EXAMINATION OF THE POTENTIAL FOR DIVERSION OR CLANDESTINE DUAL USE OF A PEBBLE-BED REACTOR TO PRODUCE PLUTONIUM

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ABSTRACT

This paper explores the susceptibility of Pebble-Bed Reactors (PBRs) to be used overtly or covertly for the production of plutonium for nuclear weapons. The basic assumption made for the consideration of overt production is that a country would purchase a PBR with the ostensible motive of producing electric power; then, after the power plant was built, the country would divert the facility entirely to the production of weapons material. It is assumed that the country would then have to manufacture production pebbles from natural uranium. The basic assumption made for covert production is that the country would obtain and use a PBR for power production, but that it would clandestinely feed plutonium production pebbles through the reactor in such small numbers that the perturbation on power plant operation would be very difficult to detect. This paper shows the potential rate of plutonium production under such constraints. It is demonstrated that the PBR is a very poor choice for either form of proliferation-intent use.

1. Introduction

The Pebble Bed Reactor (PBR) concept is receiving emphatic renewed interest. For example, an international consortium [1] is intent on developing and deploying such a reactor in the near future, with the ultimate goal of international commercialization and deployment of large numbers in developing countries and elsewhere. This optimistic business assessment stems from the numerous inherently and passively safe features of the reactor concept. Furthermore, modular design allows high technology fabrication to be shifted to centralized locations with deployment in low technology markets. The possible (and in some fuel cycle patterns, necessary) recirculation of the fuel pebbles and the online de-fueling and refueling of these reactors raise questions about their potential use as production facilities for weapons materials. However, these features also allow the reactors to operate with very little excess reactivity. In a previous study [2], it was demonstrated that the dual use of a PBR (simultaneous production of power and weapons materials) would be detected easily and promptly in the case where the production pebbles are designed to resemble the legitimate fuel pebbles closely. In this paper, additional scenarios are considered. These include more sophisticated cases of covert dual use with illicit production pebbles introduced into the core, overt diversion of the facility for weapons materials production, and construction of an even more suitable replacement facility using equipment removed from the original reactor. The principal assumptions of the study are presented in the next section. Then the scenarios considered are outlined. They are followed by a description of the various models and methods used. The subsequent section presents model results. The conclusion section summarizes the principal findings of this study.

2. Technological and Safeguards Context Assumptions

In this study, it assumed that a country purchases a PBR presumably for the legitimate purpose of producing energy (electricity and/or process heat, etc.). The purchasing country is assumed not to possess front-end fuel cycle capabilities or technology. Thus, it could not produce enriched fuel to supplement fuel that it acquires from an external supplier. It is assumed that the reactor owners and all possible reactor fuel suppliers subscribe to an established safeguards regime in which no new fuel is supplied until previous batches of spent fuel are returned or accounted for and safeguarded, as appropriate. Under these conditions, the illicit dual use of the facility would require the manufacture of production pebbles by the reactor owner, their illicit introduction into the reactor, and their retrieval and extraction from the reactor fuel cycle prior to their detection by safeguard related systems. The principal controlling mechanism is the requirement that fresh fuel supplies be subjected to the concomitant return of corresponding batches of already used fuel. This requirement is based on the knowledge that the fuel utilization and the refueling patterns of a PBR used efficiently for power production are very highly and reliably predictable [3]. The fuel requirements for continued efficient operation can reliably and precisely be correlated to the power production at the facility. Thus, any significant departure from the known legitimate efficient utilization patterns would raise suspicions. The fuel vendor(s) and international safeguard organizations will know the fuel management plan that corresponds to the legitimate intended use of the reactor. Any change in fuel utilization will require satisfactory explanation.

3. Dual Use and Diversion Scenarios

Three principal scenarios have been identified in this study. These are (i) the covert dual use of the facility, (ii) the overt diversion of the facility as built, and (iii) the construction of an alternate facility using equipment diverted from the original facility ("cannibalization").

