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The checkered operational history of high-temperature gas-cooled reactors

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FEATURES

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ABSTRACT
The high-temperature gas-cooled reactor (HTGR) has long been considered a promising nuclear technology, and several countries are either considering the construction of new HTGRs or pursuing research into the field. In the past, both Germany and the United States spent large amounts of money to design and construct HTGRs, four of which fed electricity into the grid. Examining the performances of these HTGRs offers a useful guide to what one can expect from future HTGRs, if and when more are constructed, and reasons to reject that option altogether.

KEYWORDS
HTGR; high-temperature gas-cooled reactor; pebble-bed reactor; commercial viability; nuclear power; advanced reactors

In January 2016, as part of its initiative to accelerate the commercialization of what it calls "advanced nuclear reactors," the US Energy Department announced that it would provide up to $40 million to X-energy, a company developing a pebble-bed high-temperature gas-cooled reactor (HTGR) design (Fountain 2016). The United States is not alone in these efforts; China has been constructing one in Shandong province since 2012 and, earlier this year, signed a memorandum of understanding with Saudi Arabia on the construction of an HTGR (WNN 2016). And last year, the Indonesian national nuclear agency Batan entered into an agreement with the German company Nukem Technologies, a subsidiary of Russian nuclear company Rosatom, to build a similar high-temperature reactor (Cetak 2015; Anonymous 2015; NUKEM 2015).

Proponents of HTGRs often claim that their designs have a long pedigree. As the X-energy website puts it: "The Xe-100 is a revolutionary design for a commercial nuclear reactor, but it builds on the experience of over 70 years of research, testing, and demonstration in HTGR projects worldwide" (X-energy 2016). But if one examines that very same experience more closely – looking in particular at the HTGRs that were constructed in Western Europe and the United States to feed power into the electric grid – then one comes to other conclusions. This history suggests that while HTGRs may look attractive on paper, their performance leaves much to be desired. The technology may be something that looks better on paper than in the real world.

Early history

The idea of a pebble-bed high-temperature reactor with a graphite moderator was first proposed in 1942 by Farrington Daniels (McDowell et al. 2011, 2). Two years later, in a report from the Metallurgical Laboratory at the University of Chicago in October 1944, Daniels elaborated on the possibility of building a "high-temperature pebble pile" using uranium carbide and graphite operating at 1,500–2,000°C, to be cooled by circulating either helium or boiling bismuth (Daniels 1944). ("Pile" was the term used during that period for a nuclear reactor.) The main purpose Daniels envisioned for this pile was the production of plutonium for nuclear weapons (Daniels 1944, 6).

HTGRs come in two varieties. One is the pebble-bed reactor that Daniels proposed. The other is a closely related design variant, the prismatic block reactor, where, as the name suggests, the fuel is in the form of prisms – large hexagonal graphite blocks – instead of pebbles. (Even the word "pebble" is somewhat of a misnomer; the finished product is closer in size to a billiard ball.)

Both varieties are, as the term HTGR suggests, designed to operate at high temperatures, and the coolant – the material that carries away the heat produced by fission reactions – is a gas, usually helium. A typical operating temperature for the light water reactors that dominate today's nuclear energy landscape is 300°C. In contrast, temperatures inside the core of a HTGR could be 800°C or more. It is because of this high operating temperature that helium is used for cooling; using liquid water would necessitate extremely high

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Figure 1. In pebble reactors, the fuel consists of small (roughly 6 cm in diameter) uranium particles, coated with several ceramic layers and graphite.

pressures, or the water would instantly be transformed into steam.

The fuel in both designs uses particles of uranium oxide, surrounded by several layers of materials containing carbon (Figure 1). In turn, these small balls are combined in two different ways. In the case of prismatic reactors, the coated particles are pressed together in the form of fuel rods, which are placed in narrow channels within graphite blocks. For pebble-bed reactors, approximately 12,000 of these are embedded in a graphite sphere – the pebble. These pebbles then are fed to the reactor continuously and come jostling down the reactor core (Figure 2). As they exit out of the reactor, based on estimates of whether an adequate fraction of the uranium in the pebble has undergone fission, these pebbles are either fed back into the reactor core or removed from circulation and stored as spent fuel. (Dealing with the spent fuel is a complication we will not address here.) Both designs have their advantages and disadvantages, although in recent years the pebble-bed reactor design has been a little more popular.

