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Evaluation of Covert Plutonium Production from Unconventional Uranium Sources

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Abstract

The potential for a relatively non-advanced nation to covertly acquire a significant quantity of weapons-grade plutonium using a gas-cooled, natural uranium-fueled reactor based on relatively primitive early published designs is evaluated in this article. The economic and technical issues that would influence the design decisions of a covert ^{239}Pu production program are considered.

Several unconventional uranium acquisition approaches were explored. Methods for extracting uranium from enrichment tails, seawater, and coal ash sources were considered. The evaluation indicated that uranium extraction from coal ash or in-situ leaching from underground deposits could be performed in economical manner that might be difficult to detect by the international community. These two methods were estimated to be within the technical capabilities of an under-developed nation. Calculations performed using the Monte Carlo N-Particle code (MCNP) showed that extracting uranium from enrichment tails would not be a technically feasible source for reactor fuel fabrication because the ^{235}U concentration inside the enrichment tails would not be high enough to maintain criticality in the relatively unsophisticated reactor design considered.

The SCALE code package was used to perform reactor physics and depletion calculations used to evaluate the effect of different combinations of uranium irradiation time and reactor power density had on plutonium production rates and isotope concentrations. The results of these simulations were used to estimate the desirability of the modeled plutonium for use in a weapon with published material attractiveness figures of merit. All the modeled reactor conditions produced material that was highly attractive for use in a nuclear weapon.

Historical examples of early gas-cooled reactors were used to examine the complexity associated with building various gas-cooled reactor designs. These examples were compared to simulated reactor conditions. The choices that a covert unsophisticated nuclear weapons program might consider when designing a reactor were evaluated. An air-cooled design was found to be a simple and cost effective solution for a group interested in producing a small number of significant quantities (8 kg) of plutonium.

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I. Introduction

Nuclear security policy must often address the question, "How much effort should be devoted to making systems proliferation resistant?" To answer this question a quantitative analysis of probable threats should be attempted. Time and expense is spent securing different stages of the reactor fuel supply chain. The material moving through these secured stages is classified as safeguarded and transfers are restricted by agencies acting under the authority of international treaties. The international safeguards regime is designed to make acquiring the materials needed to create a nuclear weapon or key components associated with a nuclear weapon very difficult. This article examines the difficulty associated with obtaining fissile material for a nuclear weapon outside of the safeguarded fuel supply chain.

The working hypothesis in this paper is that a rogue state or sub-national group would employ a relatively simple air-cooled graphite reactor, based on early weapons state reactor designs. This hypothesis is rooted in the assumption that the group would not have access to safeguarded materials and information needed to produce enriched uranium. The group is also assumed to have no access to any other safeguarded material including used nuclear fuel. Under this scenario, the uranium reactor fuel and graphite moderator are fabricated from raw materials from safeguards exempt sources. Expanding the safeguards regime to cover these unconventional sources of material is assumed to be cost-prohibitive.

A preliminary analysis of the minimum required raw material flows based on historical examples and simulated models is presented. These raw material estimates provide a method of analyzing the physical requirements associated with an undeclared weapons program using the described methods and resources. The raw materials required by a covert program to produce one significant quantity of plutonium annually can be used to estimate the minimum size of the reactor core and supporting structures needed given a particular reactor configuration. Comparisons drawn between the historical and modeled examples are used to inform assumptions regarding choices that a covert program would make. Assessments such as this can serve as a first-order metric for evaluating the relative feasibility of detecting various clandestine programs.

II. Historical Reactor Examples

The gas-cooled reactors built for plutonium production and research purposes during the first three decades following WWII provide examples of designs that unsophisticated groups might imitate today. The gas-cooled reactors built by the U.K. and France are of particular interest because these two nations designed, constructed and operated their initial units without any outside assistance. These indigenous projects were completed with the limited resources that their postwar economies could furnish. Neither country was capable of marshaling the research and industrial forces that the United States and Soviet Union used during the Cold War. Instead, the French and British governments took advantage of the relatively low cost and complexity associated with fissile material production in low power gas-cooled reactors.