Covert Dual Use. In the first scenario, a small number of production pebbles are covertly introduced into the reactor to produce weapons materials while the reactor is still producing power. The goal of the reactor owner would be to produce weapons material at the maximum rate possible at which the effects on the legitimate fuel cycle use would be undetectable. In this scenario, the reactor owner expects to continue receiving replacement fresh fuel from the supplier. The maximum-dissimulation case of this first scenario was considered in a previous study [2]. In that study, it was assumed that illicit fuel pebbles were manufactured by the reactor owner and used as production targets in the reactor. Those illicit pebbles were assumed identical to legitimate fuel pebbles in all respects except uranium enrichment. Thus, they included the same physical features and compositions, save for the replacement of enriched uranium with natural uranium. In that earlier study, it was shown that this scenario was very impractical for the production of weapons materials and that it resulted in very early detection because of shortfalls in power production and an unjustified increase in fresh fuel needs. In that early study, the production pebbles were "optimized" to resemble the legitimate ones as much as possible. In this paper, a variant of the first scenario is considered in which the illicit pebbles are optimized to minimize the perturbation on the multiplication factor that they cause (and thus minimize their impact on neutron economy).

Overt Facility Diversion. The second scenario assumes that the reactor owner forgoes the reliance on an external fresh fuel supplier and operates the facility solely with indigenous natural uranium pebbles. In this scenario, all the reactor physical characteristics are retained, except for the use of an alternate fuel. The fuel is optimized to attempt to minimize the reactor critical size. It is shown in this paper that the original reactor cannot achieve criticality under these conditions and hence that the overt complete diversion of the facility is a physical impossibility without the connivance of a fuel supplier.

Facility Cannibalization. The third scenario examines the extreme and highly unlikely hypothesis of the "cannibalization" of the original reactor to construct a replacement facility capable of criticality. This scenario assumes that only specialized hardware and components are transferred from the original facility and used in the construction of the new one. In this scenario, it is necessary for a completely new reactor building and pressure vessel to be constructed. In this scenario, as in the previous one, no more regular fuel pebbles would be available, and the reactor owners would have to supply their own natural uranium-based fuel.

This study shows that a PBR fueled only by natural uranium pebbles would be large enough to be detectable by reconnaissance satellites. It also shows that adding natural-uranium production pebbles to the regular fuel pebble flow stream at undetectable rates would not only lead to slow production of weapons material but would also produce plutonium of very marginal quality. If higher quality plutonium is sought, the time to accumulation of sufficient materials for practical weapons use is shown to be extremely large, and not compatible with the speedy production of even a modest arsenal.

4. Methodology and Computational Models

There exist many ways by which covert production of weapons materials could be detected; here, it is assumed that a decrease in fuel utilization of more than 5% (or a commensurate increase in fuel requirements) would cause suspicion. Similarly, a discrepancy between energy production and fuel consumption or fuel requirements would raise suspicion. Furthermore, a departure of discharged fuel pebble isotopics from the nominal values that correspond to optimal plant operation would also be reasons for suspicion, because the isotopic distribution in an optimally operated PBR, a consequence of the asymptotic loading pattern, is likely unique and accurately predictable. The models developed in this study, as in the preceding one, rely on these measures to demonstrate that the PBR is not a good choice for production of weapons materials. The models developed in these studies are conservative. That is, they are devised so that their predictions are consistently more pessimistic than reality. For example, the quantity of concern [4] is taken as the lower range of a mass of weapons-grade Pu-239 that could conceivably be fashioned into a weapon regardless of the actual quality expected from the mode of production. This would assume a very sophisticated design and access to advanced technologies. Thus, in this study, about 5 kg of Pu-239 is the quantity of concern, regardless of the presence of additional Pu isotopes. Finally, it is noteworthy that the information presented in this paper contains a large number of approximations. It follows that the results, as presented, imply a certain degree of uncertainty. However, the orders of magnitude, the trends and the conclusions of the study are to be regarded as correct. The constraints on the various scenarios to weapons-material production were explored by constructing numerical models for analysis by the Monte Carlo code MCNP [5] and the new PBR fuel-cycle analysis code PEBBED [3]. These models are described in turn below.

