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Optimal Moderation in the Pebble-Bed Reactor for Enhanced Passive Safety and Improved Fuel Utilization

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The concept of optimal moderation is introduced as a reactor configuration in which any change in the fuel-to-moderator ratio causes a reduction in reactivity. It is shown that such a configuration cannot persist over time in a reactor with stationary fuel, but can do so in a reactor with moving fuel, such as a pebble-bed reactor. It is further shown by the example of pebble-bed versions of the proposed Next Generation Nuclear Plant that such optimal moderation in gas-cooled reactors leads to significant advantages in response to water ingress, fuel utilization, and resistance to nuclear weapons proliferation.

KEYWORDS: ***Optimal moderation, asymptotic equilibrium cycle, pebble-bed reactors, water ingress, fuel utilization, nonproliferation***

1. Introduction

The dominant nuclear power technology at the beginning of the twenty-first century is that of light water reactors (LWRs). In these reactors, the fuel within the core is replenished at periodic intervals of one year to eighteen months. In the time between refueling outages, the fuel itself is not expected to be mobile. In such reactors, after a number of refueling events, the core configuration attains a state known as the "asymptotic loading pattern" or the "asymptotic equilibrium" core. However, despite this nomenclature, the core keeps changing between reloading events. Thus, the asymptotic loading pattern is not really a steady state; rather, it merely indicates that subsequent reloading configurations will be essentially the same as this "asymptotic" pattern. During operation, even in the asymptotic pattern, the state of the core continues to change. This continuing change of the core makes the realization of certain optimization objectives difficult if not outright impossible. One particular objective that cannot be met *continuously* with fixed fuel cores, such as LWRs, is that of optimal moderation. Here optimal moderation is meant as the moderation state that would exist exactly between over- and undermoderation (the concept is described further below). In this paper, it is shown how optimal moderation, in the sense just stated, can be achieved and maintained for the bulk of the operating life of a pebble-bed reactor (or for any reactor with continuous refueling and defueling). Some of the safety and economic beneficial consequences of operating in the optimal moderation state are also described.

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In the next section, it is explained what optimal moderation is and why a fixed-fuel reactor cannot be easily operated in the optimal moderation mode continuously. The following section discusses the asymptotic loading and burnup pattern in a continuously fueled and defueled pebble-bed reactor. The feasibility of optimal moderation through the proper design of the fuel elements of the PBR is discussed in Section 4. Section 5 summarizes the design methodology and discusses the modeling and computational tools used in this study. The sixth section presents results of the study, including examples of the beneficial effects of maintaining optimal moderation throughout the operation of the reactor. The last section summarizes the results of this paper and discusses the implications of its findings.

2. Moderation Shifts in Operating Fixed-Core Rectors

Light water power reactors are commonly built and operated, by design, to be undermoderated. Undermoderation is the condition where the addition of more moderating material causes a net increase in the thermal neutron population (and hence in the multiplication factor, k_{eff}). The underlying physical phenomenon is a competition between neutron thermalization and neutron absorption by the moderator. In LWRs, this competition between thermalization and absorption is, by design, won by thermalization. The reason for this choice is that in an undermoderated reactor a density decrease in the coolant, which is also the moderator, would result in a decrease in the thermal neutron population (and thus in the reactor power) and therefore in negative reactivity feedback. Hence, the undermoderated design is desirable for safety reasons. The level of undermoderation shifts during a cycle, but not enough to result in overmoderation. For example, in a boiling water reactor (BWR), as the core ages (i.e., depletes as it is exposed to a neutron flux), the level of undermoderation and the void coefficient of reactivity gradually change [1]. (The void coefficient of reactivity indicates the expected change in reactivity as the void fraction in the coolant is increased.) However, the initial undermoderation of the fuel loading pattern for any given cycle is large enough to ensure that negative void reactivity feedback is maintained throughout the cycle. This behavior is further complicated by the presence of burnable poisons and the normal presence of operational levels of boiling [2]. Whereas overmoderation is undesirable for safety reasons, undermoderation leads to a less than ideal utilization of the fuel. Indeed, undermoderation means that some neutrons will be lost or absorbed that could have otherwise induced fission reactions in a more highly moderated reactor. Therefore, neither overmoderation nor undermoderation is an ideal state for the most efficient use of the neutrons generated in operation. Such an ideal use is discussed next.

The ideal use of neutrons is in producing further fission events. Such a use would correspond to a configuration of fuel, moderator, and other materials that ensures the highest possible effective multiplication factor. Such a configuration, where either addition or removal of moderator would reduce k-effective, is defined here as an optimally moderated configuration. One could envision a fixed-core reactor that is constructed to be thus optimally moderated. For example, this could be the case at the beginning of a cycle, i.e., just after refueling. In such a reactor, fuel depletion (and other composition changes that result from neutron interactions) would result in a nearly immediate departure from the optimal moderation once the reactor is operated. Such departure may even result in an overmoderated configuration, which is prone to positive void reactivity feedback, an undesirable feature from the safety standpoint. Similarly, if optimal moderation were to arise later than immediately upon refueling, further depletion would again result in immediate departure from the desired state. From these considerations, it is apparent that optimal moderation in a fixed-fuel reactor cannot be maintained once the reactor is operated and therefore cannot be relied on as the normal operating mode. This conclusion applies to LWRs as well as to other fixed-fuel rectors such as the prismatic gas-cooled high temperature reactor and variants thereof. The foregoing conclusions apply even to the asymptotic equilibrium cycle described in the introduction. Furthermore, for LWRs, once the reactor departs from optimal moderation, the expected ensuing overmoderation is undesirable. For fixed-core gas-cooled, graphite-moderated reactors the positive void reactivity feedback is not an issue since the coolant has very little reactivity impact. However both under- and overmoderation may have a detrimental effect on the neutron economy.