While the British and French nuclear industries did eventually develop sophisticated fuel enrichment and reactor technologies that were on par with the United States and Soviet capabilities, the initial relatively simple reactors are likely candidates for imitation by modern day covert plutonium production programs. The urge to duplicate older reactor designs is strengthened by the wealth of information about these designs available in open literature. The British design for the Calder Hall units was reproduced on a smaller scale by North Korea to produce plutonium for the North Korean weapons program. The historical reactor examples described in this section provide information regarding the probable field of reactor designs from which an unsophisticated nation might select.

A. Early UK Reactors

The air-cooled Windscale Piles and CO2-cooled Calder Hall units were able to produce plutonium that was highly attractive for use in weapons. The Windscale and Calder Hall designs allowed the British government to produce nuclear devices with less sophisticated technologies than the water-cooled designs used by the United States and Russian nuclear weapons programs. The construction and operation of the reactors were indigenous efforts that could be replicated by modern states today. The Windscale reactors had an average power density of 1 megawatt thermal per metric ton of natural uranium (MWt/MTU) **[*1*]**, and the Calder Hall design operated at 1.53 MWt/MTU **[*2, 3*]**. These low power densities resulted in plutonium that contained over 90% ^{239}Pu.

The Windscale reactors were closed after the 1952 fire in Pile 1. Calder Hall was only the first in a series of Magnox (**Mag**nesium **Ox**ide) reactors that the British government would build. The later more advanced CO2-cooled reactors were able to operate at higher temperatures, efficiently producing commercial power and weapons grade plutonium. Over time the power density of the new reactors increased with Hinkley Point producing 2.65 MWt/MTU in 1965 **[*2*]**. The more advanced Magnox reactors featured control systems of greater complexity than the Calder Hall and Windscale units. These features were incremental improvements built into the reactor designs as the British government gained operational experience. Because these reactors have been in operation for decades and many have begun or completed the decommissioning process, a large amount of detailed information regarding the British Magnox designs is available in open literature. A nation-state might attempt to replicate on a smaller scale parts of the later Magnox designs in a non-power generating reactor. Significant cost and time savings could be realized because sophisticated control and safety systems that were later implemented in the commercial power Magnox fleet maybe unnecessary for a for a program solely focused on producing weapons.

B. French G-Series at Marcoule

The French G1 reactor was brought online in 1956 and featured an air-cooled design similar to the earlier British Windscale piles **[*4*]**. This reactor had a 42 MWt power rating and, unlike the Windscale piles, it produced a small amount of electricity. The G1 reactor was constructed in 15 months **[*5*]** and contained 1,200 tonnes of graphite **[*6*]** and 100 tonnes of fuel **[*4*]**. The G2 reactor was completed in 1958 **[*5*]** and operated as a weapons-grade plutonium production and commercial power plant. The G2 plant had a higher power density with 200 MW of thermal output when loaded with 120 tons of natural uranium. G2 used CO2 as its primary coolant instead of air because graphite is chemically reactive with the oxygen in air at the high temperatures needed to efficiently produce power **[*7*]**. These two reactors when combined with the later G3 reactor produced the majority of the French defense industry's plutonium during their respective periods of operation.

C. The U.S. Chicago Pile, X-10 and Brookhaven

The United States first built the Chicago Pile on a squash court at the University of Chicago for criticality experiments. Chicago Pile was followed by the air-cooled X-10 reactor in Oak Ridge, which produced small amounts of plutonium for the WWII effort and functioned as a test bed for technology that would be used in later larger scale plutonium production facilities. The U.S. built and operated the air-cooled Brookhaven graphite research reactor that was capable of producing 9 kg of weapons grade plutonium a year **[*8*]**. This reactor produced 30 MW of thermal power and contained 60 tons of natural uranium fuel. The reflector and shielding were made from 4.5 feet of graphite and concrete, respectively. This simple reactor was identified by J.R. Lamarsh as an ideal candidate for emulation by a weapons seeking state **[*9*]**.

D. North Korean Example

The North Korean government built a 5 MWe, CO2-cooled, natural uranium-fueled, research reactor based on declassified U.K. plans for the Calder Hall reactors **[*10*]**. This reactor is capable of producing approximately one significant quantity (SQ) of plutonium metal (defined by the IAEA as 8 kg) per year. The plutonium produced in the reactor is removed from the spent fuel at a reprocessing plant based on the design used at the multinational Eurochemic Mol-Dessel plant in Belgium.

