Please cite this article in press as: Moormann et al., Caution Is Needed in Operating and Managing the Waste of New Pebble-Bed Nuclear Reactors, Joule (2018), https://doi.org/10.1016/j.joule.2018.07.024

Joule

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COMMENTARY

Caution Is Needed in Operating and Managing the Waste of New Pebble-Bed Nuclear Reactors

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The high-temperature gas-cooled reactor (HTGR) is an innovative concept that aims to improve the safety and economics of nuclear power. Conceived in the 1950s, the design avoids several safety challenges posed by traditional light-water reactors (LWRs). For example, HTGRs feature a low-power-density, high-heat-capacity core that allows longer response times; a refractory SiC-coated fuel and passive cooling to resist core melting; and a non-corrosive helium gas coolant. Despite these conceptual benefits, HTGR prototypes struggled with a series of engineering problems. Recently, an ambitious, full-size, pebble-bed HTGR called HTR-PM has been completed and is nearing operation.[1] This reactor does not have a high-pressure, leak-tight containment able to prevent the release of radioactive dust in the event of a serious accident; and plans for storing the reactor's spent fuel may also provide inadequate protection against fire and other threats. No reactor is immune to accidents, and because prior HTGR experiments have revealed unexpected behavior, we urge caution and a spirit of scientific inquiry in the operation of HTR-PM.

Reactor Safety

One of HTR-PM's predecessors, the German-built AVR, illustrates the ways in which pebble-bed HTGRs have surprised operators with unforeseen problems in the past.[2–7] At AVR, the physical reactor began to differ more and more from the safety model's conceptual reactor with the passage of time. The emergence of localized hot spots in the core, combined with an unexpected level of dust generation, caused severe contamination throughout the core. Almost 100 TBq of residual ^{90}Sr and ^{137}Cs, mostly adsorbed onto dust, was found in the primary loop after AVR was defueled, making it the most heavily ^{90}Sr-contaminated facility in the world.[6,8,9] There is also about 1.5 TBq ^{90}Sr in the AVR containment building,[10] as well as soil and groundwater contamination.

These problems were partly the result of operational mistakes. As operating experience with pebble-bed reactors remains limited, there is a particular need to focus on risks arising from the human factor. For example, at AVR, operating staff had intentionally deactivated the moisture sensors so the reactor could be restarted.[2] As a consequence, 27 tons of water entered the reactor core when a steam generator leaked. The water had the potential to cause a more serious criticality accident, which fortunately did not occur.

One of the primary sources of safety margin for HTR-PM comes from its fuel. The protective layers must prevent radiotoxic fission products (FPs) from escaping into the reactor and the environment. HTR-PM uses a design in which fine grains of uranium oxide and FPs are encapsulated by thin layers of graphite, SiC, and pyrolytic carbon. The ∼35-μm-thick SiC layer is the primary barrier to FP escape and will not melt under accident scenarios. However, it can still release FPs by diffusion or cracking. For example, in order to confine FPs over the ∼2 years the fuel will be in the core, the diffusivities of FP across the SiC barrier need to be well below $10^{-17}\ m^2/s$. The actual diffusivities of

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several FPs—such as Ag, Eu, and Cs—remain uncertain because of radiation-enhanced effects and Pd corrosion.[11–16] FP containment also requires maintaining high-quality fuel fabrication over time to ensure the thin SiC barrier does not fail from mechanical defects. As an illustration of the challenging mechanical environment of pebble-bed reactors, it recently became clear that more than 500 fuel pebbles had failed at AVR, compared with the 215 initially thought at the end of operation.[17] The broken pebbles had become trapped in the reactor and were not discovered during operation.[8]

Computational models for predicting pebble-bed HTGR operating conditions remain limited. In particular, they cannot adequately describe the creation of high-temperature regions in the reactor core. Uncertainties in friction, wear, and fracture behavior under operating conditions limit the ability to predict the structural evolution of pebble-bed cores, along with consequent changes for neutronics, cooling, and ultimately temperature, which can lead to SiC-barrier failure. This is exacerbated by the lack of in-pile instrumentation to monitor the actual temperature and other parameters of the core in real time. For example, in 1987, AVR operators found evidence that the temperature had deviated by at least 200°C beyond what they expected: the helium outlet temperature was 950°C, but 1,280°C melt wires had melted in monitoring pebbles. In Germany's THTR-300, a subsequent pebble-bed design, evidence of temperature deviations up to 150°C were found. The new HTR-PM core should run cleaner than AVR because the helium outlet temperature was reduced from 950°C to 750°C, but the potential to deviate from target temperatures remains. Unexpected FP releases from temperature excursions will accumulate in the core. As the core becomes increasingly contaminated with time, the consequences of a potential accident become more severe.

In pebble-bed HTGRs, dust is generated by pebble wear, fracture, irradiation sputtering, and corrosion. Early designs assumed the dust from wear would be low, but it was later discovered that the friction of graphite surfaces in dry helium is much higher than in ambient air, resulting in unanticipated dust. FPs that have escaped from pebbles adsorb onto the dust, rendering the FPs mobile and able to escape the reactor in a loss-of-coolant event. While the first published results on dust from the HTR-10 experimental reactor[18] (HTR-PM's immediate predecessor) look encouraging, the data do not fully represent the operating conditions that the larger HTR-PM will face during its life, including the larger mechanical loads on pebbles due to HTR-PM having a taller core, temperature excursions, and possible ingress of reactive substances that may not be detected as quickly as expected. The amount of dust in AVR was estimated to be 95 kg, most of it below 1 μm in diameter.[19] Strong disturbances, such as an earthquake or rapid depressurization during a loss-of-coolant accident, could re-suspend radioactive dust.[20] If the dust-gas mixture is vented to the atmosphere, the consequences could be significant.

