

Small Modular Reactors

No Solution for the Cost, Safety, and Waste Problems of Nuclear Power

BY ARJUN MAKHIJANI AND MICHELE BOYD

Some proponents of nuclear power are advocating for the development of small modular reactors (SMRs)¹ as the solution to the problems facing large reactors, particularly soaring costs, safety, and radioactive waste. Unfortunately, small-scale reactors can't solve these problems, and would likely exacerbate them.

There has been a proliferation of proposed SMR designs, but none have applied for certification by the Nuclear Regulatory Commission yet. The NRC says that it expects to receive its first SMR design certification application in 2012.² There are three general types of SMRs being discussed for certification and possible deployment in the United States.

► LIGHT WATER REACTOR DESIGNS

are generally scaled down variants of today's large commercial pressurized water reactors, though they may include new technologies and components not used in existing reactors. Starting in FY2011, DOE plans to provide taxpayer money to the nuclear industry to fund part of the NRC's design certification process for up to two light water reactor SMRs. The options currently include:³

► *International Reactor Innovative and Secure (IRIS)* by an international consortium

led by Westinghouse: This 335 MWe reactor would use conventional pressurized water fuel rods in 17x17 bundles with all of the main system components inside the reactor vessel.

► *NuScale Power Reactor by NuScale Power*: This 45 MWe reactor would use pressurized water fuel rods in 17x17 bundles that are one-half the length of conventional rods. Each module would be in a separate containment, but would operate in the same large pool of water. NuScale Power plans to apply to the NRC to certify a 12-module facility. The modules would be refueled every two years.

► *mPower Reactor* by Babcock & Wilcox Company: This 125 MWe reactor would use pressurized water fuel rods in 17x17 bundles that are one-half the length of conventional rods. The core, coolant pumps,

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and steam generators are designed to be in the reactor vessel. The modules would be refueled every five years.

► **NON-LIGHT WATER DESIGNS**, such as high-temperature gas-cooled reactors, use helium gas as the coolant and graphite to moderate it. Only two high-temperature gas-cooled reactors have operated commercially in the United States: Peach Bottom in Pennsylvania and Fort St. Vrain in Colorado. Neither of these reactors is still operating. The Fort St. Vrain reactor, with a lifetime capacity factor of 14.5 percent, was the country's worst operating commercial reactor.⁴ DOE has chosen the high-temperature gas-cooled reactor as its Next Generation Nuclear Plant and plans to submit a design certification application in FY2013.⁵ DOE is considering the following designs:⁶

► **Pebble Bed Modular Reactor:** This 165 MWe reactor would be a helium-cooled, graphite-moderated reactor with a core comprised of 450,000 fuel "pebbles" (or spheres) the size of billiard balls. Fuel pebbles would be continuously added at the top of a cylindrical reactor vessel and travel slowly to the bottom, where they would be removed and recirculated through the reactor up to ten times.⁷ Every one of the 450,000 fuel pebbles must be manufactured with a high degree of precision and quality, for instance, none should have any cracks. Each pebble or sphere would have 12,000 microspheres of fuel (or coated fuel kernels), making for a total of over five billion coated fuel kernels in each reactor.

► **Gas-Turbine Modular Helium Reactor (GT-MHR)** by General Atomics: This 285 MWe reactor would use graphite spheres containing enriched uranium fuel kernels (10-19.9 percent enriched) inserted into hexagonal graphite blocks. The design is based on the Fort St. Vrain reactor.

► **New Technology Advanced Reactor Energy System (ANTARES)** by Areva: This 285 MWe reactor would use graphite spheres containing enriched uranium fuel kernels (10–19.9 percent) inserted into hexagonal graphite blocks. The generator is different from the GT-MHR design.

