LA-13209-MS

Estimation of Feasible Unreported Plutonium Production in Thermal Research Reactors in the Potential Nuclear Weapon States

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Editied by Chris Pearcy, Group CIC-1
Prepared by Sharon Hurdle, Group NIS-7

Footnote, if there is one

LA-13209-MS

UC-940
Issued: January 1997

Estimation of Feasible Unreported Plutonium Production in Thermal Research Reactors in the Potential Nuclear Weapon States

Jared S. Dreicer

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

ESTIMATION OF FEASIBLE UNREPORTED PLUTONIUM PRODUCTION IN THERMAL RESEARCH REACTORS IN THE POTENTIAL NUCLEAR WEAPON STATES

by

Jared S. Dreicer

ABSTRACT

As of December 1995, 284 research reactors (research, test, training, prototype, critical assemblies, and electricity-producing) were operational worldwide; 149 of these were in nonnuclear weapon states (NNWS).[1] As part of the Global Nuclear Material Control Model effort, we previously estimated that in one year an upper bound maximum of roughly one-quarter of a metric ton (250 kg) of plutonium could be produced in 80* thermal research reactors, based on their reported power output.[2] Those calculations were based on a study by Moriarty and Bragin[3] concerning the unreported plutonium production at six research reactors, which indicated 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. We concluded that the International Atomic Energy Agency (IAEA) Safeguards Criteria[4] needed to be reevaluated and strengthened in two ways: (1) an approach for research reactors that can produce less than 1 SQ/yr should be developed but when multiple research reactors exist, the aggregated production capability should be utilized for the SQ value and (2) the 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 <u>feasible</u> maximum operating power rather than the declared power. In this paper we focus on the cumulative maximum unreported plutonium production over the period of operation for research reactors in the potential nuclear weapon states† (PNWS) estimating the upper bound maximum plutonium production based on both the research reactor declared power level and at a feasible power level 50% greater than declared. There are currently 12 research reactors in the PNWS (Algeria, Iran, Iraq, Libya, North Korea, and Syria), including the two shut down in Iraq and one under construction in Syria. Of the nine operational research reactors, five are thermal reactors that have a power rating of 1 MW(th) or greater and

* At the end of 1993 there were 303 operational research reactors worldwide of which 155 were in the NNWS and 80 of the 155 had a declared operating power of 1 MW(th) or greater.

† Potential nuclear weapon states in this context means those states that are perceived to have, or have, openly demonstrated or expressed a desire to have a nuclear weapons capability.

could be utilized to produce plutonium. Of the remaining four, three are critical assemblies and one is a miniature neutron source reactor. We estimate that in one year a maximum of roughly 9 kg of plutonium could be produced in these five operational thermal research reactors combined, based on their reported power output. We also estimate that prior to shutdown of Iraq's reactors roughly 10 kg of plutonium could have been produced. Further, we have calculated the quantity of plutonium and the number of years that would be required to produce an SQ of plutonium in these five operational thermal research reactors, and one of the shutdown Iraqi reactors, as well as the total amount aggregated for the PNWS.

I. INTRODUCTION

International agreements and treaties in the arms control and disarmament, and material protection, control, and accounting (MPC&A) arenas have been established between the US and the former Soviet Union (FSU). As a result, the possibility of a nuclear-related military exchange is effectively nonexistent between these powers. Further, the ongoing progress between the US and the FSU, and international developments regarding a Comprehensive Test Ban Treaty and Fissile Material Cut-Off Treaty, indicate a definite reversal in the trend toward vertical proliferation. Presently the predominant threat to US national and international security appears to be the global proliferation of fissile material related to excess obtained from military weapons. This is true even though the total quantity of nonseparated plutonium contained in stored commercial spent fuel and currently separated commercial plutonium is considerably greater than the excess and dismantled separated weapons plutonium. However, if the plutonium is recycled (plutonium is separated from the spent fuel) for the closed fuel cycle then the plutonium in commercial spent fuel may continue to be separated. 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,[5] regardless of whether or not the closed fuel cycle is pursued by more states. A study by the National Academy of Sciences[5] (NAS) and the National Security Science and Technology Strategy[6] (NSSTS) both initiatives from the highest levels of the US government, indicate the need to deal with this excess military and commercial fissile material by supporting a system and procedures for global MPC&A as part of a disposition program. One of the primary recommendations of the NAS study is "that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and HEU worldwide."[5] 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."[6]