The North Korean example is particularly salient in that it provides a useful case study with several parallels to the type of scenario proposed within this study.

III. Raw Material Acquisition

By examining the potential raw material sources a covert program might exploit, we can draw conclusions about the speed and costs associated with producing the fissile material. The technical and economic feasibility of various raw material acquisition paths are discussed in this section and detectable actions associated with each of these paths are considered.

A. Uranium Sources Considered

An unsophisticated group would likely use a simple reactor design at a low power density if sufficient supplies of natural uranium were available. Large purchases of uranium are generally transferred to a conversion facility and then enriched prior to being delivered to the buyer **[*11*]**. International proliferation safeguards increase after the conversion and enrichment stages.

Natural uranium purchased on the open market in quantities necessary to produce significant quantities of weapons-usable plutonium would likely result in detection by the international community. Sales to buyers that are not first delivered to a conversion facility would likewise raise suspicion. Stealing a sufficient amount of natural uranium might be difficult and would alert intelligence services of the covert plutonium production program before the first material has entered the reactor. A group attempting to acquire tonnes of natural uranium metal without drawing attention from concerned agencies may therefore need to pursue unconventional sources.

The uranium could be covertly acquired using standard mining techniques if uranium deposits exist in an area controlled by the group. Likely techniques include open pit mining or in situ leach mining from uranium deposits. Alternatively, an actor could choose to exploit unconventional uranium resources, including extraction from seawater or coal ash.

1. Open Pit Mining

Open pit mining could be used to extract uranium ore from a known subterranean deposit. This form of extraction is relies on traditional mining methods and equipment. Open pit mining operations also have the largest infrastructure that is visible from the surface, increasing the likelihood of detection. The true purpose of an open pit uranium mine could be concealed by declaring that mining activities are being directed at another element found in the uranium ore.

2. Leach Mining

Leach mining or in-situ solvent extraction can be more easily concealed than an open pit mining operation. The observable infrastructure at the surface is minimal in comparison to the open pit method. Leach mining for uranium can be concealed by either disguising the process as an effort to extract another material via hydraulic fracturing or conceal the entire project. A leach-mining project's primary observables that could lead to detection are the above ground infrastructure, solvents that are purchased to

extract the uranium and the process waste streams.

3. Seawater Extraction

Cost estimates have been performed on the technology and procedures needed to extract uranium from seawater **[*12*]**. The estimates have shown that seawater extraction is considerably more expensive than traditional mining methods. Seawater extraction technology is still in the development phase as well and large purchases of necessary materials might arouse suspicion.

4. Coal Ash Extraction

Bottom coal ash from certain coal sources contains sufficient uranium to make solvent based extraction methods competitive with open market uranium prices **[*13, 14*]**. When these solvent based methods are combined with bottom coal ash containing higher concentrations of uranium the process is considerably more cost-effective than seawater extraction methods **[*11*]**. The ratios of initial coal mass to bottom ash mass and bottom ash mass to uranium mass contained in bottom ash vary widely. Low-ash coal are generally 2-5% of bottom ash, typical range is 10-20%, and maximum 50% of bottom ash content. Typical uranium concentrations in bottom ash ranges from 10 ppm to 200 ppm, but can reach 2% in extreme cases (Nejdek mine), depending on the coal type **[*15*–*17*]**.

Bottom coal ash is a highly reused commercial material and as such it can easily be purchased on the open market. Meanwhile, *in situ* leaching and coal ash extraction processes requires less capital investment and present a smaller observable footprints than the open pit mining processes.

5. Uranium Enrichment Tails

This study also evaluated the feasibility of reusing unprotected uranium enrichment tails that contain less than 0.3% ^{235}U; these enrichment tailings are generally stored in low-security areas and do not fall under international safeguards agreements.

B. Nuclear-Grade Graphite

While nuclear-grade graphite is a controlled material, the availability of graphite for a primitive reactor is unlikely to be a significant barrier since manufacturing of high-purity graphite is a well-known and mature technology **[*18*]**. Therefore, in this analysis, we assume the resources spent on obtaining the graphite are a minor contribution to the overall effort and cost.

