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Initial Assessment of Erosion/Abrasion Issues Related to Gas-Cooled Reactors

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August 2023

OAK RIDGE National Laboratory

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Materials Science and Technology Division

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ABBREVIATIONS

ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
FFHS	fuel handling and storage system
GCR	gas-cooled reactor
GTHTR300C	Gas Turbine High-Temperature Reactor 300 for Cogeneration
GT-MHR	gas turbine–modular helium reactor
HHA	Subsection HH, Subpart A (of the ASME BPVC)
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor
HTTR	high-temperature test reactor
JAEA	Japan Atomic Energy Agency
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PBMR	pebble-bed modular reactor
TRISO	tristructural-isotropic
VHTR	very high-temperature reactor

ABSTRACT

The US Department of Energy's Oak Ridge National Laboratory (ORNL) is investigating the graphite erosion concern detailed in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section III, Division 5, "High Temperature Reactors." The special consideration in Subsection HH, Subpart A, Article HHA-3143, "Abrasion and Erosion," was described in ASME BPVC Section III, Division 5, which was accepted with exception/limitation in a US Nuclear Regulatory Commission (NRC) Technical Review. This report describes ORNL's initial assessment of abrasion/erosion issues related to Gas-Cooled Reactors (GCRs). It includes comprehensive research of erosion-related reports and publications to further study the proposed gas flow velocity limitation to the erosion effect in graphite structure in the ASME BPVC. This report also proposes that a nondimensional fluid parameter, the Reynolds number, might be a better alternative than gas flow velocity for comparing erosion effects caused by fast-flowing helium coolant in GCRs, primarily in the presence of carbonaceous dust).

1. INTRODUCTION

1.1 EROSION CONSIDERATION IN ASME BPVC CODE

A nuclear reactor needs a coolant agent circulated through the core to remove or transfer the enormous heat from chain reactions. Possible coolants include water, heavy water, air, carbon dioxide, helium, molten salt, and a sodium–potassium alloy. The faster the coolant can circulate in the core, the more heat can be removed or transferred to keep the core working under the allowable temperature regime. GCRs are Generation IV nuclear reactors. They use graphite as the structural element (neutron moderator and reflector), tristructural-isotropic (TRISO) fuel, and helium gas as the coolant. TRISO particles can be packed for loading in the reactor in two different basic ways. Correspondingly, GCRs have two basic design concepts—prismatic-core and pebble-bed reactors—which differ by internal geometry of graphite components and by operating conditions. Naturally, helium fluid dynamics, including temperature and local flow rates, are very different in the two reactor concepts. The enhanced performance of both reactor concepts is related to their higher operating temperatures, which means higher power output and more compact architecture. When more heat is generated by fission, a more efficient cooling system is needed, which in turn requires a pressurized thermal agent flowing rapidly between the core and the power conversion unit that generates electricity.

However, a high-speed coolant may introduce unexpected erosion effects to its flowing path, particularly after a long service time. Therefore, the ASME BVPC Section III Division 5[1] includes a special consideration in Article HHA-3143, "Abrasion and Erosion," which says:

> *… (b) Erosion shall be evaluated in areas where the mean gas flow velocity in the cross section of the channel exceeds 330 ft/sec (100 m/s)." This text can be traced back to its first published version in 2010.*[2]

After the NRC's most recent technical review of the 2017 Edition of ASME Code, Section III, Division 5, "High Temperature Reactors,"[3] the code was formally endorsed by the NRC with some exceptions and

[1] ASME BPVC SECTION III, Division 5, HHA-3143 "Abrasion and Erosion," 2021.
[2] ASME BPVC SECTION III, Division 5, HHA-3143 "Abrasion and Erosion," 2010.
[3] U.S. NRC, Technical Review of the 2017 Edition of ASME Code, Section III, Division 5, "High Temperature Reactors."

limitations, specifically the mention of gas flow velocity as specified in Article HHA-3143(b), described as follows:

> *...the staff also notes that the mean gas flow velocity limit may not be generically applicable to all high-temperature, gas-cooled reactor designs. Therefore, the staff is not endorsing the provisions of HHA-3143 that set the mean gas flow velocity limit of 100 meters per second (330 feet per second) for evaluating the effects of erosion on the graphite core component (GCC) design. Designers should determine the mean gas flow velocity limit above which an evaluation of erosion is necessary and justify that the limit is adequate for the GCC design.*

A clear distinction between two technical terms—erosion and corrosion—is useful. Both terms relate to the slow attack and wearing of solids under environmental action. Although the two terms may sometimes be used interchangeably, the significant difference between them relates to the mechanism that causes the damage. Erosion is produced by physical actions under the exposure to environmental factors (e.g., high-speed impact, free-moving particles in a fluid), whereas corrosion is produced by chemical actions (e.g., oxidation). Abrasion is another wear effect caused by friction and rubbing away of solids. Continuous neutron bombardment of graphite may also produce lattice displacements or atomic-scale erosion. These actions are illustrated in Figure 1.

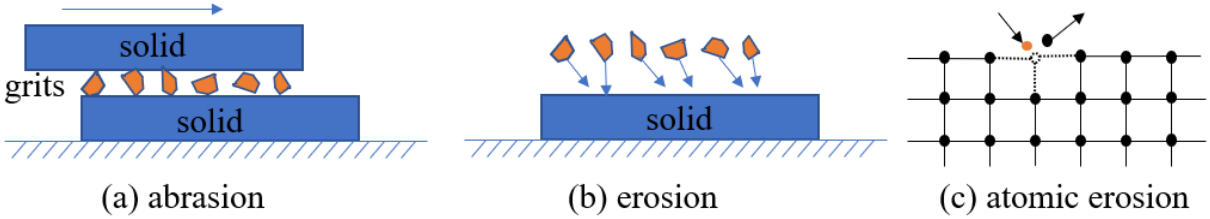

Figure 1. Schematic illustration of physical wear effects: abrasion, erosion, atomic erosion.

In nuclear reactors, graphite materials are exposed to a variety of physical and chemical environmental factors, with various possible effects. Fast-flowing coolant gas over graphite surfaces may mobilize dust particles remnant from machining operations or formed by friction and attrition between graphite components that are subjected to thermal stress and irradiation-induced dimensional changes. Additionally, dust particles carried out by high-velocity coolant gas flow may wear solid graphite surfaces, and this process may require designers' attention. These physical (or mechanical) wear processes are classified as erosion.

By contrast, slow (chronic) oxidation of graphite by trace impurities in the coolant during normal operation or fast oxidation (acute) after an unlikely ingress accident would also cause local wear and (possibly) dimensional changes of affected graphite parts, but they are clearly corrosion processes caused by chemical factors. For example, rapid graphite corrosion at high temperatures caused by air ingress may cause preferential oxidation of the graphite binder and spallation of fine graphite particles, as observed for NBG-18 graphite oxidized at 750°C.[4] Combined situations of erosion and corrosion are also possible. For example, erosion might expose new graphite surfaces to further oxidation. Meanwhile, the dust generated by acute graphite oxidation might be carried out by the gas flow and cause more mechanical erosion of remote graphite surfaces. This document focuses on the conditions that might produce erosion and on the potential erosion effects on GCRs.

[4] C.I. Contescu, T.D. Burchell, Characterization of porosity development in oxidized graphite using automated image analysis techniques, ORNL/TM-2009/192. Oak Ridge National Laboratory (2009).