The combined quantity of plutonium produced as a result of the military weapon and civilian energy fuel cycles is significant. By the end of 1993 the combined quantity of plutonium produced was estimated to be 1,095 MT.[5] Table 1 summarizes the decomposition of this military and civilian plutonium inventory. The civilian-related plutonium inventory represented about 77% of the total. The military inventory was roughly a third the size of the civilian inventory, but only about 17% of the civilian plutonium was separated. The military plutonium inventory is distinguished by several factors; first, 100% of the military inventory is separated and secondly 91% of it is weapons-grade, some in weapon component form. Therefore, imminently resolving the proliferation concerns of this military inventory is critically important because of the menacing implications of the military plutonium.

.

Table 1. Global Civilian and Military Plutonium Inventories

Global Inventory, End 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 Ref. 7.

In light of these facts it is easy to understand why global proliferation concerns are focused on the excess and dismantled weapons-grade nuclear material resulting from past military production. Regardless, it is important that the alternative means of plutonium production in research reactors not be neglected and their implications dismissed. The premise of this study is that even though the risk and impact of illicit plutonium production in research reactors by the PNWS appears quantitatively insignificant relative to the existing military and commercial-related plutonium (tens of kilograms versus hundreds of metric tons), feasible production needs to be understood.

Now that vertical proliferation is waning, indigenous fissile material production or the proliferation of fissile material related to excess military or commercial fuel cycles are the likely sources for horizontal proliferation. Horizontal proliferation and terrorist proliferation will be the fundamental proliferation threats in the future. The possibility of horizontal proliferation in a number of states creates the requirement to better understand, influence, and curtail the underlying impact of indigenous production. In order to be better prepared for proliferation events similar to recent experiences in Iraq and North Korea, prior estimates of the indigenous production capability are necessary. These estimates will provide an understanding and appreciation of the technical capabilities present in these states, as well as quantify the possible fissile material source for these states. Nuclear safeguards provide the mechanism and ability to influence and curtail indigenous production capability. Simply defined, nuclear safeguards are technical and inspection measures for verifying that nuclear materials are not being diverted from civil to weapons uses (see Appendix A for a detailed discussion of nuclear safeguards). To better comprehend the quantity and distribution of plutonium in the PNWS that could result from unreported production in thermal research reactors, we conducted these calculations using the Global Nuclear Material Control Model.[8,9]

II. GLOBAL NUCLEAR MATERIAL CONTROL MODEL

The Global Nuclear Material Control Model (GNMCM)[8,9] characterizes site and facility information, nuclear material inventory data, and nuclear material production capabilities worldwide. 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 graph*

* 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).

theory, safeguards and security, disposition, and proliferation. This study was conducted by utilizing the proliferation capabilities where the estimates for the plutonium production in all thermal research reactors in the world were computed. 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 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.

III. FEASIBLE PLUTONIUM PRODUCTION IN RESEARCH REACTORS IN THE PNWS

At the beginning of 1996 there were 284 operational research reactors (research, test, training, prototype, critical assemblies, and electricity producing) worldwide, listed in the IAEA research reactor database. Of the 284 research reactors worldwide, 149 of these were in NNWS and 12 (1 under construction) were in the PNWS (Algeria, Iran, Iraq, Libya, North Korea, and Syria). The 12 research reactors include two shut down in Iraq and one under construction in Syria. Of the nine operational research reactors, five are thermal reactors that have a power rating of 1 MW(th) or greater and could be utilized to produce plutonium. The four remaining are critical assemblies (LWSCR, GSCR, and HWZPR) and a miniature neutron source reactor (MNSR). Table 2 provides a brief summary of these 12 research reactors.