IV. Plutonium Production and Detection

Because the focus of this article is on an unsophisticated group secretly trying to produce a nuclear weapon, the speed, size and complexity of the entire operation must be considered. The total mass and isotopic composition of the plutonium contained in irradiated fuel exiting the reactor will directly influence the design of the plutonium extrication facility and the weapon's implosion system. A balance would be struck between the lengths of the irradiation period, mass of natural uranium needed and the physical qualities of the final plutonium to make optimal use of the group's resources and minimize the probability of detection. The designer's control mechanisms for these competing goals are the reactor's fuel load capacity and power density parameters. This section articulates how plutonium is evaluated for use in weapons and how perceived detection capabilities might influence a weapons program.

A. Plutonium Attractiveness

The reactor would need to have sufficient residual reactivity (ρ) to remain critical throughout the entire irradiation period. The amount of residual reactivity required is a function of burnup, which is a function

of irradiation time and reactor power level. Higher effective fuel burnups (i.e., through longer irradiation times and/or higher specific powers) produce more plutonium, but the plutonium contains a higher percentage of undesirable isotopes including ^{240}Pu. An increase in these isotopes potentially results in greater worker dose rates and increased heat generation. ^{240}Pu also complicates the bomb design process due to its high spontaneous fission rate, which makes assembling a supercritical mass difficult. Lower effective burnups (achieved through lower power densities and shorter irradiation times) result in plutonium that has a greater percentage of ^{239}Pu and is subsequently more attractive for use in weapons. The lower power densities and smaller irradiation periods also require the use of considerably more initial natural uranium to produce one significant quantity of plutonium. Los Alamos National Laboratory published two figures of merit for calculating nuclear material attractiveness for use in fissile weapons **[*19*]**. This measure was developed in consultation with weapons experts to provide an open-source metric for material attractiveness. The Figure of Merit formulae are given as Equations 1 and 2.

$$\mathrm{FOM}_1 = 1 - log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left(\frac{D}{500}\right)^{\frac{1}{log_{10}2}}\right) \quad (1)$$

$$\mathrm{FOM}_2 = 1 - log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{MS}{6.8\cdot 10^6} + \frac{M}{50}\left(\frac{D}{500}\right)^{\frac{1}{log_{10}2}}\right) \quad (2)$$

The Figure of Merit formulae terms include heat content in watts/kg of plutonium (h), the bare sphere critical mass in kg (M), and absorbed dose rate in rad/hr to a human target standing one meter away from a sphere consisting of 20 percent of one bare sphere critical mass (D). The FOM_2 formula (Equation 2) additionally considers the effect of the spontaneous neutron emission rate per kg of Pu (S) as it relates to premature detonation ("fizzle") in a weapon design, resulting in lower than expected yield. The FOM_1 formula is intended to evaluate the material attractiveness from the perspective of a group that is not concerned with a weapon failing to fission the entire plutonium mass or a group that is capable of designing around such constraints, such as a state with relatively advanced nuclear capabilities.

The U.S. government has experimented with plutonium containing less than 90 percent ^{239}Pu and produced viable weapons designs. These designs are more difficult to construct and the FOM_2 formula accounts for the design difficulties encountered when larger percentages of spontaneously fissioning isotopes are present. The FOM_2 formula was developed to describe attractiveness from the perspective of a group that is interested in building a reliable and high-yield weapon but does not have the ability to create a more complex device capable of fissioning the vast majority of ^{239}Pu present in a bare sphere critical mass contaminated with larger amounts of ^{240}Pu. The FOMs are interpreted in the following manner by Bathke et al. [19]:

FOM	**Weapons Utility**
> 2	Preferred
1-2	Attractive
0-1	Unattractive
< 0	Unattractive

Material deemed preferred is usable by a group with minimum weapons design capabilities and material deemed attractive is consider to be usable but greater effort and sophistication might be required. Unattractive material may still be usable in a fissioning weapon but far greater effort and sophistication will be required. The attractiveness of the material as indicated by the two formulae is governed by the group's capabilities and their objectives.

B. Detection Timeliness Goals

The IAEA has released timeliness guidelines for the detection of undeclared activities and materials related to the production of nuclear weapons **[*20*]**. Under these guidelines, plutonium in irradiated or "spent" fuel would ideally be detected within 1–3 months. Plutonium that has been separated from the fuel by reprocessing would ideally be detected within 7–10 days, and uranium reactor fuel containing less than 20% ^{235}U enrichment has a detection goal of 1 year. These goals have been used in this study to determine potential time frames for processes in a covert production program.