Whereas LWRs are designed to be undermoderated, graphite-moderated reactors are designed, when possible, in such a way as to allow the effective control of the positive reactivity insertion that would result from potential (though possibly hypothetical) water or hydrogen ingress events. For example, in the design of the HTR-Modul pebble-bed reactor [3], the moderation level (i.e., fuel-to-moderator ratio) is chosen such that the negative reactivity worth of available control rods is sufficient to offset the positive reactivity insertion expected from a water ingress event. In continuously refueled and defueled reactors, the tailoring of the moderation level need not stop at considerations on control rod worth. In fact, because of the very low level of excess reactivity that can be achieved for an actually working reactor and because of the existence of a true asymptotic fuel loading and burnup distribution pattern, the core can be designed to remain continuously ideally moderated. The remainder of this paper explores one approach to building optimal moderation into the design of a pebble-bed reactor and demonstrates some of the benefits thus derived.

3. Asymptotic Fuel-Loading and Depletion Profile in a Circulating-Fuel PBR

In a continuously fueled and defueled pebble-bed reactor, an equilibrium asymptotic fuel loading and burnup distribution pattern arises relatively soon after initial loading and persists for the bulk of the operating life of the reactor. It was previously demonstrated [4,5] that this asymptotic loading pattern is determined uniquely once a small set of design and operational parameters are fixed. Such parameters include fresh fuel enrichment, fuel discharge burnup cutoff, average pebble flow rate, the core thermal power, core dimensions, heavy metal loading per pebble, and ratio of pebble flow rates in inner and outer zones (for two-zone cores). Because of this uniqueness, and the small number of determining parameters, it is possible to optimize the design of a PBR for any specific objective by varying only that small number of parameters (especially if some parameters are fixed *a priori*, such as the reactor size or its overall power). Alternately, an enhanced, without necessarily being optimized, design may also be pursued by varying these parameters. An obvious application of this idea is to enhance safety against water ingress events while improving the economy through the realization of an appropriate desirable asymptotic pattern. Such an approach is illustrated in the next three sections. An application of the optimization opportunity stemming from the features just discussed is presented in a companion paper [6].

4. Optimal Moderation via Fresh Fuel Design

The moderation state in a pebble-bed reactor can be tailored by varying, among other things, the design of the fresh pebbles. In this section, proof that optimal moderation can be achieved merely through this artifact is provided. The proof relies on a set of MCNP [7] models.

The fuel elements in a pebble-bed reactor are spheres such as shown in Figure 1. These spheres are made of two zones. A graphite matrix with interspersed fuel kernels constitutes the inner zone.

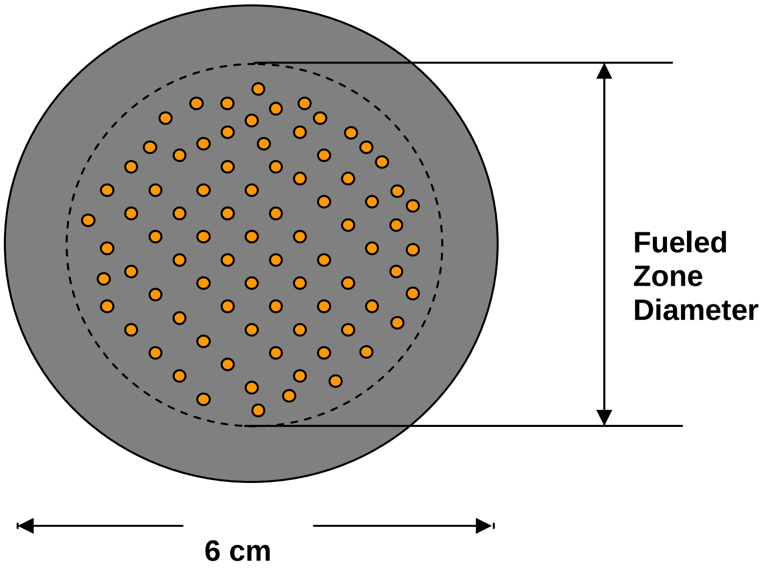

Figure 1. Conceptual design of pebble-bed reactor fuel

It is assumed that the kernels in the fuel are manufactured as TRISO particles. Such particles are multi-layered spherical grains. The structure of TRISO particles is illustrated in Figure 2.

The level of moderation in a core is governed by the moderator-to-fuel ratio. In the design of a reactor core there are many ways in which this ratio can be adjusted. For example, the amount of reflection can be changed by using both an inner and an outer core reflector and by varying the depth of said reflectors. Another, more practical and more effective, approach is to vary the relative amount of fuel and moderator in the fuel pebble. In this study, altering the design of the TRISO particle is deliberately avoided. Furthermore, the overall size of the pebble is also deliberately kept the same as that of the pebbles used in previous [8], existing [9], and planned [10] pebble-bed reactors. With these choices, the fuel handling equipment in a plant that would use the modified fuel would be essentially the same as in previous designs. Abiding by these constraints, varying the moderator-to-fuel ratio reduces to varying the size and configuration of the fueled inner zone within the pebble. For example, a central core of pure unfueled graphite may be assumed, or a hollow center. Another alternative is to vary the radius of the fueled zone, while maintaining its overall configuration. Thus, a modified pebble would be similar in configuration (and manufacturing simplicity) to the one shown in Figure 1, with the exception of a smaller or larger internal fueled zone, and a commensurately thicker or thinner outer shell, respectively. The variation of the fuel-to-moderator ratio is sufficient in seeking optimal moderation because in gas-cooled pebble-bed reactors, the helium coolant is essentially neutronically transparent. Therefore it contributes almost nothing to the overall neutron moderation, and it follows that variations in its properties, such as temperature and density, have almost no effect on moderation.