The five operational thermal research reactors (ARR-1, ES-SALAM, TRR, IRT-1, and IRT-DPRK) are capable of producing plutonium. As part of the GNMCM project we estimated that in one year about 9 kg of plutonium could be produced in all combined. This estimate was based on the following assumptions: a one-year period, a reactor load factor (LF) of 0.90, fertile targets (^{238}U), a thermal power for the research reactors of 1MW or more, and the application of the declared maximum operating power.

These calculations are based on a study by Moriarty and Bragin[3] concerning 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 analysis of the results from the study of these six large thermal research reactors; it has not been verified to be applicable to fast reactors or critical assemblies. 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 of 0.85.”[3] 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. 3. 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:

$$\text{EMPu [kg/yr]} \approx 0.224 \frac{\text{kg}}{\text{MW(th) yr}} \times \text{Operating Power Level [MW(th)]} \;.$$

Table 2. Summary Information for Research Reactors in the PNWS through September 1995

Country	Reactor Code	Reactor Name	Operating Power Level (kW(th))	Criticality Date (Mn/Yr)	Number Years Oper.	Shutdown Date
Algeria	DZ-0001	ARR-1	1000.0	03/89	6.50	
Algeria	DZ-0002	ES-SALAM	15000.0	02/92	3.58	
Iran	IR-0001	TRR	5000.0	11/67	27.83	
Iran	IR-0002	LWSCR	-	06/92	3.25	
Iran	IR-0003	GSCR	0.001	06/92	3.25	
Iran	IR-0004	HWZPR	0.001	06/93	2.25	
Iran	IR-0005	MNSR	30.0	03/94	1.50	
Iraq	IQ-0001	IRT-5000	5000.0	06/67	27.25	91/03
Iraq	IQ-0002	TAMMUZ-2	500.0	03/87	4.00	91/03
Libya	LY-0001	IRT-1	10000.0	03/83	12.50	
N. Korea	KP-0001	IRT-DPRK	8000.0[a]	08/65	30.08	
Syria	SY-0001	MNSR	30.0	Under Construction		

Source: Derived from Refs.1 and 2.
[a]This research reactor has been declared as being 5000.0 kW(th)[1]and also as 8000.0 kW(th).[2]

We have calculated the EMPu, the number of years that would be required to produce an SQ, and the aggregated EMPu for the respective research reactor power levels. As mentioned previously the aggregate EMPu for the five research reactors totals roughly 9 kg. Table 3 summarizes this data by providing values based on the declared operating power level. For example, a research reactor operated at 5 MW(th) power with a load factor of 0.90 is estimated to be capable of producing plutonium at a rate of 1.12 kg/yr and would take roughly 7.14 years to obtain 1 SQ.

Table 3. Number of Thermal Research Reactors Within Declared Power Range and the Estimated Plutonium Production (EMPu) in the PNWS

Declared Operating Power Level (MW(th))	Number of Reactors	EMPu @ LF = 0.90 (kg/yr)	Years to produce 1 SQ (yr/SQ)	Aggregated EMPu for Reactor Power Level (kg/yr)
1 - 5	2	0.224 - 1.120	35.71 - 7.14	1.344
6 - 10	2	1.344 - 2.240	5.95 - 3.57	4.032
11 - 15	1	2.464 - 3.360	3.25 - 2.38	3.360
Total	5[a]	-	-	8.736

[a]This includes the following five reactors: ARR-1, ES-SALAM, TRR, IRT-1, and IRT-DPRK.