C. Difficulties Associated with Reprocessing Detection

The PUREX process **[*21*]** is the most common plutonium extraction method and is assumed to be the path that an unsophisticated group would take. The off-site detection of noble gases released during undeclared reprocessing activities is dependent on the distance between the detector and the reprocessing instillation, rate of reprocessing, spent fuel characteristics, and environmental factors including the weather and background radiation **[*22–24*]**. If a reprocessing facility is located in an area that experiences rapid fluctuations in the atmospheric concentration of the noble gas isotopes being measured, then the lower level of detection might be above the concentration resulting from the reprocessing activities **[*25*]**. The simplest way to avoid detection would be to site the facility in a sufficiently remote location such that any released plume would be too dilute to detect.

V. Description of Simulations Performed

A. MCNP Criticality Searches

Research conducted on behalf of the U.S. Arms Control and Disarmament Agency **[*18*]** showed that graphite purchased on the commercial market, outside of the regulated nuclear supply chain, commonly contains 1-3 ppm boron-equivalent contamination. Often suppliers do not report the boron content of graphite. This paper assumes that a product containing less than 2-ppm boron-equivalent contamination can be acquired on the open market by testing production lot samples prior to purchase.

The effect that boron contamination in the moderating graphite has on criticality was measured for boron concentrations between 0 and 2 ppm using MCNP 6.1 **[*26*]**. A series of criticality simulations were performed during which the fuel fraction and square lattice pitch were varied for each contamination level. The simulations ascertained the lower limit of ^{235}U concentration in the fuel elements required for criticality. The modeled reactor had a fuel temperature of 400◦C and a graphite temperature of 300◦C, which were used with ENDF/B-VII.0 cross-section data at 600 K.

B. Reactor physics & isotopic depletion

The TRITON module in the SCALE code **[*3*]** was used to model the rate of plutonium production for the $^{236\text{-}242}$Pu isotopes in a graphite reactor with 2-ppm boron contamination. The MCNP criticality searches were used to determine that a square lattice pitch of 22 cm would be appropriate in the SCALE simulations given the average fuel fraction and fuel radius used in early gas reactors and the 2-ppm boron contamination in the modeled graphite. A 2-D model consisting of an infinitely reflected square lattice with each cell composed of a 3.5106 cm diameter uranium slug positioned at the center of a 22 cm pitch was created to conduct the criticality searches. This configuration is shown in Figure 1. A similar geometry that included stainless steel cladding was used to perform the calculations described below and the variation in results between the clad fuel rods and unclad fuel rods was found to be negligible.

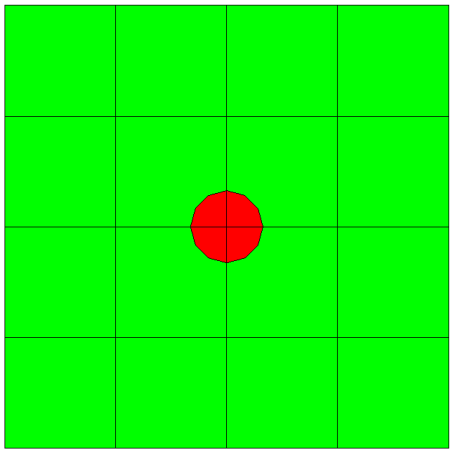

Figure 1. Scale 6.1 single pin cell geometry. The 3.5106 cm diameter uranium slug is shown at the center of the 22 cm pitch. The entire area outside of the fuel slug is modeled as graphite.

The model simulated power densities between 0.1 to 3.16 megawatts thermal per metric ton of initial natural uranium fuel (MWt/MTU). This range of power densities was chosen based on the previous operational experience of the U.K. and French reactor fleets. The irradiation time in the reactor was varied between 1 and 365 days for each power density. TRITON modeled the isotopic mass composition of the spent fuel 90 days after being re- moved from the reactor. The heat generation rate and $^{236-242}$Pu isotopic concentration values were also modeled during the simulations.