1.2 PREVIOUS STUDIES OF EROSION IN GRAPHITE

Graphite does not melt. It sublimates at high temperatures in vacuum. Sublimation rates measured at ORNL between 2,100°C and 2,200°C were in the range of 1–10 mg/h in high vacuum (10^{-4} Pa).[5] However, when the measurements were repeated in presence of 1 atm static helium cover gas at 2,075°C, sublimation rates (~0.19 mg/h) were about 30 times less than in vacuum at the same temperature. This result confirms theoretical predictions that a static gas (1 atm) would reduce the mean free path of carbon atoms formed by sublimation and would cause their return to the graphite surface.[6]

An experiment performed in 1950 for the US Atomic Energy Commission studied high-speed gas erosion of nuclear graphite at elevated temperature.[7] The effect of heated helium jets on machined graphite parts was investigated after all precautions were made to outgas the graphite parts and to eliminate the presence of oxygen from the helium gas. Eventually, a 2,000°C helium jet of about 2,740 m/s (corresponding to 0.3 Mach in helium gas) was directed onto a graphite surface maintained at 2,000°C. Repeated runs showed that, after an initial period of about 1 h in which graphite particles remnant from machining were blown free, no further erosion was observed up to 23 h, provided that the helium gas was free of reactive impurities. The results were assessed by comparing electron microscopy images recorded at various exposure times and magnification up to 50×. Except for the optical visualization comparisons, no erosion rate or graphite mass loss was reported in this study. Regarding the slow wear effect from erosion, the time interval of 23 h might be too short to observe significant mass loss with good accuracy.

The nozzle that generates thrust for solid-propellant rockets is exposed to a high-temperature and high-pressure environment with wear occurring from the combustion gas. A recent study investigated the combined action of thermochemical corrosion and mechanical erosion on nozzle throat heat-resistant materials made of graphite and carbon–carbon composites.[8] A high-speed oxy-acetylene torch was applied to graphite or carbon–carbon composites at speed of 1,009 m/s. The test temperature ranged from 600°C to 1,600°C for 120 s test periods. The authors estimated that the mechanical erosion rate was about 0.01 mm/s on graphite or carbon–carbon composites. Considering an average density of 1.7 g/cm^3 for carbon materials, the recession rates in the oxy-acetylene torch (roughly 60 mg/h) is much higher than the graphite sublimation rate[6] in static helium atmosphere at a higher temperature (2,075°C). This experiment may be regarded as an example of combined oxidative corrosion and mechanical erosion. Although the nature of gas phase particles causing erosion was not specified, they might have been unoxidized carbon grains removed by the fast helium jet from the receding graphite surface. The chemical and physical processes might accelerate each other, therefore making it difficult to accurately isolate the mechanical erosion contribution. In addition to the measured wearing rates, the study correlated erosion rate with specimen density and porosity. A higher erosion rate was observed in graphites or carbon–carbon composites with higher porosity or lower density.

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[5] J.R. Haines, C.C. Tsai, Graphite sublimation tests for the muon collides/neutrino factory target development program, ORNL/TM-2002/27. Oak Ridge National Laboratory (2002).
[6] C.C. Tsai, YT.A. Gabriel, J.R. Haines, D.A. Rasmussen, Graphite sublimation tests for target development for the muon collider/neutrino factory, Fusion Engineering 2005, 21st IEEE/NPS Symposium (September 2005). DOI: 10.1109/FUSION.2005.252931. September 2005.
[7] . L. Green, The erosion of graphite by high temperature helium jets, Atomic Energy Research Department, North American Aviation, Inc. NAA-SR-77 (1950).
[8] Kim Y, Cho J. Surface Erosion analysis for thermal insulation materials of graphite and carbon–carbon composite. Applied Sciences, 9 (2019) 3323.

1.3 EROSION THEORY AND KEY PARAMETERS

1.3.1 Differences between ductile and brittle materials

Abrasion and erosion are forms of wear caused by contact between a solid material and particles entrained in a fluid stream. Abrasive wear is the loss of material by the passage of hard particles over a surface.[9] Erosive wear is caused by the impact of particles from a fluid stream against the solid surface of an object. The concept of erosion is well defined by ASTM G76-18[10]: *"...progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles."* Erosive wear occurs in a wide variety of machinery, and typical examples are the damage to gas turbine blades when an aircraft flies through dust clouds and the wear of pump impellers in mineral slurry processing systems. Compared with abrasion and erosion, corrosion relies on chemical reactions rather than physical changes. Physical effects such as abrasion and erosion can interact with chemical erosion to accelerate the wear or mass loss on graphite.

When a particle impacts a surface, it generates scar shapes on the surface. These shapes depend on many parameters, including surface material, particle size and properties, flow velocity, and impact angle. The erosion mechanism is different for ductile materials (e.g., metals) and brittle materials (e.g., graphite).[11] As illustrated in Figure 2a, erosion on ductile materials depends on plastic deformation properties, via a so-called micro-cutting process. The impact of particles on ductile materials creates a crater, which may grow after multiple particle impacts. Material is piled up in the crater until it is eventually removed by continuous particle impacts. This general mechanism may have many variants because the properties of particles, solid material, and flow conditions vary.[12] By contrast, the erosion mechanism of brittle material (illustrated in Figure 2b) is better understood. Erosion of brittle materials such as graphite is caused by crack formation and development. A particle hitting a brittle material surface creates lateral and radial cracks. These cracks grow under continuous particle impacts and divide the surface into smaller pieces, which can eventually be removed by other particles impacting the surface.[13]

[9] G. Stachowiak, AW. Batchelor, Engineering Tribology (4th Edition) - 11.3 Erosive Wear. Elsevier, 2014.
[10] ASTM G76-18, Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets, Annual Book of ASTM Standards, ASTM International, West Conshohocken, Pennsylvania, 2018.
[11] M. Parsi, K. Najmi, F. Najafifard, S. Hassani, B.S. McLaury, S.A. Shirazi, A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications, J. Natural Gas Sci. Eng. 21 (2014) 850-873.
[12] J. Finnie, Erosion of surfaces by solid particles, Wear 3 (1960) 87-103.
[13] S. Srinivasan, R.O. Scattergood, Effect of erodent hardness on erosion of brittle materials, Wear 128 (1988) 139-152.

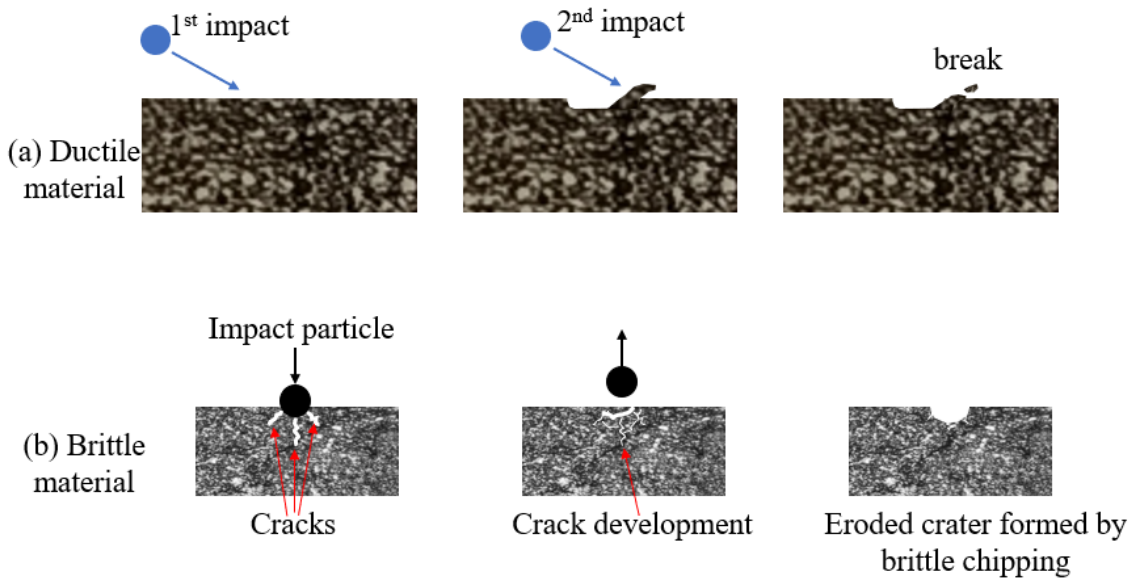

Figure 2. Expected mechanisms for erosion of ductile materials (top) and brittle materials (bottom).[11]

Because of the industrial importance of erosion, numerous experimental and theoretical studies on erosion caused by solid particles can be found in the literature. Erosion modeling efforts led to the development of multiple models based on various scenarios and formalized in tens of equations and even more physical parameters. Several excellent comprehensive reviews of these models are available elsewhere.[11, 12, 13, 14,15]

Surface erosion caused by fluid/gas impact strongly depends on the fluid/gas properties, target surface properties such as surface roughness, surface porosity, surface stiffness, the impact conditions such as impact angle, and flow conditions such as laminar state or turbulent state.[16] Figure 3 illustrates the effect of impact angle on the erosion of different types of solid materials. A recent study showed that erosion rate by a gas flow on graphite and carbon–carbon composite could be correlated to surface porosity according to Eq. (1):[8]

$$\dot{r}_m = a_2 c^* a_1 (\log P)^2 \quad (1)$$

where $\dot{r}_m$ is the mechanical erosion rate, P is the porosity, c* is the characteristic exhaust velocity, and a_1 and a_2 are constants.