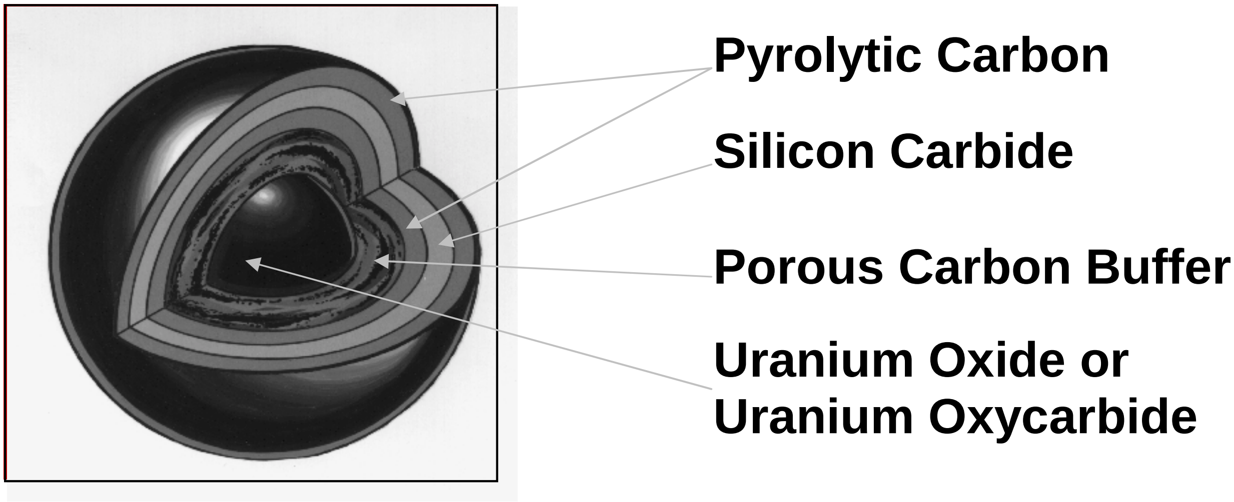

Figure 2. TRISO Fuel Particle

Using a cell code such as COMBINE [11] or MICROX-2 [12], one can show that by varying the radius of the fueled region from 2.5 cm down to 1.5 cm, for example, the infinite multiplication factor (k_∞) rises, reaches a maximum value, then decreases [13]. For the multiplication factor in a finite-dimension core, a similar proof is obtained using a doubly heterogeneous MCNP model.

The MCNP model devised for this study is a doubly heterogeneous cylindrical reactor 10 m high and 3 m in diameter, with a 1 m reflector all around and a gap 1 m high between the top of the core and the upper reflector. Both the pebbles and the TRISO particles are assumed to be arranged in body-centered cubic lattices. The uranium enrichment in fresh TRISO particles is assumed to be 8%, but the U-235 concentration is reduced, and a generic fission product is added, until the reactor is critical. This is an artificial composition, since all the pebbles are assumed to be identical, but the purpose of the model was to demonstrate the optimal moderation phenomenon and not to represent an actual reactor. The density of TRISO particles in the fueled zone is 172.2 per cm^3, for a total of 11,271 particles per pebble. As the radius of that zone is varied, the infinite multiplication factor (k-effective) varies. The results of these changes are shown in Figure 3. It is clear that even for a finite core optimal moderation is achievable with fuel and materials typical of PBR designs. It is also clear that for this static reactor configuration (i.e., no fuel motion and no depletion) the usual location at 2.5 cm is not optimal for the interface between the fueled and unfueled zones.

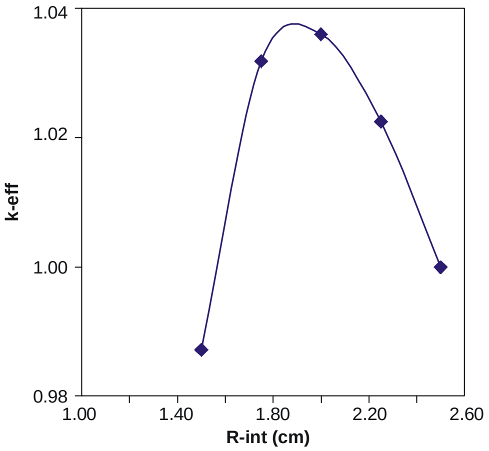

Figure 3: Dependence of k_{eff} on moderation

If a reactor is constructed using a pebble with the fueled/nonfueled interface at about 1.9 cm, then the maximum neutron multiplication is achieved. In such a reactor, the neutron economy is the most efficient and moderation is at its peak. If such a configuration can be maintained throughout the operating life of a reactor, then these economic benefits as well as some safety benefits would be realized. In the next section, the methodology for designing such a sustainable optimally moderated asymptotic pattern is presented. The subsequent section presents results that demonstrate the expected advantages of an optimally moderated pebble-bed reactor.