These calculations represent an upper bound estimate on the plutonium production potential; more accurate neutronic calculations require specific knowledge concerning reactor operation, fuel, and target configurations. The actual rate of plutonium production in a reactor is ultimately dependent on a number of production factors including: the type, quantity, design, location, and heat dissipation of the target material; the load factor, irradiation time, and power level related to reactor operations; the product of irradiation time and flux magnitude (fluence); and the reactivity. For a more complete discussion of all these production factors see Binford's report[10] and for an abbreviated discussion see Moriarty and Bragin's report.[3] These production factors each impact the production of plutonium and all are important, but of concern in this study is the power level. The plutonium production rate corresponds to the power level which is proportional to the flux. The primary thermal criterion of this type of reactor is the requirement to prevent nucleate boiling anywhere in the core; this typically requires that the fuel surface temperature not surpass the saturation temperature by more than 10^{o}C on average. This thermal principle limits the power level at which this type of reactor can operate because of the correlated heat load. Heat dissipation is the dominant design consideration. Adequate heat dissipation keeps the fuel's surface temperature slightly (several degrees) above the saturation temperature at the maximum flux produced by the power level. Typically, for safety these reactors have been designed and engineered to exceed this thermal criterion. This results in a fundamental problem from the nonproliferation perspective, that the specified threshold only refers to the <u>declared</u> operating power of the reactor, not the <u>feasible</u> maximum power level. Thus, without any (perhaps minor) engineering modifications it is possible to operate a reactor at up to 40%–50% greater power, since as a rule the reactors have been conservatively designed from a thermal perspective. To increase the power level a number of variables can be exploited: raising the reactor pressure which increases the saturation temperature (for tank-type reactors which have a closed primary-coolant system), increasing the heat transfer area of the target material, increasing the velocity of coolant flow, increasing the capacity of the secondary cooling system, prior to inlet decreasing the temperature of the primary coolant, and carefully arranging the target configuration. Ultimately, "a reactor with a declared nominal maximum operating power of 25 MW(th) could be operated at 35 MW(th) or more."[3] The values in Table 4 indicate that the feasible reactor power level has an important impact on the quantity of plutonium produced and the time to produce an SQ. Operating the research reactors at a feasible 50% greater power level results in a 50% increase in the EMPu and a 33% reduction in the time to produce 1 SQ. For the five PNWS thermal research reactors combined, the total quantity of plutonium that could be produced increases to 13.104 kg/yr.

For those states that are signatories of the NPT, Article III requires states to accept international safeguards for verifying that no "diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices"[11] has taken place. The IAEA negotiates a Safeguard Agreement with each signatory (approximately 175). There are basically two types. The first type (Type 153) is termed full scope or comprehensive safeguards because, in accordance with the NPT, it applies to all nuclear materials, equipment, and facilities in a state. The second type (Type 66) applies safeguards to a specific quantity of material, piece of nuclear equipment, or facility. Safeguards implemented by the IAEA are only tasked with verifying the accuracy of a state's nuclear material declarations, which is intended to verify nonproliferation and to increase the risk of the timely detection of diversion, which is intended to deter proliferation. Safeguards implemented by the IAEA are only responsible for material control and accountancy, which is verified by inspection, audit, and technical means. For those states that are not signatories to the NPT there is still the potential that nuclear safeguards may be required as defined by Article III Section 2.0.

Section 2.0 requires that an NPT signatory state that transfers nuclear technology to a non-NPT signatory, to ensure that the recipient state place that nuclear technology under international safeguards by establishing the second type of safeguards agreement. When Algeria, Iran, Iraq, and N. Korea received the research reactors, facility-specific international safeguards were eventually implemented either because of bilateral agreements or in connection with the supply of nuclear technology under the NPT, and not because they were NPT signatories. All four subsequently became NPT signatories. Libya was an NPT signatory when it was supplied the research reactor. Table 5 shows the NPT signatory status and the date of entry, the status of international safeguards, the date safeguards were initiated (agreement in force), and the duration of any gap in safeguards coverage for the PNWS with thermal research reactors (this excludes Syria).

Table 4. Number of Thermal Research Reactors Within Declared Power Range and the Estimated Plutonium Production (EMPu) Using the Feasible Power Range (50% Greater than Declared) for the Thermal Research Reactors in the PNWS

Declared Operating Power Level (MW(th))	Number of Reactors	EMPu for Feasible Power Level @ LF = 0.90 (kg/yr)	Years to produce 1 SQ Feasible Power (yr/SQ)	Aggregated EMPu for Feasible Reactor Power Level (kg/yr)
1 - 5	2	0.336 - 1.680	23.81 - 4.76	2.016
6 - 10	2	2.016 - 3.360	3.97 - 2.38	6.048
11 - 15	1	3.696 - 5.040	2.16 - 1.59	5.040
Total	5*	-	-	13.104

*This includes the following five reactors: ARR-1, ES-SALAM, TRR, IRT-1, and IRT-DPRK.

