752
26 - 30	5	5.82 - 6.72	1.37 - 1.19	32.704
31 - 35	0	6.94 - 7.84	1.15 - 1.02	-
36 - 40	3	8.06 - 8.96	0.99 - 0.89	26.880
> 40	5	> 9.18	< 0.87	97.440
Total	80	-	-	252.336

SAFEGUARDS CRITERIA IMPROVEMENTS

The factors that effect the rate and ability to produce plutonium in a reactor also provide indicators and observables for an inspector. Some of these include deviation from normal reactor operation (low burnup, high power, high fuel/core throughput, shutdown frequency variance, and change in research activity), engineering changes that increase cooling capacity or target access, and the presence of fertile material, targets or stored irradiated fertile material. Binford[7] and Moriarty and Bragin[3] should be reviewed for a more specific and lengthy discussion of these indicators. The Safeguards Criteria[6] provide the means to identify and interpret many of these observables, especially if the research reactor has a power rated at 25 MW(th) or larger. Some of the recent improvements in safeguards technology facilitate the safeguards approach. Improvements in containment and surveillance as well as automated accounting and record keeping provide the ability to more cost effectively meet safeguards goals. The Safeguards Criteria require that, to confirm the absence of unrecorded production of direct-use material at research reactors, an "analysis shows that the reactor could not produce 1 SQ of plutonium"[6] per year but "for reactors with thermal power of 25 Mwt or less, no analysis is required."[6] The choice of a thermal power threshold of 25 MW(th) or greater requiring increased scrutiny has two potential safeguards problems associated with it. The first problem pointed out by Binford[7] and again by Moriarty and Bragin[3] is that the specified threshold only refers to the declared maximum operating power of the reactor. Typically reactors have been conservatively designed, so that without any engineering modifications it is possible to operate a reactor at up to 40%–50% greater power. That is, "a reactor with a declared nominal maximum operating power of 25 MW(th) could be operated at 35 MW(th) or more."[3] Because this could be achieved without engineering modifications, safeguards criteria related to design verification are ignored and it has an important impact on the time to produce an SQ. The second problem is that of multiple research reactors each producing small quantities of plutonium such that safeguards criteria are not triggered or indicated. This was mentioned by Binford, "it is much easier to conceal the annual production of a small quantity—one or two kilograms of plutonium—than that of a 'significant' quantity"[7] and is abstractly related to the sixth conclusion in Moriarty and Bragin.[3] This study is only related to thermal research reactors, when other small potential production sources are considered, the combination of multiple production potentials provides an impetus to more carefully consider criteria that address the consolidated quantity.

CONCLUSIONS

To strengthen the Safeguards Criteria, an approach for research reactors that can produce less than 1 SQ/yr should be investigated and techniques developed; in particular, when multiple research reactors exist, the aggregated production capability should be utilized for the SQ

Table 3. EMPu and Number of Years to Produce a SQ in NNWS Thermal Research Reactors ≥1MW(th).

NNWS	EMPu (kg/yr)	Years. to SQ
Algeria	3.584	2.23
Argentina	1,120	7.14
Australia	2,240	3.57
Austria	1,120	7.14
Bangladesh	0.672	11.90
Belgium	23,296	0.34
Brazil	1,120	7.14
Bulgaria	0.448	17.85
Canada	30,688	0.26
Chile	3,360	2.38
Czech. Rep.	2,240	3.57
Denmark	2,240	3.57
Egypt	0.448	17.85
Germany	17,696	0.45
Greece	1.120	7.14
Hungary	1.120	7.14
India	31,584	0.25
Indonesia	6,944	1.15
Iran	1.120	7.14
Iraq	1,120	7.14
Israel	6,944	1.15
Italy	11,872	0.67
Japan	19,824	0.40
Korea, N.	1,792	4.46
Korea, S.	2,688	2.97
Libya	2,240	3.57
Malaysia	2,240	3.57
Mexico	.224	35.71
Morocco	.448	17.85
Netherlands	7,168	1.11
Norway	6,048	1.32
Pakistan	2,016	3.96
Peru	2,240	3.57
Philippines	.672	11.90
Poland	8,960	0.89
Portugal	.224	35.71
Puerto Rico	.448	17.85
Romania	3,808	2.10
S. Africa	4,480	1.78
Sweden	11,648	0.68
Switzerland	8,960	0.89
Taiwan	9,184	0.87
Thailand	.448	17.85
Turkey	1,344	5.95
Venezuela	.672	11.90
Yugoslavia	2,240	3.57
Zaire	.224	35.71

value in Section 4[6] not just under Section 13[6] ("Entire States"). This investigation should be conducted in association with developing a safeguards and design information reverification approach for states that have numerous research reactors and that takes into account the potential maximum operating power rather than the declared power. We believe that enhanced safeguards techniques and technology need to be investigated and for their effectiveness to be determined.

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