Pebble Design Optimization Model. The objective of the production process is to transmute U-238 into Pu-239. The production pebble design is assumed to comprise a natural uranium metal sphere surrounded by a graphite shell for moderation. In this paper, these illicit production pebbles are optimized to minimize the impact from their introduction into a PBR using legitimate pebbles. An infinite lattice of these pebbles is modeled, assuming a body-centered cubic arrangement. The packing fraction for this arrangement is 0.67, which is larger than the normally observed values in the vicinity of 61% [6]. The latter value corresponds to a random arrangement, which cannot be modeled in MCNP. Other MCNP models using the body-centered cubic lattice structure [7] have adjusted the packing fraction by reducing the pebble radius, so that the pebbles do not actually touch. In an infinite lattice, this approach introduces no error, but if the array of reduced-radius pebbles were truncated into a finite region, streaming errors would be introduced. In order to have the same pebble arrangement in infinite and finite reactors, in this paper, the pebbles were allowed to be full size, and the larger packing fraction was accepted. This approximation causes the effective multiplication factor k_{eff} to be larger than it would be in reality, so it is a conservative approximation.

The production pebble is composed of a natural uranium metal sphere within a graphite shell. The uranium sphere was allowed to be either solid or hollow. Two different pebble radii were considered: the base case radius was 3.0 cm, and the radius in the other case was 2.0 cm. The inner void radius and the fuel-graphite interface radius were varied parametrically. As shown in the Results section, it was found that for either pebble radius and for any void radius the maximum value of k_∞ occurs for essentially the same value of the ratio of uranium volume to graphite volume.

MCNP Models for Reactor Diversion and Cannibalization. The second MCNP model is a finite cylinder with the same lattice arrangement as that used in optimizing the pebble design and with the pebble design selected to have the optimal uranium-to-graphite volume ratio. The core is surrounded by a graphite reflector 1 m thick, and there is an open space 1 m high between the top of the core and the bottom of the upper reflector. Some PBR studies [8] with MCNP have defined an "exclusion zone" [9] at the core periphery to eliminate partial pebbles, but no exclusion zone is defined here. The radius and height of the core were varied to seek a practical critical configuration. It is emphasized that these models specify the same fresh pebble composition throughout the core, and they take no account of the various partially burned states of the pebbles. Thus, the actual reactor would need to be even larger than the size determined by these MCNP models.

PEBBED Models for Reactor Dual Use, Diversion and Cannibalization. To assess the practicality of clandestine use of the PBR, in which covert production of weapons materials is carried out simultaneously with production of electricity, the optimally moderated weapons-production pebbles found in the first part of the study were added to the regular pebbles in a PEBBED model. PEBBED computes the asymptotic steady-state distribution of burnup, pebble composition, and neutron flux, so this model does not suffer the drawback of uniform composition that was inherent in the MCNP model. PEBBED follows the production and depletion of nuclides specified by the user. In this study, U-235, U-238, the Xe and Sm fission-product chains, and the plutonium isotopes were included among these nuclides. For various proportions of regular and production pebbles, the consequences to the fuel cycle were found. The assessment of the facility cannibalization scenario was also conducted using the PEBBED code. In this instance, the code was used to find the minimum size of a reactor with a square-cylindrical core that uses the optimized natural uranium pebbles with a packing fraction of 61%, running with the OTTO ("once through then out") cycle.

