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Safeguards Challenges for Pebble-Bed Reactors Designed by People's Republic of China

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Global Nuclear Security Technology Division

SAFEGUARDS CHALLENGES FOR PEBBLE-BED REACTORS DESIGNED BY PEOPLE'S REPUBLIC OF CHINA

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ABBREVIATED TERMS

AEC	Atomic Energy Commission
AVR	Atomversuchsreaktor
CANDU	CANada Deuterium Uranium (reactor)
DOE	U.S. Department of Energy
HEU	high enriched uranium
HTR	high-temperature reactor
HTR-PM	High-Temperature Reactor–Pebble-Bed Module
HTTR	High-Temperature Engineering Test Reactor
IAEA	International Atomic Energy Agency
INET	Institute of Nuclear and New Energy Technology
LEU	low enriched uranium
LWR	light-water reactor
NGNP	Next Generation Nuclear Plant (U.S. program)
PBR	pebble-bed reactor
PRC	People’s Republic of China
PWR	pressurized-water reactor
RSA	Republic of South Africa
SFR	sodium-cooled fast reactor
SNF	spent nuclear fuel
THTR	Thorium High-Temperature Reactor

EXECUTIVE SUMMARY

People's Republic of China (PRC) is operating a 10 MW(t) pebble-bed reactor (PBR) known as HTR-10. HTR-10 is a test reactor built to develop the construction technology for larger modular high-temperature PBRs for the commercial production of electricity and process heat. As with any new class of reactors, safeguards challenges must be addressed. Although safeguards challenges are associated specifically with HTR-10 as an operating facility, more significant safeguards challenges will be associated with PBRs if deployed in large numbers within PRC and elsewhere.

The report examines the safeguards challenges associated with the operating HTR-10 test reactor, the prototypical High-Temperature Reactor–Pebble-Bed Module (HTR-PM) that PRC is designing and building, and the commercialization of this new class of reactors. The report includes recommendations on methods to improve safeguards if PBRs are deployed widely.

The HTR-10 is a PBR in which coated-particle fuel microspheres are incorporated into graphitized carbon spheres (pebbles) with diameters of 6 cm. The reactor consists of a bed of pebbles that is refueled continuously by the flow of pebbles through the reactor core. As the pebbles exit the core, they are examined by radiation monitors to infer burnup. Pebbles with low burnup are recycled back to the reactor. Fresh pebbles replace the removed pebbles, which are stored as spent nuclear fuel (SNF). The reactor is cooled by helium. The heat from the hot helium is used to produce high-temperature steam at conditions similar to those found in traditional coal- and oil-fired power stations. The power conversion systems are those traditionally used in fossil power plants. The HTR-10 has a power output of 10 MW(t), whereas the commercial power plant will have multiple dual-module reactors, where each module is 250 MW(t) generating 100 MW(e) per module.

Unlike conventional light-water reactors (LWRs), the reactor moderator (graphite) and fuel are combined to form the fuel assembly; consequently, the concentration of uranium in the fuel is more than an order of magnitude more dilute than in other nuclear fuels. Over 80,000 SNF pebbles [~16 metric tons (MT)] would be required to be reprocessed to obtain a significant quantity of direct-use but reactor-grade plutonium (8 kg), and over 8000 fresh pebbles (~1.6 MT) would be required to obtain a significant quantity of indirect-use uranium (75 kg) enriched to less than 20% ^{235}U.

Simultaneously, the Republic of South Africa (RSA) is designing a PBR with a somewhat different design and different commercialization strategy. The U.S. Next Generation Nuclear Plant (NGNP) program is considering a PBR as one of three options for its HTR program with a goal of initial operation by 2018. The primary proponent of the PBR in the United States is Westinghouse Electric Company, which is also a partner with the RSA-chartered company PBMR Pty. All of these reactor programs are based on the original development of PBRs in the Federal Republic of Germany in the 1970s, where two helium-cooled PBRs were built, operated, and decommissioned. A baseline of experience with this class of reactor and fuel type is well documented. While the PRC, RSA, and U.S. reactor designs and strategies are somewhat different, many of the same safeguards issues apply to these proposed reactors.

PRC has defined development of a commercial PBR as one of its top 16 development projects. The main development contracts were signed on December 25, 2006, and initial operation of the two-unit precommercial plant is expected by 2013. Consequently, the PRC PBRs will likely be the first HTRs ready for commercial deployment. If the PRC program is successful, it implies a revolution in reactor technology with major worldwide implications—including major implications for safeguards. PBRs are different from traditional LWRs in five major ways.

1. *Modularity*. The PBR is a small modular reactor that could be deployed for electricity generation in many parts of the developing world. Its small size and other characteristics would also allow its use in

nontraditional markets, including oil refining, oil recovery from shale oil and tar sands, heat for biomass-to-liquid-fuel plants, and other possible process-heat markets. In each of these markets, the PBR would provide high-temperature heat (Forsberg 2008). In the longer term, the high-temperature heat may also be used for hydrogen production.

2. *Fuel and fuel cycle*. This reactor uses a different type of fuel than traditional water-cooled reactors, with radically different physical and safeguards characteristics.

3. *Safety*. The combination of small size (250 MW(t)) and choice of fuel allows the use of passive safety systems, resulting in radical simplification in nuclear plant design, a potentially higher level of safety, and much less dependence on plant operators for safety.

4. *Plant design*. The reactor plant concept is fundamentally different from any existing commercial nuclear reactor. Traditional commercial reactors have a single reactor per plant. PRC proposes multiple modular reactors per plant with the multiple reactors coupled to a single power conversion system. This implies that multiple reactors share the turbine generator, cooling towers, and auxiliary systems—including fueling and defueling systems. This design (1) enables the use of passive nuclear safety systems in a power plant with a large electrical output, (2) allows instant scale-up after demonstrating the modular reactor to any size plant by changing the number of modular reactors per plant, and (3) uses PRC's fossil power plant manufacturing infrastructure to supply the balance of plant. PRC can also manufacture the reactor pressure vessels (which have a small diameter).

5. *Manufacturing economics*. This design is associated with a radically different manufacturing model based on mass production of the nuclear components. Instead of building different sizes of reactors for different customers, the standardized reactor system is potentially more economical through its mass production. It is a reactor plant design chosen to take economic advantage of PRC strengths: (1) a rapidly growing electrical demand that can support mass production of modular reactor units and (2) economies of scale in the balance of plant using the large PRC manufacturing capability developed for balance-of-plant equipment in coal plants. If successful, the PBR may dominate reactor sales to the developing world.

To analyze safeguards challenges for these reactors, five reference threats (diversion scenarios) were defined: (1) fissile material theft by a subnational group for construction of a nuclear weapon, (2) clandestine diversion of fissile materials by the host state for construction of a nuclear weapon, (3) clandestine production of fissile materials in the facility by the host state, (4) abrogation by the host state of its participation in the Nuclear Nonproliferation Treaty and conversion of the facility to the production of nuclear weapons, and (5) radiological sabotage by subnational groups. Four safeguard challenges were examined.

1. *Diversion of stored SNF*. Two challenges can be addressed with traditional safeguards techniques: (1) ensure SNF is not diverted and (2) ensure there is no substitution of nonfuel pebbles for SNF pebbles in storage systems. Safeguards challenges are simplified relative to other SNF because the physical quantities (in terms of volume and mass) that must be stolen are far larger for an equivalent amount of plutonium. The assessment identifies two new potential technologies to improve PBR safeguards that are dependent on the unique characteristics of PBR fuel but may not be applicable to other nuclear fuels.

    - *Assay of SNF in storage.* The SNF pebbles have several unique characteristics relative to other types of SNF: (1) the burnup is roughly identical for each pebble and thus creates an SNF with a nearly uniform radiation field (uniform within the storage tank); (2) the low-density carbon with highly dispersed heavy metal content does not shield gamma rays as effectively as metal-clad fuel; and (3) the low nuclear cross-section helium coolant or even the low macroscopic nuclear cross section of low-density gaseous nitrogen (if it were substituted for more expensive helium when the SNF is in storage) implies that signals from the SNF tank are not significantly distorted or reduced by the coolant. This combination of characteristics defines potentially a new technical approach to detect substitution of dummy fuel for SNF, recognizing that very large quantities of fuel must be substituted to constitute a practical diversion risk. Channels can be left in SNF storage containers to allow calibrated gamma and neutron probes to measure the radiation versus height, or dual channels with a neutron source in one channel and the neutron detector in the other can be used to detect changes in the neutron multiplication in the stored SNF between the source and the detector as an indicator of missing fuel. Nonuniformity of the signal beyond that expected for most aged pebbles raises a flag. Calibrated systems allow inventory measurements to be made. It is a unique safeguards approach that is possible because of the unique characteristics of the PBR SNF. With traditional LWR SNF, self-shielding within the fuel assembly does not allow reliable safeguards assay of the interior of the assembly.

- *Tags*. The small pebbles and reactor characteristics make traditional SNF accounting by serial number impracticable. With commercial deployment, there will be many millions of pebbles. However, if a large number of such reactors is deployed, there are strong safeguards incentives for the ability to identify the origin of a pebble if a fresh or SNF pebble is recovered by the police or border patrol. Unlike a conventional LWR fuel assembly, any diversion will involve very large or many shipments because of the small quantity of fissile material per pebble. The large number of shipments increases the chances that some such fuel will be intercepted by police or border patrols. This suggests consideration of tags. Tags are small particles added to products to identify the lot (date and location of manufacture). The tags would assist the police in tracking the source of any illicit pebbles that are intercepted. Tags are used in a variety of commercial products and in some countries are required in conventional explosives as a method to track diversion of these products.