5. Design Methodology for an Optimally Moderated PBR

The results of the previous section demonstrate that material compositions, including fuel, that constitute the core of a gas-cooled graphite-moderated pebble-bed reactor can be adjusted to produce an optimally moderated core. The results of the previous section pertained to a static core and ignored the effects of operation (and hence depletion) that would terminate the optimally moderated state. In this section the tools and methodology necessary for the design of a continuously optimally moderated core are presented.

Since the asymptotic fuel and burnup distribution persists indefinitely into the operating life a PBR, proving that said asymptotic state could be an optimally moderated one would prove the feasibility of continuously optimally moderated cores. Using the tools presented in this section, the results of the next section provide this proof.

5.1 Computational Tools and Models

The principal tools used in this portion of the study are the INEEL-developed PEBBED code for pebble-bed reactor design and fuel cycle analysis, the COMBINE code for cross section preparation, and the MICROX-2 code for neutron diffusion data preparation. Additional tools include interfacing codes. The capabilities of the three principal codes used, as relevant to the present study, are summarized below.

5.1.1 Overview of the PEBBED Code

The INEEL code PEBBED [4] is used for self-consistent analysis of neutron flux and isotopic depletion and buildup in a PBR with a flowing core. The code can treat arbitrary pebble recirculation schemes, and it permits more than one type of pebble to be specified. At the INEEL, the PEBBED code has already been applied to treat a variety of practical PBR problems such as a two-zone concept originally considered as a candidate for the PBMR in South Africa. Another is the PBR version of an OUT-IN fuel cycle in which fresh pebbles are circulated in an outer annulus until an intermediate threshold burnup is attained, and then transferred to the inner central column for the remainder of their core lives. Output from PEBBED includes the spatial distribution of the burnup and of the principal nuclides throughout the reactor core and in the discharged pebbles. The code allows estimation of refueling needs and predicts the power production.

5.1.2 Overview of the COMBINE Code

The COMBINE-6 [11] code was used in this study. This code solves the B-1 or B-3 approximation to the Boltzmann transport equation in one dimension for a homogeneous bare slab. The homogeneous region includes all of the materials in the fuel particles, carbon matrix, graphite shell, and surrounding coolant. Spherical geometry was specified for the thermal disadvantage factor calculation, for which COMBINE uses the ABH [14] method. A homogenized fuel region with a 2.5-cm radius, a graphite shell region with a 3-cm external radius, and a coolant region with a 3.509-cm external radius were used as input for the ABH calculation. An overall effective Dancoff factor, calculated as a function of fuel zone radius per reference [15], was used to account for the neighboring pebbles. The cross sections were from the ENDF/B-6 library. All COMBINE cross sections in this paper use a 75-group structure.

5.1.3 Overview of the MICROX-2 Code

MICROX-2 is an integral transport theory code [12] evolved from an earlier version developed by General Atomics. Developed and tested at the Paul Scherrer Institute in Switzerland, MICROX-2 was used in calculations and analysis of experiments performed at the HTR PROTEUS facility, also in Switzerland [16, 17]. The code solves the B1 neutron balance equations in a one-dimensional two-region unit cell and produces the neutron spectrum that is used for cross section collapsing. The two regions are coupled by collision probabilities based on spatially flat neutron emission. Dancoff factors (the same as those used in the COMBINE calculations) and bucklings correct the one-dimensional cell calculations for multi-dimensional lattice effects. MICROX-2 prepares the broad-group neutron cross sections for use in diffusion and transport codes. It can process up to 11 mixtures and a maximum of 13 fission spectra for each spatial region. It has three geometry options: spherical, cylindrical and planar (slab).

5.1.4 Application of MICROX-2 to PBR analyses

The pebble cell is defined in spherical geometry. Region 1 is the inner fuel region, which contains the fuel kernels in the graphite matrix. The pure graphite shell and the coolant zones are homogenized into one region to make Region 2. See Figure 4 below.

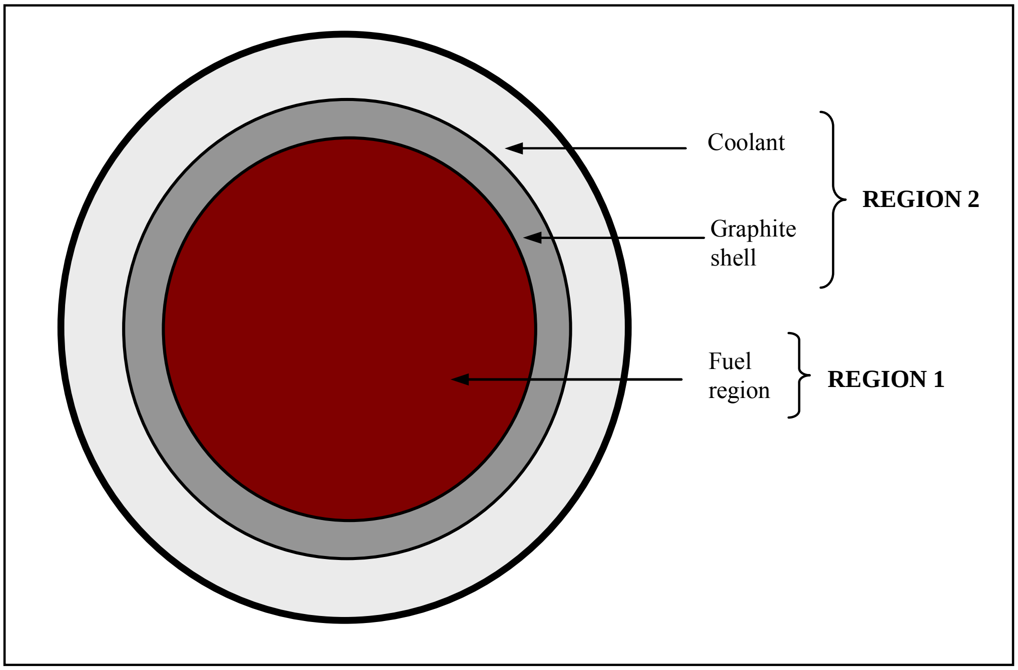

Figure 4. MICROX-2 Spherical Geometry Model

Since MICROX-2 is a one-dimensional lattice cell code, it is necessary to take into consideration the actual multi-dimensional and multi-cell lattice geometry using Dancoff factors and a collision probabilities treatment for the fueled region.