► **LIQUID METAL FAST REACTOR DESIGNS**

do not use a moderator to slow neutrons down. The coolant is liquid metal, such as sodium or potassium. Fast reactors have never been commercialized anywhere in the world because they are expensive and unreliable and pose serious safety hazards.⁸ Both sodium and potassium burn when in contact with air and explode when in contact with water. Two SMR sodium-cooled fast reactor designs under development are:

► **Super-Safe, Small and Simple Reactor (4S)** by Toshiba: This reactor would be fueled with either enriched uranium or with plutonium. Two sizes are proposed—10 MW and 50 MW: the 10 MW version would use 24 percent plutonium fuel or 20 percent enriched uranium; the 50 MW version would use 11.5 percent plutonium fuel. The reactor would be sealed in a cylindrical vault underground with turbine-generator housed in an aboveground building. The reactor is supposed to operate for 30 years without refueling. Toshiba has proposed to build a free demonstration reactor in Galena, Alaska.

► **Power Reactor Inherently Safe Module (PRISM)** by GE Hitachi Nuclear Energy: The standard facility would consist of nine 155 MWe reactor modules, each with its own below-ground silo connected to a separate generator.⁹ The nine reactors would be grouped into three "power blocks" each of which would consist of three reactors. One control center would be used to manage all nine reactors. The total amount of

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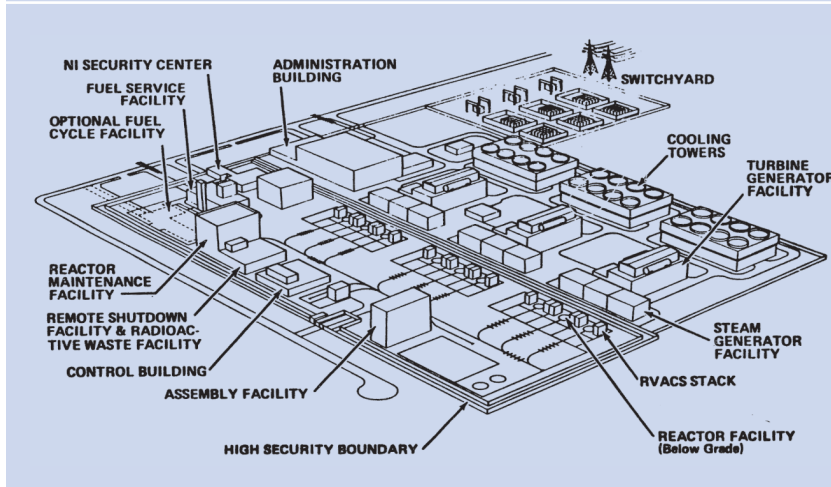
electricity produced per facility would be 1,395 MWe.¹⁰

Inherently more expensive?

SMR proponents claim that small size will enable mass manufacture in a factory, enabling considerable savings relative to field construction and assembly that is typical of large reactors. In other words, modular reactors will be cheaper because they will be more like assembly line cars than hand-made Lamborghinis. In the case of reactors, however, several offsetting factors will tend to neutralize this advantage and make the costs per kilowatt of small reactors higher than large reactors. First, in contrast to cars or smart phones or similar widgets, the materials cost per kilowatt of a reactor goes up as the size goes down. This is because the surface area per kilowatt of capacity, which dominates materials cost, goes up as reactor size is decreased. Similarly, the cost per kilowatt of secondary containment, as well as independent systems for control, instrumentation, and emergency management, increases as size decreases. Cost per kilowatt also increases if each reactor has dedicated and independent systems for control, instrumentation, and emergency management. For these reasons, the nuclear industry has been building larger and larger reactors in an effort to try to achieve economies of scale and make nuclear power economically competitive.