2. *Online refueling of target ^{238}U-loaded spheres for plutonium production*. This can be detected by two mechanisms: (1) pebble inspection to determine by the radiation signal that a target pebble has not been inserted into the reactor and (2) fuel cycle records. The use of a large number of targets to obtain a reasonable amount of plutonium implies power and reactivity shortfalls in the reactor. That is, the fresh fuel loading or enrichment will increase to provide the neutrons lost due to the target pebbles replacing enriched uranium pebbles. If the SNF enrichment is increased, uranium assay of the SNF pebbles will change. If the same uranium enrichment is used, more pebbles will be required to maintain power levels, the SNF discharge rate will increase, and the SNF pebbles will have a lower burnup.

3. *Reprocessing of SNF*. The low fissile-fuel density in the SNF relative to other types of reactor fuel and the more complex reprocessing methods required imply larger processing facilities and more signals per kilogram of plutonium recovered. The characteristics of this fuel suggest that this penalty will be large for small facilities but may not be significant in larger facilities.

4. *Dirty bomb potential*. A *dirty bomb* is the use of conventional explosives to disperse radioactive materials such as SNF. The dirty bomb potential for PBR SNF may be significantly lower than for other SNF because the fuel is in the form of robust coated particles embedded in a larger graphitized matrix. Based on several considerations, there is a significant potential that conventional explosives would destroy the graphite matrix but not the SNF microspheres. The microspheres would be dispersed up to several hundred feet but would not likely create highly hazardous windblown respirable particles.

Several recommendations follow from this analysis.

- *The feasibility of measuring the fissile inventories in beds of PBR SNF in storage with radiation probes should be investigated.* This would be a uniquely valuable safeguards technique because it measures the properties of safeguards interest directly with a quick and potentially inexpensive method.

- *The dirty bomb potential for PBR fuel relative to other fuel types should be determined experimentally.* If this fuel is confirmed to have unique intrinsic capabilities against use in a dirty bomb, that confirmation may have major implications on the types of reactors to deploy in less secure regions of the globe. Such knowledge may also provide a basis for development of future nuclear fuels that are intrinsically resistant to use in dirty bombs rather than relying solely on physical protection methods to prevent construction of dirty bombs.

- *The use of tags for identification of fuel lots should be considered.* This is not relevant with a test reactor or pilot plant because there are only one or two sources for any illicit pebble that is found. However, if the PBR is deployed widely, tags provide another line of deterrence and potential interception of diverted materials. If any nuclear fuel is diverted and intercepted, the use of tags uniquely identifies the origin of the fuel and its history (manufacturing source, lot number, manufacturing date). As demonstrated by the use of tags in conventional explosives, that information often allows law enforcement to quickly track down the criminal element.

- *An assessment of the difficulty of reprocessing PBR SNF relative to other SNFs should be undertaken to develop an understanding of the relative economics and thus incentives to reprocess.* PBR SNF differs from LWR SNF in two major characteristics. The uranium enrichment in PBR SNF is higher; thus, the residual enriched uranium (not plutonium) is the primary fissile material of value for recycles. Second, differences in process flowsheets suggest that PBR SNF is a difficult fuel to reprocess on a small scale (such as in an illicit production facility) relative to other types of SNF but that the relative economics might change as the reprocessing facility size increases. Understanding these differences would provide a guide to many safeguards issues associated with PBR SNF.

SAFEGUARDS CHALLENGES FOR PEBBLE-BED REACTORS DESIGNED BY PEOPLE'S REPUBLIC OF CHINA

Charles W. Forsberg and David L. Moses

ABSTRACT

People's Republic of China (PRC) is operating a 10 MW(t) pebble-bed reactor (PBR) as a test reactor (the HTR-10) and is designing and building a prototypical PBR plant with two modular reactors (each 250 MW(t)) feeding steam to a single turbine generator. Because the prototype is a high-priority project for PRC, it will likely be the world's first modular high-temperature reactor ready for commercial deployment. The plant design features multiple modular reactors feeding steam to a single turbine generator where the number of modules determines the plant output. The design and commercialization strategy are based on PRC strengths: (1) a rapidly growing electric market that will support low-cost mass production of modular reactor units and (2) a balance-of-plant system based on economies of scale that uses the same mass-produced turbine generator systems used in PRC coal plants. If successful, in addition to supplying the PRC market, this strategy could enable PRC to be the leading exporter of nuclear reactors to developing countries. The modular characteristics of the reactor match much of the need elsewhere in the world.

PBRs have major safety advantages and a radically different fuel compared with current light-water reactors. The fuel, not the plant systems, is the primary safety system that prevents and mitigates the release of radionuclides under accident conditions. The fuel consists of small (6 cm) pebbles (spheres) containing coated-particle fuel in a graphitized carbon matrix. The fuel loading per pebble is small (~9 g of low-enriched uranium), and hundreds of thousands of pebbles are required to fuel a nuclear plant. The uranium concentration in the fuel is an order of magnitude less than in traditional nuclear fuels. These characteristics make the fuel significantly less attractive for illicit use (weapons production or dirty bomb), but its unusual physical form may require changes in the tools used for safeguards. This report describes PBRs, the differences between PBRs and other reactor types, and safeguards challenges. Safeguards are recommended based on the assumption that the reactor is commercialized successfully and is deployed widely.

1. INTRODUCTION

1.1 OVERVIEW

People's Republic of China (PRC) is operating a 10 MW(t) pebble-bed reactor (PBR) known as the HTR-10 (Fig. 1). It is a test reactor that was built to develop the technology for construction of high-temperature PBRs for the production of electricity and process heat. As with any new class of reactors, safeguards challenges must be addressed. Safeguards challenges are associated with this operating facility; however, larger safeguards challenges are associated with PBRs if deployed in large numbers in PRC and elsewhere. PBRs are modular, small reactors. Because of these and other characteristics, the PBR is the leading contender as the small reactor type to be deployed in several developing countries. In this context, the development of safeguards for the HTR-10 is important because it is the pilot for a potentially much larger set of future reactors.

Fig. 1. HTR-10 outside the Beijing Research and Power Reactor.

This paper addresses safeguards in the context of both the HTR-10 and the larger context of being the prototype for a class of reactors. The paper is organized into the following sections.

- *Threat definition (Chapter 2).* Potential threats are defined to provide a starting basis for safeguards.
- *PRC PBRs (Chapter 3)*. The characteristics of the reactor system and fuel are described, as is the PRC strategy for design, development, and deployment. The characteristics of the reactor will determine where it may be deployed, which, in turn, has major implications on safeguards.
- *Fuel characteristics (Chapter 4)*. The fuel cycle and characteristics of spent nuclear fuel (SNF) are described.
- *Safeguards challenges (Chapter 5)*. Each of the safeguards challenges are examined with recommendations on methods to strengthen safeguards.
- *Recommendations and conclusions (Chapter 6)*. Four recommendations to improve PBR safeguards are made assuming large-scale deployment of this technology.

1.2 PEBBLE-BED REACTOR HISTORY

The PBR has a long history. The history provides an understanding of the incentives to develop this reactor and the status of the technology. The PBR concept was first proposed in 1944 by staff working on the Manhattan Project at the University of Chicago Metallurgical Laboratory (Daniels 1944). The original concept looked at both helium cooling and liquid heavy-metal cooling. Alkaline liquid metals were not considered because alkaline liquid metals react with carbon. The author of the 1944 report subsequently sought commercial patents for the gas-cooled PBR concept as commercial interest increased and the earlier work was declassified (U.S. Patent 2809931, "Neutronic Reactor System," October 15, 1957; U.S. Patent 2910416, "Neutronic Reactor," October 27, 1959).

After the end of World War II, analytical and experimental work on helium-cooled PBR concepts was performed for the U.S. Atomic Energy Commission (AEC) by Oak Ridge National Laboratory (ORNL) (Amorosi 1947, ORNL staff 1958 and 1962) with fuel and materials support work performed by Battelle Memorial Institute. Conceptual design and testing work was also performed by an AEC-contracted architect-engineering firm (Sanderson and Porter 1958), with additional fuel and materials support work performed by Battelle Memorial Institute (Smalley and Rosenberg 1961). The AEC-funded domestic PBR development program ended in the early 1960s, but an AEC-funded technical assistance program at ORNL continued in support of and in collaboration with the Federal Republic of Germany's Nuclear Research Center (KFA) in Jülich. This earlier work involved irradiation testing at ORNL of the first batch of German test fuel for a proposed experimental PBR where the initial batch of fuel elements had been ordered from Union Carbide Corporation (Scott, Morgan, and DeCarlo 1965). The ORNL-KFA collaboration on PBR technologies development (principally materials, fuels, and analytical modeling of reactor physics, thermal hydraulics, and fuel cycle cost) continued until the late 1980s under bilateral agreements between the U.S Department of Energy (DOE) gas-cooled reactor programs and KFA.

The further development and commercial deployment of PBRs was carried out in Germany with Brown, Boveri, and Cie Aktiengesellschaft seeking the first European patents for their designs in France (FR 1265484, "Nuclear Reactor Whereby the Fuel in the Shape of Balls or the Like Is Poured into the Reactor Core," May 23, 1961) and Great Britain (GB 834978, "Nuclear Reactor with Gas Cooling," May 18, 1960). As discussed in Sect. 3, one helium-cooled experimental PBR and one helium-cooled demonstration power PBR were constructed, operated, and decommissioned in Germany between 1967 and 1990. The program in Germany was shut down after a decision by the German government ultimately to phase out nuclear energy.

The PRC reactor programs examined the concept and began research in the 1970s (Xu 1999). This included cooperative programs with the Germans. In 1992 PRC approved the building of a pebble-bed test reactor, the HTR-10 with a 10 MW(t) power output, at the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University, Beijing. Construction started in 1995 and the reactor achieved criticality in December 2000. In January 2003 it achieved full power and was connected to the electrical grid.

The combination of the need for energy and the potential of the PBR resulted in the PRC government making the PBR project a national priority—one of the 16 highest priority development projects (Zhang 2007). The goal is to have a full-scale pilot plant operating by 2013. The plant will have two reactors, each with an output of 250 MW(t). The preliminary design was scheduled for completion in 2007 with submittal of the preliminary safety analysis report. A construction permit is to be issued with the first pouring of concrete in the 2008–2009 time period. Because of the high priority of this project, the PRC pilot plant will likely be the first operating full-scale PBR.