Table 5. NPT Signatory Status and Initiation of Safeguards in the PNWS with Thermal Resarch Reactors

Country	NPT Signatory	IAEA Safeguards	Reactor	Criticality Date	Safeguards Initiated	Duration Not Covered
Algeria	NO	YES YES	ARR-1 ES-SALAM	03/89 02/92	02/23/89 06/02/92	0.00 0.00
Iran	YES - 5/15/74	YES	TRR	11/67	12/04/67	0.00
Iraq	YES - 2/29/72	YES	IRT-5000	06/67	02/29/72	4.75
Libya	YES - 7/08/80	YES	IRT-1	03/83	07/08/80	0.00
N. Korea	YES - 4/10/92	YES	IRT-DPRK	08/65	07/20/77	11.94

IV. FEASIBLE PRODUCTION SITUATIONS

In order to place these estimated plutonium production values in perspective, four cases will be presented that report the cumulative maximum plutonium production (CMPu). The CMPu (kg/years-operating) reflects the total quantity of plutonium that could have been produced based on the number of years that each research reactor operated. The cases are defined by the four possible combinations of the declared operating power level, the feasible (50% greater) operating power level, the presence of safeguards, and the lack of safeguards for each research reactor. For each research reactor either there were no safeguards implemented or the research reactor had already been placed under nuclear safeguards at the time it went critical or sometime during its period of operation. The upper bound estimates for each of the four cases are based on the assumptions previously mentioned: 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 declared or the feasible (50% greater) operating power. Additionally, the tables for the four cases include the 5 MW(th) shut-down Iraqi research reactor (IRT-5000) along with the other five operational research reactors. The Iraqi research reactor has been included because it was in operation up until it was shut down in March 1991, as a result of the Gulf conflict. The following estimated values reflect the theoretically feasible maximum plutonium production in the worst case. That is, assuming the optimal plutonium-producing environment given the research reactors: that with no safeguards present it was possible to produce at this level, and if safeguards were implemented at some point after the research reactor first went critical, then it was possible to operate at this level up until the initiation of safeguards (this applies to the IRT-5000 and IRT-DPRK).

Case 1 reports the CMPu for the research reactors operating at the declared power level with (A) no safeguards during the entire period of operation and (B) taking into account the duration of safeguards. Case 2 reports the CMPu for the research reactors operating at the feasible power level with (A) no safeguards during the entire period of operation and (B) taking into account the duration of safeguards.

CASE 1A: Declared Operating Power Level with No Safeguards

Table 6 summarizes the period of operation, EMPu, number of years required to produce an SQ of plutonium, and CMPu for six PNWS reactors, assuming declared operating power. The first CMPu column values in Table 6 assume that no safeguards were implemented during the entire period of operation for each facility. The CMPu (kg/years-operating) reflects the total quantity of plutonium that could have been produced given the number of years that each research reactor operated, applying the same assumptions previously mentioned and assuming unimpeded plutonium production opportunity during the period of operation.

Without the difficulties related to masking illegitimate operation of a research reactor due to the lack of safeguards and the desire to produce plutonium in their research reactors, each PNWS could have produced more than an SQ during the period of operation. A load factor of 0.90 could be achieved without the need to mask plutonium production activity and conceal fertile materials. The combined total CMPu for the PNWS is 157.077 kg, with Iran, Iraq, Libya, and N. Korea contributing 31.169 kg, 30.52 kg, 28.0 kg, and 53.903 kg, respectively. The EMPu (.224 + 3.36 = 3.584), number of years operated (6.50 + 3.58 = 10.08), and CMPu (1.456 + 12.0288 = 13.485 kg) for Algeria reflects the aggregate for the ARR-1 and ES-SALAM research reactors.