The first HTGR was of the prismatic block variety and constructed in the United Kingdom. The origins of this 20 megawatt (MW) thermal test reactor named "Dragon" date back to 1956, when the UK's Atomic Energy Research Establishment conducted some exploratory studies (Lockett and Huddle 1960). Eventually, the reactor became an international project under the aegis of the Organization for Economic Co-operation and Development, although the United Kingdom paid the majority of the operational costs (Patterson 1976, 39).

During its operational lifetime, Dragon faced a number of problems, especially with its heat exchangers – a reactor component that allows the heat produced by the fission reactions inside the nuclear core to be transferred out of the reactor without any escape of radioactive materials. Although the tests conducted before the reactor was put into service gave, in the words of two members of the UK Atomic Energy Authority, "reassuring results," when the reactor was started up, it experienced "severe and rapid" corrosion on the water side of the heat exchangers, which resulted in the leakage of helium into the secondary circuit (Lockett and Hosegood 1968, 6). Luckily, no water leaked into the primary circuit; but by 1968, after only four years of operation, all six of Dragon's heat exchangers had to be replaced (Gray and Watts 1968).

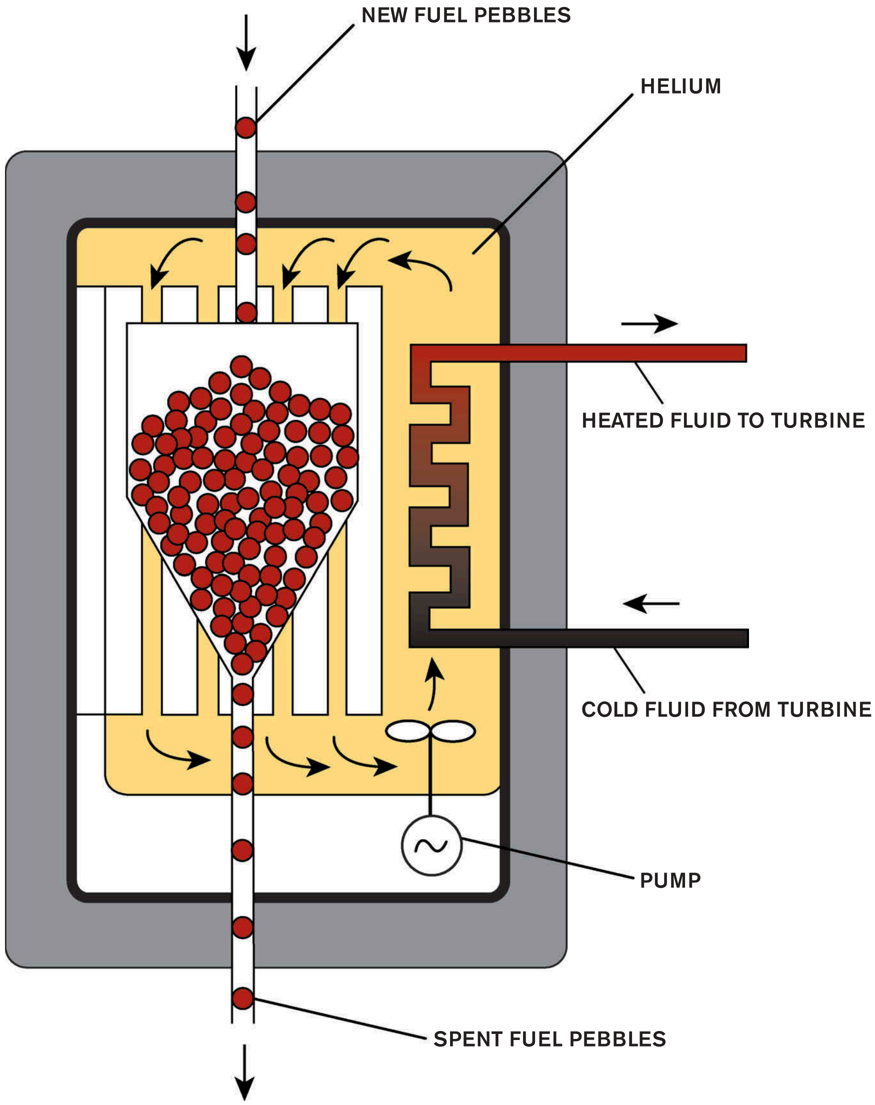
And that was not all: Dragon's helium purification system also suffered a number of leaks (Beck, Garcia, and Pincock 2010, 49–50). The reactor only operated for about 12 years before the United Kingdom cut off funding because it envisioned no future for HTGRs in the country (Patterson 1976, 39).