Because PRC has extraordinary energy demands, a successful project would likely result in rapid deployment of PBRs there and potentially elsewhere. If the reactor is deployed rapidly in PRC, the reductions in unit costs from mass production could make the reactor very competitive economically. PRC is unique in that it is the only country with a sufficiently large demand for power plants to apply mass production to nuclear power reactor construction.

2. THREATS

Defining the potential threats is the starting point for work in safeguards, physical protection, and proliferation resistance. Five reference threats have been defined for use herein based on the DOE Advanced Fuel Cycle Initiative analysis of threats conducted in May 2005.

1. *Fissile material theft by a subnational group for construction of a nuclear weapon.* The most important barriers are those that limit access to the material (remote storage in a high-radiation environment, make it difficult to transfer (mass, volume, and radiation), make it difficult to process (chemical form and radiation), and make it difficult to design a weapon (fissile isotopics).

2. *Clandestine diversion of fissile materials by the host state for construction of a nuclear weapon.* The most important barrier to clandestine diversion from a declared facility is effective safeguards. Intrinsic attributes of the materials and facilities make different safeguards monitoring techniques either easier or more difficult. High radiation levels, for example, ease surveillance by providing large signatures but also complicate inventory measurement.

3. *Clandestine production of fissile materials in the facility by the host state.* The most important barrier to clandestine diversion from a declared facility is effective safeguards. Intrinsic attributes of the materials and facilities make different safeguards monitoring techniques either easier or more difficult.

4. *Abrogation by the host state of its participation in the Nuclear Nonproliferation Treaty and conversion of the facility to the production of nuclear weapons.* The most important barriers for abrogation are international reactions and the intrinsic characteristics of the materials, which cause long delays in the recovery of fissile materials.

5. *Radiological sabotage by subnational groups.* A *dirty bomb* uses explosives to disperse radioactive materials. The most important barriers are those that limit access to the material (remote storage in a high-radiation environment), make it difficult to transfer (mass, volume, and radiation), and limit the damage that can be done by the construction of a dirty bomb (ease of dispersion of radioactivity).

3. MODULAR HIGH-TEMPERATURE PEBBLE-BED REACTORS

This chapter describes the common generic characteristics of all gas-cooled PBRs, the specific characteristics of modular high-temperature PBRs, and the unique characteristics of the PRC PBR. It provides the basis to understand safeguards requirements and the commercialization potential of the PRC reactor. The commercialization potential is important because this reactor potentially could be deployed in large numbers in developing countries to generate electricity and process heat. Such widespread use has added implications for safeguards.

3.1 FUNCTIONAL REQUIREMENTS AND CAPABILITIES

The development of the modular high-temperature PBR is a consequence of historical technical developments and limitations in existing nuclear power reactors. To understand the incentives and driving forces for a modular PBR and the PRC program, an understanding of the technology development and the limitations of existing reactors is required.

Today almost all commercial nuclear power reactors are light-water reactors (LWRs). They are safe and economically competitive in much of the world. The dominance of LWRs is a consequence of several factors.

- *Steam technology*. Since the development of the steam engine in the 1800s, most of the world's power plants have been steam plants. Wood, coal, or oil is burned to heat water that is converted to steam. The steam originally was used to power railroads and mills. Today it is used to power steam turbines to produce electricity. The massive scientific, engineering, and industrial experience with steam made it easier to develop LWRs than to develop reactors with other coolants.

- *Naval requirements*. Following World War II, there were strong incentives to develop a nuclear submarine that could stay under water for long periods. The primary technical constraint was space. For a variety of technical reasons, physically small LWRs with multiple-megawatt power outputs can be built. These capabilities matched naval requirements. Because submarines are military products, massive resources were available for the subsequent development of LWR technology; the AEC Naval Reactors program was responsible for technology transfer to the AEC-owned first commercial LWR prototype at Shippingport, Pennsylvania.

The relatively small power output of naval reactors and their reliance on highly enriched uranium (HEU) for fuel make such reactors highly uneconomical in the commercial world. To make LWRs economically competitive, the reactor power output was increased dramatically and a fuel using low-enriched uranium (LEU) was developed. However, this creates two safety challenges.

- *Decay heat*. The nuclear fission process produces a radioactive ash containing fission and activation products. This includes many short-lived radioactive isotopes that decay to longer-lived or stable isotopes. The decay process produces heat. If the decay heat in a large reactor is not removed after reactor shutdown, the reactor core will overheat and melt. This occurred in the Three Mile Island accident when the reactor was shut down but the reactor core was not cooled adequately. If the reactor is small enough and the (ceramic) core can withstand the high temperatures, the decay heat can conduct through the reactor walls sufficiently fast that the temperature limits of the fuel are not exceeded and, consequently, the reactor fuel does not fail with the release of radioactivity.

- *Reactivity control*. If the reactor power level is not controlled, the reactor can produce more heat than can be removed from the reactor core. If this occurs, the reactor core will be destroyed. This occurred in the Chernobyl accident.

Safety can be assured by adding appropriate safety systems; however, such systems are expensive and require highly skilled personnel. The cost of the safety systems provided added incentives to build larger reactors to reduce the cost of nuclear power per unit of electrical output.

LWRs are significantly less efficient than other types of power plants. Efficiency is the fraction of the thermal heat produced by the power plant that can be converted to electricity. Power plant efficiency depends on temperature and increases with reactor coolant exit temperature. For a variety of technical reasons, it is impractical to build high-temperature LWRs.

The incentives for higher efficiency nuclear power plants with potentially better economics led to the development of high-temperature reactors (HTRs) with a ceramic core structure, a new fuel type (coated-particle fuel), and helium cooling. Efforts to commercialize these reactors failed due to a combination of technical development difficulties and the slowdown in nuclear plant orders after the Three Mile Island accident.

The recognition of the high cost of safety systems, both in dollars and public acceptance, led some nuclear engineers to ask whether an economical reactor could be built with inherent and passive safety systems. This led to the concept of the modular HTR that addressed the two safety challenges in a new way.

- *Decay heat.* If a reactor is sufficiently small, decay heat can be removed by conduction of heat through the sides of the reactor to the environment. No complex emergency decay heat removal systems are required. The allowable size of a passively safe reactor depends on the temperature at which the fuel fails. If the fuel can go to very high temperatures, a larger reactor is possible because the reactor can reach higher temperature without fuel failure and at higher temperatures more heat can be conducted through the reactor walls to the environment. The development of high-temperature fuel, with allowable fuel temperatures under accident conditions of 1600°C, enabled reactors of a few hundred megawatts to be built with such passive safety systems.

- *Reactivity control.* HTR fuel has one other useful characteristic. As it becomes hotter, its nuclear properties change and the reactor will shut itself down.

These developments led to the passively safe, modular PBR. The question remains as to whether the radically simplified, smaller, modular HTR is economically competitive with the large LWR and its complex safety systems. The term *modular* refers to the smaller size of the reactor, which may allow a less-expensive factory fabrication of major systems. The smaller size and better safety characteristics would make such a reactor highly attractive if it were economically competitive. The early German studies suggested the possibility that such reactors might be economically competitive. PRC concluded that there is a reasonably high probability that the economics will be favorable. If that is the case, it is a potential revolution in nuclear engineering.

The PRC conclusion is based partly on their unique industrial development. Mass production results in major reductions in per unit costs. Thus, the economics of a modular HTR partly depends on building a sufficient number of modular reactors to gain manufacturing economies. The extraordinary growth of the PRC electrical system creates a market where such mass production may be economically viable. If such a manufacturing system develops, modular nuclear reactors also could be exported on a large scale. (The large size and output of individual LWRs make it difficult to obtain a sufficient fraction of the world electrical market to obtain large economies through mass production of nuclear components.)

3.2 REACTOR AND FUEL

The distinguishing characteristic of PBRs is the coated-particle fuel in a graphite matrix compacted into spherical pebbles—typically 6 cm in diameter (Fig. 2). The reactor core is a bed of pebbles. The core for the German Thorium High-Temperature Reactor (THTR) is shown in Fig. 3. The vertical structures are graphite channels for control rods. The coolant in a PBR is high-pressure helium that flows downward through the pebble bed. In PBRs, several different power cycles can be coupled to this reactor. The helium can be used to heat water and produce high-temperature steam at temperatures that match fossil power plants and that are significantly above LWR steam conditions, allowing for higher efficiency Rankine cycles than those achievable in LWRs. Alternatively, the helium can be coupled directly to a power turbine to produce electricity at even higher thermal efficiencies. PBRs can be built as modular reactors or as large reactors.