5. Results

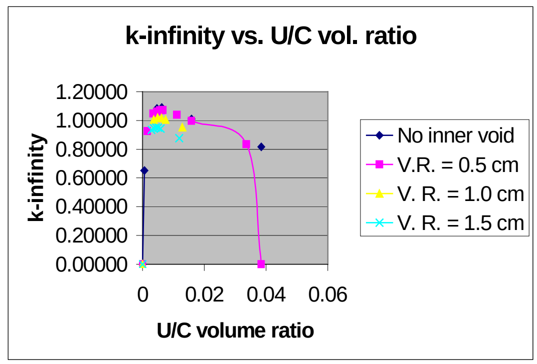

Figure 1. k_∞ vs. U/C Volume Ratio

The model results for the pebble design optimization study are shown in Figure 1 for pebbles 3 cm in overall radius. The figure shows the variation of k_∞ with the uranium-graphite ratio for several values of void radius of the fuel sphere. For each value of the inner void radius, k_∞ attains some maximum value as the volume ratio varies. Figure 1 also shows how this maximum value of k_∞ varies with the inner void radius. The greatest maximum value is seen to occur when the void radius is zero – i.e., when the fuel sphere is solid. The same conclusions are reached for pebbles of 2 cm overall radius. The uranium-to-graphite volume ratio at which k_∞ is greatest for each value of the void radius was compiled for both pebble sizes considered. Although some scatter in the values for this ratio was found, it is attributed at least in part to statistical effects from MCNP modeling. Since the departure from the average value of this ratio is small, it seems appropriate to assume that the fuel-to-moderator ratio at which the highest value of of k_∞ occurs is the same value, regardless of the details of the pebble design. This means that the most successful production of Pu-239 would be achieved by using a pebble with this volume ratio, which we take to be 0.00564, the average of all the values found. This corresponds to a solid uranium inner sphere radius of 0.533 cm, or only 17% of the radius of the pebble.

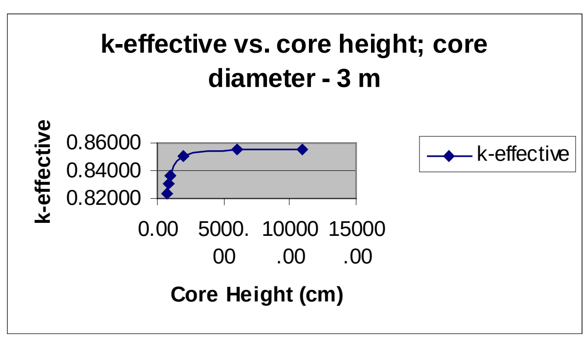

Figure 2. Criticality Search for a 3-m Diameter Core

For the various finite-reactor MCNP models, investigations were performed only for pebbles of 3-cm overall radius, optimized for maximum k_{eff}. As determined above, the fuel zone sphere is solid and the fuel-graphite interface radius is the optimally moderated value of 0.533 cm. Criticality searches were performed for two basic reactor configurations. The first one is based on a core diameter of 3 m, which is similar in scale to proposed PBR designs, and thus corresponds to the facility diversion scenario. In this search, the core radius is kept constant, but the core height is varied. Figure 2 shows the variation of k_{eff} with core height in this search. It is clear that the reactor can never become critical in this configuration. A PEBBED analysis of this scenario is redundant and was not attempted.

A second search was performed using MCNP models. This search assumed a "square cylindrical" core – i.e., the core height is equal to the core diameter. For an unreflected reactor, this is approximately the configuration that gives the minimum critical volume [10]. Since the dimensions are not constrained to those of the original reactor design, this search corresponds to the cannibalization scenario. Figure 3 shows the variation of k_{eff} with core volume. The figure shows that the reactor becomes critical when the core volume is 450 m^3, which corresponds to height and diameter of 8.3 m. This is a very large core for a PBR, requiring 2.7 million pebbles, an order of magnitude more than in a typical PBR power plant design. Furthermore, the critical volume predicted by this model applies only to the condition with all fresh fuel, and to the artificially exaggerated packing fraction in the body-centered cubic lattice. A practical production reactor would have to be even larger.