The experience with Dragon notwithstanding, both Germany and the United States continued research into this field, eventually constructing two commercial HTGRs each. And the operating records of their HTGR reactors have been similarly discouraging. (There were serious attempts to develop HTGR technology in France and Japan as well. But only Japan got as far as building even a small test HTGR; its operations did not encourage the Japanese nuclear establishment to proceed further.)

Let us look at these completed reactors in more detail, in the chronological order in which construction on them began.

Arbeitsgemeinschaft Versuchsreaktor

Despite the origins of HTGRs in the English-speaking world, it was left to Germany to construct the first prototype HTGR that actually generated electricity and was connected to the electrical grid. During the first few decades of the nuclear age, the German government was very keen on HTGRs. Until 1972, government expenditures on HTGRs exceeded expenditures on all other kinds of reactor designs – with the exception of fast breeder reactors (Keck 1981, 49). The



Schematic of a Pebble Bed High Temperature Gas Cooler Reactor.
Image courtesy Wikicommons.

Figure 2. Pebble-bed_reactor_scheme.

"Arbeitsgemeinschaft Versuchsreaktor" (AVR), was one of the first reactors of any kind to be constructed in Germany. This prototype pebble-bed reactor generated 46 MW of heat and 15 MW of electricity; construction of the reactor started in 1961, and the reactor first became critical in August 1966, with commercial operations starting nearly three years later, in May 1969 (IAEA 2014).

But the AVR experienced a number of problems. In part, this large number resulted from the very long time that the reactor was operational – from 1966 to 1988 – which has been unusual for HTGRs. A second reason was that the AVR operated at temperatures that were higher than any other commercial nuclear power reactor (Simnad 1991, 30).

One continuing problem was the accumulation of graphite dust produced from the fuel pebbles as they went through the core. This dust was then picked up by the helium that circulated to cool the reactor and the surfaces of various reactor components that were in the path of this helium collected a layer of graphite dust. This had safety implications: the dust can become a conduit for radioactive materials – chiefly fission products – to go from the core to the coolant circuit, which could then be released into the atmosphere if there is an accident (Schlögl 2009, Slide 4). Estimates of the amount of total dust vary from about 46 to 200 kg (Schlögl 2009). Dust has been a major problem during the decommissioning of the reactor because it represented, in the somewhat strong words of Edgar Wahlen, Jürgen Wahl, and Peter

Pohl – three of the scientists associated with the reactor – "a permanent and virtually undepletable source of serious contamination" (Wahlen, Wahl, and Pohl 2000).

Like other HTGRs, the AVR also had problems with its steam generator. In 1978, one of the tubes in the steam generator developed a leak (NRC 2001), resulting in approximately 27 tons of water entering the core of the reactor – also known as a "water ingress" (Ziermann 1990, 137). The problem proved difficult to resolve. This ingress of water was too much for the gas purification plant to clean, and various parts of the reactor core and other components became wet; fixing the problem required the plant to shut down for 15 months (Beck, Garcia, and Pincock 2010, 45). The leak resulted in the contamination of soil at the reactor site (AVR 2011). Ironically, the leak was discovered when the reactor had been shut down to repair a safety valve (Beck, Garcia, and Pincock 2010, 45).

Besides water, oil has also leaked into the reactor core of the AVR (Moormann 2008b), which led to the chemical decomposition of the oil and the production of contaminated dust. The radioactive fission products observed in the coolant and the dust included tritium, carbon 14, cobalt 60, strontium 89 and strontium 90, silver 110, iodine 131, and cesium 134 and cesium 137 (Schlögl 2009).

These high levels of fission product contamination within the reactor were likely the result of the core gas temperatures being much higher than anticipated (Moormann 2008a). In turn, this is related to the difficulties in monitoring pebble temperatures because there was no instrumentation within the core. One test showed that the temperatures of approximately 20% of a special set of pebbles, which were introduced explicitly to monitor the temperature, had exceeded 1,280°C – over 300°C greater than the 950 C that the system was designed for (NRC 2001). In other words, predicting pebble flow and their temperature levels through the core was problematic.