5.2 Asymptotic Pattern Iterations

The computation of the effective multiplication factor for an asymptotic reactor core presupposes the availability of diffusion theory nuclear data compatible with the ultimately sought asymptotic state. That is, the neutron spectrum used in generating the data (multigroup cross section and diffusion coefficients) must be the neutron spectrum that would exist when the reactor core is in the asymptotic state. *A priori*, that spectrum is not known, and therefore the corresponding nuclear data are not available. Two approaches are possible for producing the needed data.

In the first of these approaches, a library of data is generated using a model that begins with an infinite domain of fresh pebbles and gradually depletes them to the cutoff discharge burnup. A data library is thus generated for all possible depletion states of a pebble. Since the pebble-bed reactor includes pebbles at various stages of depletion in every region, the average state of depletion of any given region (and leakage in and out of adjacent regions) determines the neutron spectrum in the region under consideration. One option in this approach is to use data from the library directly, using data from pebbles at the average depletion level of the core region under consideration. A second option in this approach is to generate macroscopic data using a mix of data from the library, at the various levels of depletion, in proportion to the number of pebbles present in the core region (or modeling zone) under consideration that are at the corresponding levels of depletion. This first approach has obvious shortcomings and neither of its variants are used in this work.

The second approach to diffusion data preparation, adopted in this work, follows an iterative scheme. Microscopic nuclear data are initially assumed, corresponding to the average burnup level of the entire core (or any reasonable arbitrary burnup level, including fresh fuel). The data are prepared using the MICROX-2 code. The data are then used in the PEBBED code to determine the corresponding asymptotic loading and burnup pattern and the corresponding nuclide number densities and their respective distributions. The newly determined nuclide number densities are then input into the MICROX-2 code, the spectrum computation is repeated, and an updated set of diffusion theory microscopic data is generated. The process is then repeated until convergence.

The product of the iterative process just described is a plausible design for a PBR asymptotic core, including the distribution of nuclides, and the corresponding set of nuclear data based on a consistent spectrum. Each time the design of the fuel pebble is varied, a different outcome is obtained from the iterative process. The search for an optimally moderated core consists of systematically varying the design of the fresh fuel pebble and logging the characteristics of the resulting asymptotic core. The optimally moderating fresh fuel pebble is the one that yields the asymptotic core design with the highest value of the effective multiplication factor. That core is the optimally moderated core for that combination of fuel enrichment, moderator choice, and core dimensions.

Once an optimally moderated core design is obtained, its properties are studied via further models. For example, the response of the core to water ingress is investigated by assuming the gradual addition of water vapor into the coolant phase (or the gradual substitution of water vapor for portions of the coolant). The sequence of required computations starts with an evaluation of the nuclear data (e.g., using MICROX-2). Input to this evaluation are the nuclide number densities of the optimally moderated asymptotic core augmented with the relevant concentration of water vapor and helium coolant. The resulting nuclear data are then used in a criticality calculation (without further depletion). The process is repeated as needed for increased water inventory in the core region.

6. Some Continuously Optimally Moderated Cores and Selected Properties

The methodology of the previous section has been applied to a large number of possible reactor designs. The bulk of those results are reported elsewhere [6, 13, 18]. In this section, the features that pertain to optimal moderation and its consequences are presented for several of the designs.

The nature of the asymptotic fuel loading and burnup distributions can be affected by, among other things, the design of the fresh fuel pebbles. As explained above, in this study, any changes to the pebble design were subjected to the constraint that all hardware of previous designs remain applicable. Thus the size of the pebbles is unchanged. A further simplifying choice is the assumption that the only parameter in the pebble design that is allowed to vary is the radius of the interface between the fueled and the nonfueled zones within the pebble and consequently the number of fuel kernels present. The first result shown below is the demonstration of a continuously optimally moderated core. It is followed by results that illustrate the properties of such a core.

6.1 Feasibility of Continuously Optimally Moderated Core

In Figure 5, the change in the effective multiplication factor is shown for two possible pebble-bed reactors as the radius of the fueled zone in fresh pebbles is varied.

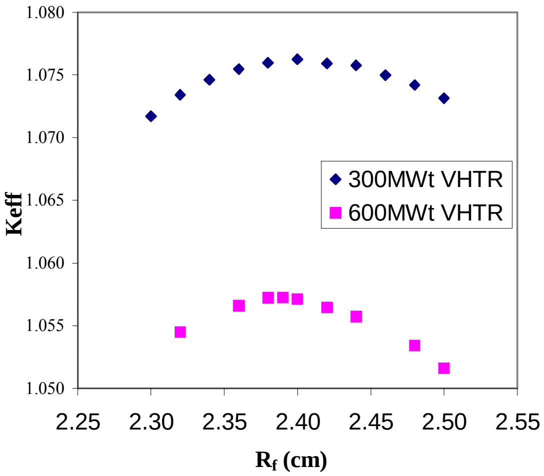

Figure 5. Effective multiplication factor versus radius of pebble fueled zone.