Proponents argue that because these nuclear projects would consist of several smaller reactor modules instead of one large reactor, the construction time will be shorter and therefore costs will be reduced. However, this argument fails to take into account the implications of installing many reactor modules in a phased manner at one site, which is the proposed approach at least for the United States. In this case, a large containment structure with a single control room would be built at the beginning of the project that could accommodate all the planned capacity at the site. The result would be that the first few units would be saddled with very high costs, while the later units would be

A schematic of a 1,395 MWe PRISM facility with 9 modules



NRC, *Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor: Final Report*, February 1994. (NUREG-1368) at <http://www.osti.gov/bridge/purl.cover.jsp?purl=/10133164-2ZfTJr/native/>, Figure 1.2

less expensive. The realization of economies of scale would depend on the construction period of the entire project, possibly over an even longer time span than present large-reactor projects. If the later-planned units are not built, for instance due to slower growth than anticipated, the earlier units would likely be more expensive than present reactors, just from the diseconomies of the containment, site preparation, instrumentation and control system expenditures. Alternatively, a containment structure and instrumentation and control could be built for each reactor. This would greatly increase unit costs and per kilowatt capital costs. Some designs (such as the PBMR) propose no secondary containment, but this would increase safety risks.

These cost increases are unlikely to be offset even if the entire reactor is manufactured at a central facility and some economies are achieved by mass manufacturing compared to large reactors assembled on site. Furthermore, estimates of low prices must be regarded with skepticism due to the history of past cost escalations for nuclear reactors and the potential for cost increases due to requirements arising in the process of NRC certification. Some SMR designers are proposing that no prototype be built and that the necessary licensing tests be simulated. Whatever the

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process, it will have to be rigorous to ensure safety, especially given the history of some of proposed designs.

The cost picture for sodium-cooled reactors is also rather grim. They have typically been much more expensive to build than light water reactors, which are currently estimated to cost between \$6,000 and \$10,000 per kilowatt in the US. The costs of the last three large breeder reactors have varied wildly. In 2008 dollars, the cost of the Japanese Monju reactor (the most recent) was \$27,600 per kilowatt (electrical); French Superphénix (start up in 1985) was \$6,300; and the Fast Flux Test Facility (startup in 1980) at Hanford was \$13,800.¹¹ This gives an average cost per kilowatt in 2008 dollars of about \$16,000, without taking into account the fact that cost escalation for nuclear reactors has been much faster than inflation. In other words, while there is no recent US experience with construction of sodium-cooled reactors, one can infer that (i) they are likely to be far more expensive than light water reactors, (ii) the financial risk of building them will be much greater than with light water reactors due to high variation in cost from one project to another and the high variation in capacity factors that might be expected. Even at the lower end of the capital costs, for Superphénix, the cost of power generation was extremely high—well over a dollar per kWh since it operated so little. Monju, despite being the most expensive has generated essentially no electricity since it was commissioned in 1994. There is no comparable experience with potassium-cooled reactors, but the chemical and physical properties of potassium are similar to sodium.

Increased safety and proliferation problems

Mass manufacturing raises a host of new safety, quality, and licensing concerns that the NRC has yet to address. For instance, the NRC may have to devise and test new licensing and inspection procedures for the manufacturing facilities, including inspec-

tions of welds and the like. There may have to be a process for recalls in case of major defects in mass-manufactured reactors, as there is with other mass-manufactured products from cars to hamburger meat. It is unclear how recalls would work, especially if transportation offsite and prolonged work at a repair facility were required.

Some vendors, such as PBMR (Pty) Ltd. and Toshiba, are proposing to manufacture the reactors in foreign countries. In order to reduce costs, it is likely that manufacturing will move to countries with cheaper labor forces, such as China, where severe quality problems have arisen in many products from drywall to infant formula to rabies vaccine.

Other issues that will affect safety are NRC requirements for operating and security personnel, which have yet to be determined. To reduce operating costs, some SMR vendors are advocating lowering the number of staff in the control room so that one operator would be responsible for three modules.¹² In addition, the SMR designers and potential operators are proposing to reduce the number of security staff, as well as the area that must be protected. NRC staff is looking to designers to incorporate security into the SMR designs, but this has yet to be done.¹³ Ultimately, reducing staff raises serious questions about whether there would be sufficient personnel to respond adequately to an accident.

