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Accident Scenarios Involving Pebble Bed High Temperature Reactors

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ABSTRACT
Proponents of high temperature gas cooled reactors argue that the reactor type is inherently safe and that severe accidents with core damage and radioactive releases cannot occur. The argument is primarily based on the safety features of the special form of the fuel. This paper examines some of the assumptions underlying the safety case for high temperature gas cooled reactors and highlights ways in which there could be fuel failure even during normal operations of the reactor; these failures serve to create a radioactive inventory that could be released under accident conditions. It then describes the severe accident scenarios that are the greatest challenge to high temperature gas cooled reactor safety: ingress of air or water into the core. Then, the paper offers an overview of what could be learned from the experiences with high temperature gas cooled reactors that have been built; their operating history indicates differences between actual operations and theoretical behavior. Finally, the paper describes some of the multiple priorities that often drive reactor design, and how safety is compromised in the process of optimizing other priorities.

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Introduction

One of the strong selling points of High Temperature Gas cooled Reactors (HTGR) is what is sometimes called inherent safety.[1] For example, a group involved in designing the Chinese HTGR asserts: "The *inherent safety features* of modular HTGR power plants guarantees and requires that under *all conceivable accident scenarios* the maximum fuel element temperatures will never surpass its design limit temperature without employing any dedicated and special emergency systems [e.g., core cooling systems or special shut-down systems, etc.]. This *ensures* that accidents [e.g., similar to light water reactor (LWR) core melting] are not possible so that unacceptable large releases of radioactive fission products into the environment *will never occur*"(emphasis added).[2] Proponents of HTGRs are so confident of its safety that

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gsgs.

they would like the reactor to be deployed without an emergency cooling system and with only a "vented low pressure containment," which would allow any releases of radioactive materials during accidents to be vented into the environment, instead of the conventional pressurized containment used in LWRs.[3] There are also proposals to deploy HTGRs without an emergency planning zone (EPZ) outside the reactor site boundary, much less than the roughly 10 mile (16 km) radius currently used at U.S. nuclear power plants. Just recently the U.S.-based company X-Energy claimed that in its pebble bed high temperature gas-cooled Xe-100 reactor, "the fuel cannot melt down in an accident, so a reactor should be able to be safely located close to population centers."[4] What is left unsaid in such statements is that a fuel melt down is not the only accident scenario that can result in a release of radioactivity.

This paper presents the case that serious accident scenarios that release radioactivity into the environment are indeed possible for HTGRs, focusing on pebble bed reactor (PBR) designs that are currently favored for construction. Because the designs of HTGRs are different from LWRs, they may not undergo the exact same accident scenarios as what occurred at the LWRs in Three Mile Island (United States) in 1979 or Fukushima (Japan) in 2011. Likewise, HTGR designs are also different from the RBMK design that suffered the accident at Chernobyl (Ukraine) in 1986. (There is, however, a similarity in that both the RBMK and HTGR designs use graphite to moderate neutrons, and, as we discuss below, graphite fires can be a source of radioactive releases.) In the case of LWRs, the major concern is an accident involving the loss of coolant or coolant flow followed by fuel meltdowns. In contrast, the two chief accident sequences that are significant at HTGRs are the ingress of either air or water into the reactor core. Under some circumstances, both could lead to radiation doses to nearby populations. Thus, although it is technically correct that fuel meltdowns are not of concern in HTGRs, this does not make the HTGR inherently safe.[5]

Even otherwise, there are good reasons to question any decision to deploy HTGRs without a robust, pressurized containment or with a significantly reduced EPZ. Containments are a tried and tested passive safety feature. It was the pressurized containment of the Three Mile Island-2 nuclear reactor that prevented most of the radioactive fission products released during the March 1979 meltdown from escaping into the surrounding countryside. Likewise, the EPZ is an independent source of reducing the potential impact on public health in the event of an accident. The accident in Fukushima and the evacuation of populations in areas surrounding the reactor "demonstrated that even a 10-mile-radius zone is inadequate in the case of a severe accident at a conventionally sized reactor … [and] Radiation levels high enough to trigger evacuation were detected at least 20 miles away and those high enough to trigger long-term resettlement were detected more than 30 miles from the Fukushima site."[6] This implies that, if and when HTGRs are constructed, they should be deployed with safety features such as pressurized containments and larger EPZs.