The two reactors addressed in Figure 5 are 300 MWth and 600 MWth versions of the Very High Temperature Reactor (VHTR). Each of the points on the figure corresponds to a converged PEBBED/MICROX-2 solution of the combined search for the asymptotic equilibrium fuel loading and burnup pattern and the corresponding consistent nuclear data. The 300 MWt core displays peak moderation for a fuel region radius of 2.4 cm while the 600 MWt core peak moderation is shifted slightly to 2.39 cm. As expected, the optimal pebble design depends on the size and power of the reactor. Though not demonstrated here, the optimal pebble design may also depend on other core design parameters. Since the same particle packing fraction is assumed within the fueled zone, the fuel region radius numbers correspond to a particle loading of about 9971 particles per pebble for the 300 MWt core and 9847 particles per pebble for the 600 MWt design. Since each point in Figure 5 corresponds to an asymptotic equilibrium pattern, the possibility of continuously optimally moderated operating reactor is demonstrated. The safety, fuel economy, and nonproliferation advantages of these designs are discussed in the next three subsections.

6.2 Consequences of Optimal Moderation on Water Ingress Reactivity Insertion

The GT-MHR employs a shutdown cooling system in which decay heat carried by the helium in the core during periods when the reactor is shut down is passed to a water loop in a heat exchanger near the core. Therefore, the potential exists for water to enter the core, should a major malfunction occur. It is possible that a similar system might be required for the pebble-bed VHTR; therefore, an analysis of water ingress into the pebble-bed core is presented here.

Initial studies of the effect of water ingress into the coolant spaces between the pebbles were performed using COMBINE-generated cross-sections. The “Dry” peak corresponding to optimally moderated fuel was found to occur at a fuel region radius of 2.33 cm, substantially different from that computed using MICROX-2 cross-sections. However, the results of the water ingress calculations qualitatively agree with subsequent MICROX-2 runs and the previous MCNP study and thus are presented here in order to illustrate the observed improvements.

Figure 6 displays the effect of water ingress on core multiplication factor as computed with a full-core MCNP model. In the figure it can be seen that a moderate rise in the multiplication factor occurs, followed by a subsequent drop.

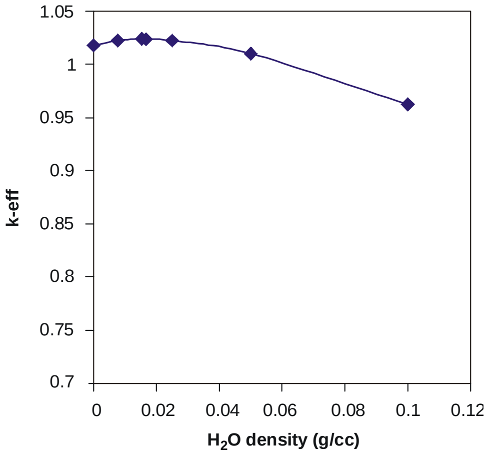

Figure 6. Assessment of reactivity changes caused by water ingress in uniform PBR core with pebbles optimized for a dry core (MCNP model).

The reactivity insertion is modest, even at its maximum. The concentration of water at this maximum reactivity insertion corresponds to a liquid water inventory of approximately 0.5 m^3 in the core region. Such an amount of water could penetrate the core region only gradually, and only under the assumption of a major malfunction. In the early stages of the insertion only smaller amounts of water, and concomitantly only smaller reactivity insertions, will be plausible. The consequence of this gradual insertion of reactivity in conjunction with feedback effects is discussed elsewhere [13]. The MCNP results of Figure 6 do not account for the motion or the depletion of the fuel. For these effects, the PEBBED/COMBINE or the PEBBED/MICROX-2 combinations of codes must be used. Figure 7 shows the effect of water ingress for various fueled zone radii obtained using the PEBBED/COMBINE system.

The curve labeled “dry” pertains to cores with no water present. The rise and subsequent fall in the curve represent the change in core reactivity as the radius of the fueled region within the pebble is changed. In the modeling, the overall core size and other characteristics (including core dimensions, fuel circulation patterns, etc.) remain unchanged. Each point on the “dry” curve is the result of a converged iteration process using the PEBBED and the COMBINE codes. That is, each of these points represents a converged determination of the asymptotic equilibrium cycle core material distribution and related fluxes for the given pebble configuration and the corresponding compatible set of cross sections. The other curves correspond to data obtained by assuming various concentrations of water vapor mixed in the helium coolant. These curves are obtained without further depletion in the core being simulated. Therefore, each point