CASE 1B: Declared Operating Power Level and Duration of Safeguards

The last two columns of Table 6 summarize the number of years the research reactors actually operated without safeguards implemented and the CMPu during operation without safeguards. These two columns again utilize the declared operating power and assume safeguards were implemented during either the entire period or were applied at some point during the period the facility was in operation. The CMPu (kg/years-operating) reflects the total quantity of plutonium that could have been produced given the number of years that each research reactor operated under safeguards, applying the same assumptions previously mentioned and assuming impeded plutonium production opportunity during the period of operation.

Assuming that the international safeguards were effective from the point in time that a facility was placed under safeguards, there are two states with interesting facilities: Iran and N. Korea. Table 6 provides the actual period of time that the research reactors in these two states operated but were not under safeguards. The IRT-5000 in Iran first went critical on 06/67; however, international safeguards were not implemented until essentially 03/72, for a total period of 4.75 years unsafeguarded. The IRT-DPRK went critical on 08/65 and did not have international safeguards implemented until essentially 08/77, for a total period of roughly 12.0 years unsafeguarded. The combined total CMPu during the period each research reactor was not under safeguards is 26.716 kg. The IRT-5000 could have produced 5.32 kg of plutonium during those 4.75 years and the IRT-DPRK could have produced 21.396 kg of plutonium during those 11.94 years.

Table 6. Case 1: Cumulative Maximum Plutonium Production (CMPu) for Declared Operating Power Level with No Safeguards During Entire Period of Operation and Accounting for Duration of Safeguards Implementation

States	# of Reactors	EMPu (kg/yr)	Years to SQ	# Years Oper.	CMPu No Safeguards (kg/yrs-oper)	# Years Oper. No Safeguards	CMPu With Safeguards (kg/yrs-oper)
Algeria	2	3.584	2.23	10.08	13.485	0.00	0.000
Iran	1	1.120	7.14	27.83	31.169	0.00	0.000
Iraq	1	1.120	7.14	27.25	30.520	4.75	5.320
Libya	1	2.240	3.57	12.50	28.000	0.00	0.000
N. Korea	1	1.792	4.46	30.08	53.903	11.94	21.396
Total	6[a]	9.856	0.81	-	157.077	-	26.716

[a]This includes the following six reactors: ARR-1, ES-SALAM, TRR, IRT-5000, IRT-1, and IRT-DPRK.

CASE 2A: Feasible Operating Power Level with No Safeguards

Table 7 summarizes the period of operation, EMPu, number of years required to produce an SQ of plutonium, and CMPu for six PNWS reactors, assuming feasible (50% greater than declared) operating power. The first CMPu column values in Table 7 assume no safeguards were implemented during the entire period of operation for each facility. The CMPu (kg/years-operating) reflects the total quantity of plutonium that could have been produced given the number of years that each research reactor operated, applying the same assumptions previously mentioned and assuming unimpeded plutonium production opportunity during the period of operation.

Again and even more relevant in this case, without the difficulties related to masking illegitimate operation of a research reactor due to the lack of safeguards and the desire to produce plutonium in their research reactors each of the PNWS could have possibly operated their research reactor at up to 50% greater than declared power. This would have resulted in each PNWS having produced significantly more than an SQ during the period of operation. A load factor of 0.90 could be achievable without the need to mask plutonium production activity and conceal fertile materials. The combined total CMPu for the PNWS is 235.611 kg, with Iran, Iraq, Libya, and N. Korea contributing 46.754 kg, 45.78 kg, 42.0 kg, and 80.85 kg respectively. The EMPu (.336 + 5.04 = 5.376), number of years operated (6.50 + 3.58 = 10.08), and CMPu (2.184 + 18.0432 = 20.2272 kg) for Algeria reflects the aggregate for the ARR-1 and ES-SALAM research reactors.

CASE 2B: Feasible Operating Power Level and Duration of Safeguards

The last two columns of Table 7 summarize the number of years the research reactors actually operated without safeguards implemented and the CMPu during operation without safeguards. These two columns again assume feasible operating power and also assume safeguards were implemented during either the entire period or were applied at some point during the period the facility was in operation. The CMPu (kg/years-operating) reflects the total quantity of plutonium that could have been produced given the number of years that each research reactor operated under safeguards, applying the same assumptions previously mentioned and assuming impeded plutonium production opportunity during the period of operation.

