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Design of a Very High Temperature Pebble-Bed Reactor Using Genetic Algorithms

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Efficient electricity and hydrogen production distinguish the Very High Temperature Reactor as the leading Generation IV advanced concept. This graphite-moderated, helium-cooled reactor achieves a requisite high outlet temperature while retaining the passive safety and proliferation resistance required of Generation IV designs. Furthermore, a recirculating pebble-bed VHTR can operate with minimal excess reactivity to yield improved fuel economy and superior resistance to ingress events. Using the PEBBED code developed at the INEEL in conjunction with a Genetic Algorithm for core optimization, conceptual designs of 300 megawatt and 600 megawatt (thermal) Very High Temperature Pebble-Bed Reactors have been developed. The fuel requirements of these compare favorably to the South African PBMR. Passive safety is confirmed with the MELCOR accident analysis code.

KEYWORDS: VHTR, Pebble-bed reactor, Design, Optimization, Genetic Algorithm

1. Introduction

We present the conceptual design of a Very High Temperature Reactor (VHTR) using a recirculating pebble-bed core. The design approach uses a reactor physics code specifically designed for pebble-bed reactors (PBRs) to generate core neutronic and thermal data rapidly for the asymptotic (equilibrium) core configuration. The passive safety characteristics are confirmed using a more sophisticated accident analysis code and model. The uniqueness of the asymptotic pattern and the small number of independent parameters that define it suggest that the PBR fuel cycle can be efficiently optimized given a specified objective. In this paper, candidate core geometries are evaluated primarily on the basis of core multiplication factor and peak accident fuel temperature. Peak pebble temperature during operation and pressure vessel fast fluence are considered as well. A design that achieves the criticality and passive safety objectives can be analyzed and further optimized with more detailed and sophisticated models. For this study, 300 MW_t and 600 MW_t designs were generated.

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2. Background and approach

2.1 VHTR - Characteristics and Design Objectives

The Very High Temperature Reactor is one of six advanced concepts chosen by the Department of Energy for further research and development under the Generation IV program. Of the six concepts, the VHTR offers the greatest potential for economical production of hydrogen as well as electricity because of the high outlet temperature of the helium coolant (1000 °C). This outlet temperature is one of only two absolute requirements for the candidate designs in this study. Also required is that the VHTR be passively safe; i.e., no active safety systems or operator action are required to prevent damage to the core and subsequent release of radionuclides during design basis events. The worst such event, the depressurized loss-of-forced-cooling scenario (D-LOFC), is bounded by a depressurized conduction cooldown (DCC) transient in which helium pressure and flow are lost. During a DCC, the negative temperature reactivity shuts down the chain reaction. However, passive safety also requires that the subsequent decay heat must be removed from the core by conduction and radiation before the fuel reaches failure temperatures. For TRISO-particle-based gas reactor fuel, a conservative limit on fuel temperatures is the widely accepted value of 1600 °C.

Other desirable objectives of a VHTR design include acceptable operating peak fuel temperature (<1250 °C) and pressure vessel fluence (<3x1018 n/cm2). Of course, criticality is assumed so a range of acceptable core multiplication factors (keff) was identified that allowed enough margin for excess control reactivity and minor fission products not modeled in the code. The fuel is composed of 8% enriched UO2 in coated particles embedded in a graphite matrix.

The hot graphite in the core reacts with air and water, so ingress of these materials may result in core damage. This is compounded by the fact that ingress may also inject positive reactivity at a rate that will result in fuel failure before the negative reactivity feedback of the subsequent temperature increase can prevent it. Proper design must include an assessment of water and air ingress reactivity.

A parameter unique to the recirculating pebble-bed reactor is the rate at which pebbles flow through the core. During normal operation, pebbles trickle through the core and drop out of a bottom discharge tube. Typically three or four pebbles are released every minute. The burnup of each pebble is measured to determine if it is to be reloaded at the top or delivered to a spent fuel container for subsequent processing to disposal. The total pebble flow rate is limited by the speed at which pebble burnup can be measured. For this study, pebble flow was limited to 4500 pebbles per day (about 1 every 20 seconds) for every 300 MWt of core power to allow for adequate burnup measurement time using at least two parallel fuel measurement channels.