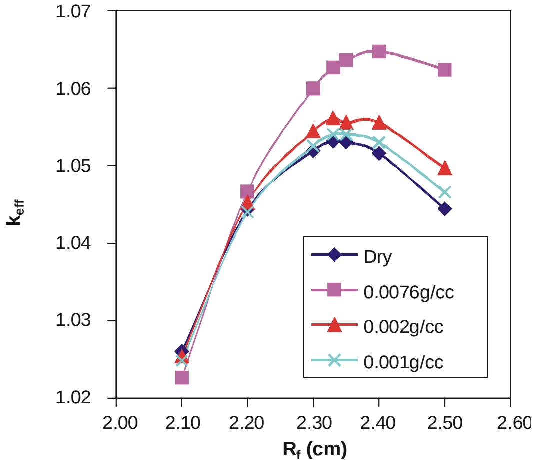

Figure 7. Multiplication factor versus fuel zone radius (PEBBED/COMBINE model)

corresponds to a computation in which the COMBINE (or MICROX-2) code is invoked only once to produce the proper cross section set that reflects the composition as altered by the presence of water and the corresponding altered neutron spectrum. Clearly, the initial reactivity effect of steam ingress is positive for cores using pebbles with interface radii greater than about 2.15 cm. The magnitude of the reactivity insertion decreases with decreasing fuel radius. Therefore, the steam ingress effect for the optimally moderated pebbles is significantly less than for the standard pebble design. Below 2.15 cm, the COMBINE/PEBBED results indicate that steam ingress has a negative reactivity effect. In Figure 8, this effect is clearly demonstrated, as the curve corresponding to 2.1 cm fuel radius remains always below the zero reactivity insertion line. That is, the reactivity insertion is negative for all water concentrations when the fueled zone radius is 2.1 cm. In Figure 8, all curves are expected to pass through the origin of coordinates, albeit after a path that is not necessarily linear.

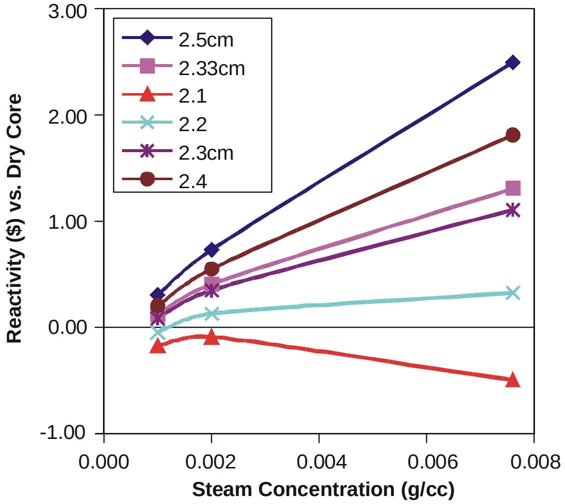

Figure 8. Reactivity insertion versus steam concentration.

It is shown elsewhere [13] that the effect on water ingress induced reactivity insertion is significant both at the average nominal operating fuel temperature and at a temperature 100 °C higher. In Figure 91 of that report, it can also be seen that, for an optimally moderated dry core, the effect of increased temperature offsets the reactivity insertion from water ingress for a steam concentration of 0.0076 g/cm^3. The figure also shows that for standard design pebbles, the water reactivity insertion is larger than the decrease caused by a similar rise in temperature.

6.3 Application of the Water Ingress Reactivity Reduction Effect to the NGNP

Water ingress calculations were used in the design and optimization of the pebble-bed version of the Next Generation Nuclear Plant (NGNP) being considered at the INEEL [13]. This application was performed using the PEBBED code in conjunction with diffusion theory data generated using the MICROX-2 code. The iteration schemes described in Section 5 were applied. Figure 9 illustrates the effect of water ingress for passively safe 300 MWt and 600 MWt NGNP pebble-bed reactor core designs using both standard (2.5 cm radius fueled zones) and optimizing (for "dry" configuration) fuel pebbles. As expected, the optimizing pebble fueled zone is slightly different in the two reactors (2.40, versus 2.39 cm, respectively for the 300 and 600 MWt cases). These designs are two possibilities for the pebble version of the NGNP. For both cases, the optimized fuel clearly demonstrates a decreased reactivity insertion compared to standard pebble-bed reactor fuel. The 600 MWt core indicates a greater susceptibility to reactivity excursions compared to the 300 MWt cases. Peak reactivity insertions are listed in Table 1.