[14] J.G.A. Bitter, A study of erosion phenomena, Part 1, Wear 6 (1963) 5-21.
[15] J.G.A. Bitter, A study of erosion phenomena, Part 2, Wear 6 (1963) 169-190.
[16] R. Tarodiya, A. Levy, Surface erosion due to particle-surface interactions – A review, Powder Technology, 387 (2021) 527-559.

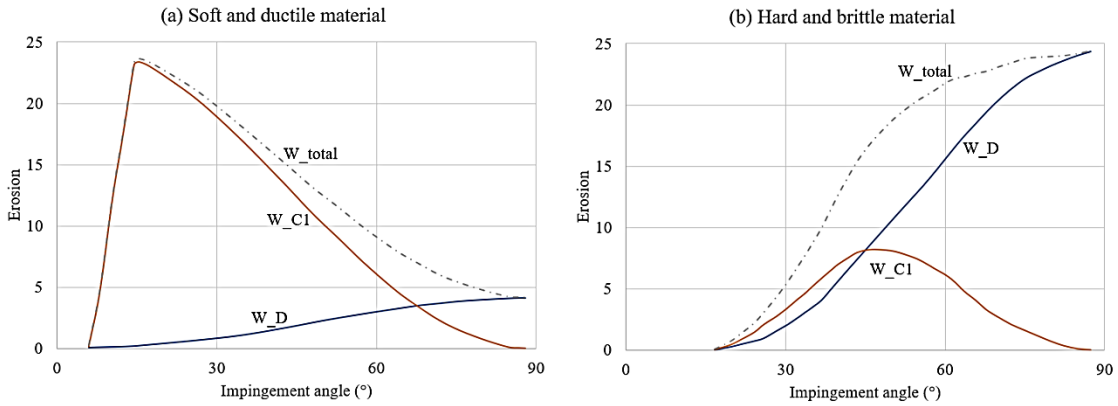

Figure 3. Demonstration of impact angle effect on different materials erosion: soft and ductile (a) and hard and brittle (b).[14,15]

1.3.2. Basic physical parameters in flowing fluids

Basic physical parameters of fluid in the flow channel can be calculated from the channel geometry and fluid measurements. As shown in Figure 4a, V_{vol} denotes the fluid volume moved in a time interval t, and d is the distance that the fluid flows from one section area to another one in that time interval. The fluid velocity can be calculated as $\bar{v} = d/t$. For a channel with fixed section area (A in Figure 4a), the volume flow rate Q and mass flow rate Q_{mass} can be expressed by Eqs. (2) and (3), respectively:

$$Q = \frac{V_{vol}}{t} = \frac{Ad}{t} = A\bar{v} \tag{2}$$

$$Q_{mass} = Q\rho = A\bar{v}\rho \tag{3}$$

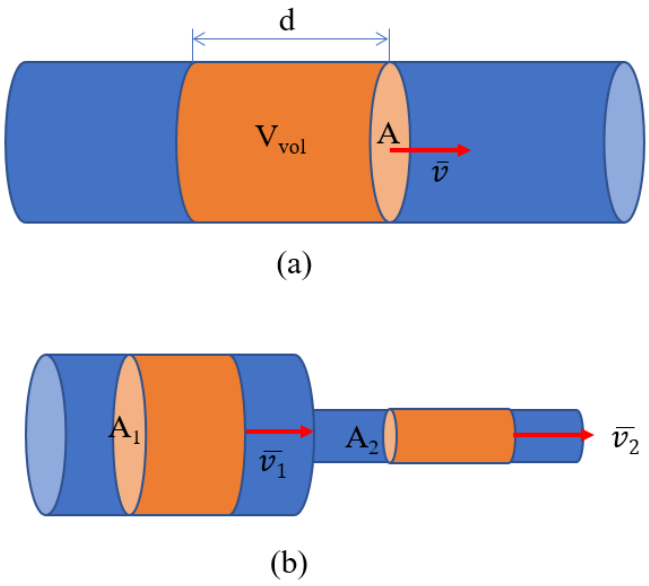

Figure 4. Fluid in channel, (a) volume, velocity and cross-section area; (b) velocities at different cross-section areas.

When the fluid flows through channels with variable section area, such as A_1 and A_2 shown in Figure 4b, the same amount of fluid must flow past any point in the tube in a given time to ensure continuity of flow by assuming the fluid is incompressible (liquid and low Mach-number gas). In that case, the fluid velocity in different section areas is related to corresponding section area according to Eq. (4):

$$A_1 \bar{v}_1 = A_2 \bar{v}_2 \tag{4}$$

For an ideal gas, its density changes with the surrounding pressure and environment temperature. Their relationship is described by the ideal gas law given by Eq. (5):

$$\frac{PV_{vol}}{T} = nR \tag{5}$$

where P is the pressure, and T is the absolute temperature, V_{vol} is the gas volume, n is the number of moles, and R is the universal gas constant. Given a fixed number of moles, the right side of Eq. (5) becomes a constant. The density of gas is expressed by its mass m divided by volume V_{vol}. In that case the relation of the same gas at different temperature and pressure states can be described by Eq. (6).

$$\frac{P_1}{\rho_1 T_1} = \frac{P_2}{\rho_2 T_2} \tag{6}$$

The gas flow velocity in coolant channel describes part of the flow state that directly affects erosion. Furthermore, gas coolant properties such as density and viscosity and the geometry features of the channel such as diameter can change the flow state and eventually affect the erosion result. As discussed in Section 4, the Reynolds number, a dimensionless parameter that describes the flow character, may be considered as a complementary indicator along with gas velocity for evaluation of erosion effects in systems with similar solid and particulate matter components (i.e., graphite materials in contact with a dusty coolant flow containing carbonaceous particulates).

This report focuses solely on the investigation of possible erosion-generating conditions and erosion effects in consideration of article HHA-3143 (b) of ASME BVPC Section III Division 5. By studying the basic theory of erosion and the coolant flow velocity in different reactor designs, more information can be provided to evaluate the erosion effect on the coolant's surrounding structure such as graphite channels.

2. GAS COOLANT CASE STUDY

2.1 GRAPHITE REACTOR DESIGNS

GCRs are Generation IV nuclear reactors, along with several other rector designs selected for development and deployed through a wide international collaboration effort. GCRs use graphite as the structural element (neutron moderator and reflector), TRISO fuel, and helium gas as the coolant. The two basic design concepts for GCRs are prismatic-core and pebble-bed reactors. They differ by internal geometry of graphite components and by operating conditions, but they both use helium as the coolant. Naturally, helium fluid dynamics, including temperature and local flow rates, are very different in the two reactor concepts.

Prismatic-core reactors use stacks of hexagonal graphite fuel elements in their annular core. The fuel elements contain parallel channels for fuel compacts surrounded by channels for helium coolant gas flow. The fuel compacts contain TRISO microspheres dispersed in a carbonaceous matrix material. This design evolved from the original concepts developed in the United States and Germany in the late 1940s and materialized in the commercial US reactors at Peach Bottom (1966–1974) and Fort St. Vrain (1979–1989)

and in the experimental reactors in the United Kingdom (Dragon), Germany (THTR-300), and Japan (high-temperature test reactor [HTTR]).