Two helium-cooled PBRs have been built, operated, and decommissioned. The Arbeitsgemeinschaft Versuchs-Reaktor, later redesignated as the Atomversuchsreaktor (AVR), was a small experimental and test reactor operated by KFA-Jülich in Germany, and the THTR was a prototypical power reactor owned

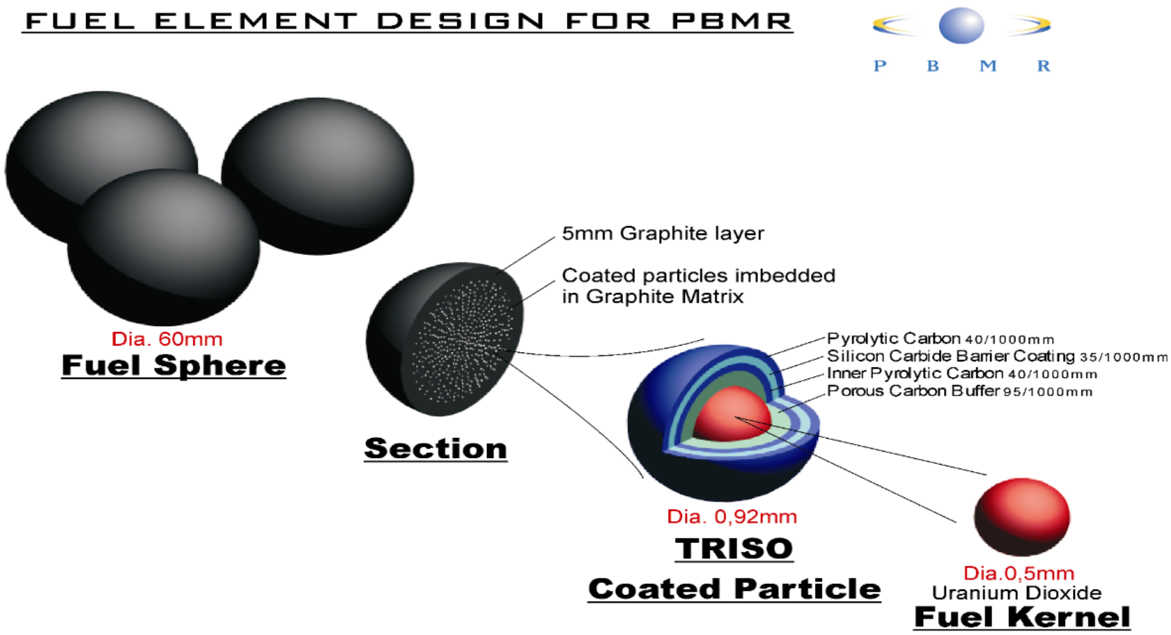

Fig. 2. Pebble-bed reactor fuel.

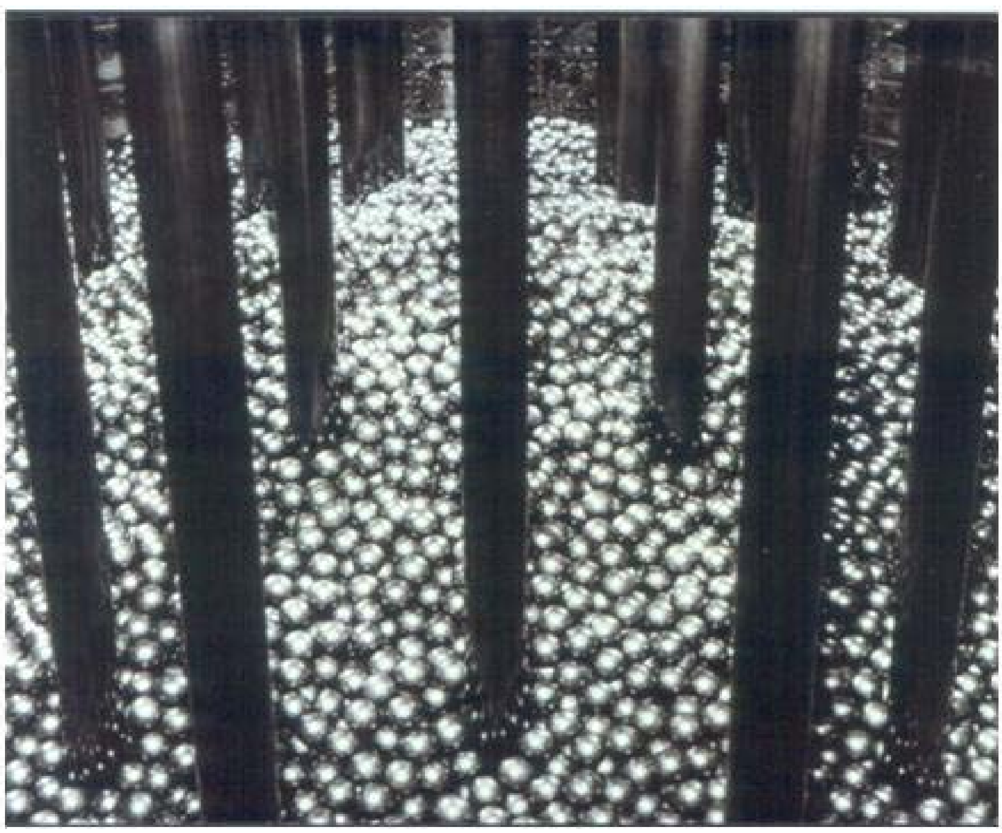

Fig. 3. Core of the German Thorium High-Temperature Reactor.

by the German state of North Rhine Westphalia and the German company Hochtemperatur-Kernkraftwerk GmbH. The AVR operated initially on an HEU/Th fuel cycle as was also used in the THTR, but later the AVR used a mixture of HEU/Th and LEU. The PBRs have always used the single particle fuel system as opposed to the U.S. prismatic design that uses a two particle (fissile and fertile) system where the two particles have different dimensions for reactor physics reasons and would allow ease of separation upon deconsolidation of fuel compacts for reprocessing.

The characteristics of all the PBRs built or under development are summarized in Table 1. The prototypes designed both by PRC and the Republic of South Africa (RSA) are refueled online at temperatures up to 950ºC at full power and full helium pressure. PRC and RSA PBRs are based on the LEU fuel cycle, whereas earlier PBRs used HEU/Th fuel.

Two designs of HTR fuel are currently in use: prismatic fuel assemblies and pebbles. Both use the same type of coated-particle fuel, but the graphite matrix incorporating the fuel particles has a different geometry and size. Two reactors with hexagonal prismatic fuel assemblies have been built: (1) the decommissioned Fort St. Vrain reactor in the United States and (2) the operating 30 MW(t) High-Temperature Engineering Test Reactor (HTTR) in Japan.

In the 1960s and 1970s, two other reactors, both now decommissioned, used a different fuel type—annular fuel in cylindrical graphite tubes. The two reactors were Peach Bottom Unit 1 in the United States and the Dragon Project test reactor in the United Kingdom. Peach Bottom Unit 1 used an annular fuel region of coated particles with an inner graphite spine and an outer annular graphite clad to form the cylindrical tube. The Dragon Project test reactor used a lattice of hexagonal graphite tubes into which cylindrical tubular fuel elements were slid using either graphite-clad, annular coated-particle fuel with a central cooling hole or columns of cylindrical fuel pellets of coated-particle fuel arranged in the graphite tube in a formation resembling a telephone dial around the central cooling hole. The refueling of these reactors is fundamentally similar to refueling LWRs because both types of reactors have large fuel assemblies; to refuel, the reactor is shut down and the fuel blocks are replaced.

Table 1. Characteristics of pebble-bed reactors built or under development

Characteristic	AVR	THTR	HTR-10	PBMR	HTR-PM
Country	Germany	Germany	People's Republic of China	Republic of South Africa	People's Republic of China
Initial operation	1967	1984	2004	2013	2013
Status	Shut down 1988	Shut down 1990	Operating	Under design	Initial site work
Reactors per plant	1	1	1	1	2
Heat, MW(t)	46	750	10	400	2 × 250
Power cycle	None	Steam	Steam	Brayton	Steam
Power, MW(e)	15	307	Not applicable	165	200
T_{out}, °C	950	750	700	900	750
T_{in}, °C	270	250	250	500	250
Pressure, bar	11	40	30	90	7
Fuel	HEU/Th and later LEU	HEU/Th	LEU	LEU	LEU
Number of pebbles during operation	~40,000	~670,000	~27,000	~452,000	

PBRs use a very different refueling strategy. A slow continuous flow of pebbles goes through the reactor core while the reactor is operating. Pebbles are continuously added at the top of the core and removed at the bottom. The pebbles pass through the reactor core several times before being fully expended. Extracted pebbles are sent through a burnup-determining radiation detector that either sends the pebble to disposal as SNF or recycles it back to the core for additional burnup. This enables the PBRs to operate with very low excess nuclear reactivity and relatively low enrichments. A simplified schematic of the refueling system is shown in Fig. 4.

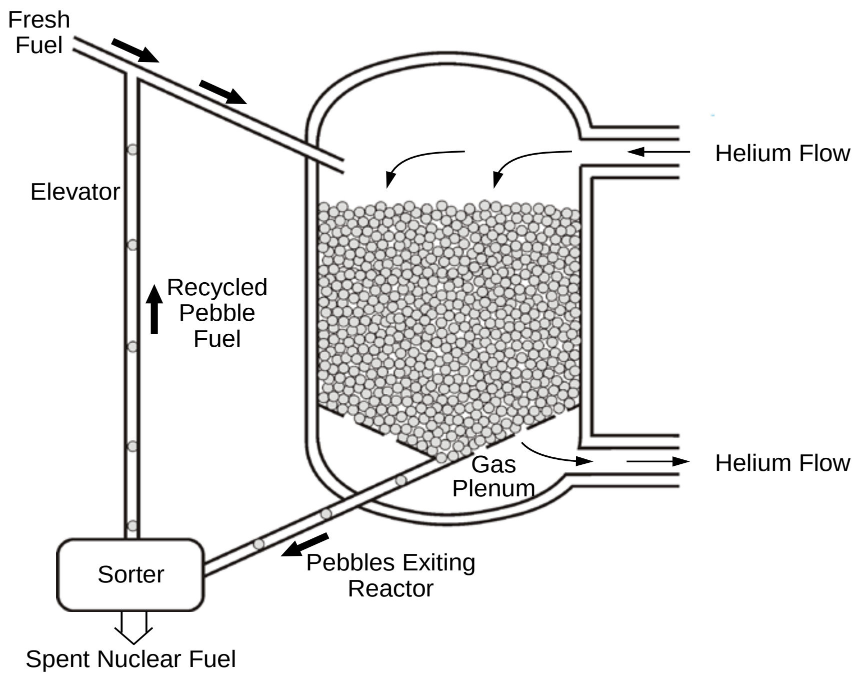

Fig. 4. Refueling schematic for a helium-cooled pebble-bed reactor.