Assuming that international safeguards were effective from the point in time that a facility was placed under safeguards, as in Case 1B, there are two states with interesting facilities; Iran and N. Korea. Given the actual period of time that the research reactors in these two states operated but were not under safeguards, the combined total CMPu is 40.075 kg. The IRT-5000 could have produced 7.98 kg of plutonium during the 4.75 years and the IRT-DPRK could have produced 32.095 kg of plutonium during the 11.94 years.

Table 7. Case 2: Cumulative Maximum Plutonium Production (CMPu) for Feasible Operating Power Level with No Safeguards During Entire Period of Operation and Accounting for Duration of Safeguards Implementation

States	# of Reactors	EMPu (kg/yr)	Years to SQ	# Years Oper.	CMPu No Safeguards (kg/yrs-oper)	# Years Oper. No Safeguards	CMPu With Safeguards (kg/yrs-oper)
Algeria	2	5.376	1.49	10.08	20.227	0.00	0.000
Iran	1	1.680	4.76	27.83	46.754	0.00	0.000
Iraq	1	1.680	4.76	27.25	45.780	4.75	7.980
Libya	1	3.360	2.38	12.50	42.000	0.00	0.000
N. Korea	1	2.688	2.98	30.08	80.850	11.94	32.095
Total:	6*	14.784	0.54	-	235.611	-	40.075

*This includes the following six reactors: ARR-1, ES-SALAM, TRR, IRT-5000, IRT-1, and IRT-DPRK

V. CONCLUSIONS

The values resulting from these calculations reflect the theoretically possible maximum plutonium production in the worst case, for both declared and feasible power levels. That is, advantageous plutonium producing-factors (target material, reactor operation, reactivity, and fluence) are assumed. For the cases where safeguards were implemented, we have assumed that the safeguards were effective. The conclusions from our previous study[12] indicate that the 1991 IAEA Safeguards Criteria[4] may in fact accommodate an opportunity for a proliferant state with one or more small (25 MW(th) or less) thermal research reactors. We concluded that the IAEA Safeguards Criteria[4] needed to be reevaluated and strengthened in two ways: (1) an approach for research reactors that can produce less than 1 SQ/yr should be developed and when multiple research reactors exist, the aggregated production capability should be utilized for the SQ value, and (2) the 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 feasible maximum operating power rather than the declared power. Applying the IAEA Safeguards Criteria[4] to this study, implies that the research reactors in the PNWS may not have been adequately safeguarded. This results from the fact that none of the research reactors analyzed have a declared power level greater than 15 MW(th) (or a feasible power level greater than 22.5 MW(th)) and none could produce 1 SQ in less than 2.38 years. From a proliferation standpoint, there should be concern. It should be noted that in this study we mentioned (footnote to Table 2) the discrepancy regarding the declared power level of the North Korean IRT-DPRK; from a worst case perspective we chose to utilize the greater power level. We are currently investigating the ramifications and impact on possible plutonium production for the different declared power levels.

REFERENCES

1. Nuclear Research Reactors In the World, Reference Data Series #3, IAEA-RDS-3/09 (IAEA, Vienna, 1995).
2. Nuclear Research Reactors In the World, Reference Data Series #3, IAEA-RDS-3/09 (IAEA, Vienna, 1993).
3. T. F. Moriarty and V. N. Bragin, "Unreported Plutonium Production At Large Research Reactors," *Nucl. Mater. Manage.* **XXIII**, 1173-1178 (1994).
4. International Atomic Energy Agency - Safeguards Criteria, 1990-11-21, 1990.
5. National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (National Academy Press, Washington, D.C., 1994).
6. Office of Science and Technology Policy, National Security and International Affairs Division, National Science and Technology Council, Committee for National Security, *National Security Science and Technology Strategy* (Washington, D.C., 1995).
7. D. Albright, W. Arkin, F. Berkhout, R. Norris, and W. Walker, *SIPRI Yearbook 1995 Armaments, Disarmament, and International Security* (SIPRI, Oxford University Press, 1995).