The safety concern associated with air ingress results from the use of graphite (carbon) as the moderator in the reactor and the potential for the graphite to react with the air that has entered the reactor; the combination of air and hot graphite could result in a variety of chemical reactions and physical effects leading to deterioration of the fuel and possible radioactivity releases.

The ingress of water could result in chemical reactions between water and graphite. But this is not the most serious concern. All HTGRs are undermoderated systems and thus water ingress also results in an increase in the reactivity of the system because of the additional moderating influence of water on neutrons. Both these accident sequences have been the subject of extensive research.[7] Despite this body of work, there are still significant questions about the safety of PBRs that are as yet unanswered, especially in light of the experience with the HTGRs constructed so far.

This paper starts with a brief description of HTGR designs and the role played by the design of the fuel in the safety case. This is followed by discussions of the two most important accident scenarios, air and water ingress. Next, the paper discusses uncertainties in the understanding of phenomena that occur during severe accidents, and the multiple priorities that govern reactor design. It ends with a brief discussion of the implications of these accident possibilities.

Brief description of HTGR designs

High temperature gas cooled reactors, as their name suggests, operate at high coolant temperatures (around 800°C as compared to around 300°C in the case of LWRs), and use a gas, typically helium, to transport the heat generated in their cores. In these reactors, the fuel is surrounded by two layers of pyrolytic carbon and a single layer of silicon carbide to create a fuel particle with an approximate diameter of 1 millimeter.[8] These multiple layers are supposed to contain the radioactive materials produced when the fuel nuclei undergo fission. These particles of fuel and surrounding layers are called tristructural-isotropic (TRISO) fuel (see Figure 1). As discussed below, the use of TRISO fuel is considered an important safety feature of HTGRs.

The two types of HTGRs constructed so far differ in how the TRISO fuel is placed in the reactor. In a prismatic HTGR, the TRISO fuel particles are formed into prismatic rods and inserted into holes in a larger graphite structure. In PBRs, approximately 11,000 of these TRISO fuel particles are embedded in each graphite sphere, the pebble, which has a diameter of about 6 centimeters.[9] These pebbles are fed to the reactor continuously and constantly move down through the core. At any given time, the reactor core contains thousands of these pebbles. Continuous fuel exchange is considered an advantage because the reactor does not have to be shut down periodically for fuel replacement. However, when it comes to safety, fuel that moves during operation necessarily results in uncertainties about the exact composition of the core and the location of the fuel.

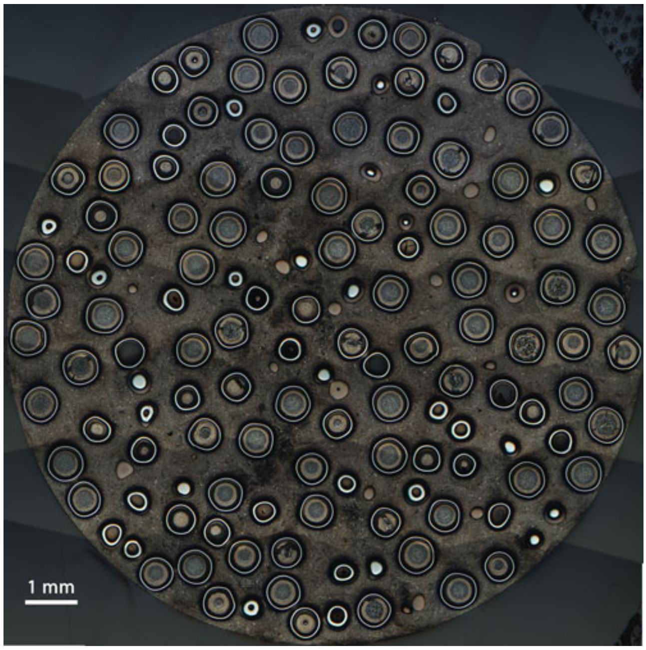

Figure 1. Cross-section of a fuel pellet containing TRISO particles at 10 mm scale.[10]

The safety of HTGRs is reinforced by other design features, such as a lower power level and power density, the amount of fissionable material in each pebble (earlier designs used up to 11 g of uranium per pebble but this has been lowered to 7 g),[11] and a large height to diameter ratio for the reactor vessel that holds the pebbles, which results in a greater surface area to volume ratio of the core. Such measures allow for passive cooling by convection and radiation.