For all its problems, however, the AVR still has the best performance figures of all HTGRs reported in the International Atomic Energy Agency's (IAEA) Power Reactor Information System database – arguably the most authoritative database of information on the operating experiences of the nuclear power industry. According to this database, over its lifetime, the AVR generated 62% of the electricity it could have generated if it operated at full capacity all the time (IAEA 2014). This number, however, should be placed in context: The AVR generated a mere 15 MW of electricity; in comparison, most reactors under construction today are designed to generate between 1,000 and 1,700 MW of electricity.

Around the same time that construction of the AVR started in Germany, construction of a somewhat similar reactor was about to start across the Atlantic.

Peach bottom I

The Peach Bottom I reactor was the first HTGR to operate commercially in the United States, and the first in the world to produce electrical power (McDowell et al. 2011). Like Dragon, its core was made of prismatic blocks, but the Peach Bottom reactor produced far more power: 115 MW of heat and 40 MW of electricity (IAEA 2014). The reactor reached initial criticality in March 1966, but just two months later the plant had to be shut down for steam generator repair work (Everett III and Kohler 1978; Kantor, Menzel, and Schlicht 1968). It was only in June 1967 that the plant started commercial operations (IAEA 2014).

In January 1968, the reactor had to be shut down again. Prior to the shutdown, technicians detected an increase in radioactivity in the helium circulating through the core, indicating that one or more fuel elements had failed, or that there had been a rupture of the cladding somewhere (Everett III and Kohler 1978, 323). The reactor was restarted after the failed fuel element was replaced, but later that same year the reactor had to be shut down again, because the radioactivity levels in the helium continued to increase. Eleven additional failed fuel elements were detected this time. In January 1969, the reactor was restarted with fresh fuel, but again radioactivity levels in the helium increased; instead of shutting down the reactor, however, it was operated at a lower power level.

But by October 1969, the reactor had to be shut down once again; the count this time was 78 failed fuel elements. This time around the entire core was replaced with a new fuel design; in July 1970, the plant was restarted. This core performed more satisfactorily, but in October 1974, when it was time to replace the core, the plant's owners decided to shut down the plant because the plant simply did not make enough profit to justify the cost of new fuel and meeting regulatory requirements (Everett III and Kohler 1978, 326).

In the two years (1973 and 1974) that the reactor's electricity generation was recorded on the IAEA's Power Reactor Information System database, Peach Bottom's load factors were 55.9 and 57.9%. (Load factors are the ratio of the actual amount of electrical energy generated by a reactor to what it should have produced if it had operated at its design level continuously.) In other years, the electricity generated evidently was not reported to the IAEA. As a point of comparison, according to data from the IAEA, the overall load factor for the entire fleet of nuclear power plants in the United States in 2014 was 92.4% (IAEA 2015, 11).

Peach Bottom suffered from another problem as well: approximately 100 kg of oil accidentally got into the reactor (Beck, Garcia, and Pincock 2010, 39). Operators learned about it indirectly, when they found high concentrations of methane and other hydrocarbons in the helium coolant (Burnette and Baldwin 1981, 133). Their suspicion was confirmed when they found that virtually all the metallic components inside the reactor where the coolant circulated were coated with a thin layer of graphite dust. The dust had evidently been deposited on more than one occasion, including this ingress of oil, and was contaminated by radioactive cesium and strontium. In turn, the high levels of oil vapor or hydrocarbons in the helium coolant contributed to failure of the safety system that would monitor moisture levels (Burnette and Baldwin 1981, 133).

But even while Peach Bottom was experiencing all these problems, its larger cousin was being built in Colorado.

Fort St. Vrain

Construction of the reactor at Fort St. Vrain, Colorado, the second HTGR in the United States (McDowell et al. 2011, 7), started in September 1968. Fort St. Vrain had a prismatic core and generated 842 MW of heat and 330 MW of electricity. Although the reactor reached criticality in January 1974, it took over five years, until July 1979, for the reactor to be stable enough to be declared operating commercially (IAEA 2014). Helium leaks and moisture ingress – which first occurred in August 1974 – were some of the reasons for the lengthy period between criticality and commercial operations (Cadwell et al. 1975, 3–4). Another problem was a series of fluctuations of the core temperature (Olson, Brey, and Warembourg 1982). Fort St. Vrain was declared permanently shut down a decade later, in August 1989.