Pebble-bed modular reactors (PBMRs) use TRISO microspheres dispersed through a carbonaceous matrix and shaped as 6 cm spheres (pebbles). The reactor's cavity is made of nuclear graphite blocks that constrain the fueled pebbles between a central free-standing column and the outer reflector made of interconnected graphite blocks. Fuel pebbles move slowly downward in the graphite cavity and are recirculated several times before eventually being replaced at some limit of burn-off. The heat released by uranium fission is removed by a stream of helium, which is injected in the upper plenum, flows through the porous pebbles bed, and exits from the lower plenum to be cleaned, recompressed, and redirected to the reactor's top. The AVR reactor constructed in 1960 in Germany was such a pebble-bed prototype reactor.[17] During regular operation, pebbles are forcibly cooled by a downstream flow of helium, which is introduced to the reactor top through the helium riser conduit. In a different design, the HTR-PM Chinese reactor also contains vertical cooling gas channels machined inside the graphite reflector where helium flows upward to the top of the core and from there flows down through the core.[18]

The enhanced performance of both reactor concepts is related to their higher operation temperatures, which means higher power output and more compact architecture. Operating at high temperatures is made possible by using graphite for the internal components and helium inert gas for the coolant. The higher heat generated by fission requires an efficient cooling system, which in turn requires a pressurized thermal agent flowing rapidly between the core and the power conversion unit that generates electricity. A fast flow rate of helium coolant may raise concerns about possible erosion effects at the interface between helium gas and the solid graphite components. Because these basic reactor concepts have differences in configuration and operation conditions, the erosion problems must be examined separately for each reactor type. The abrasive wear in pebble-bed designs is not included in the current assessment because the wear is mostly caused by the relative motion between pebbles and container wall rather than the cooling gas flow.

Erosion of graphite components in GCRs may be caused by various mechanisms, depending on the operating regime of the two design concepts. The fuel elements and reflectors in prismatic-core reactors are large graphite blocks stacked in tall columns and secured by a system of dowels and pins. Although they would be exposed to dimensional changes from neutron irradiation and thermal stress, they will be mostly immobile, so abrasive erosion is expected to be limited. The fuel elements have gas-flow channels, which extend long distances in the vertical direction. Clean helium gas (free of oxidants and dust particles) is not expected to cause wear, as indicated by independent experiments.[6,7] However, if carbonaceous dust particles were present in the helium coolant, then they may erode graphite by the mechanism described for brittle materials. Knowing that erosion rates increase approximately with the second power of gas-phase linear velocities, flow conditions in various prismatic reactors were analyzed to determine the range of flow velocities between the inlet and outlet of helium flow channels. Based on experience with prismatic-core reactors, the dust source must be investigated, and the quantity of dust generated must be bounded.

Pebble-bed reactors are designed to operate with fuel pebbles in slow but continuous movement in the reactor cavity. This reactor type will generate significantly more dust compared with prismatic-core reactors. Dust will be produced by friction between pebbles, between pebbles and reflector graphite blocks, and between pebbles and pebble-handling mechanisms. Information on dust generation in pebble-

[17] A. Koster, R. Matzie, D. Matzner, Pebble-bed modular reactor: a generation IV high-temperature gas-cooled reactor, Proc. Inst. Mech. Eng. A 218 (2004) 309-316.
[18] S. Ximing, C. Zhipeng, S. Jun, L. Yuan, Z. Yanhua, L. Fu, S. Lei, CFD investigation of bypass flow in HTR-PM, Nucl. Eng. Des. 329 (2018) 147-155.

bed reactors is discussed in the following subsections. The amount of dust that might be generated depends on the helium flow path, regime, and local velocities at various points in the reactor.

2.2 CASE STUDY OF SEVERAL GAS COOLED REACTORS

2.2.1 Prismatic-Core Reactors

2.2.1.1 General Atomics GT-MHR

A typical example of the prismatic-core high-temperature gas-cooled reactor (HTGR) is the General Atomics gas turbine–modular helium reactor (GT-MHR) illustrated in Figure 5.[19] The prismatic core consists of 11 concentric rings of hexagonal columns of fuel elements and graphite reflector blocks. The active core region forms an annular ring about 8 m tall of hexagonal fuel elements stacked to form 102 columns between the inner reflector column and the outer reflector blocks. The average width of the graphite fuel elements is 360 mm, and their average height is 793 mm. Each fuel element has 210 fuel channels along with 102 and 6 flow channels with diameters of 15.88 and 12.70 mm, respectively.[20] The blocks are vertically connected with dowel pins, and the axial channels for helium flow extend into the top and bottom reflector blocks above and below the core, for a total length of 10 m. The helium coolant, at a nominal pressure of 7.07 MPa, enters the reactor core at 400°C from the top and exits at about 850°C from the bottom.[21] A higher temperature and higher efficiency version of the General Atomics concept—the very high-temperature reactor (VHTR)—is designed to operate between about 623°C and 1,000°C at coolant pressures of 4.0–7.07 MPa.[22] Various versions of these reactors are designed for thermal powers between 300 and 600 MW.

[19] M.B. Richards, A.S. Shenoy, L.C. Brown, R.T. Buckingham, E.A. Harvego, K.l. Peddicord, S.M.M. Reza, J.P. Coupey, Final technical report for the period September 2002 through September 2006, GA-A25401 (2006).
[20] R.W. Johnson, H. Sato, R.R. Schultz, CFD analysis of core bypass phenomena, INL/EXT-09-16882 Rev. 1. Idaho National Laboratory (2010).
[21] B.W. Travis, M.S. El-Genk, Numerical simulation and turbulent convection heat transfer correlation for coolant channels in a very-high-temperature reactor, Heat Transfer Engineering 34 (2013) 1-14.
[22] B.W. Travis M.S. El-Genk, Thermal-hydraulics analyses for 1/6 prismatic VHTR core and fuel element with and without bypass flow, Energy Conversion Management 67 (2013) 325-341.