There are many designs of PBRs depending upon whether they are modular or large reactors. Figure 5 shows the PRC design for their modular PBR prototype with a power output of 250 MW(t). The prototype plant will have two such reactors. Other modular reactor designs (e.g., RSA) are similar, but the power plant designs are different. The PRC reactor system consists of two vessels. The larger vessel contains the reactor core—a vertical cylinder with a tube at the bottom for the pebbles to exit the reactor vessel. The pebble bed is surrounded by a graphite reflector that has control rods. The vessel is long and narrow so that under accident conditions, decay heat from the fuel can conduct through the reactor vessel and ultimately escape to the environment.

The smaller vessel contains a steam generator and a helium blower. Cold helium enters the top of the reactor vessel (left side), is heated as it flows down through the reactor core, and flows to the second vessel. The second vessel contains a heat exchanger with water inside the tubes and helium on the other side. The hot helium converts the water to high-temperature steam. After the helium has cooled and given its heat to the steam, it goes through a helium recirculator at the top of the second vessel and flows back to the reactor vessel.

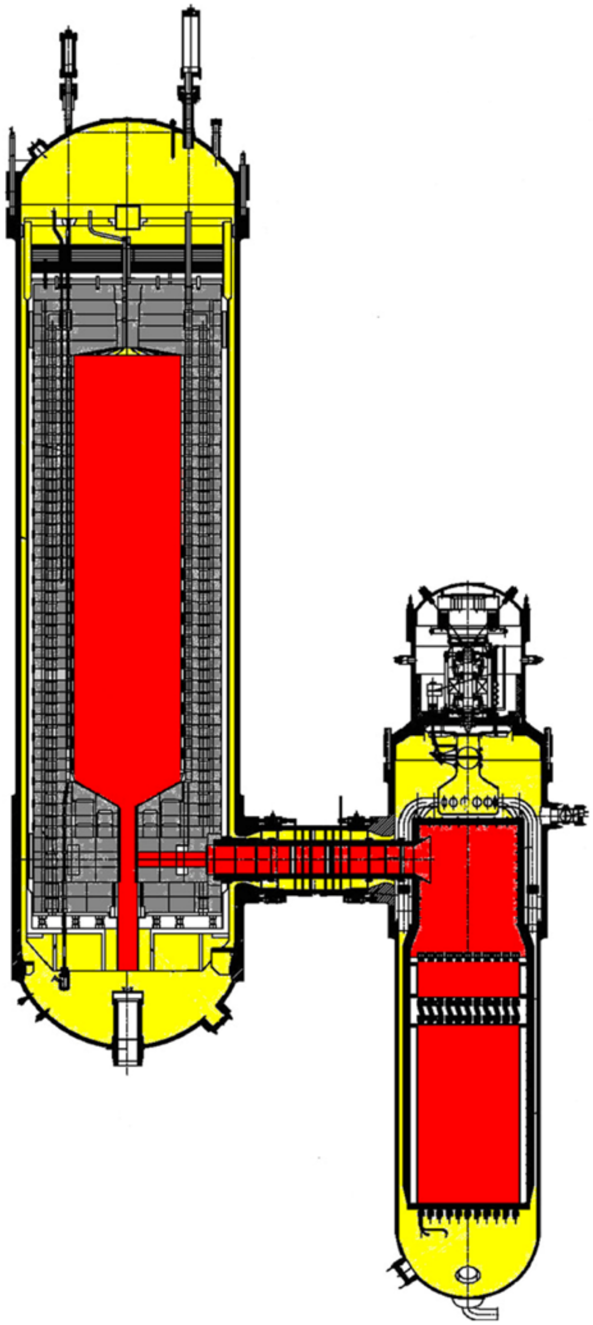

Fig. 5. PRC modular 250 MW(t) PBR prototype with steam generator.

3.3 PLANT DESIGN FOR THE PRC PEBBLE-BED REACTOR

The design of the PRC PBR plant (Zhang 2007) differs radically from any existing commercial reactor. All existing commercial reactors have a single reactor connected to a power conversion system such as a steam turbine and electrical generator. In a few cases where the reactor is very large and no matching steam turbine could be built, multiple turbines are connected to a single reactor. The PRC PBR developers propose a different approach. Multiple reactors in a single plant will be connected to a single steam turbine and electric generator. The reactors are modular to reap the safety advantages of the modular reactor size and the economies of mass production for manufacturing the nuclear system. All other components of the plant (steam turbine, generator, cooling towers, auxiliary systems, refueling systems) are common to all the reactors in the plant. This has potentially major implications.

- *Flexible unit size.* With this approach, once two reactor modules working together have been demonstrated, reactor plants of any size can be produced simply by changing the number of reactor modules per plant but not the reactor design. PRC proposes up to 19 double-module units per plant.

- *Balance-of-plant components.* The concept takes advantage of economies of scale in all nonreactor power plant components such as steam turbines, generators, cooling towers, and fuel handling systems.

- *Compatibility with fossil power plant components.* The PBR modular reactors are being designed to produce high-temperature, high-pressure steam that matches that from the more efficient fossil power plants (Zhang et al. 2006). This enables the large-scale manufacturing infrastructure associated with fossil plants to be used for production of the balance-of-plant components such as steam turbines. In contrast, existing LWRs produce steam at temperatures and pressures significantly lower than those found in traditional fossil plants and thus must have steam turbines specifically designed to match the nuclear reactor.

- *Nuclear reactor mass production.* The nuclear reactor design is chosen for simplified manufacture with gains in manufacturing economy.

Associated with this decision was a major effort to simplify the reactor module to the maximum degree possible. A decision in August 2006 took the reactor module from the originally envisioned 458 MW(t) to 250 MW(t). Cost estimates indicated less than a 5% difference in the cost per kilowatt-electric capacity between building a single 458 MW(t) reactor and two 250 MW(t) reactor modules. This design change greatly reduced the complexity of the reactor module for a variety of technical reasons and substantially lowers the technical risk. The major simplification is a cylindrical core rather than the more complex annular core required with the larger power output. Table 2 summarizes the differences between these two designs. PRC is building the 2 × 250 MW(t) plant with an electrical output of 200 MW(e). Figure 6 shows the reactor layout of the 2 × 250 MW(t) plant.

PRC's development and deployment strategy for their PBR is highly innovative and takes full advantage of unique PRC strengths—(1) the world's largest internal market, sufficient in size to support economical mass production of the nuclear components and (2) the world's largest manufacturing capability to produce balance-of-plant components of systems found in fossil-fired plants. Some perspective of this extraordinary manufacturing capacity can be obtained by examining the country's current rate of electric power plant construction. PRC is building the equivalent of two 500-MW(e) coal-fired power stations per week and a capacity equivalent to the entire United Kingdom power grid each year (MIT 2007). If PRC is successful in creating an economical modular reactor with enhanced safety, such a radical change in nuclear technology could make PRC the world leader in the sale of commercial nuclear reactors to other countries. It will be a decade or longer before it is known if the strategy is successful.

Table 2. Key design parameters of two versions of the PRC PBR prototype[a]

Design parameter	Previous design	Current design
Plant size, MW(t)	458	2 × 250
NSSS modules	1	2
Core thermal power, MW	458	500 (plant)
Diameter of core internal reflector, m	2.2	0
Diameter of core outer reflector, m	4	3
Core height	11	11
Primary helium pressure, MPa	9	7
Core outlet temperature, °C	750	750
Core inlet temperature, °C	250	250
Fuel enrichment, %	9.5	8.9
Relative reactor pressure vessel weight	1	2 × 0.57
Relative graphite weight	1	2 × 0.60
Relative metallic internals weight	1	2 × 0.86
Relative blower power	1	2 × 0.57
Control rods	24	2 × 10
Small absorption sphere systems	8	2 × 20
Fuel discharge systems	3	2
Relative volume of reactor plant building	1	0.96
Reactor protection systems	1	2
Main control rooms	1	1
Helium purification systems	2 × 100%	2 × 100%
Fresh fuel and SNF systems	1 × 100%	1 × 100%
Emergency electrical systems	2 × 100%	2 × 100%

[a]For both plant designs, the peak steam temperature is 535°C with a pressure of 13.5 MPa. Plant efficiency is 40%.