TRISO fuel

The form of the fuel is an essential element in the safety case for HTGRs. As two members of the South African nuclear regulatory organization described it in the case of the pebble bed modular reactor that they were tasked with reviewing, the "safety design philosophy … is based on the premise that the fuel adequately retains its integrity to contain radioactive fission products for all normal operating and design basis accident conditions, thereby allowing radiological safety to be assured."[12] Or as a panel convened by the U.S. Nuclear Regulatory Commission described it, "TRISO-coated particle fuel particles are intended to stay intact and effectively retain and contain fission products during normal operation as well as during postulated accidents."[13] Thus, the argument goes, if the fuel remains integral even under a design basis accident, then the radiological inventory is safely contained within the fuel particles and the graphite matrix of the pebbles. This results in a relatively low source term for radioactive releases and consequently low or acceptable environmental impact that is within the limits of what a regulatory body will allow.

Typically, safety assessments of HTGRs consider 1600°C as the temperature limit for fuel failure.[14] Above this temperature, "the maximum accident fission product releases increase."[15] Safety assessments, therefore, are satisfied with just showing that the maximum temperature reached during an accident scenario is lower than 1600°C; for example, a study carried out on the possibility of recriticality after hypothetical accidents concludes that the high temperature reactor design being investigated shows inherent safety potential because the maximum temperature reached under a specific scenario deemed by the authors as an "extreme combination" of hypothetical conditions is only 1536 °C.[16]

The assumption about a firm limit of 1600 °C below which no fission products will escape from the pebbles is misleading. Even under normal operating conditions, a small fraction of the fission product inventory of the fuel particles does diffuse through particle coatings and the matrix of the pebble. This diffusion is enhanced if there are defective coatings, which cannot be completely avoided for industrial scale manufacture of fuel pebbles. The rate of diffusion of radioactive isotopes through the particle coating and the graphite matrix is strongly dependent on the temperature as well as the specific radionuclide.[17] For example, even under normal operating conditions, the release fraction of argentum-110m (silver-110) is ten to fifteen times the corresponding fraction for cesium-137.[18] The mechanism for such transport is still unclear.[19] Because of this diffusion, even standard operation of a PBR leads to higher releases of some nuclides, especially silver-110m and cesium-137, into the pressure vessel in comparison to LWRs.[20] Both cesium-137 and silver-110m are gamma emitters and their release from the fuel pebbles has implications for operability, economics, and, most relevant to this paper, safety.

Fission products that are released from the fuel, such as strontium-90, can adhere to the dust prevalent inside the reactor (described below) and form an inventory that can be released during depressurization accidents. The quantity of fission products escaping from the pebbles during an accident scenario will depend on the period the reactor has operated, especially if some fraction of these operations were at temperatures above the normal operating temperature (although below 1600°C). Measurements done at the Arbeitsgemeinschaft Versuchsreaktor (AVR) showed fuel damage even at 1400°C.[21]

There is also evidence of a variety of other mechanisms that could cause fuel particle failure. For example, the integrity of silicon carbide layer is compromised by palladium, a fission product that is produced during reactor operations.[22] Gaseous fission products inducing internal pressure, irradiation-induced shrinkage, migration of fuel particles due to a temperature gradient in the graphite, chemical interactions between fission products and the layers of coatings on the fuel or between the graphite matrix and the coating layers, and silicon carbide degradation due to high burnup are some of the other mechanisms that lead to fuel particle failure, especially under high burnup conditions.[23] The burnup dependence of fuel particle failure is also not fully understood.[24] Particle failure can also occur during an air or water ingress accident.[25] And finally, a substantial number of pebbles get damaged or broken during movement within the core.[26] At the Thorium

High-Temperature Reactor, approximately 17,000 pebbles were damaged,[27] a figure that is remarkable when considering that the reactor operated for less than three years.

Summing up, the 1600°C limit, or even a lower temperature limit for that matter, is misleading and overestimates the retention behavior of the particle. Whether, and how much, radioactivity will be released during an accident will depend on the maximum temperature reached, the duration of that temperature, the fuel performance under corrosive conditions,[28] the irradiation history and fuel fabrication failures. These parameters are only predictable to a certain extent in advance and come with higher uncertainties than is desirable for the safety case of a nuclear reactor, especially when the developers hope to deploy the reactor without a pressurized containment or an EPZ.