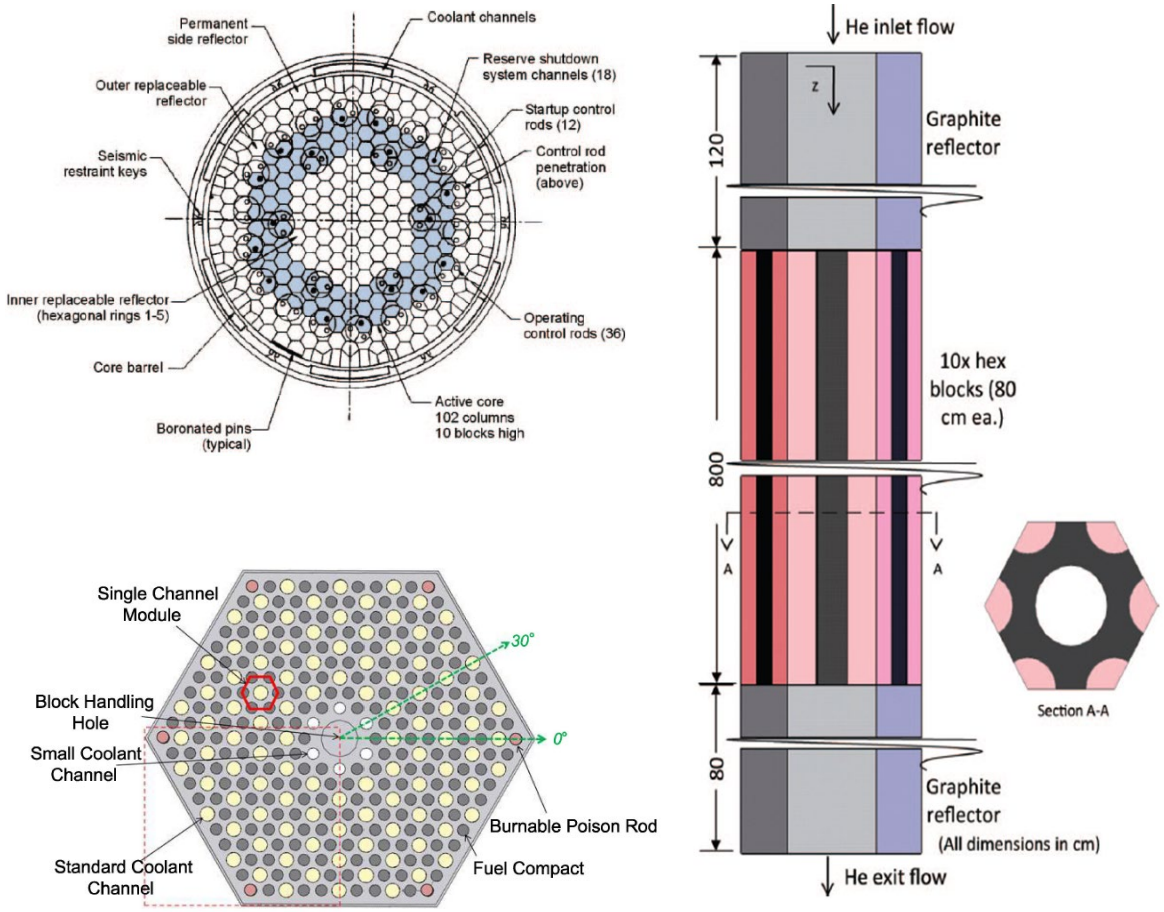

Figure 5. Cross section of General Atomics prismatic-core reactor design (top) and of a hexagonal fuel element (bottom)[22] along with a simplified view of a small (15.9 mm diameter) helium flow channel.[20]

2.2.1.2 Areva ANTARES reactor

The ANTARES project developed by Framatome Areva NP is an evolution of the GT-MHR concept, with a principally similar design.[23] Fuel assemblies are hexagonal prismatic blocks with "flat-to-flat" size of 360 mm and height of 800 mm. The fuel part of the reactor contains 72 columns, 10 blocks high, of type 1 fuel assemblies and 30 columns of type 2 fuel assemblies. The type 1 fuel assemblies contain 108 coolant channels, and type 2 fuel assemblies contain 89 coolant channels for a total of 10,446 coolant channels with the same diameters (1.6 cm) in both types of fuel assemblies. The coolant flows into the core from the top of the reactor, through the fuel assemblies, and is collected at the base and directed to the power-conversion unit. The total mass flow rate of helium is 316 kg/s, 72% of which flows through the fuel assemblies at a total pressure of 5 MPa. The remaining helium flows through bypass paths between fuel assemblies. The average mass flow rate in every channel is 0.0218 kg/s.[24,25]

[23] J.-C. Gauthier, G. Brinkmann, B. Copsey, M. Lecomte, ANTARES: The HTR/VHTR project at Framatome ANP, Nucl. Eng. Des. 236 (2006) 526-533.
[24] X. Yu, L. Brissonneau, C. Bourdeloie, S. Yu, The modeling of graphite oxidation behavior for HTGR fuel coolant channels under normal operating conditions, Nucl. Eng. Des. 238 (2008) 2230-2238.
[25] O. Cioni, M. Marchand, G. Geffraye, F. Ducros, 3D thermal hydraulic calculations of a modular block type HTR core, Nucl. Eng. Des. 236 (2006) 565-573.

2.2.1.3 GTHTR300C reactor by JAEA

The GTHTR300C design by the Japan Atomic Energy Agency (JAEA)[26, 27] is a passively safe Generation IV reactor plant design that enables production and coproduction of electricity, hydrogen, and industrial process heat. It uses TRISO coated fuel particles, and the active core is cooled by the circulated helium gas. The fuel assembly is a so-called pin-in-block type, which is composed of fuel rods and a hexagonal fuel block manufactured from nuclear graphite. A fuel rod consists of 12 hollow fuel compacts with 9 mm inner diameter and 26 mm outer diameter. The fuel compacts are vertically stacked on the bottom plate of a central rod. The active core of the GTHTR300C consists of 90 fuel columns in an annular ring, as shown in Figure 6, and it is about 5.5 m in outer diameter, about 3.6 m in inner diameter, and about 8 m in height. Inner and outer reflector regions consist of 73 columns and 48 columns (including control rod columns), respectively. A fixed reflector region surrounds these regions. A fuel column consists of 8 layers of hexagonal fuel blocks and 2 layers of graphite blocks placed as top and bottom reflectors. Each fuel block, 0.41 m across flats and about 1 m in height, has 57 fuel rods (shown in Figure 7) in its 57 coolant holes. Dowel pins and sockets for fixing fuel blocks are arranged respectively at the top and the bottom of three corners in the block. Burnable poisons are inserted in the holes under three dowel pins. Coolant helium gas flows downward in annular spaces around fuel rods and removes the heat from fuel rods. The cross-section area of coolant channel in each fuel rod can be calculated by coolant channel diameter and the fuel rod diameter shown in Figure 7. Multiplied by the total columns (90) and fuel blocks (57), the total cross-section area for helium gas coolant is 3.40 m^2. According to design specifications, the helium mass flow rate is 403 kg/s, pressure is 6.9 MPa, and average temperature (average of inlet and outlet temperature) is 807°C (1,080 K).

[26] Status report 101 - Gas Turbine High Temperature Reactor (GTHTR300C) https://aris.iaea.org/PDF/GTHTR300C.pdf

[27] T. Mouri, T. Nishihara, K. Kunitomi, Nuclear and thermal design for high temperature gas cooled reactor (GTHTR300C) using MOX fuel. Transactions of the Atomic Energy Society of Japan, 6 (2007) 253-261 (Japanese).

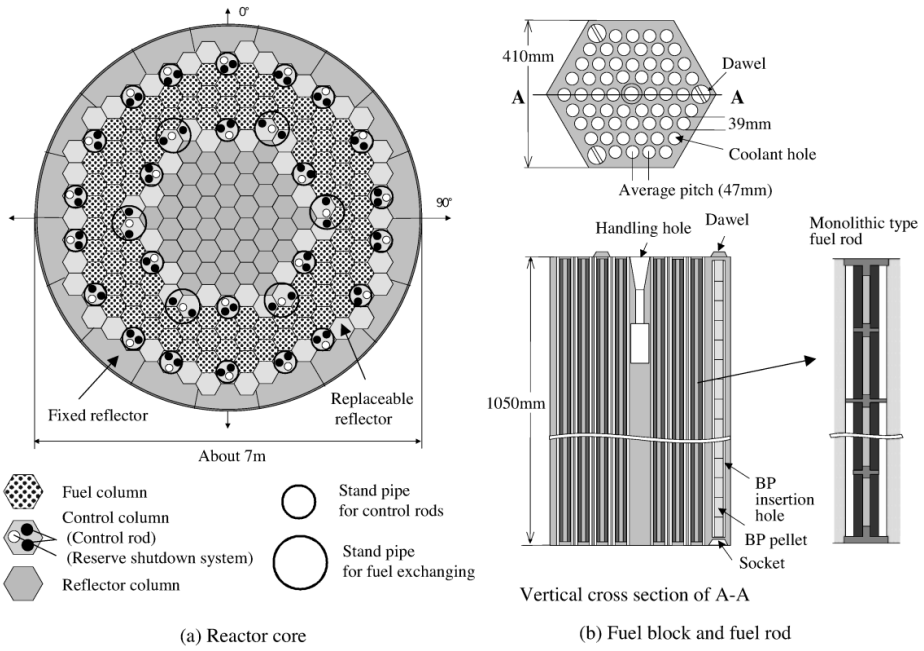

Figure 6. Horizontal view of GTHTR300C reactor core and fuel element.[26,27]