We know a lot about the problems experienced by Fort St. Vrain during its short operational lifetime, because they were tracked by the Oak Ridge National Laboratory between 1981 and 1989 for the Nuclear Regulatory Commission (ORNL 2003, vii). During this period, Oak Ridge reported 279 unusual events, which its subsequent report said included "29 water incursion events and failures of moisture detection systems;" "2 air or other unwanted gas incursion events and failures of gas detection systems;" "3 fuel failures or anomalies;" and "2 failures or cracks in graphite, pipes, and other reactor structural components" (ORNL 2003, vii). Among these, incursion of moisture was deemed the issue with the most significant implications for the plant's safety. Of particular concern was the resulting degradation of the control rod drives and reserve shutdown systems. An incident with great safety significance occurred on June 23 1984 when six control rod pairs failed to fully insert in response to the scram signal (ORNL 2003, 12) which indicated a "failure to completely guarantee a plant shutdown when required" as Oak Ridge reported in 2003 (ORNL 2003, viii).

Thanks to numerous shutdowns, the performance of Fort St. Vrain was very poor. Between 1979 and 1989, when its electricity production figures were reported, its highest load factor was just 28.1%; overall, its lifetime load factor was a mere 15.2% (IAEA 2014). It is no wonder then that a *New York Times* article about the 1988 decision to shut down the reactor was titled "Safest Reactor Is Closing Because It Rarely Runs" (Wald 1988), a reference to the HTGR design being promoted as being very safe.

An official from the Public Service Company of Colorado – the utility that operated the reactor – explained the decision to shut down Fort St. Vrain by saying: "Electrical generation from this plant throughout this period has not been good… Also, throughout this period, there has been substantial increase in operations, maintenance, and fuel costs, which could not be offset by the sale of electricity from the plant" (Brey 1991, 47). In a nutshell, the reactor was a financial failure.

The Fort St. Vrain experience was so uneconomical that no US utility ever since has considered ordering an HTGR. This is in complete contrast to the mid-1970s, when Fort St. Vrain was being put into service; at that time, US utilities were considering constructing up to 10 HTGRs (Agnew 1981, 63; McDowell et al. 2011, 3). Those proposals that moved from merely considering to signing actual contracts were all canceled. In the case of one project to be constructed in Fulton, Pennsylvania, the reactor vendor, General Atomic, ended up having to reimburse Philadelphia Electric Company $64 million and 2 million pounds of uranium (WSJ 1976).

Meanwhile, things overseas were not much better.

Thorium high-temperature reactor

Following on Germany's experience with its HGTR prototype – the previously mentioned AVR – the country started on the commercial version, called the thorium high-temperature reactor (THTR), that was designed to generate 300 MW of electricity. Like its predecessor, the new reactor was to follow the pebble-bed reactor design for HTGRs; construction was started in 1971 by the German utility, Hochtemperatur-Kernkraftwerk GmbH. The plant went critical much later, in September 1983. And it took a further four years – until June 1987 – for the reactor to begin delivering commercial power (IAEA 2014). The reactor was shut down the following year, and on 29 September 1988 it was declared to be permanently shut down. During the roughly two years that it was deemed to be in commercial operation, the THTR had a load factor of 41.3%.

Like the AVR prototype, the THTR also experienced high levels of graphite dust production, estimated at 16 kg of dust per full power year of operations (Cogliati, Ougouag, and Ortensi 2011, 2369). Despite the AVR experience, the designers of the THTR had not expected such problems with graphite dust. Nor was dealing with the dust easy: At least one attempt to remove the dust ended up releasing radioactive materials that spread outside the reactor site, although only at low levels (NRC 2001).

In part, the dust levels seem to have resulted from the fuel pebbles frequently breaking. Many of these pebbles seem to have broken when the control rods, used to regulate the chain reaction, were inserted forcefully into the reactor core (NRC 2001). One such broken pebble probably became stuck in a pipe that was used for feeding pebbles into the core in 1985 and delayed operations at the reactor, and this was one of the causes of the long lag between the reactor becoming critical and being termed commercial (Fig 2010, 11). As with the AVR, predicting pebble flow based on experiments proved deceptive, and fuel pebbles passed significantly faster through the central part of the THTR core and significantly slower through the core's peripheral regions than expected (NRC 2001).