Of the various types of proposed SMRs, liquid metal fast reactor designs pose particular safety concerns. Sodium leaks and fires have been a central problem—sodium explodes on contact with water and burns on contact with air. Sodium-potassium coolant, while it has the advantage of a lower melting point than sodium, presents even greater safety issues, because it is even more flammable than molten sodium alone.¹⁴ Sodium-cooled fast reactors have shown essentially no positive learning curve (i.e., experience has not made them more reliable, safer, or cheaper). The world's first nuclear reactor to generate electricity, the EBR I in Idaho, was a sodium-potassium-cooled reactor that suffered a partial meltdown.²² EBR II, which was sodium-

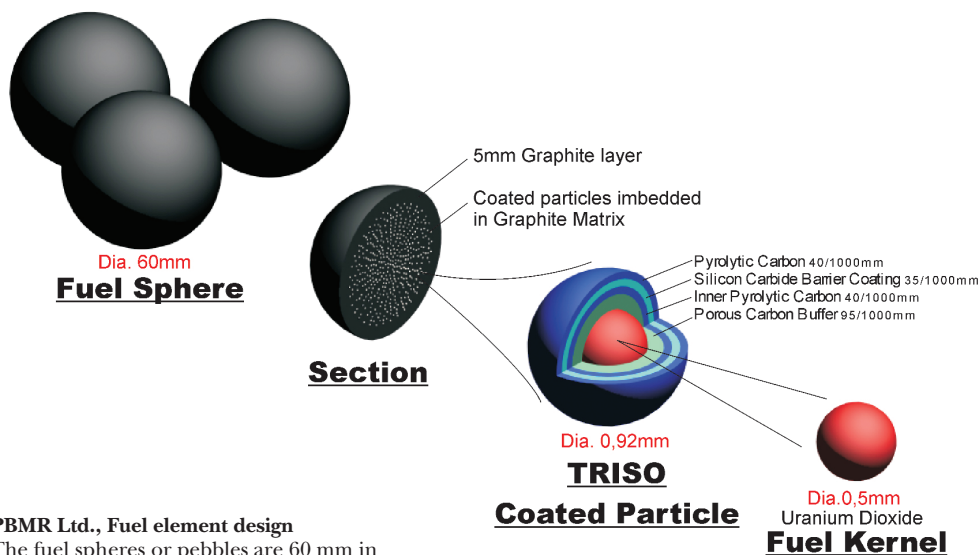
CASE STUDY: **Pebble Bed Modular Reactor (PBMR)**

The Pebble Bed Modular Reactor (PBMR) is a high-temperature gas-cooled reactor that uses helium as the coolant and graphite as a moderator. The fuel consists of uranium oxide or uranium carbide, enriched to considerably higher levels than present light water reactors (about 9 percent or more). The kernels are coated with silicon carbide and contained in billiard-ball-sized pyrolytic graphite “pebbles” (spheres). Each pebble would contain about 12,000 tiny fuel kernels or grains. The heat generated from the chain reaction is carried away by an inert cooling gas—generally proposed to be helium. In principle, the fuel pebbles move slowly but steadily through the reactor and are replaced by new pebbles, enabling continuous operation. Each pebble would be used up to ten times by refeeding it into the reactor after some cooling. Gas temperatures are much higher than water temperatures in light water reactors; in theory, this can lead to higher efficiency electricity production and/or other applications, such as hydrogen production.

However, graphite catches fire in the presence of air, which would rush into the reactor in the event of a loss of coolant (helium) accident. In such an event the graphite, which the pebbles contain, would burn. Proponents claim that the silicon carbide coating would resist fire; however, the billions of grains of fuel must not only be generally free of cracks at manufacture but remain free for the entire time they are in the reactor despite the generation of fission product gases as the reactor operates. In this context, it is important to remember that the burden of proving safety in the context of a loss of coolant accident is quite heavy for a graphite-moderated reactor, since the worst power-generation reactor accidents by far have both occurred in graphite-moderated reactors and have been accompanied by graphite fires. In case a steam cycle is used for power generation, it is essential to design the reactor so that there is no possibility of water entering the core in case of a loss of coolant accident.¹⁵

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FUEL ELEMENT DESIGN FOR PBMR



PBMR Ltd., Fuel element design

The fuel spheres or pebbles are 60 mm in diameter, which is slightly smaller than a tennis ball. The PBMR fuel is based on a German fuel design consisting of coated uranium particles contained in a molded graphite sphere.