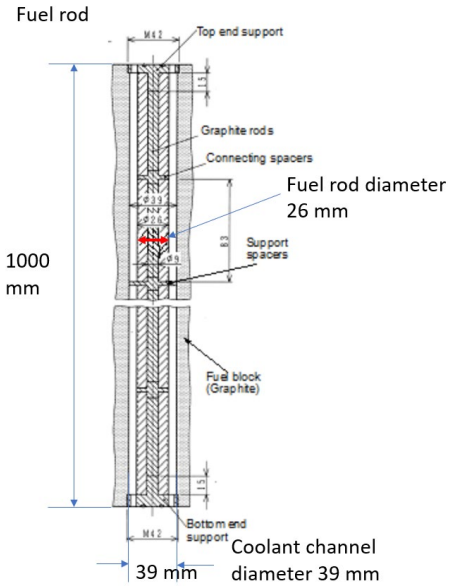

Figure 7. Geometry of fuel rod and coolant channel in GTHTR300C.[26]

Unlike the General Atomics and Areva designs, the GTHTR300C fuel is not contained in a graphite sleeve (Figure 7). Instead, pin-in-block fuel assemblies consist of 12 hollow fuel compacts with 9 mm inner diameter and 26 mm outer diameter. They are vertically stacked on the bottom plate of the central rod. The coolant flows through annular channels between coolant channel inner diameter (39 mm) outer fuel rods diameter (26 mm). This configuration enhances heat transfer efficiency and allows for a 100°C higher operation temperature.[26]

2.2.1.4 Comparison of helium flow conditions in several prismatic-core reactors

Using the details on various prismatic core designs, linear flow velocities (meters per second) in coolant channels can be calculated. Starting parameters for this calculation were total operating pressure, temperature range (including inlet/outlet temperatures), design-based mass flow rates (kilograms per second), and geometric dimensions of open flow channels. The purpose of calculating linear flow velocities is to compare the helium linear flow rates in various prismatic reactor designs against the threshold value of 100 m/s singled out by the rules on abrasion and erosion in the HHA-3142 clause of ASME BPVC Section III Division 5.[1]

Table 1 summarizes details of four different design concepts: General Atomics HTGR,[20,21,22] a variant of Areva VHTR,[24,25] and two different HTGR designs by JAEA.[26] Interestingly, although total core coolant mass flow rates vary in a narrow range (316-360 kg/s) the coolant linear velocities are quite different because of different channel geometries, operating pressures, and operating temperatures. It is difficult to evaluate the potential of developing erosion conditions on graphite by counting the coolant linear velocities only.

Data in Table 1 show that the linear velocities of helium flow in the narrow channels of fuel assemblies vary from 34–42 m/s at the low-temperature gas inlet to 44–58 m/s at the high-temperature gas exit. These calculated values do not account for the loss of flow rate caused by parasitic bypass and cross-flow paths that are expected to occur between vertical fuel elements columns (bypass flow) and between vertically stacked fuel elements (cross flow).[28] Calculations of these effects indicate that the capacity loss of the flow-through channels may be 5%–11% of total flow for the General Atomics design [22] and up to 27% of total flow for the Areva design.[20] The loss of flow through the gas channels in the fuel elements would reduce the cooling capacity of the core and may cause a minor increase in fuel temperature.

Moreover, accidental obstruction of gas-flow channels may have serious consequences. As shown by a previous report,[25] obstruction of flow channels would severely reduce the cooling capacity and may not be alleviated by simply rebalancing the flow through the still-open channels, where the linear velocities may increase above the levels shown in Table 1. Such accidental damage to the fuel elements' configuration, reducing the cooling capacity, may even lead to unacceptably high fuel temperatures above the safe limit of 1,600°C. In the very unlikely scenario of such a beyond-design event, the abnormal increase of the linear velocity above the threshold set by HHA-3142 would be less important than the fuel damage and subsequent radioactivity release. [25]

[28] L, Wang, Q. Liu, K, Fukuda, Numerical solution of heat transfer process in a prismatic VHTR considering core bypass and cross flow, NURETH-16, Chicago, IL, August 30 – September 4, 2015; http://glc.ans.org/nureth-16/data/papers/13434.pdf.

Table 1. Comparison of coolant flow character in four prismatic-core reactor designs

		General Atomics	Areva	JAEA	
		VHTR	HTGR	Power only	Power & H2
Reactor total thermal power (MW)		600	600	600	600
Operating pressure (MPa)		7.07	5	6.9	5.1
Core height (m)		8	8	8.4	8.4
Number of fuel columns		102	102	90	90
Number of FA in a fuel column		10	10	8	8
Number of He channels per FA block		108	108	57	57
Coolant channel diameter (mm)	large channels	15.9	16	39 (ID)	39 (ID)
	small channels	12.7		26 (OD)	26 (OD)
Total core coolant flow (kg/s)		330	316	403	324
Channel coolant mass flow rate (kg/s)	large channels	0.0306	0.0218	0.0584	0.0470
	small channels	0.0178			
Large channel coolant velocity (m/s)	inlet	42	35	34	34
	outlet	58	58	44	48
Small channel coolant velocity (m/s)	inlet	38	n/a	n/a	n/a
	outlet	52			
Core inlet temperature (°C)		641	500	663	594
Core outlet temperature (°C)		990	1000	950	950
Dynamic viscosity (Pa.s)	inlet	4.33E-05	3.85E-05	4.46E-05	4.18E-05
	outlet	5.45E-05	5.48E-05	5.33E-05	5.33E-05
Reynolds number	inlet	56,620 / 41,234	45,082	34,520	22,025
	outlet	44,984 / 32,760	31,673	28,885	17,273

Notes: FA = fuel assemblies; ID = inner diameter of coolant channels; OD = outer diameter of fuel rods

2.2.2 Pebble-Bed Reactors

In pebble bed reactors, the TRISO fuel particles are dispersed in spherical pebbles and embedded in a carbonaceous graphite matrix. In a particular design,[17] the reactor core is 11 m high, with a graphite reflector of 2 m in diameter and an annular fuel region 0.85 m wide. The core contains 450,000 pebbles: the average packing density is 0.61. Pebbles are circulated an average of six times before the fuel is burned off to the desired limit. The average fuel temperature is 780°C, with a maximum of 1,130°C.[17] During regular operation, pebbles are forcibly cooled by a downstream flow of helium, which is introduced to the reactor top through the helium riser conduit. From the reactor top, the gas descends and passes through the porous bed of spherical pebbles where its temperature increases, and it is eventually collected at the reactor bottom and redirected to the power turbine and the auxiliary helium processing units.[29] In a different design, the HTR-PM Chinese reactor also contains vertical cooling gas channels carved inside the graphite reflector.[18] Information on linear helium velocity at different reactor locations are scarce in the literature. Figure 8 shows a schematic of the thermal hydraulic model used to analyze pebble-bed HTR operation under anticipated occurrences and design-basis events.[30] The highest velocity (~35 m/s) is expected at the top end of the helium riser duct entering the upper plenum. This state is confirmed by the flow schematics for the Chinese HTR-PM,[18] according to which the bypass flow in the cooling channels carved in the graphite reflector has even smaller velocities (5 m/s at the cold inlet, 10

[29] P.J. Venter, M.N. Mitchell, Integrated design approach of the pebble bed modular reactor using models, Nucl. Eng. Des. 237 (2007) 1341-1353.
[30] R. Steward, D. Reger, P. Balestra, Demonstrate capability of NEAMS tools to generate reactor kinetics parameters for pebble-bed HTGRs transient modeling, INL/EXT-21-64176. Idaho National Laboratory (2021).

m/s at the hot outlet). These values are all below the 100 m/s limit introduced by HHA-3142 in the ASME code.