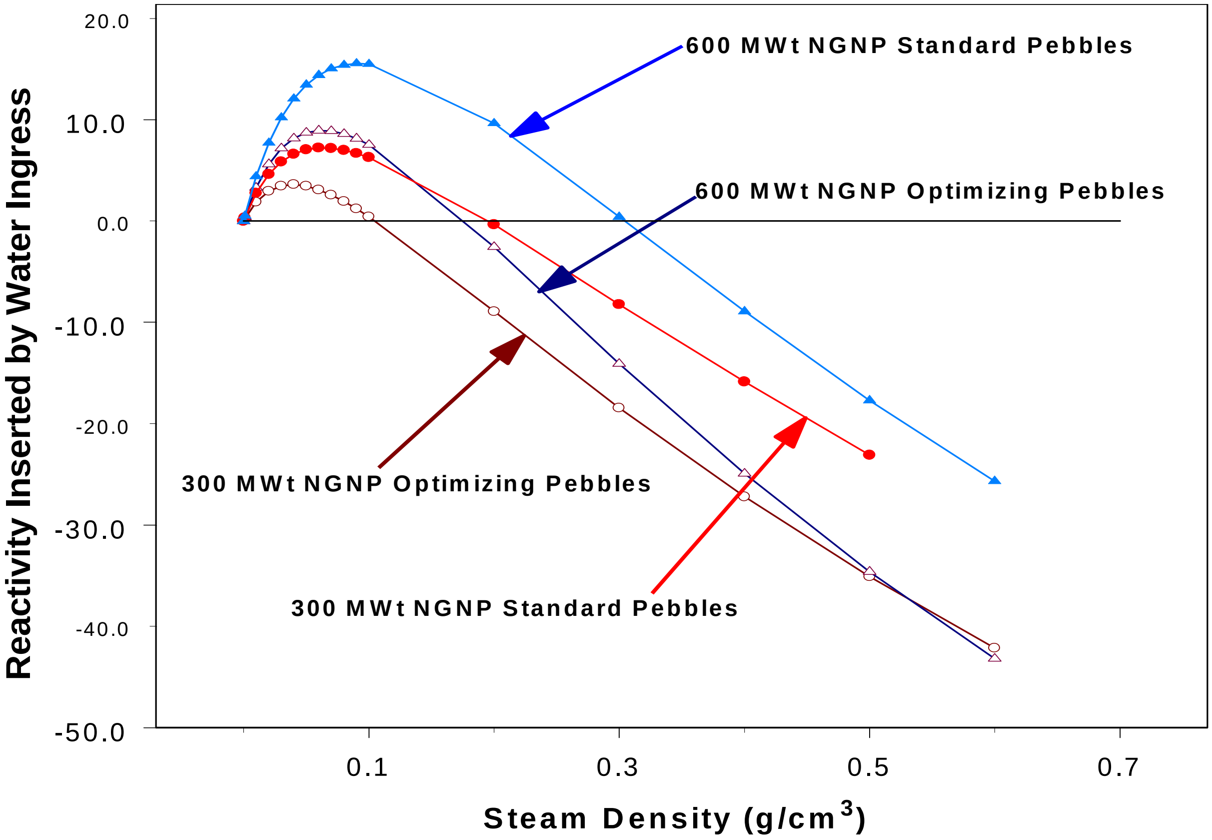

Figure 9. Core reactivity ($) versus steam ingress.

Table 1. Peak water ingress reactivity insertion for various PBR configurations.

	Peak Insertion ($)	Water Density (g/cm^3)
300MWt –Standard Fuel	7.21	0.06
300MWt – Optimized Fuel	3.61	0.04
600MWt –Standard Fuel	15.09	0.09
600MWt – Optimized Fuel	8.94	0.06

The peak reactivity insertions from steam ingress for the optimized pebbles are roughly half as great as those for the standard pebbles. For the 600 MWt pebble-bed NGNP, the peak reactivity insertion is of the same magnitude as that for the prismatic NGNP, but slightly better (from Figure 28 of Reference 13, one can calculate a peak reactivity insertion of about $11 at operating temperature, at a steam density of about 0.11 g/cm^3). It is noteworthy that the reduction of reactivity insertion that is made possible by the use of optimal moderation in the pebble-bed reactor concept is not available to the prismatic version of the gas-cooled, graphite-moderated, NGNP. Furthermore, in the pebble-bed case, as shown in Figure 8 above, the reactivity insertion from water ingress can be made as low as desired by tailoring the pebble design.

6.4 Consequences of optimal moderation on fuel utilization and economy

The optimally moderated designs are shown to result in enhanced utilization of the fuel resource. From the PEBBED output, it is determined that the PBMR-268 design (268 MWt) uses 12.6 grams of heavy metal per MWd of net energy produced. In contrast, the optimally moderated NGNP-300 (300 MWt) uses 10.9 grams per MWd produced. This is an improvement of about 14% in the fuel utilization. Similarly, the optimally moderated NGNP-600 displays an advantage over the NGNP-600 using standard pebbles. This enhanced use of the fuel resource results in a better economy and in better meeting the sustainability criterion of Generation-IV reactors.

6.5 Consequences of optimal moderation on nonproliferation characteristics

An examination of the PEBBED output for the PBMR-268 and both the optimally moderated NGNP-300 and NGNP-600 demonstrates that the discharge isotopics in the two later designs are more proliferation-resistant than those of the former. The PBMR-268, using standard pebbles, is expected to discharge on the order of 184 mg of plutonium per MWd of produced energy. The figure drops to 168 and 176, respectively, for the NGNP-300 and the NGNP-600. In addition to the lower discharge per unit energy produced, the Pu-239 isotope fraction of total plutonium is slightly lower for the latter two reactors than for the former (37% and 38% versus 41%). These characteristics confer upon the optimally moderated design a slight advantage with respect to proliferation resistance, though the characteristics of the PBMR-268 are already very good in this regard.

7. Conclusions

Optimal moderation in the context of this paper is defined as the condition in which either the addition or removal of moderating material will produce a decrease in k-effective. Such a condition, though desirable, cannot be sustained permanently in fixed-fuel reactors (such as light-water reactors). When it is possible, a permanent optimal moderation configuration confers substantial advantages for both safety and fuel utilization. An optimally moderated core can only be sustained in time if a steady state distribution of (optimal) compositions can be achieved, as in a pebble-bed reactor with moving fuel. It is not possible except for short periods of time in a batch-loaded reactor with stationary fuel. The addition of water, while indeed adding moderating material, is complicated by the absorptive properties of hydrogen. Nevertheless, the reactivity insertion caused by water ingress in an optimally moderated core is much less than that in a core with the traditional pebble design. Furthermore, it is possible to select a fuel-to-moderator ratio in which the addition of water causes no reactivity insertion at all.

The optimal moderation principle is demonstrated by MCNP models of uniform pebble-bed cores, and then it is confirmed for example asymptotic equilibrium pebble-bed cores by the PEBBED code. The advantages in water ingress accidents and fuel utilization are demonstrated. A small improvement in resistance to nuclear weapons proliferation is also shown. In addition to these advantages, optimal moderation makes possible smaller critical cores that in turn allow the design of higher power passively safe reactors. Such developments are discussed elsewhere [6].

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