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CASE STUDY: PBMR | CONTINUED FROM PAGE 5

Since the PBMR design is proposed to be modular, the cost issues raised above for other SMRs would also apply. Finally, proliferation is a greater concern than with light water reactors, since the PBMR would use uranium at higher enrichments than light water reactors or use plutonium fuel. Use of thorium as a fertile material is possible, but it would require plutonium or enriched uranium to sustain the initial chain reaction. It also results in the production of fissile uranium-233.¹⁶

Disposal of graphite fuel in a geologic repository would also present new challenges since essentially all work on repository design has been premised either on light water reactor spent fuel (consisting of uranium dioxide fuel pellets) or vitrified high level waste.

The PBMR was originally designed by German companies, but they abandoned the design in 1991 when it became clear that no country would buy it. A 15 MW prototype PBMR, known as the AVR, operated in Germany from 1967–1988. A report released in 2008 by the Jülich Research Center on its pebble bed reactor design revealed significant technical problems with the AVR, including unexpectedly high operating temperatures. In addition, radioactive graphite dust was generated when the “pebbles” moved against each other, which increases problems in decommissioning and could pose a serious safety problem in an accident. Finally, the report recommended containment structures, which would increase the cost of the design significantly.¹⁷

In 1993, the South African national utility Eskom began working on a version of the PBMR design. In 1999, Eskom created PBMR (Pty) Ltd. to do a feasibility study, which was

never released. Meanwhile, some of the investors, including the US utility Exelon, pulled out and no demonstration reactor was sufficiently funded or seriously planned. The estimated cost of the demonstration reactor increased from \$223 million to \$1.8 billion.¹⁸ After spending over \$1 billion on PBMR (Pty) Ltd. in the past 11 years, the government of South Africa announced in July 2010 that it would stop funding the project and that the company’s operations would be shut down in August 2010.¹⁹

In the early 2000s, Exelon was interested in having the US Nuclear Regulatory Commission certify the South African PBMR design. NRC’s initial review resulted in a slew of technical and safety questions, such as the issue of extremely high operating temperatures, which were not addressed before Exelon withdrew from the project.²⁰

Since 2003, China has been operating a small, 10 MW test PBMR reactor and has plans to construct a larger demonstration reactor. China has been changing its design along the way, but it is unknown whether or not technical problems have arisen.²¹

Despite 50 years of research by many countries, including the United States, the theoretical promise of the PBMR has not come to fruition. The technical problems encountered early on have yet to be resolved, or apparently, even fully understood. PBMR proponents in the US have long pointed to the South African program as a model for the US. Ironically, the US Department of Energy is once again pursuing this design at the very moment that the South African government has pulled the plug on the program due to escalating costs and problems.

cooled reactor, operated reasonably well, but the first US commercial prototype, Fermi I in Michigan had a meltdown of two fuel assemblies and, after four years of repair, a sodium explosion.²³ The most recent commercial prototype, Monju in Japan, had a sodium fire

18 months after its commissioning in 1994, which resulted in it being shut down for over 14 years. The French Superphénix, the largest sodium-cooled reactor ever built, was designed to demonstrate commercialization. Instead, it operated at an average of less than

7 percent capacity factor over 14 years before being permanently shut.²⁴

In addition, the use of plutonium fuel or uranium enriched to levels as high as 20 percent—four to five times the typical enrichment level for present commercial light water reactors—presents serious proliferation risks, especially as some SMRs are proposed to be exported to developing countries with small grids and/or installed in remote locations. Security and safety will be more difficult to maintain in countries with no or underdeveloped nuclear regulatory infrastructure and in isolated areas. Burying the reactor underground, as proposed for some designs, would not sufficiently address security because some access from above will still be needed and it could increase the environmental impact to groundwater, for example, in the event of an accident.