The models used in this effort did not include control elements. This is not unreasonable for normal operation of a PBR. Continual refueling allows these reactors to operate with very little excess reactivity. Excess reactivity (a few percent Δk/k) for power adjustments can be included and held down by control rods, but even this is not necessary. Nominal power variations can be effected through coolant inventory- or flow-induced thermal feedback. Two independent shutdown mechanisms are required to achieve cold shutdown: control rods are inserted or absorber spheres are blown into outer reflector channels. This is adequate for modular PBRs with small diameter cores. For larger units, radial leakage may not be large enough to yield sufficient rod worth for cold shutdown. However, designs for larger cores usually feature an inner cylindrical reflector of solid graphite, the primary purpose of which is to act as a heat reservoir and reduce the thermal conduction path out of the fuel. Control rods can be inserted into this inner reflector; a region of very high neutron importance. Nonetheless, during normal operation, control rods are only partially inserted into the reflector, if at all, and thus were not modeled in this study.

The lack of excess reactivity also results in a highly proliferation-resistant power plant, as indicated in previous studies. Any diversion of neutrons from power production would either lead to prohibitively slow production of weapons materials or be easily detectable.

2.2 Analytical Tools

2.2.1 Design Using PEBBED

The INEEL code PEBBED 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 multiple pebble types and multiple trajectories (pebble loading patterns). At the INEEL, the PEBBED code has already been applied to treat a variety of practical PBR problems such as a two-zone concept considered as a candidate for construction in South Africa. That core consists of two concentric zones with different pebble types (pure graphite and a fuel-graphite mixture). 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. The partially spent pebbles are then transferred to the inner central column for their remaining passes through the core. Output from PEBBED includes the spatial distribution of the burnup and of the principal nuclides throughout the reactor core and among the discharged pebbles. The code allows estimation of refueling needs and predicts the power production.

More recently, the code was used to design the Very High Temperature Reactors as part of a conceptual design effort to develop the Next Generation Nuclear Plant for the United States Department of Energy [1] . Both 300 MWt and 600 MWt versions were designed using a direct search method in which the geometry and other core characteristics of a known pebble-bed reactor design were modified to meet the requirements of the VHTR.

The large number of core configurations required of a sensitivity study or conceptual design effort prohibits the extensive use of sophisticated thermal-hydraulic models. Fortunately, the nature of coolant flow in a pebble-bed and the large height-to-diameter ratio allow for reasonably accurate determination of mean and peak fuel temperatures using one-dimensional models. Coolant flow and heat transfer correlations appropriate for pebble beds have been implemented to provide estimates of the temperature distribution in the core during normal operation. A one-dimensional radial transient conduction-radiation calculation is used to determine the peak fuel temperature during a depressurized loss-of-flow accident.

2.2.2 Confirmation of PEBBED DCC Calculation

For confirmation of passive safety, the thermal-hydraulics code MELCOR was used to confirm the ability of PEBBED to estimate the peak fuel temperature during a severe accident. MELCOR is an integrated systems level code developed at Sandia National Laboratory to analyze severe accidents. It has been used extensively to analyze LWR severe accidents for the Nuclear Regulatory Commission. However, because of the general and flexible nature of the code, other concepts such as the pebble-bed reactor can be modeled. For the analysis presented in this report a modified version of MELCOR 1.8.2 was used. The INEEL modifications to MELCOR 1.8.2 were the implementation of multi-fluid capabilities and the ability to model carbon oxidation. The multi-fluid capabilities allow MELCOR to use other fluids such as helium as the primary coolant.

MELCOR models of three test designs (a 268 MWt PBMR, a 300 MWt VHTR, and a 600 MWt VHTR) were constructed and used to simulate a DCC accident. (The planned power output of the PBMR has since been raised to 400 MWt.) The power profile of a core identified from PEBBED calculations as a promising VHTR candidate is used by MELCOR to establish the steady-state temperature distribution that is the starting point for a full transient analysis.