During the 1988 shutdown, inspection of a hot-gas duct between the reactor core and a steam generator found that various bolts and other components had been damaged (Bäumer et al. 1990, 164). Although the parent company and the plant supplier did try to justify continued operation of the THTR despite the various damaged components, the plant was never restarted because the owners could not get the federal German government and the state government to cover the increased financial risks (Bäumer et al. 1990; McDowell et al. 2011). With that, the saga of pebble-bed reactors in Germany ended.

Although Germany abandoned this technology, it did migrate to other countries, including China and South Africa. Of these, the latter case is instructive: South Africa pursued the construction of a pebble-bed reactor for a decade, and spent over a billion dollars, only to abandon it in 2009 because it just did not make sense economically (Thomas 2009; Auf der Heyde and Thomas 2002). Although sold by its proponents as innovative and economically competitive until its cancellation, the South African pebble-bed reactor project is now being cited as a case study in failure (Hipkin 2013). How good the Chinese experience with the HTGR will be remains to be seen.

What can we learn?

From these experiences in operating HTGRs, we can take away several lessons – the most important being that HTGRs are prone to a wide variety of small failures, including graphite dust accumulation, ingress of water or oil, and fuel failures. Some of these could be the trigger for larger failures or accidents, with more severe consequences (Moormann 2008a; Englert, Frieß, and Ramana, Forthcoming). Such failures have also been observed in experimental reactors that are not considered here, including the Chinese pebble bed HTR-10 and Japanese prismatic High Temperature Test Reactor (Beck, Garcia, and Pincock 2010). Other problems could make the consequences of a severe accident worse: For example, pebble compaction and breakage could lead to accelerated diffusion of fission products such as radioactive cesium and strontium outside the pebbles, and a potentially larger radioactive release in the event of a severe accident. Even in the absence of accidents, the environment can suffer: Operation of the AVR for about two decades had caused soil contamination and decommissioning it has proven very complicated and hugely expensive.

More significant are the implications for economic competitiveness. Discussions of the commercial viability of HTGRs almost invariably focus on the expected higher capital costs per unit of generation capacity (dollars per kilowatts) in comparison with light water reactors, and potential ways for lowering those (UNDP 2000, 314–315; Zhang et al. 2006; Zhang and Sun 2007). In other words, the main challenge they foresee is that of building these reactors cheaply enough. But what they implicitly or explicitly assume is that HTGRs would operate as well as current light water reactors – which is simply not the case, if history is any guide. For example, a presentation at an August 2015 IAEA technical meeting assumed a load factor of 95% in calculating the cost of electricity generation at a HTGR (Blench 2015). This exceeds the best performance ever seen at a commercial HTGR – namely the AVR with a load factor of 62% – by over 50%. Going from a 95% capacity factor to a 62% capacity factor would result in an increase in the cost of generation by more than 40%.

Another lesson we can learn from the history of poor performance is that HTGRs might not operate for very long. Many of the problems the HTGRs constructed so far have experienced persisted for years and years, to the point that the reactors were shut down well before their operating licenses expired. A short lifetime, again, would affect its economics. A decrease in operational lifetime from 60 to 20 years would result in an increase in the cost of electricity generated by about 15%.

Nuclear reactors already face challenges in competing in the electricity marketplace, and a number of reactors have shut down in the United States and elsewhere simply because they have become financially unviable – especially in the face of cheap natural gas and the steady emergence of renewables (Ramana 2016; Schneider and Froggatt 2015). Given this state of affairs, the operational record of HTGRs makes it even less likely that they would succeed commercially.

Although there has been much positive promotional hype associated with high-temperature reactors, the decades of experience that researchers have acquired in operating HTGRs has seldom been considered. Press releases from the many companies developing or selling HTGRs or project plans in countries seeking to purchase or construct HTGRs neither tell you that not a single HTGR-termed "commercial" has proven financially viable nor do they mention that all the HTGRs were shut down well before the operating periods envisioned for them. This is typical of the nuclear industry, which practices selective remembrance, choosing to forget or underplay earlier failures (Sovacool and Ramana 2015). In contrast, a critical examination of the experience so far offers a useful guide as to what to expect from future HTGRs – if and when they are constructed – and, from that vantage point, the outlook does not look very promising. Given this bleak prognosis, spending tens of millions of dollars on such a technology will likely amount to throwing good money after bad.

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