An alternative to the pebble-bed design that would ameliorate many of the above problems is the prismatic HTGR design. Prismatic reactors would be easier to instrument for monitoring core conditions in real time and would also generate much less dust from fuel wear. Consequently, a depressurization accident at a prismatic HTGR should release less radiation.

All HTGR cores are designed to remain free of oxidizing water. A heat exchanger passes heat from the dry helium coolant to water-based steam generators. Historically, steam generators leak with a probability of about 0.001 (large leak) to 0.1 (small leak) per steam generator per year.[21] As such, a water ingress accident is likely to happen and is considered a design-basis accident. Even though multiple active-safety mechanisms are designed into the reactor, their working as expected will depend on detailed hardware conditions and human factors. Since the core is under-moderated, a small injection of water steam will increase core neutron reactivity, which can be automatically compensated by the Doppler-broadening effect brought on by the rise in the fuel temperature (-3.14 pcm/K or 178 K per dollar of reactivity increase,[22] 1 dollar ≈ 563 pcm[23]). However, if the water-vapor density in the core exceeds 0.03 g/cm^3 without control-rod compensation, the graphite will overheat, damaging the fuel. Furthermore, if water vapor infiltrates parts of the core with density >0.05–0.1 g/cm^3, a positive void coefficient of reactivity[24] will result, which will cause core heterogeneity and can confuse the operator and lead to an incorrect response that exacerbates the accident.

While construction of a pebble-bed HTGR is a very valuable research project, the still-incomplete understanding of core behavior, dust physics, and fuel materials means one needs to proceed cautiously. Important behaviors are not fully understood, the graphite reflectors may not last more than 30 years, and the safety systems may not be able to cope with a beyond-design-basis accident. Of particular note, HTR-PM is not surrounded by a robust, airtight containment to protect the public (by contrast, new LWRs such as EPR and HPR1000 have a double containment). Instead, HTR-PM uses a very-low-pressure vented containment. If a rupture of the high-pressure helium cooling system occurs, the primary coolant along with entrained dust and radioisotopes will be rapidly vented to the atmosphere, unfiltered, through a chimney once the containment reaches 0.2 atm overpressure.[25]

Even though HTR-PM benefits from passive-safety features as described at the outset of this article, there are still credible severe-accident scenarios. Indeed, no complex, energy-intense plant of any kind can be regarded as severe-accident proof; and every major nuclear accident to date was unforeseen at the time the reactor-safety model was established. Given the limited experience with pebble-bed reactors, and that HTR-PM does not have the backup protection of a high-pressure, airtight containment, vigilance and caution must be applied. The reactor should be operated as a true experiment, and severe-accident plans are needed despite the conceptual safety improvements.

Waste Management

A final consideration for HTR-PM is the special nuclear-waste challenge it poses. The fuel consists of fine grains of encapsulated uranium embedded in a larger graphite pebble. This results in very large volumes of spent fuel—more than ten times that of LWRs per unit of electricity generated. The spent fuel is, in principle, flammable and will accrue to multiple core-load equivalents of radioactive FP over the lifetime of the reactor. In the case of AVR, Germany employs heavy casks with 37-cm-thick walls to store about 2,000 spent-fuel pebbles per cask. In contrast, HTR-PM plans to employ canisters with 2-cm-thin walls, 1.74 m in diameter, and 4.18 m tall. Each would store 40,000 spent-fuel pebbles per canister.[26] Five canisters are to be stacked on top of each other, in rows of eight, with expected storage time of 50 years.[27] With the open-air ventilation cooling scheme proposed,[28,29] chloride-induced stress-corrosion cracking of the canister body can become a problem, exacerbated by salt mists from the coast; fire hazards need to be mitigated in such a dense storage site; and the 2-cm-thick canister wall, made from 304L stainless steel, can be penetrated by rifle bullets. These canisters do not provide adequate protection against credible hazards.

Recommendations

In view of the history of previous pebble-bed HTGR reactors, the following precautionary measures are recommended for HTR-PM reactor. (1) Store spent fuel underground. (2) Perform an extended startup phase with continuous addition of monitoring pebbles and slowly increase the temperature of the core to quantify temperature deviations and other core parameters. (3) Anticipate air ingress accidents[30] by equipping the installations with passively activated rapid-sealing foams and halon-type fire-suppression gas to prevent O_2-graphite reactions in the reactor and waste-storage areas. Cutting off the O_2 supply may be the best defense against worst-case accidents. (4) Continuously monitor levels of ^{110m}Ag and ^{137}Cs inside the core, which might give early hints of whether problematic radioactivity concentrations have occurred. The highest activity, and thus the highest safety risk, will be found at the end of the reactor's life owing to dust accumulation. Regular removal of dust from internal surfaces is recommended. (5) Retrofit the chimney of the very-low-pressure vented containment with fast-acting electrostatic precipitators or wet scrubbers to stop the majority of radioactive dust from being released to the atmosphere. Other options might be to design an inflatable balloon of fireproof fabric, or water-sand filter, that allows gases to escape but which retains most of the dust. (6) Consider large-volume waste-treatment options to reduce fire and corrosion risks. One may also consider shifting to a novel fuel form[31] that improves traceability, FP retention, and reduces wear and dust generation.

The continued development of the pebble-bed HTGR concept is a laudable effort. However, the limited experience of these reactors places HTR-PM in a situation similar to the early LWRs of the 1960s, which experienced a range of unexpected behaviors and accidents. HTGRs are rich for experimental study, but we urge caution in operating the HTR-PM at scale, and in storing its fuel.

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https://doi.org/10.1016/j.joule.2018.07.024