The peak fuel temperatures predicted by PEBBED's simple one-dimensional radial calculation and the more sophisticated MELCOR model are compared in Table 1.

Table 1: DCC Test Case Parameters and Comparison of Peak Accident Temperatures

	PBMR-268	VHTR-300	VHTR600
Outer Radius (cm) Inner reflector/core annulus/outer reflector	~87/175/251	110/225/301	40/175/251
Core height (cm)	840	940	900
Mean Power Density (W/cm^3)	3.3	3.5	5.5
Peak Power Density (W/cm^3)	6.8	6.1	8.8
DCC Peak Temperature (^{o}C) and time to peak (hrs)			
PEBBED	1419 (42)	1490 (34)	1773 (74)
MELCOR	1406 (45)	1476 (27)	1772 (62)

The results of these test cases indicate that PEBBED is able to estimate the peak core temperature reasonably well during a severe accident. Furthermore, because the PEBBED thermal-hydraulics calculation is one-dimensional and relatively fast, it can be incorporated into a stochastic design effort in which a large number of cases are constructed and analyzed.

The PEBBED/MELCOR models all include a stainless steel core barrel, a 30 cm gas gap between the outer reflector and core barrel, a 5 cm gap between barrel and steel pressure vessel, and a 30 cm gap between the vessel and the concrete containment. A natural circulation (air) reactor cavity cooling system (RCCS) is assumed to function as designed during design basis events. This allows the use of constant outer wall temperature boundary conditions.

2.2.3 Automating PBR Design with a Genetic Algorithm

A manual search for a reactor design as presented in reference **Error! Bookmark not defined.** is inefficient and unlikely to result in the best possible design. A much more sophisticated approach is desired. Recently, an optimization feature was added to PEBBED to perform design studies. The new tool was developed with funding from a DOE Nuclear Energy Research Initiative grant. Preliminary results of its application to the PBR are provided here. PBRs with different fuel loading patterns have been optimized using this tool and the results will be presented in future publications. The results of a search for an improved 600 MWt VHTR are presented here.

The advanced optimization component now available in PEBBED is based upon a genetic algorithm. A genetic algorithm is a stochastic search method in which a randomly generated population of test designs is analyzed. The attributes (genes) of test designs with the greatest fitness values, as specified by the user, are combined to generate a new population of presumably more fit individuals. Selection of the fittest designs, mixing or crossover of genes, and even the random mutation of genes are performed in a process that is a close analog of biological evolution.

A relatively simple algorithm was developed for PEBBED without much "tuning" of parameters that may significantly improve the execution time. However, the method is shown to be more effective than the manual search employed in the previous study.

2.3 Multivariable Genetic Algorithm Optimization in PEBBED

2.3.1 Genes, Traits, and Fitness

PEBBED allows the user to specify the variables (genes) over which the search is to be performed. For this design study, variables included the inner reflector radius, the fuel annulus width, and the core height. These variables were allowed to vary over a range specified in an input file containing the optimization parameters. The user then specifies the core characteristics or traits that determine fitness. For this study, traits included equilibrium core eigenvalue, maximum DCC fuel temperature, outer reflector radius, and ratio of required pumping power to total thermal power. Peak operating fuel temperature, maximum particle power, and reactivity can also be selected as traits in PEBBED but were neglected in this study.

The way in which these traits are factored into the overall fitness is specified by the user in a 4-point interpolation scheme. As an example, the maximum accident fuel temperature fitness is illustrated in Figure 1.

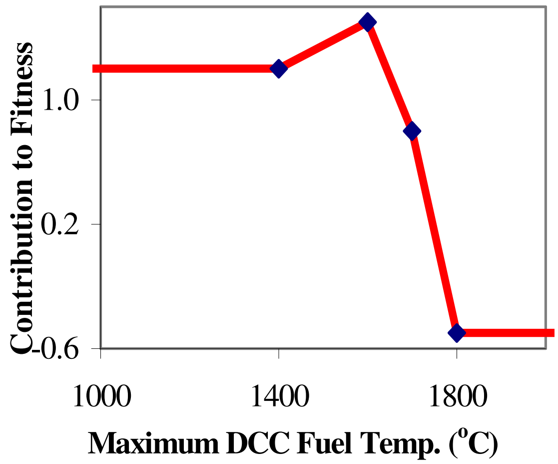

Figure 1: Example of a four-point peak fuel temperature contribution to the fitness specification.