C. Radiation Dose

The ORIGEN module for depletion and decay analysis **[*27*]** was used to model the neutron and gamma flux from a sphere containing 20% of 1 SQ (1.6 kg) of plutonium with an isotopic distribution matching the result from each of the prior TRITON simulations. The flux was separated into energy bins and multiplied by ICRP fluence to dose conversion coefficients to acquire a dose rate in rad/hr. **[*28*]**. The dose rate was multiplied by a solid angle of 0.14 steradians, which represents a human standing one-meter away from the sphere with an exposed surface 1.75 meters tall and 0.11 meters wide. The solid angle calculations used for the dose rate model are shown in Equations 3 and 4.

$$\Omega = 4\arccos\sqrt{\frac{1+\left(\frac{x}{2z}\right)^2+\left(\frac{y}{2z}\right)^2}{\left(1+\left(\frac{x}{2z}\right)^2\right)\left(1+\left(\frac{y}{2z}\right)^2\right)}} \tag{3}$$

$$\Omega = 4\arccos\sqrt{\frac{1+\left(\frac{1.75}{2}\right)^2+\left(\frac{0.11}{2}\right)^2}{\left(1+\left(\frac{1.75}{2}\right)^2\right)\left(1+\left(\frac{0.11}{2}\right)^2\right)}} \approx 0.14sr \tag{4}$$

VI. Results

A. Enrichment Tails

Figure 2 shows the result of the criticality search performed on the graphite-moderated pin cell model for a variety of fuel enrichments. The simulations were designed to determine the minimum uranium enrichment required to achieve a critical configuration (k_{inf} = 1) given a boron contamination level. The plot shows that the lowest enrichment for a graphite- moderated reactor as a function of boron equivalent impurities in graphite is 0.615% when the graphite contains 2-ppm boron.

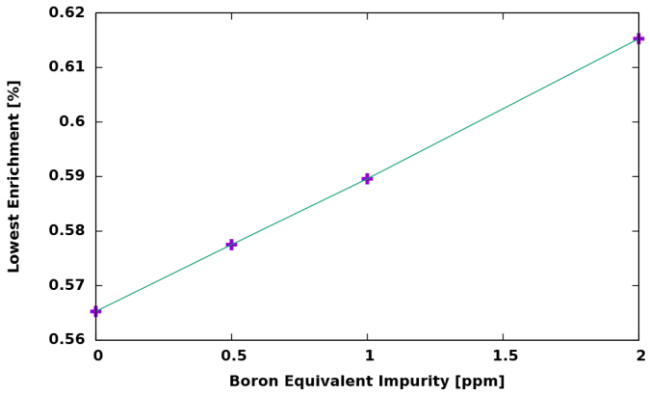

Figure 2. Enrichment requirements for a critical reactor with varying concentrations of boron in the graphite.

The ^{235}U concentration in the uranium hexafluoride waste stream from a typical light water fuel enrichment plant contains less than 0.3% ^{235}U enrichment. Tails therefore cannot be considered a viable option for graphite reactor fuel.

B. Criticality with 2ppm Boron Contamination

Figure 3 shows the required fraction of fuel volume to graphite volume in each lattice cell, lattice pitch, and uranium enrichment for a gas-cooled graphite reactor with 2-ppm boron contamination.