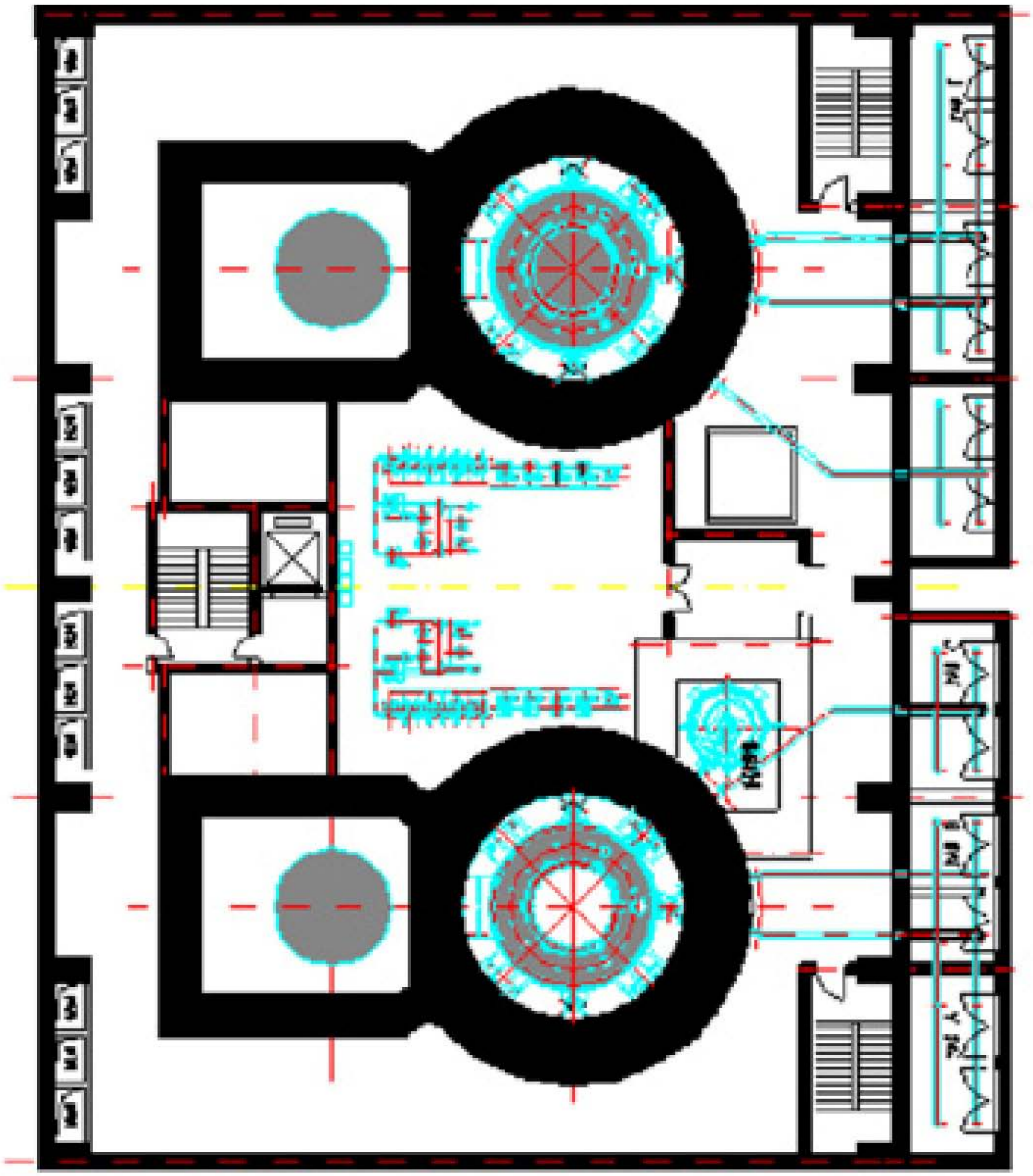

Fig. 6. Layout of the two-reactor PRC prototype PBR plant.

4. FUEL CHARACTERISTICS AND FUEL CYCLE OPTIONS

4.1 FUEL CHARACTERISTICS

The characteristics of fresh fuel and SNF primarily determine the requirements for safeguards and physical protection. The generic characteristics of pressurized-water reactor (PWR) and PBR fuels are compared in Table 3. PWR (and almost all other types of reactor fuel) are bundles of metal tubes containing oxide fuel pellets. Over half of the world's reactors are PWRs. The table shows the dramatic differences between traditional power reactor fuels and PBR fuel.

Table 3. Intrinsic properties of traditional PWR fuel and PBR fuel

Characteristic	PWR	PBR
New assembly		
Height and width, cm	405.9/21.4	6 (sphere)
Mass per assembly, g/assembly	657,900	204
Volume per assembly, cm^3/assembly	186,000	113.1
Fuel loading, g U/assembly	461,400	9
Fuel density, g U/cm^3 of assembly	2.5	0.080
Enrichment, mol % ^{235}U	5.0	8.9
Burnup, GWd/ton heavy metal	60	80
Burnup variability in a single assembly	Very large	Uniform
Burnup variability in SNF inventory	Medium	Small
SNF fissile properties		
Pu/ LEU SNF assembly, g/assembly		0.04
SNF Pu isotopic, mol %		
Pu-238	3.8	1.9
Pu-239	51.8	36.8
Pu-240	23.0	27.5
Pu-241	14.2	18.1
Pu-242	7.2	15.7
Accident containment fuel	No	Yes
Fuel with moderator	No	Yes

4.2 PROPERTIES OF FRESH PEBBLE-BED REACTOR FUEL

4.2.1 Uranium

Typical ^{235}U enrichments of fresh PBR fuel are between 8 and 10% versus 3 to 5% for fresh LWR fuel. This is a consequence of several factors and complex economic and technical (reactor physics and fuel performance) trade-offs.

Safety

The PBRs being designed in PRC and RSA are passively safe; that is, in the event of an accident, no active systems are required to prevent significant release of radionuclides to the atmosphere. Safety is an intrinsic characteristic of the reactor that allows removal of decay heat without violating fuel integrity temperature limits. This design goal impacts uranium enrichments in both the fresh fuel and the SNF.

There are two fundamental accident initiators in nuclear reactors: reactivity-driven accidents (such as Chernobyl) and inadequate cooling accidents (such as Three Mile Island). In an undercooling, decay-heat-driven accident, reactor cooling is lost or insufficient, and the decay heat from the SNF heats the fuel until it fails. Modular PBRs avoid this type of accident by limiting the reactor core diameter so as to allow the decay heat in the fuel during a loss of forced-cooling accident to be removed from the reactor by conduction horizontally through the fuel, reflector, and reactor vessel to the environment. The power output per meter of core height is limited. To increase core power levels, the core height is increased.

This safety characteristic implies that from a neutronic perspective, modular PBRs are small reactors. In a small reactor, there is significant neutron leakage from the reactor core. To maintain nuclear criticality, the fuel enrichment must be increased relative to a large reactor. In effect, the designer has bought intrinsic reactor safety partly at the cost of higher enrichments for the fresh fuel and SNF.

Fuel Performance

Fuel enrichment is determined partly by the desired fuel burnup—the total energy output per kilogram of uranium in the reactor core. Higher fuel burnup requires high enrichment levels in the initial fuel to provide the required ^{235}U. High burnup is desirable because it minimizes the amount of fuel fabrication per unit energy output; however, the higher enrichments imply more fuel enriching—an expensive activity. There is also another technical factor in the choice of burnup. In LWRs, fuel cladding limits burnup and thus the fuel enrichment. Coated-particle fuels have much better performance; thus fuel performance is not limited as much by fuel burnup. The designer can go to higher burnups and enrichments if the economics are favorable.

Uniform Burnup

The PBR design results in relatively uniform burnup of all fuel. This provides more efficiency than that associated with LWRs, where the uranium toward the top and bottom of the fuel assembly does not see high power levels. PWR core reload designs attempt to achieve flat axial power distributions by the core plan arrangement of fresh and irradiated fuel elements during reloading.

4.2.2 Plutonium

PBRs have a neutronically harder (higher average thermal energy) neutron spectrum with a significant epithermal component due to a dependence on scattering from a heavier moderator (carbon in graphite), whereas LWRs tend to have a softer (lower average thermal energy) thermal neutron spectrum. The combination of a high burnup and a harder thermal spectrum creates plutonium in PBR SNF with high concentrations of the higher-atomic-mass plutonium, which is much less desirable for use in nuclear weapons (see Table 3).

4.3 PROPERTIES OF SPENT NUCLEAR FUEL

4.3.1 Burnup

Burnup is the most important nuclear property of SNF fissile material. High burnup makes the fuel less attractive to diversion because of its higher radioactivity, lower quality plutonium isotopics, and less total plutonium produced per unit of energy produced. Coated-particle fuels have the highest demonstrated burnup, with a demonstrated maximum burnup exceeding 600,000 MWd/ton with highly enriched fuel. The PRC PBR is designed with low-enriched fuel. The various economic factors resulted in a planned burnup of about 80,000 MWd/ton. The high intrinsic burnup capability of this fuel provides high safety and operational margins for commercial PBR fuel.

PBRs will have higher burnups than LWRs. LWR fuel burnups are limited by the fuel clad to ~60,000 MWd/ton. LWR SNF burnup is near several other limits which imply that major changes in burnup are not likely unless there are major changes in fuel design. In addition to the clad limits, existing fuel fabrication plants are licensed to a fuel enrichment of only 5% ^{235}U, and significant investment in the fuel fabrication plants would be required to produce fuel at higher enrichments.

PBR and CANDU fuels share one unique characteristic, uniform burnup. In LWR SNF assemblies, the average burnup is not uniform throughout the fuel assembly: the actual burnup may be 50% higher than average in the axial center of the rod and be 10% of average at the very end of the fuel assemblies. Consequently, one can obtain plutonium of different burnups by selecting different regions of the LWR fuel rod. Every LWR SNF assembly has some low-burnup fuel, but in normal operation all PBR SNF has the combination of more uniform burnup and high burnup. This combination is unique to PBRs.

4.3.2 Chemical Properties

The chemical characteristics of a fuel assembly are determined by the functional requirements for the SNF. All nuclear fuels have two common functional requirements: (1) contain fissile materials, fertile materials, and fission products during normal operations and (2) enable the efficient transfer of heat to the reactor coolant. High-temperature coated-particle fuels, such as pebble-bed and prismatic fuels, have two additional functional requirements: (1) contain fissile materials, fertile materials, and fission products during accident conditions and (2) incorporate the moderator into the fuel assembly. These two added functional requirements radically change the design of these fuel elements and have potentially dramatic impacts in terms of safeguards relative to traditional light-water reactor fuels.

Unlike other fuels, coated-particle fuels are designed to maintain integrity under accident conditions—including containment for limited periods at temperatures up to 1650°C. The major safeguards implications are described here.

- *Fissile material recovery.* The containment requirement implies a multi-barrier fuel, which significantly hinders recovery of fissile fuel in reprocessing facilities. Unlike typical pin-type metallic-clad fuel assemblies of all other major fuels, coated-particle fuels have layers of pyrolytic carbon, silicon carbide, and graphitized carbon that increase the volume of material that must be processed per gram of plutonium that can be recovered. Furthermore, there is no option of cleanly dissolving a fuel matrix, such as UO_2 that contains the plutonium and fission products. Virtually all the proposed processes for fissile materials recovery will dissolve various silicon impurities and have high loadings of carbon fines. These impurities do not prevent the reprocessing of these fuels, but they complicate it more than any other proposed commercial nuclear fuel. The negative impact of high concentrations of silica gel agglomerates on reprocessing uranium silicide–aluminum and uranium–silicon–stabilized aluminum research reactor fuels has been documented in the literature (Paige and Rohde 1968). These fuels are intrinsically more difficult to reprocess.