If this trait were the only one to be specified in an optimization run, the algorithm would be driven toward a set of genes that yield a peak accident fuel temperature of 1600 °C. Above this value, the fitness value drops and even goes negative as a value of 1800 °C is approached. Negative values can be used to strongly penalize designs that exhibit completely unacceptable traits such as exceeding fuel failure temperatures during a DCC transient.

The contributions from all selected traits are summed to yield the overall fitness of the individual. For example, in the VHTR 600 MWt design, the core eigenvalue, maximum DCC fuel temperature, outer reflector radius, and height were the selected traits. The numerical specifications for these traits are shown in Table 2.

Table 2: Fitness Specification for the VHTR-600

Point	**k_{eff}**	**F_k**	**DCC Peak Temp. °C**	**F_t**	**Outer Reflector Radius (cm)**	**F_r**	**Pumping Power/Core Power**	**F_p**
1	1.04	0	1400	1.2	0	0.3	0	0.3
2	1.05	0.9	1575	1.3	100	0.3	0.05	0.15
3	1.073	1.0	1700	0.5	305.5	0	0.10	0
4	1.08	1	1800	-0.5	330	0	0.15	-0.4

The eigenvalue fitness contribution peaks at 1.073, the value obtained for a known reference design. Control elements and minor fission products are neglected in this model so that the core eigenvalue is expected to be higher than 1.0. The contribution of the peak DCC temperature was lowered to 1575 oC to provide a bit of safety margin. This is a slightly more stringent specification than the 1600 oC limit employed in the manual search.

The radius of the outer reflector is minimized for economic reasons: to keep the size of the pressure vessel down. The pressure vessels of proposed gas-cooled reactors are very large compared to their LWR counterparts and present a manufacturing challenge. Penalizing large diameters can help to avoid impractical designs even if they are passively safe. However, the overall magnitude of this fitness contribution is less than that from the core eigenvalue and maximum DCC fuel temperature because (so the authors assume in this work) it is more important to make a critical, passively safe reactor than a small one.

For small modular PBRs (< 400MWt), pumping power is not significant (1-3 MW) even though it is still larger than a comparable prismatic core. Pumping power rises with the cube of the mass flow rate so that for high-power pebble-bed reactors the required pumping power can be a significant fraction (~ 5%) of the total thermal power output. For this reason, pumping power was added as a trait and chosen for the VHTR-600 MW optimization. Figure **2** illustrates the fitness contribution from the ratio of pumping power to core power.

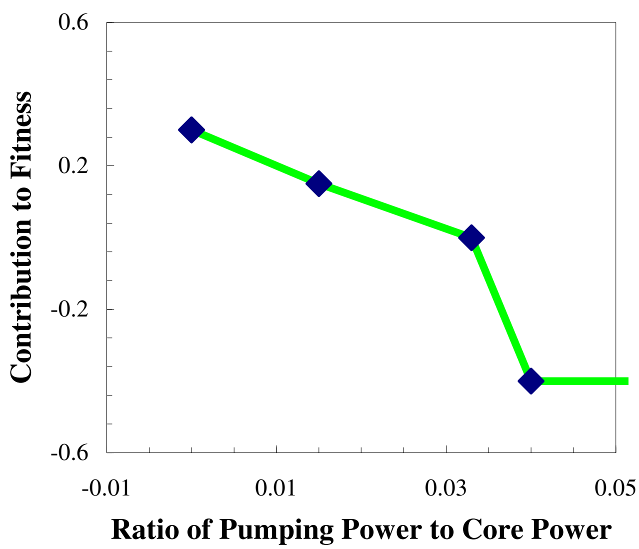

Figure 2: Pumping power contribution to fitness.

The solution will be driven toward lower ratios (i.e., shorter cores) with a heavy penalty above 0.03.