More complex waste problem

Proponents claim that with longer operation on a single fuel charge and with less production of spent fuel per reactor, waste management would be simpler. In fact, spent fuel management for SMRs would be more complex, and therefore more expensive, because the waste would be located in many more sites. The infrastructure that we have for spent fuel management is geared toward

light-water reactors at a limited number of sites. In some proposals, the reactor would be buried underground, making waste retrieval even more complicated and complicating retrieval of radioactive materials in the event of an accident. For instance, it is highly unlikely that a reactor containing metallic sodium could be disposed of as a single entity, given the high reactivity of sodium with both air and water. Decommissioning a sealed sodium- or potassium-cooled reactor could present far greater technical challenges and costs per kilowatt of capacity than faced by present-day above-ground reactors.

Not a climate solution

Efficiency and most renewable technologies are already cheaper than new large reactors. The long time—a decade or more—that it will take to certify SMRs will do little or nothing to help with the global warming problem and will actually complicate current efforts underway. For example, the current schedule for commercializing the above-ground sodium cooled reactor in Japan extends to 2050, making it irrelevant to addressing the climate problem. Relying on assurances that SMRs will be cheap is contrary to the experience about economies of scale and is likely to waste time and money, while creating new safety and proliferation risks, as well as new waste disposal problems.

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Notes

1. This fact sheet addresses small modular reactor designs for which the U.S. Nuclear Regulatory Commission may receive design certification applications in FY2011. It does not include some designs that are being researched but that are not on the NRC list, notably the travelling wave reactor. IEER will produce a separate report later in 2010 on this reactor. “Small modular reactors” are defined by DOE as reactors that would produce 300MWe or less and are made in modules that can be transported. (U.S. Department of Energy Office of Nuclear Energy, *Small Modular Reactors*, Factsheet, February 2010, http://nuclear.energy.gov/pdfFiles/factSheets/2011_SMR_Factsheet.pdf).

2. Written Testimony of Gregory B. Jaczko, Chairman, United States Nuclear Regulatory Commission to the Senate Committee on Environment and Public Works Subcommittee on Clean Air and Nuclear Safety, May 5, 2010, <http://www.nrc.gov/about-nrc/organization/commission/comm-gregory-jaczko/jaczko-statement-5-05-10.pdf>.

3. The descriptions of all eight reactors are based on the following, unless otherwise noted: W. Borchardt (NRC Executive Director for Operations) to the Commissioners, *Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs* (Policy Issue Information) (SECY-10-0034), March 28, 2010, <http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2010/secy2010-0034/2010-0034scy.pdf>, Enclosure, p. 1 and Attachment 1.