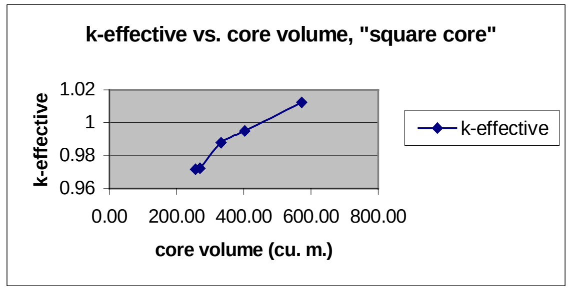

Figure3. k_{eff} for Square-Cylindrical Core Reactor

The PEBBED analysis of the cannibalization scenario reactor, completely fueled with optimized production pebbles, showed that a square-cylinder core, 11.1 m in diameter and height, operated on the OTTO cycle, could produce high-purity Pu-239 fast enough to manufacture the mass of concern (5 kg of Pu-239) in two years. This reactor also assumes a 1-m thick reflector on every side with a gap between the top reflector and the core. This configuration clearly results in an extremely large PBR; its volume is 2.39 times as large as that of the 8.3-m reactor identified in the MCNP analysis, and about 27 times as large as that of a practical PBR power plant. Such a reactor would be easily detected by satellite surveillance systems [11]. Numerous other technological challenges for the construction of such a reactor and further drawbacks of this choice of a reactor for weapons materials production exist. They are discussed elsewhere [12].

Production pebbles of the optimized design (i.e., natural uranium spheres 0.533 cm in radius within graphite shells 3 cm in external radius) were introduced into the PEBBED model of the fuel cycles of two realistic PBR designs. These designs are representative of two reactors that have been proposed for the generation of electric power: the HTR Modul 200 design and the Eskom PBMR design. PEBBED is capable of applying different recirculation schemes to different pebble types. In this study, the "driver" legitimate fuel pebbles were recirculated an average of 10 times, but the illicit production pebbles were removed after their first pass through the reactor for optimal plutonium isotopics. Introducing natural uranium into the core reduces the core reactivity. Thus, in order to maintain criticality the legitimate fuel pebble injection rate could be increased and/or their discharge burnup could be reduced. In this study, the fuel pebble injection rate was increased by 5%, an upper limit for the reduction, above which suspicion and detection would be immediate. The number of passes in a fuel pebble's life was held constant at 10, leading to a reduction in average discharge burnup. Then the production pebble injection rate was found that would restore criticality to the core. In this way, the increased demand for increased reactivity was split between lower burnup at discharge and increased injection rate.

For the PBMR, the average discharge burnup was found to decrease from 80.6 to 75.7 MWd/kg, and the production pebble flow rate was found to be 2.674 pebbles per hour. This production rate would take five years to produce 5 kg of Pu-239. However, the plutonium would be of very poor quality for weapons: the Pu-239 would only constitute 78% of the total plutonium. This low quality is due to the relatively slow passage of the production pebbles through the core. Furthermore, the decrease in legitimate pebble burnup and the increased fuel utilization would result in detection in the presence of a reasonable safeguards system. It is noteworthy that in this scenario the pebble flow rate cannot be increased in order to improve isotopics, as that would negate the assumption of *covert* dual use. For the Modul-200, the plutonium quality is similar and the production rate is even slower.

6. Conclusions

It has been shown that the dual use of a PBR to produce energy and clandestinely produce plutonium for a weapon is impractical and slow, and the plutonium yielded would be of very poor quality. It has also been shown that a PBR designed to produce weapons-quality Pu-239 using natural uranium fuel is achievable in principle. However, it would have to be very large, and it could not be entirely built by adapting a PBR initially designed for energy production using regular enriched fuel or by reusing its specialized hardware components in a new facility. The production rate of Pu-239 would be very low and incompatible with the goal of accumulating an arsenal. Such a large reactor would be remotely detectable by satellites.

It must be noted that the study ignored many issues of paramount importance to the safety and practicality of the various scenarios (dual use/cannibalization). For example, the design of the pebbles is likely to be improper for the retention of fission products and generated gases. Ensuing releases could cause health and safety concerns and would most likely make the facility easier to detect. The study could also be used for the identification of safeguard steps and procedures and for the identification of sensitive equipment. Such an extended study should be conducted.

7. Acknowledgement

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