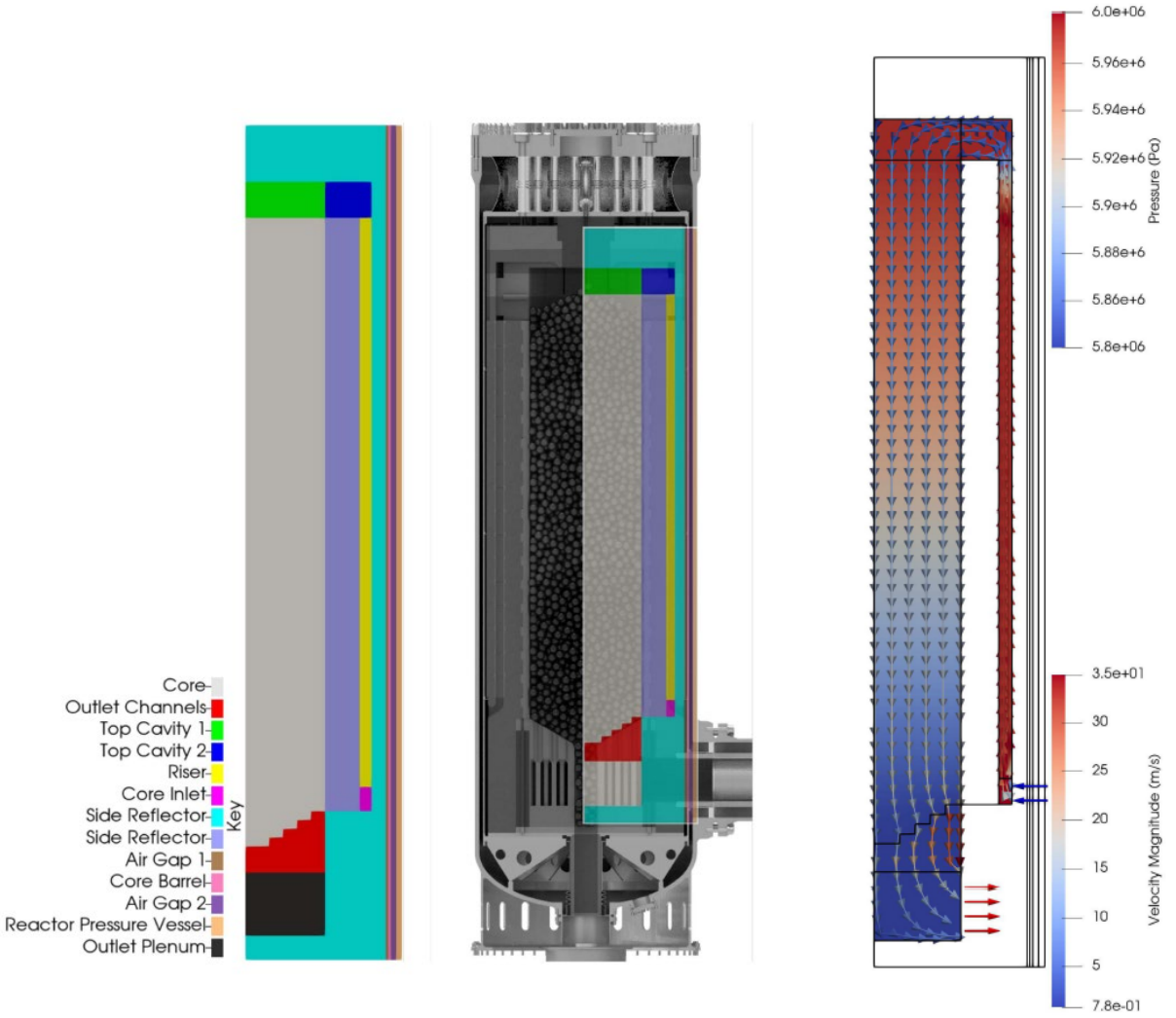

Figure 8. Thermal-hydraulic model (left) and the same model overlapped over the PBMR open-source figure (center) along with the pressure distribution obtained from computational fluid dynamics calculations (right). The helium flow streamlines are overlapped on the pressure distribution.[18]

3. THE DUST PROBLEM

As mentioned previously, experimental results in extreme conditions did not indicate sustained erosion of graphite surfaces in contact with a flow of clean helium gas (free of oxygen and dust particles) even at extreme conditions (high temperature, high velocity). The only effect observed was mobilization of dust remaining after machining in the first hour of a 23 h experiment.[7]

However, mechanical erosion is expected if the gas stream carries solid particles (dust), as is often encountered in numerous technical fields, such as the oil and gas industry. Helium purity used in HTRs is controlled to strict limits of chemical composition and should also be free of solid particles and dust. However, total elimination of dust is not always possible.

Experience with HTR reactors identified three types of carbonaceous dust: graphite from mechanical action in the core, carbon from decomposition of hydrocarbons introduced through oil contamination, and carbon from decarburization of steel alloys.[31, 32, 33, 34] In current and future reactors, the use of new materials (alloys, graphites) may produce different amounts of dust than reported from past studies. The rate of dust generation in the German AVR, which did not have dust removal facilities, and new results for the pebble-bed HTR-10 converge at values in the range of 30–100 kg/year normalized to 400 MW (thermal) per pebble-bed HTR unit.[30]

The primary mechanisms for dust production in modern HTGRs are (1) wear caused by relative movement of graphite components, (2) wear caused by expansion and contraction of graphite, and (3) failure of fuel elements, mainly caused by static pressure, collision, discharge, wear, and by reactions with impurities.[34] Continuous cycling of fuel elements in pebble bed reactors is the main source of dust in this type of reactor. Two sources have been identified: reactor core (pebble bed, side reflectors, and the bottom reflector) and the fuel handling and storage system (FFHS). The total dust produced in the core was estimated to be 28 kg/year, whereas the dust source from the FFHS is 20 kg/year.[32] By contrast, dust generation in prismatic-core HTR is expected to be far less because the friction mechanism is mostly absent, as confirmed by the International Atomic Energy Agency.[35, 36]

Dust formed by friction and abrasion between carbonaceous components in HTRs is assumed to have the shape and size of primary particles (grains) of those carbonaceous materials. If the dust comes from pebbles, then the size is likely tens of micrometers. Dust released by fine-grain graphites used as moderator and reflector in a prismatic-core reactor may be on the order of 1–10 μm, whereas medium-grain graphite may yield dust particles on the order of hundreds of micrometers or larger. Based on experience with Peach Bottom, Fort St. Vrain, and HTTR (Japan) reactors, the average properties of reactor dust can be summarized as follows[35]:

- 0.01 to 10 μm graphite particles
- 3 mg/m^3 concentration in gas
- 5 g/m^2 surface loading

Regarding its composition, heavy elements (e.g., iron oxides, silica) have been detected in the Peach Bottom dust by x-ray diffraction and fluorescence along with about 20% graphite and an unknown fraction of amorphous carbon, which could not be detected by those analytical methods.[34]

Dust is a major concern as a vector for transport, spreading, and redeposition of fission products that may have escaped defective TRISO particles. However, little is known about the role of dust aerosols as a

[31] M.P. Kissane, A review of radionuclide behavior in the primary system of a very-high-temperature reactor, Nucl. Eng. Des. 239 (2009) 3076-3091
[32] M.M. Stempniewicz, L. Winters, S.A. Casperson, Analysis of dust and fission products in a pebble bed NGNP, Nucl. Eng. Des. 251 (2012) 433-442
[33] Q. Sun, W. Peng, S. Yu, L. Wang, A review of HTGR graphite dust transport and research, Nucl. Eng. Des. 360 (2020) 110477.
[34] L. Xiaowei, W. Xiaoxin, S. Ii, Y, Xiaoyu, Y, Suyuan, Nuclear graphite wear properties and estimation of graphite dust production in HTR-10, Nucl. Eng. Des. 315 (2017) 35-41.
[35] P.W. Humrickhouse, HTGR dust safety issues and needs for research and development, INL.EXT-11-21097. Idaho National Laboratory (2011).
[36] Verfondern K. Fuel performance and fission product behaviour in gas-cooled reactor. IAEA-TECDOC-978. 1997.