- *Dirty bomb potential.* Nuclear materials can be used for the construction of nuclear explosives or as the radioactive components of a dirty bomb, where conventional explosives are used to disperse highly radioactive materials. The coated particles in PBR fuel are designed with multiple layers to provide different accident containment mechanisms. Based on multiple considerations, the potential consequences of using PBR SNF in dirty bombs may be orders of magnitude less than for other types of SNF. If most of the microspheres of coated-particle fuel remain intact during a conventional explosion, as expected, the radioactivity in the SNF will not be dispersed as a fine aerosol that can be transported long distances by the wind. Instead, the discrete fuel particles will fall to the ground within a few tens of meters of an explosion, where they can be collected more readily than removing embedded surface contamination. The basis for this preliminary conclusion is derived from several factors.

    — *Tags*. There is experience with using tags in conventional explosives (Haire and Forsberg 2007). Tags are added to explosives during their manufacture to help identify the source of any explosive used for illegal purposes. The tags are small particles made of multilayers of differently colored plastic, where the sequence of the colors acts as a bar code to identify a particular lot of explosives. The Swiss government requires tagging of both low and high explosives. Since 1984 the Swiss have solved some 560 cases of bombings by using these tags. What is noteworthy is that these tags survive being in the middle of the explosive. Some characteristics of these tags are similar to those of microspheres.

    — *Recycling.* A number of methods have been investigated for separating coated-particle microspheres from the graphite matrix for the purposes of reprocessing or waste management (Lotts et al. 1992). The waste management incentive is to separate the graphite from the fuel to allow separate disposal of graphite and fuel. The costs of low-activity graphite disposal are much less than the costs of SNF disposal. Under a wide variety of mild and extreme processing conditions (burning the carbon, ultra-rapid heatup, crushing, etc.), the microspheres generally remain relatively intact while the graphite structure is destroyed. Experimental studies are required in this area.

Thermal spectrum reactors require a neutron moderator to slow fission neutrons. In LWRs the moderator is water, which is separate from the fuel. In HTRs with coated-particle fuel, some or all of the moderator is a component of the fuel. In PBRs with coated-particle fuel, all the moderator (excluding the graphite in the core reflector) is incorporated into the fuel assembly. With prismatic coated-particle fuel, some or all of the moderator is incorporated into the fuel, or rather all of the fuel is incorporated into the moderator. As a consequence, coated-particle fuels have far larger masses and volumes per gram of uranium, plutonium, or other fissile materials. Two to four orders of magnitude more SNF must be diverted to acquire a significant quantity of plutonium.

4.4 FUEL CYCLES

The PBR fuel cycle is similar to other reactor fuel cycles with options for open or closed fuel cycles. After cooling, SNF can be directly disposed of or reprocessed to recover fissile materials. With current economics, once-through LEU fuel cycles are generally more economical. However, other factors such as fuel self-sufficiency or long-term goals to destroy long-lived transuranics in the SNF may dictate the reprocessing of SNF.

4.4.1 Direct Disposal of Spent Nuclear Fuel

It is generally accepted that the graphite-matrix coated-particle fuels have better repository performance than other fuels due to the corrosion resistance of the graphite and silicon-carbide coatings on the fuel (Lotts et al. 1992). These features also complicate reprocessing: a large amount of carbon (~180 g per pebble) must be removed, along with the pyrolytic carbon and silicon carbide coatings of the individual fuel particles, so that a few grams of heavy metal and fission products in each pebble can be dissolved.

Studies in Germany were performed in the 1980s on disposal of pebble SNF (Kirch et al. 1990). The conclusions reached are stated as follows:

> For the borehole disposal technique in a salt deposit, conceptual design data are available. Evaluation of the mechanical behavior of irradiated fuel elements in tests at near repository conditions has shown that standard HTR fuel particles generally survive the crushing of the element under rock pressure. However, for safety reasons, a backfill matrix such as quartz sand or cement (temperature limit 90°C) should be applied with lightweight disposal canisters to prevent element breakage. Otherwise, heavy built, self-supporting containers should be used. No corrosion due to the brine has been found on particle coatings. A large-scale emplacement test is under preparation in the German salt mine ASSE. The economical characteristics for the disposal of spent HTR fuel following this concept are being explored.

4.4.2 Reprocessing of Spent Nuclear Fuel

Virtually all existing and proposed reprocessing plants separate fissile and fertile fuel from the SNF using (1) nitric acid to dissolve the fuel and (2) solvent extraction processes to separate fissile and fertile materials from the fission products. The best known process is PUREX, but there are several other closely related processes, and newly proposed ones being developed under the Global Nuclear Energy Partnership are seeking to avoid the production of separated plutonium streams. The work to date indicates that coated-particle fuels will be significantly more difficult to process and thus have intrinsically higher resistance to illicit use.

5. SAFEGUARDS CHALLENGES

PBRs have many of the same safeguards challenges as other types of power reactors. Currently, HTR-10 is the only operating PBR. It is under International Atomic Energy Agency (IAEA) safeguards, with the IAEA verifying initial enrichment and batch number. Safeguards are associated with fresh fuel storage (weight, enrichment, batch number, number of items, isotopics), at the core exit (facility pebble counters, pebble weight, and composition by calculation), and SNF storage (number of items, burnup of each pebble, and composition by calculation). As a test reactor in a weapons state, HTR-10 is also the test bed for PBR safeguards.

There are important differences between PBRs and other types of reactors. The differences are discussed here.

5.1 DIVERSION OF FRESH AND STORED SNF

Four of the five previously described safeguards threats (fissile material theft by a subnational group for construction of a nuclear weapon, national clandestine diversion of fissile materials, national clandestine production of fissile materials, and SNF theft by a subnational group for a dirty bomb) cannot occur if PBR fuel is not diverted. Thus diversion of stored SNF is the major safeguards challenge. This challenge has two components: (1) ensure SNF is not diverted and (2) ensure there is no substitution of nonfuel pebbles for SNF pebbles in storage systems. Two strategies can address this challenge.

- *Physical inventory of the new pebbles and SNF pebbles.* Standard IAEA techniques are applicable as defined in Sect. 6.41 of IAEA 2001. Since pebbles are not serial numbered as is typical of metallic fuel assemblies and prismatic fuel, the inventory is by lot (with the number of pebbles determined by counting, gross mass, and/or radiation level). Because of the small size and characteristics of a fuel pebble, each pebble can be examined by appropriate radiation detectors to determine its age and fissile content with reasonable accuracy. The mass of a pebble (~200 g) is sufficiently small (limited self-shielding) that the measurement uncertainties are smaller than those associated with a large LWR SNF assembly with significant internal self-shielding. However, the number of pebbles and their small per pebble fissile content limit the fraction of the inventory that can be examined practically with high precision. The current safeguards strategy is based on this approach.

- *Radiation monitoring of the SNF for substitution with nonfuel pebbles.* The storage of PBR fuel is fundamentally different from other types of fuel. The storage system is composed of casks or tanks filled with pebbles—there is no SNF grid storage structure with individual storage spots for pebbles. Consequently, traditional strategies to inventory SNF do not work. Alternative strategies for inventory should be considered to ensure that dummy SNF pebbles are not substituted for SNF pebbles in storage. One potential method to accomplish this goal has been identified. It is based on the fact that SNF pebbles have several unique characteristics relative to other types of SNF: (1) the burnup is roughly identical for each pebble and thus creates an SNF with a nearly uniform radiation field, (2) the low-density carbon does not shield gamma rays as effectively as metal-clad fuel, and (3) the low nuclear-cross-section helium coolant implies that signals from the SNF are not distorted or reduced by the coolant. This unique combination of characteristics creates alternative options to detect substitution of dummy fuel for SNF. Instrument channels could be included in SNF storage containers to allow calibrated gamma and neutron probes to measure the radiation versus height. Nonuniformity of the signal raises a flag. Calibrated systems allow inventory measurements to be made. It is a unique safeguards approach enabled by the unique characteristics of this SNF.

It is important to understand how radically different PBR SNF is relative to LWR SNF. LWR fuel assemblies are large, have complex internal geometries, use metal clad, and have other internal metal hardware. With traditional LWR SNF, self-shielding within the fuel assembly may not allow reliable safeguards assay of the interior of the assembly whether using the FORK, PYTHON, or other safeguards systems in passive or active mode (Bignan et al. 1991, Ewing and Seager 1996, Guardini 2002, Rinard et al. 1990).

Diversion risks are also dependent upon the quantities of SNF that must be diverted. The risks of diversion are substantially reduced for PBRs because the fissile inventory is very dilute. Large quantities of PBR SNF must be diverted. IAEA defines a significant quantity of plutonium (direct-use nuclear material) as 8 kg (Table II in IAEA 2001). To steal 8 kg of plutonium in fully irradiated SNF requires the theft of ~78,500 pebbles (6 kg of ^{239}Pu/0.368 = ~16 kg of Pu-total in 157,000 pebbles diverted, from Kadak 2005) with a volume of ~18 m^3 (assuming a random 50% packing fraction, less if more closely packed) and a weight of ~15 MT. Table 3 gives the mass of a new PBR pebble as 204 g with only 9 g of that being uranium, implying that the logistics of diverting PBR SNF in quantities of interest are significantly more difficult than for LWR SNF. Whereas an LWR fuel assembly is 70% uranium by weight, the pebble is only 4.4% uranium by weight.

IAEA defines a significant quantity of indirect-use nuclear material (uranium enriched to <20% ^{235}U) as 75 kg; this corresponds to 8,334 fresh fuel pebbles having a mass of ~1.6 MT.