Water ingress

Water ingress, or the entry of water in the core of a HTGR, is a safety concern because of two basic technical characteristics: (1) HTGRs are under-moderated and (2) water is a better moderator than helium.[29] When water enters the reactor core, the reactivity increases, causing increased power production in the core and a temperature increase, unless negative feedback phenomena, in particular how the core behaves when the temperature increases, limits these effects. If the water ingress rate is sufficiently large, then "the negative temperature feedback is unable to compensate the positive reactivity quickly."[30] If this is the case, the temperature of the fuel elements will increase, which might lead to increased diffusion or even fuel failure, and the escape of fission products into the reactor core.

In parallel, the water ingress would also lead to chemical reactions with the hot graphite structures producing inflammable water gas, a mixture of carbon monoxide and hydrogen. The combination of the entry of steam and the production of water gas would lead to a large pressure increase and that could result in the safety valve opening and releasing radioactive isotopes and explosive gas.[31]

The ingress of water into a reactor is not a purely theoretical concern. In May 1978, about 30 tons of liquid water did enter the core of the AVR. The situation was made worse by human error since operators did not treat the water ingress with sufficient seriousness, continuing to operate the reactor at low power for several days.[32] Following the ingress, higher levels of noble gases were observed "due to the interaction between steam and defective particles."[33]

For any given accident scenario, the combination of the maximum temperature above which the probability of fuel failure is high, the negative fuel temperature feedback (reactivity coefficient), and the typical operating temperature sets the amount of reactivity increase that can be compensated through fuel temperature feedback. Typical scenarios analyzed by HTGR designers often explicitly or implicitly involve various assumptions, some of which may not be valid when analyzing a worst-case scenario. A common assumption is that only a limited amount of water has entered

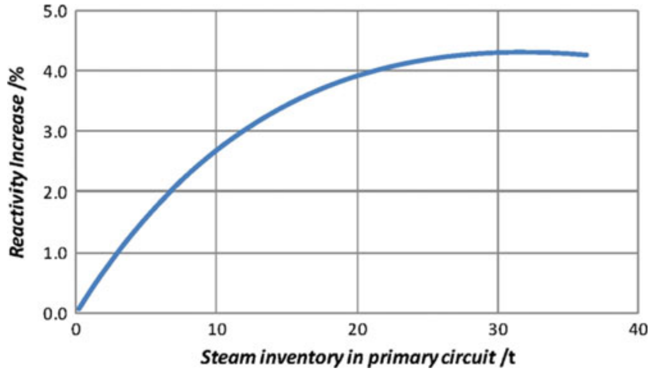

Figure 2. Reactivity increase in hot core as a function of water (steam) ingress into the primary circuit. (Source: Zheng Yanhua, Lei Shi, and Yan Wang, 2010).[34]

the reactor core.[35] However, it is possible to conceive of scenarios, albeit with low likelihoods, wherein larger quantities of water do enter the core.[36]

As a specific case, consider the water ingress scenario for the Chinese HTR-PM reactor as analyzed by scientists from the Institute of Nuclear and New Energy Technology, Tsinghua University.[37] Their calculations show that because their estimate of the fuel temperature feedback coefficient is about -4.36×10^{-5} /°C, the maximum reactivity increase that can be counterbalanced via the negative temperature coefficient without the fuel's temperature exceeding their choice of safety limit of 1620°C is about 3%.[38] Further, their own calculations suggest that once the amount of water (steam) within the primary coolant circuit exceeds about 12 tons, the reactivity increase goes above 3%, and once the amount of water exceeds about 20 tons, then the reactivity increase goes above 4% (see Figure 2). The paper does not calculate what the fuel temperature would be in the event of such a large ingress of water, but instead limits its "severest" accident scenario to an ingress of only 2.5 tons.[39] Thus, these safety assessments do not include some very severe accident scenarios, which may be low probability but high consequence. Hence these assessments may not be an adequate basis for decisions about features such as the kind of containment to be built or the size of the EPZ.

Air ingress

Air can enter the reactor if there is a break (or more than one break) in the pressure boundary. Air ingress will result in the oxidation of graphite moderator and structures in the reactor vessel and, as the accident proceeds, also the oxidation of the fuel.[40] Air ingress will increase the temperature in the reactor due to the reaction enthalpy of the oxidation process. The temperature increase, and therefore the likelihood of fuel failure, will vary across the reactor and depends on the rate at which air enters the reactor; for sufficiently large rates of air ingress, the temperature of the core could exceed 1600°C,[41] even in the case of a relative low powered (200 MWth) pebble bed reactor, resulting in massive fuel failure.[42]

Unlike the RBMK reactor in Chernobyl, where graphite burning started only after some delay, in PBRs the operating temperatures are higher than the ignition temperature of graphite (600 to 700°C).[43] As a result, burning of graphite could occur immediately in the event of a major air ingress. Further, HTGRs, like other reactors, also have other inflammable materials and as such other fires are possible; for example, on 3 October 1987, Fort St. Vrain suffered from "a relatively severe turbine building fire" due to the burning of oil used in the hydraulic system, which "impacted control room habitability."[44] Such fires could add to the potential for radioactive release by increasing the temperature of the reactor components.