cause for erosion of graphite surfaces in contact with a high-velocity moving helium coolant stream containing dust in the channels of prismatic-core reactors. Taking the aerosol transport and deposition data calculated for the Westinghouse pebble-bed design as an example,[32] a total lifetime of 60 years was assumed, with an average availability of 95% (i.e., 57 years effective run time). The total amount of graphite dust generated during this time is approximately 1,630 kg, 86% of which settles on graphite heat structures in the reactor vessel. Two-thirds of the remaining graphite dust is collected by the intermediate heat exchanger. The filter in the FFHS removes 97% of dust generated in FHSS. The airborne gas density of dust particles is represented in million particles per cubic meter (Mp/m^3). Typical values are between 200 and 400 Mp/m^3, which corresponds to roughly 1 g/m^3.[32]

4. REYNOLDS NUMBER—THE FORGOTTEN PARAMETER

A complementary dimensionless quantity indicative of global flow conditions in the channels might be necessary. However, finding a unique parameter is a difficult task considering the numerous gaps or uncertainties remaining in understanding and modeling erosion. For example, a 1995 literature review specifically focused on erosion selected 28 equations, including 33 parameters, ranked on their frequency and significance. The top three parameters were velocity, density, and impact angle.[37] A subsequent analysis[11] added target density as the fourth most frequently used parameter for describing erosion (in oil and gas industry, mainly). With such a variety between models and predictive equations, it is difficult to select the most relevant description for graphite components' erosion in HTRs.

However, given that erosion in coolant channels is determined by the flow conditions in the whole channel, which in turn depends on gas properties and their temperature dependence, it might be useful to look at a complementary parameter that globally describes the flow character. Reynolds number characterizes the flow type (laminar/turbulent) based on a combination of factors, including channel geometry, flow rate (average linear velocity), and fluid viscosity (dynamic or kinematic). The Reynolds number (*Re*) represents the ratio of inertial forces to viscous forces and is a convenient parameter for predicting whether a flow condition will be laminar or turbulent.[38] It is defined as a characteristic length multiplied by a characteristic velocity and divided by the kinematic viscosity.

$$Re = \frac{inertial\ forces}{viscous\ forces} = \frac{VL}{\frac{\mu}{\rho}} \tag{7}$$

Here, V is the flow velocity, μ is dynamic viscosity, and ρ is density. The L in Eq. (7) represents the pipe characteristic length, equal to diameter if the section area is a circle. The μ/ρ ratio is also called kinematic viscosity. In general, the laminar flow has a *Re* value below 2,300, whereas the turbulent flow has a *Re* higher than 2,900. The flow with a *Re* between 2,300 and 2,900 is in a transitional state.

The following equivalent expressions can be used for calculating Reynolds number for fluids flowing in a straight pipe:

$$Re = \frac{uD_H}{\nu} = \frac{\rho u D_H}{\mu} = \frac{\rho Q D_H}{\mu A} = \frac{W D_H}{\mu A} \tag{8}$$

where D_H (m) is the hydraulic diameter of the pipe (or its inside diameter for circular pipes)
$\underline{Q}$ (m^3/s) is the volumetric flow rate

[37] H. Meng, K. Ludema, Wear models and predictive equations: their form and content (Part 2), Wear 181-183 (1995) 443-457.
[38] Reynolds number, https://www.nuclear-power.com/nuclear-engineering/fluid-dynamics/reynolds-number/

A (m^2) is the pipe's cross-sectional area
u (m/s) is the mean fluid velocity
μ (Pa.s) is the fluid dynamic viscosity
ν (m^2/s) is the fluid kinematic viscosity
ρ (kg/m^3) is the fluid density
W (kg/s) is the mass flow rate

The use of Reynolds number as a complementary parameter for evaluating erosion effects was demonstrated in a recent work on erosion in steel pipes. In addition to the known increase of erosion rates with flow velocity, this increase was found to markedly accelerate in the presence of turbulent flow compared with equivalent conditions (slurry concentration) in laminar flow.[39] In the case of helium flow in coolant channels with various geometric configurations specific to reactor designs, the nature of fluid (helium) and that of eroding particles (carbonaceous dust) have narrower variation limits than the parameters defining the flow character and used in Reynolds number calculation. For each design concept, once the neutronic models provide heating data for the thermodynamic and structural models, thermohydraulic models determine the heat removal needs (i.e., the temperatures, pressures and gas flow rates in the reactor).[29] Starting from here, when specific mass flow rates for helium are determined, the specifics on local (or average) linear velocity, gas density, and gas viscosity are solely controlled by temperature and pressure. Using Reynolds numbers as a global flow characteristic in relation to the possible erosion effects is a logical choice.

5. SUMMARY AND PROPOSED PATH FORWARD

The ASME BPVC code[1] refers to the effect of erosion in gas cooled reactor designs in clause HHA-3143 (b) as "…erosion shall be evaluated in areas where the mean gas flow velocity in the cross section of the channel exceeds 330 ft/sec (100 m/s)."

This work involved analyzing available information on several GCR designs. The results show that helium flow rates in prismatic-core reactor cooling channels may reach velocities between roughly 30 and 60 m/s, depending on specific design geometries and local temperature and pressure conditions. The configuration of helium flow in pebble-bed reactors is different, but narrow channels direct the inlet flow to the reactor top, where velocities up to 35 m/s may be expected. These values are far below the code threshold value of 100 m/s. The clause at HHA-3143 (b) appears to be a high threshold that the analyzed GCR designs cannot reach. This threshold, by itself, provides little help in evaluating the erosion effects.

Based on the scarce experimental results available in the literature, graphite erosion in a flow of clean helium (i.e., free of oxidants and particulate matter) has not been documented, even at high velocities and high temperatures. However, this lack of evidence is not taken as a definitive conclusion. More theoretical investigations are needed for developing a realistic assessment of erosion probability initiated by helium molecular collisions on graphite surfaces. Modeling should specifically include the range of flow parameters (velocity, pressure, temperature, laminar or turbulent character), gas properties (density, viscosity, kinetic energy, collision frequency), and graphite surface properties (hardness, elastic properties, porosity, surface roughness) appropriate for the operation regime of prismatic-core and pebble-bed GCRs.

Graphite erosion is more likely in a fast-flowing gas stream containing particulate matter than in particulate-free, clean gas stream. Erosion effects of coolant gas flow on GCR internals depend on many

[39] M, Shehadeh, M. Anany, K.M. Saqr, I. Hassan, Experimental investigation of erosion-corrosion phenomena in a steel fitting due to plain and slurry seater flow, Int. J. Mechanical Mat. Eng. 9 (2014) 22; http://www.springer.com/40712/content/9/1/22.

factors, such as gas physical properties (density, viscosity), flow velocity and character (laminar of turbulent), the number density and properties of entrained particulate matter (average dimensions, shape, elastic properties), the wall surface properties (surface roughness, porosity, and stiffness, elastic properties). Despite the vast research effort on erosion phenomena at gas–solid interfaces, the basic mechanisms and governing equations remain unclear.

The ASME code suggestion of velocity as a unique property, particularly with the high-threshold velocity value of 100 m/s (330 ft/s), may not comprehensively reflect graphite erosion factors. Because velocity alone does not reflect the channel cross-section geometry and the coolant flow state, a global dimensionless parameter such as the Reynolds number appears to be a better option for evaluating graphite erosion in GCR coolant channels. This proposal is supported by the fact that the solid material properties (graphite) and particulate matter properties (carbonaceous dust) are expected to have minimal variations between different reactor concepts. This lack of variation significantly reduces the number of parameters to be considered. Although the presence of oxidant impurities in the gas coolant (oxygen, water) or of other types of solid particles (metal or ceramic microparticles) would possibly accelerate the erosion effect, these can safely be regarded as second-order effects.

More research, including appropriate erosion tests and/or simulations using computational fluid dynamics tools (such as FLUENT code) could provide fundamental knowledge on graphite erosion in GCRs.

Moreover, the actual version of the ASME code takes no consideration of the erosion effects in molten salt–cooled reactors. Further studies are needed to assess molten-salt erosion on graphite materials.