8. J. S. Dreicer and D. A. Rutherford, “Global Nuclear Material Control Model,” presented at the ANS Embedded Topical Meeting: DOE Spent Fuel and Fissile Management, Reno, Nevada, June 16-20, 1996.

9. J. S. Dreicer and D. A. Rutherford, “Fissile Material Proliferation Risk,” Los Alamos National Laboratory report LA-UR-96-895 (1996).

10. F. T. Binford, “ISPO C-50 Phase I - Diversion Assumptions for High-Powered Research Reactors,” Oak Ridge National Laboratory report ORNL-6022 (January 1984).

11. L. S. Spector, M.G. McDonough, and E.S. Medeiros, *Tracking Nuclear Proliferation: A Guide in Maps and Charts* (Carnegie Endowment for International Peace, 1995).

12. J. S. Dreicer and D. A. Rutherford, “Global Estimation of Potential Unreported Plutonium Production in Thermal Research Reactors,” *Nucl. Mater. Manage*. **XXX**, (1996).

APPENDIX A: NUCLEAR SAFEGUARDS

Nuclear material safeguards and security has three fundamental elements: material protection, material control, and material accounting. Material protection includes those activities that are required to physically protect the nuclear material, safeguards information, and essential systems from theft, diversion, or sabotage by any individual or group; material control includes those capabilities and systems that restrict access to the nuclear materials and that limit the utilization of nuclear material to authorized uses; and material accounting includes those activities that preserve information concerning the location, quantity, and type of nuclear materials. These three elements are interrelated—nuclear material safeguards must be integrated into the operation of a facility or plant and its elements must act as a cohesive system to be effective. Safeguards implemented by the IAEA address only material control and accountancy; protection is the responsibility of the state.

Material protection provides the physical elements necessary to deter, detect, delay, and respond to special (fissile) nuclear material (SNM) threat. This includes the following functions: intrusion detection, alarm and delay systems, and protective force response. Material protection is simplistically thought of as the “guns, gates, and guards” element.

Material control is a system that typically includes the following components: process monitoring, containment, surveillance, access and egress control, item verification, and anomaly resolution. Process monitoring for SNM provides methods to estimate the quantity of material in inventory and includes statistical tests to detect abrupt loss of material, quality control tests to detect process differences, and data analysis to detect patterns of loss or gain. Containment impedes direct access to nuclear material and provides an indication that the containment was violated through the use of seals on storage containers and vaults. Surveillance, such as closed circuit video camera systems, provides protection of material when it is possible to gain access to or divert the material. Access and egress control limits access to nuclear materials to only authorized personnel (e.g., through badge reader systems and personnel identification devices) and verify that unauthorized removals of nuclear material do not occur (e.g., through use of metal and radiation detectors, X-ray systems, and portal monitors) as well as prevent prohibited items from entering nuclear material areas. Item verification activities ensure that data related to the identity, location, and elemental and isotopic contents is maintained regarding items. Nondestructive assay (NDA) instruments and sensors and chemical analysis (destructive assay) are utilized to measure and determine the elemental and isotopic content of material; this permits subsequent measurement to indicate item integrity. Anomaly resolution ensures that all inventory discrepancies or diversion indications are resolved.

A material accountability system maintains current information and data on the quantity, type, and enrichments for all material within each material balance area. This system includes the following components: record-keeping, measurements, measurement control, physical inspection, material balance closure, statistical analysis, and anomaly resolution. The record-keeping system provides accounting information, including elemental and isotopic content based on physical measurement or technically estimated values for all SNM. Measurement control demonstrates that the material balance uncertainty and measurement bias are minimized. The following expression defines material balance:

material balance = book inventory - ending physical inventory ,

where *book inventory = beginning physical inventory + receipts - transfers.*

Physical inventories are conducted by on-site inspection. Material balance closure involves reconciling any differences that exist between the physical inventory and the book inventory. Error bounds for measurement values and inventory differences are established by statistical analysis. Anomaly resolution ensures that all measurement discrepancies or diversion indications are resolved.

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545