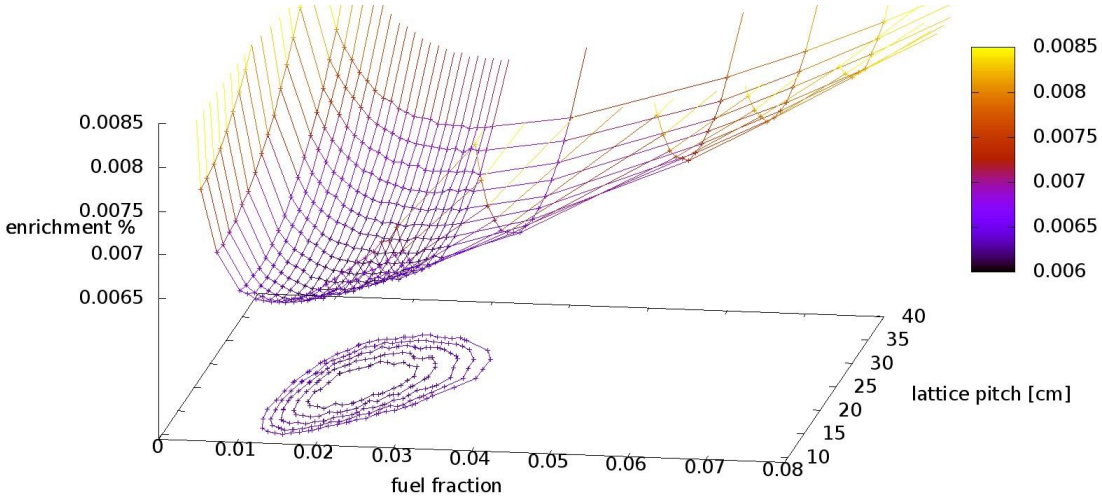

Figure 3. Enrichment vs. lattice pitch vs. fuel fraction for a critical reactor with 2 ppm boron in the graphite.

The 2-ppm contamination level would allow a reactor with a lattice pitch, fuel radius, and fuel fraction similar to the British Windscale Piles and Calder Hall designs to reach criticality-using uranium containing at least 0.65% ^{235}U.

The plutonium produced by every combination of irradiation time and power density simulated was rated "preferred" by the FOM_1 and FOM_2 formulae. The more stringent FOM_2 evaluations resulted in in a minimum score of 2.48 while the FOM_1 evaluation had a minimum of 2.51. This finding shows that plutonium produced by a group using any of the reactor design concepts previously disc used would be highly usable in a weapon. Therefore differences in the design complexity and ultimate performance of a weapon can be considered negligible if a covert program invests in a gas-cooled reactor path based on the historical designs.

Figure 4 shows the FOM_2 evaluation results, tonnes of coal ash needed to produce one SQ of plutonium and the fraction of the ^{239}Pu mass to total plutonium mass for all the irradiation time and power density combinations are displayed. The year of initial operation, power density, cladding type and cooling gas for historical reactor examples are also shown in this figure for comparison. Estimates of coal ash requirements based on 160-ppm uranium concentration in the bottom ash. The 160-ppm U value used is based on a commercial uranium extraction project **[*29*]** and the reader is advised to consider the large variability of the uranium content in the coal ash, as discussed above in Section III.A.4.