In turn, the rate at which air flows into the reactor vessel and the oxygen content that is available will depend on many reactor design features and the specific failures that lead to the accident.

Because air ingress must begin with a break, there will be a ready pathway for any radionuclides within the primary circuit to escape. Further, the heat generated during the oxidation process results in buoyancy forces that could provide the impetus for radionuclides to escape into the atmosphere and be transported to relatively higher altitudes. In short, a severe air ingress accident could lead to the escape of significant quantities of radionuclides, although it is difficult to estimate the potential source term.

Experiences with HTGRs

What goes under the name of safety analysis in reactor design is typically a claim about the behavior of a hypothetical reactor that has not been constructed so far, based on a theoretical design. Quite often an actually constructed reactor behaves differently from what may have been predicted theoretically, and thus an examination of the operational record of HTGRs that have been constructed offers insights into potential safety problems with these reactor designs.

The four commercial HTGRs constructed in Germany and in the United States as well as the test reactors constructed in the United Kingdom, Japan, and China, all testify to the difference between theoretical expectations of reactors performing smoothly and flawlessly, and actual operating experience.[45] All these operating HTGRs underwent a wide variety of small failures and unplanned events, including ingress of water or oil, and fuel failures (see Table 1).

The accumulation of graphite dust in the coolant circuit was a feature in all these reactors. The dust is typically contaminated with fission products. In the case of the relatively low powered (15 MWe) prototype AVR, the total amount of dust has been estimated at between 46 kilograms and 200 kilograms, with activity levels of 2 to 96 GBq/kg of cesium-137 and 19 to 363 GBq/kg of strontium-90,[46] and has been described by three of the scientists associated with the reactor as "a permanent and virtually undepletable source of serious contamination."[47] This is a safety hazard because the fission products can escape into the atmosphere in the event of an accident involving expulsion of coolant.

Table 1. High temperature gas cooled reactors connected to the grid (source: Ramana, 2016).[48]

Reactor	Generation Capacity (MWe)	Commercial Operation Date	Permanent Shutdown Date	Lifetime Load Factor	Problems Experienced (Select)
Peach Bottom	40	1 June 1967	1 November 1974	56.9%*	Fuel failure, oil ingress, failure of moisture monitor, graphite dust in coolant circuit
AVR	15	19 May 1969	31 December 1988	62%	Fuel failure, water ingress, oil ingress, graphite dust in coolant circuit
Fort St. Vrain	330	1 July 1979	29 August 1989	15.2%	Helium leaks, moisture ingress, failures of moisture detection systems, fuel failures, failure of control rods to insert in response to scram signal
Thorium High-Temperature Reactor	300	1 June 1987	29 September 1988	41.3%	Graphite dust, breakage of pebbles

Note. * Calculated by IAEA only for the last two years.

Uncertainties and the limits of safety analyses

There are several uncertainties about HTGRs and their operation, which in turn affects the reliability of safety assessments. Below we list some of the chief problems.

The first problem involves the behavior of fuel. The prediction or modeling of pebble flow through the core has historically been unreliable, leading to local zones of higher temperatures. Modeling is particularly difficult because standard in-core instrumentation cannot be used in PBMRs to measure parameters such as temperature distribution and power distribution in the pebble bed *during* reactor operations, in turn because such instrumentation cannot be held in place due to the flow of pebbles. Such parameters can be inferred later by examining special measurement devices that go through the reactor and are recovered after they come out (e.g., melt wires). A further problem is that the environment is highly corrosive, leading to instrument failures, and highly radioactive so that instrument replacement is very challenging. In the German AVR reactor for example it was later discovered that the maximum temperature at hot spots in the reactor was much higher than anticipated by designers, by up to 200°C or even more.[49]

The second area of uncertainty is the size of the source term. In case of air or water ingress the source term for radioactive release involves fission products that have been plated out on metallic surfaces mainly in the corners of tubes or that are attached to graphite dust. These particles can be washed or steamed off and remobilized. Should a reactor that has been operating for many years undergo an accident, the source term for release might be significantly more than estimated by theoretical calculations.[50] Understanding of the phenomenon of graphite dust production is still limited and graphite dust behavior adds to the uncertainties of source term analysis.