4. Arjun Makhijani and Scott Saleska, *The Nuclear Power Deception: US Nuclear Mythology from Electricity "Too Cheap to Meter" to "Inherently Safe" Reactors*, Apex Press, 1999, Chapter 7 is at <http://www.ieer.org/reports/npd7.html>
5. *Written Testimony of Michael R. Johnson, Director, Office Of New Reactors, United States Nuclear Regulatory Commission, to the Committee on Energy and Natural Resources, United States Senate, Hearing on Small Modular Reactors*, December 15, 2009, http://energy.senate.gov/public/_files/Johnson-Testimony121509.pdf, pp. 3 and 5
6. SECY-10-0034, op.cit. Enclosure.
7. PBMR, "How the PBMR fuel works," <http://www.pbmr.co.za/index.asp?Content=224>, viewed July 23, 2010.
8. See a comprehensive report on fast reactors by the International Panel on Fissile Materials. (Thomas B. Cochran, Harold A. Feiveson, Walt Patterson, Gennadi Pshakin, M.V. Ramana, Mycle Schneider, Tatsujiro Suzuki, and Frank von Hippel, *Fast Breeder Reactor Programs: History and Status* (IPFM Research Report 8), IFMP, Program on Science and Global Security, Princeton University, February 2010, <http://www.ipfmlibrary.org/rr08.pdf>)
9. SECY-10-0034, op. cit., Enclosure; US Nuclear Regulatory Commission, *Power Reactor Innovative Small Module (PRISM)*, June 18, 2010, <http://www.nrc.gov/reactors/advanced/prism.html>.
10. Nuclear Regulatory Commission, *Fact Sheet on Next-Generation Reactors*, January 2004, <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/next-gen-reactors.html>, Viewed on July 30, 2010.
11. Costs of demonstration breeders in 1996 dollars per thermal kilowatt are estimated in Arjun Makhijani, *Plutonium End Game*, Institute for Energy and Environmental Research, Takoma Park, MD, 2001, <http://www.ieer.org/reports/pu/peg.pdf>, Table 3 on p. 22. These were escalated to 2008 dollars using the GDP deflator from 1996 to 2008 of 1.314.
12. NRC Commissioner William C. Ostendorff, "Small Modular Reactors – Challenges and Opportunities," Keynote Address, Platts Small Modular Reactors Conference, June 28, 2010, Washington, DC, <http://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2010/s-10-021.html>.
13. SECY-10-0034, op. cit., Enclosure
14. IPFM 2010, op. cit., p. 68.
15. R. Moormann, *A Safety Re-evaluation of the AVR Pebble Bed Reactor Operation and Its Consequences for Future HTR Concepts* (Berichte des Forschungszentrums Jülich JUEL-4275) Forschungszentrum Jülich, June 2008, http://juwel.fz-juelich.de:8080/dspace/bistream/2128/3136/1/Juel_4275_Moormann.pdf.
16. For more information on thorium reactors, see: Arjun Makhijani and Michele Boyd, *Thorium Fuel: No Panacea for Nuclear Power*, Fact Sheet, Physicians for Social Responsibility and Institute for Energy and Environmental Research, January 2009, <http://www.ieer.org/factsheet/thorium2009factsheet.pdf>.
17. R. Moormann 2008, op. cit., and Steve Thomas, "The demise of the pebble bed modular reactor," *The Bulletin of Atomic Scientists*, June 22, 2009, <http://www.thebulletin.org/web-edition/features/the-demise-of-the-pebble-bed-modular-reactor>.
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19. Prega Govender, "R9bn taxpayer-funded nuclear energy plan finally grinds to halt," *Times Live*, July 18, 2010, [http://www.timeslive.co.za/business/article555632.ece/Government-pulls-plug-on-PBMR;SisekoNjobeni,"South Africa: State Cuts Off PBMR as it Fails to Find Investor, Customers," *AllAfrica.com*, February 19, 2010, <http://allafrica.com/stories/printable/201002190377.html>; Ann MacLachlan, "South African government aims to close PBMR operations in August," *Nucleonics Week*, July 29, 2010.](http://www.timeslive.co.za/business/article555632.ece/Government-pulls-plug-on-PBMR;SisekoNjobeni,%20South%20Africa:State%20Cuts%20Off%20PBMR%20as%20it%20Fails%20to%20Find%20Investor,%20Customers,%20AllAfrica.com,%20February%2019,%202010,%20http://allafrica.com/stories/printable/201002190377.html;AnnMacLachlan,%20South%20African%20government%20aims%20to%20close%20PBMR%20operations%20in%20August,%20Nucleonics%20Week,%20July%2029,%202010)
20. Jenny Weil, "Questions Remain on PBMR Fuel; NRC Research Looks at HTGRs," *Nuclear Fuel*, August 15, 2002.
21. Thomas 2009, op. cit.
22. The core was replaced and the repaired reactor operated after that until it was closed in 1963. (IPFM 2010, op. cit. p. 92).
23. IPFM 2010, op. cit. p. 95; Power Reactor Development Company, Enrico Fermi Atomic Power Plant, *Sodium—Water Reaction Incident, May 20, 1970* (Sent to the AEC on June 19, 1970).
24. IPFM 2010, op. cit., p. 10.

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