5.2 SYSTEM DIVERSION OF FRESH OR SPENT PEBBLES

The fissile content of a couple of PBR pebbles is insignificant with respect to safeguards, whereas the fissile content of a couple of LWR SNF assemblies is highly significant. One of the advantages of pebbles as a fuel form is that one has to divert large numbers of them before it becomes a major safeguards challenge. On the other hand, the inventories of fresh and spent pebbles, if PBRs are commercialized, will be measured in tens or hundreds of millions of pebbles. The relatively small number of LWR fuel assemblies allows individual serial numbers on each assembly and, in many cases, on each fuel rod. That is impracticable for pebbles because of the very large numbers and because the operating environment makes it very difficult and perhaps impossible to develop a practical method to legibly number pebbles individually.

Incentives to label each lot of pebbles are significant, however, if large numbers of reactors are built. If pebbles are found by the police or border patrols, labeled lots would enable investigators to track the fuel fabrication and reactor plant from which the pebbles originated. The greater the number of lot labels, the more precise the information would be. With labeled lots, stopping any diversion is greatly aided. Because so many pebbles must be diverted to acquire a significant quantity of fissile material, any diversion will involve many shipments, thus increasing the probability that an illicit shipment will be intercepted. *The characteristics of any attempt to divert pebbles will be significantly different from any attempt to divert other types of fresh fuel or SNF.* This is not an issue for a single test reactor or a pilot plant, but it is an issue if large numbers of PBRs are built.

The unique characteristics of PBR fuel lead to the recommendation that consideration be given to adding tags to each lot of fuel when fabricated. Tags are small particles whose chemical composition provides a unique identifier. The tags would be added during the pebble fabrication process and be incorporated into the graphite matrix. If a diverted pebble is recovered or an inspector has a question about a pebble's origin, the tags can be recovered from the pebble.

There are many types of tags. One example is microspheres of rare earths, where a lot is identified by the specific mixture of rare earths. Billions of such combinations exist. Tag recovery does require the destruction of the pebble (Haire and Forsberg 2007).

5.3 ON-LINE REFUELING OF IRRADIATED TARGETS

Two of the safeguards threats (national clandestine diversion of fissile materials and national clandestine production of fissile materials) are associated with the irradiation of special targets in a PBR (Fig. 7). PBR fuel yields a highly dilute SNF form for the recovery of plutonium. For a national proliferator using a PBR, there would be strong economic incentives to create special pebbles with high loadings of depleted uranium as targets to produce plutonium. This can reduce the number of pebbles that must be reprocessed by a factor of eight (Kadak 2005) for recovery of the plutonium. There are two strategies to detect such activities at the reactor.

- *Pebble inspection*. In a PBR, the pebbles flow through the reactor and a detector to determine which pebbles are SNF for disposal and which pebbles are to be recycled. The radiation profile of a target pebble would be very different than a fuel pebble and thus could be detected. It is also likely that a target pebble would have a higher loading of natural or depleted uranium than a normal fuel pebble. This, in turn, implies a higher weight pebble. As a practical matter for the potential proliferator, pebble inspection is how the host country would sort the special target pebbles from the rest of the fuel. There are strong incentives to use the reactor's pebble inspection system as a component of the safeguards system.

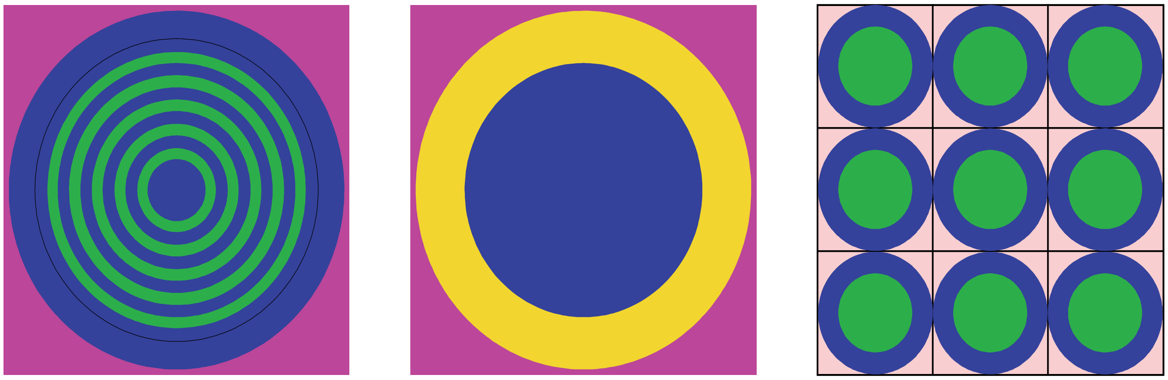

Fig. 7. Alternative target designs.

- *Fuel cycle records.* The use of a large number of targets implies power and reactivity shortfalls in the reactor. That is, the fresh fuel loading or enrichment or the SNF enrichment will increase to provide the neutrons for the target pebbles. Mismatches between fuel loadings and power output are strong indicators of misuse of the reactor. In this context, the PBR has a unique feature. All the SNF has the same burnup. This characteristic makes it potentially easier to compare power production records with fuel use to determine any potential mismatch.

5.4 REPROCESSING OF SNF

Four of the safeguards threats (fissile material theft by a subnational group for a weapon, national clandestine diversion of fissile materials, national clandestine production of fissile materials, and treaty abrogation) require the reprocessing of SNF. As noted in Sect. 4.3.2, the reprocessing challenges associated with PBR fuel are greater than with other SNFs because of the small quantities of fissile material per unit volume or weight of the SNF. Several characteristics of PBR SNF can influence safeguards.

- *Commercial reprocessing.* The high-value product from traditional commercial SNF reprocessing is plutonium. For coated-particle fuels, the plutonium content is very low on a per pebble basis. The primary high-value product is the enriched uranium, which may have sufficient enrichment to be used directly in some types of power reactors without re-enrichment. Because of the higher value of the remaining enriched uranium, a plant designed for these fuels may or may not recover the plutonium. Flowsheets could change significantly from the traditional—that is, plutonium could be rejected along with the minor actinides and fission products instead of being separated.

- *Scale of reprocessing.* Small-scale reprocessing systems have more difficulties with coated-particle fuels than with pin-type SNF (LWR, etc.). In pin-fuel systems, the fuel assembly can be disassembled mechanically (the clad rods are cut with a tube cutter). This can be done on a very small scale in a hot cell or fuel pool. All of the front-end processing options for coated-particle fuel are difficult to accomplish on a small scale; however, those difficulties are reduced as the system throughput increases. An example is burning graphite. Like fireplace fires, it is easier to maintain a large fire than a small fire. A second example is deep well injection of combustion gases. The difficulties and the costs for PBR SNF are likely to be much more sensitive to the scale of operation, with large difficulties in processing smaller quantities of SNF.

- *Signals.* The reprocessing of coated-particle fuels by any technique results in much larger radioactive off-gas streams than the reprocessing of other SNFs. The gas volumes that must be treated become a major challenge for hiding reprocessing facilities.

5.5 DIRTY BOMB POTENTIAL

The consequences of theft of SNF by a subnational group for construction of a dirty bomb depend on the characteristics of the SNF. The consequences for traditional SNF types (e.g., LWR, CANDU, SFR) are expected to be somewhat similar because of the very similar construction of these different fuels. In contrast, the consequences of incorporating graphite-matrix coated-particle fuels (Sect. 4.3.2) into a dirty bomb may be several orders of magnitude less than any other type of SNF. For this threat, a better understanding of the performance of PBR fuel in this environment is required.

6. RECOMMENDATIONS AND CONCLUSIONS

PBR fuel has characteristics very different from those of traditional LWR fuel. The fissile content of the fuel per unit volume or weight is much less than the fissile content of other fuels because the moderator and fuel are combined. Much larger physical quantities must be diverted before a significant quantity of fissile material is lost. The pebbles are small with a small fissile content per pebble, but the number of pebbles is very large. PBR SNF has a uniform and high burnup, characteristics that make the recovery and use of plutonium from this SNF significantly more difficult than from LWR SNF. Last, PBR fuel is designed as a containment system for severe accidents—a design characteristic that also makes it difficult to reprocess or misuse. These characteristics result in greater barriers to the illicit use of fissile material from PBR SNF than from other types of SNF.

The existing safeguards strategies are adequate for a test reactor or pilot plant. However, if the PRC PBR is commercially successful, safeguards strategies should be reexamined because this system (1) produces very large quantities of fuel with properties very different from traditional LWRs and (2) may be deployed much more widely under circumstances very different from a traditional LWR. PBRs could potentially become the dominant reactor type in much of the developing world. Their commercialization potential leads to the following recommendations.

- *The feasibility of measuring the fissile content of beds of PBR SNF in storage with radiation probes should be investigated.* This method may provide a relatively inexpensive means of measuring inventories of fissile materials in SNF.

- *The dirty bomb potential for PBR fuel should be determined experimentally relative to other fuel types.* Based on limited information, the dirty bomb potential of PBR SNF appears to be significantly less than with other SNF types. If confirmed, this information would (1) allow better allocation of safeguards resources and (2) indicate a technological approach to reduce the consequences of other types of SNF if used in dirty bombs.

- *The use of tags for identification of fuel lots should be considered.* The characteristics of PBR fuel imply that any diversion scenario will require many shipments. The potential for interception increases as the number of shipments increases. If PBR fuel is intercepted, knowing when and where it was made would greatly increase the probability that investigators can determine where the diversion occurred and eliminate the threat.

- *An assessment of the difficulty of reprocessing relative to other SNFs should be undertaken to develop an understanding of the relative economics and thus incentives to reprocess*. Such a study could help allocate safeguards resources to the most cost-effective areas.

Last, multiple national and international programs are developing PBRs. PRC is scheduled to have the first prototypical modular PBR. This will be shortly followed by the RSA PBR, which has a different commercialization strategy. In the United States, the Department of Energy is working with industry to assemble a consortium to build a modular HTR. There are two designs—one is a PBR and the other uses a prismatic fuel. The U.S. reactor will not be operational in the near future. Safeguards developments for any PBR will generally be applicable to all PBRs. Any safeguards program should be based on applicability to all PBRs.

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