A third area of uncertainty is coolant gas behavior. Numerical simulations of the helium gas current in the reactor are very complex and the flow dynamics in the pebble bed as well as in the whole primary circuit difficult to model.[51] Additionally temperature monitoring under the harsh extremely hot and corrosive environment in the reactor is extremely difficult. Through the kinds of measurement processes described earlier (the use of melt wires), it is possible to get measurements of the temperature of the cooling gas, but the numbers thus available only represent the peak values of temperature at the average position in the core and form an incomplete data set.

And finally, there are uncertainties about how operators will act during safety challenges and emergencies. This was the case at the German AVR reactor in May 1978 when operators took actions that were against safety requirements during water ingress.[52]

Conflicts with economic priorities

There is a separate problem with many assertions about the safety of new reactor designs: the competing priorities that determine design choices. The discussion about the possible use of a vented containment structure that we started this paper with is an illustration of this phenomenon. The main reason to even consider such a vented containment is to save on costs. Likewise, the choice of under-moderated cores that make HTGR designs susceptible to water ingress accidents is also guided by economics.[53] In these cores, there is less graphite in the reactor than necessary for optimal neutron balance to avoid having a large pressure vessel, which would be expensive. A design choice between a steam and a gas turbine is also made partly based on economic considerations. Gas turbines are more complicated and expensive but the risk of water ingress is greatly reduced.

Since the integrity of the fuel pebbles is temperature dependent, a lower temperature during normal operation increases the safety margin to fuel failure. On the other hand, a higher operating temperature allows designers to market the reactor as allowing use in industries that require heat at high temperatures, for example to liquefy coal and the catalytic dissociation of water. Again, economics pushes designers to adopt higher operating temperatures, a choice that is complicated by the difficulty in assessing the temperature profile in the core. These economic incentives for less safe designs become more important because nuclear power is already losing ground in the electricity marketplace in many countries.[54]

Conclusion

Claims about the inherent safety of HTGRs form a strong component of the argument for the construction of HTGRs by its proponents. However, as we have discussed, these claims do not account adequately for the risks associated with air and water ingress accidents or are based on contestable assumptions, including assumptions about the integrity of the fuel up to a temperature of 1600°C. There is still considerable uncertainty about the behavior of HTGRs under accident considerations. Further, as the experience with HTGRs constructed to date shows, operations at completed reactors are marred by a variety of failures and incidents that are not considered in theoretical designs. Finally, reactor designs are shaped by multiple priorities and the difficult economic challenges faced by nuclear power might lead to design choices that worsen safety.

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26. For a picture of a damaged pebble, see slide 5 of the presentation by Rainer Moormann, "Die NRW-Kugelhaufenreaktoren und ihre Hinterlassenschaften: Anmerkungen zu einer Problemtechnologie (The Pebble-Bed Reactors in North Rhine-Westphalia and their Legacy: Notes on a Problematic Technology)," Evangelische Gemeinde Nettetal-Lobberich – Cafe Vielfalt (Protestant Church of Nettetal-Lobberich - Cafe Vielfalt), Internationaler Versöhnungsbund (International Fellowship of Reconciliation), 29 July 2012, https://www.versoehnungsbund.de/sites/default/files/artikel/380/MoormannVortragLobberich1.pdf
27. "Pebble Bed Reactor Technology Readiness Study" (Areva, 2010), https://art.inl.gov/NGNP/NEAC%202010/Pebble%20Bed%20Reactor%20Technology%20Readiness%20Study%20-%20AREVA.pdf
28. A number of the fission products released during the operation of the reactor can corrode one or more of the outer carbide layers.
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31. Wolters et al., "The Significance of Water Ingress Accidents in Small HTRs"; Zhang, Dong, and Scherer, "Assessments of Water Ingress in a High-Temperature Gas-Cooled Reactor."
32. Moormann, "A Safety Re-Evaluation of the AVR Pebble Bed Reactor Operation and Its Consequences for Future HTR Concepts," 29. The water ingress stemmed from a leak in the steam generator directly above the reactor core.
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