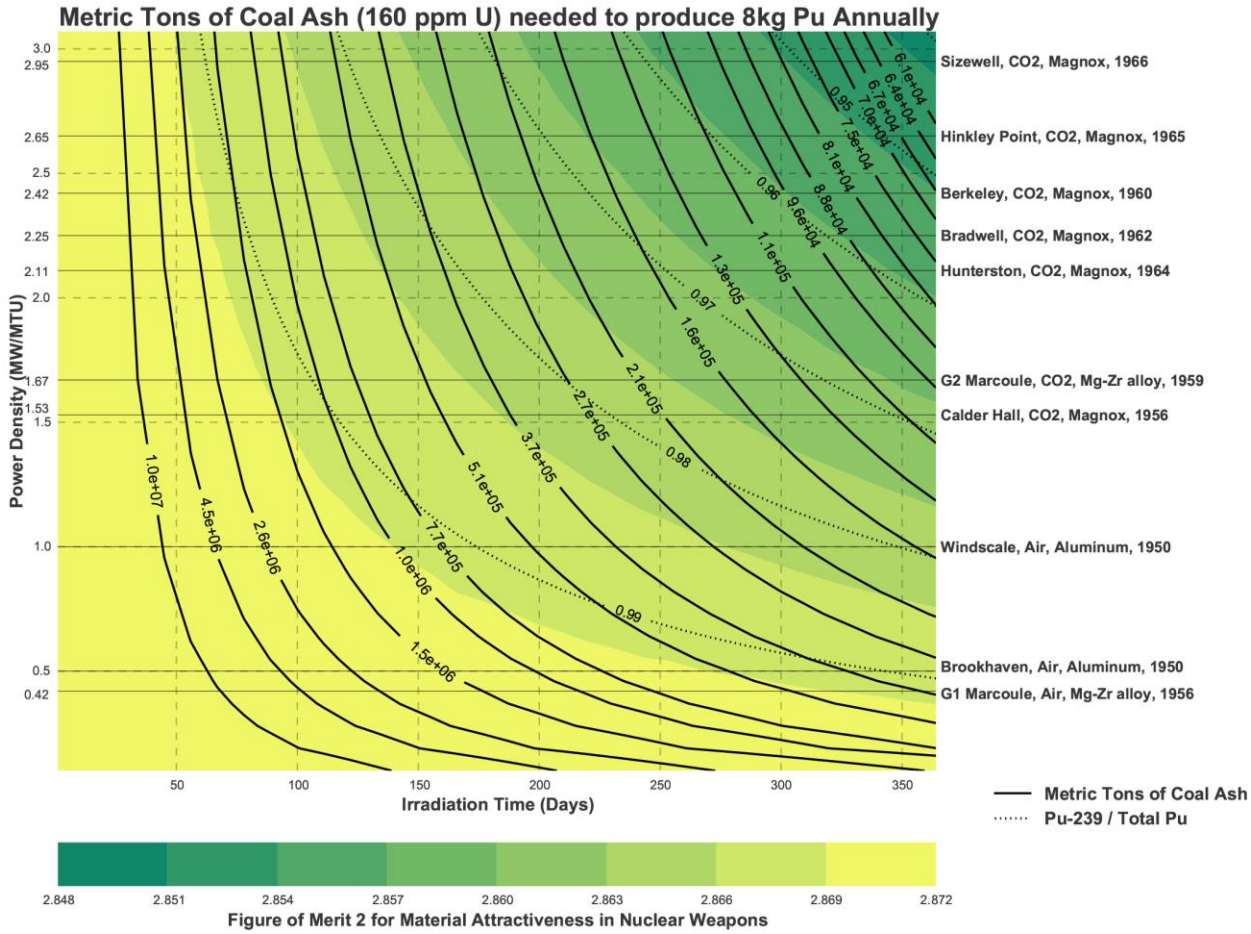

Figure 4. Grid of power density and irradiation time combinations comparing the amount of uranium bearing coal ash required to produce one BSCM, FOM_2 evaluations, ^{239}Pu to total PU mass ratio. Historical reactor examples are show as well, with their name, cooling gas, cladding material, and year of initial operation.

VII. Conclusions and Future Work

The earliest and simplest of the historical reactor examples used air as the cooling gas and operated at lower power densities than the more sophisticated later CO_2-cooled examples. The early designs that used

air-cooling would allow a group to assemble a plutonium production reactor without constructing a more complex cooling system. The low power density designs also require more natural uranium to produce a single SQ of plutonium. If the Windscale piles are taken to be the upper limit for air cooled reactor power density, then 160,000 metric tonnes of coal ash bearing 160-ppm U would be needed to produce one SQ of Pu from air-cooled design within a year. This volume of coal ash is not unreasonable given the quantity that is produced each year. Coal ash is most frequently recycled as a raw material in concrete and 160,000 tonnes could be purchased on the open market without drawing suspicion. Chemical treatment of the ash to prevent future leaching is common. Removing the uranium from the ash could be disguised as a routine pre-treatment step. Environmental sampling to know how much uranium is in each ash heap is cost-prohibitive and the expanding the current safeguards regime to restrict the flow of bottom ash or coal containing higher deposits of uranium would as a result be unfeasible.

If a group has the ability to build a CO_2-cooled reactor than higher power densities can be utilized. A reactor similar to the G2 unit at Marcoule would need to 96,000 tonnes of 160-ppm U coal ash to produce one SQ of Pu annually. This mass of coal ash might not be small enough to encourage a group seeking to produce only a few SQs of Pu a year to invest the resources needed to build the more complex recirculating CO_2-cooled reactor instead of a once through air-cooled reactor. If the group has the ability to site the reactor in a remote area with easy access to a large secondary heat sink than the CO_2-cooled reactor could be built with a higher power density and possibly smaller footprint, making detection more difficult. As the power density of the reactor rises, the appeal of the CO_2-cooled designs becomes more apparent.

Further research is required to perform a complete economic analysis of a covert program that uses coal ash as the initial source of uranium. This preliminary evaluation does show that this unconventional pathway is a technically viable option. However, the reader should note that no detailed analysis of the relative difficulty of this approach compared to more conventional proliferation pathways was made in this paper.

VIII. Acknowledgments

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