There is a complex interplay between the variables that specify core geometry and the traits that result. Core fitness specification itself is an art that can take considerable study. A full-core design involves some testing and tweaking of the fitness functions until a fully satisfactory design is obtained. However, even the relatively undeveloped algorithm employed in this study is shown to yield satisfactory results.

3.0 Results

The 600 MWt pebble-bed VHTR obtained using a manual search and reported in reference **Error! Bookmark not defined.** was used as a reference point for a genetic algorithm search. This reactor contains a solid inner reflector and a simple burnup-independent recirculation scheme. The discharge burnup was kept at a nominal 80 MWd/kgihm. A population size of 40 was chosen, from which 10 survivors were propagated to next generation.

Table **3** shows the reference gene values from the VHTR-600 designed in the previous chapter as well as the range chosen for the genetic algorithm search.

Table 3: Nominal values and gene domain for the VHTR-600 optimization.

Gene	**Reference VHTR-600 Value**	**Minimum Value**	**Maximum Value**
Inner Reflector Radius (cm)	150	1	150
Fuel Annulus Width (cm)	100	80	120
Height (cm)	950	750	1,050

Table 4 lists the results of the manual search and the one obtained using the genetic algorithm. The genetic algorithm run required 29 hours of CPU time on a Dell Precision 650 workstation.

Table 4: Selected results of VHTR-600 manual and automated design runs.

	VHTPBR-600 (Manual Search)	**VHTPBR-600 GA search**
Inner Reflector Radius (cm)	150	147.8
Fuel Annulus Radius (cm)	250	246.6
Outer Reflector Radius (cm)	326	322.6
Height (cm)	950	991.9
K_{eff}	1.073	1.073
Maximum DLOCA Fuel Temperature (°C)	1,584	1,573
Pumping Power (MW)	26	28
Maximum Operating Fuel Temperature (°C)	1,028	1,025
Peak Particle Power (W)	0.14	0.14

The genetically designed core is slightly thinner than the reference design. The accident temperature fitness specification peak of 1575 °C is slightly lower than the reference design value of 1584 °C. To achieve the more stringent criterion, the core width was narrowed to provide a shorter conduction length to the reflectors. To recapture the desired core eigenvalue, the height of the core was raised by 42 cm. The fitness benefit of achieving the target eigenvalue was somewhat offset by an increase in the required pumping power (2 MW more than the reference design).

The outer diameter of the pressure vessel is 7.45 meters, smaller than the General Atomics prismatic GT-MHR [2] by 21 cm, but the active core is two meters taller. A proper sensitivity study should be performed to find the optimal tradeoff between diameter and height. This specification could then be incorporated directly or indirectly into the fitness specification in future design efforts.

The major downside of a large pebble-bed, compared to the prismatic HTGR, is the tremendous pumping power requirement, 26-28 MW for a 600 MWt core. This requirement effectively makes the VHTR-600 a VHTR-570 and undercuts much of the advantages derived from the superior neutron economy of the pebble-bed core. One way to compensate may be to have the coolant pass radially through the bed rather than axially in a concept recently proposed by Muto and Kato [3]. This improvement alone may make the difference in economic viability. PEBBED's temperature correlations are not currently able to handle cross flow so this is an option that cannot yet be explored.

4.0 Conclusion

A simple genetic algorithm is shown to provide an effective means of designing pebble-bed reactors. A four-point fitness specification allows the user to specify with great flexibility which core characteristics determine a good design and how the fitness varies with these traits. The requisite genetic operators of selection, crossover, and mutation that have been devised for this work do yield improvements over a reference design obtained via a manual search; further study of these and other operators may result in improved computational efficiency.

The technique can be applied to reactor designs with different core configurations and fuel loading patterns but for this work was limited to the design of a 600 MWt Very High Temperature Reactor. The new design is slightly thinner and taller than one that was obtained in a manual search, largely because of a more stringent accident fuel temperature specification.

Considerable improvement in computational efficiency may result from a study of different algorithm parameters and operators. Further development and applications of this tool are under way.

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