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Abstract-*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, 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.*

I. 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. Pumping power 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.

II. BACKGROUND AND APPROACH

II. A. 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.[1] 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 lifetime pressure vessel fluence ($<3\times10^{18}$ n/cm^2). Of course, criticality is assumed so a range of acceptable core multiplication factors (k_{eff}) 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 UO_2 in coated particles embedded in a graphite matrix.

The hot graphite in the core reacts with air and water so that 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 MW_t of core power to allow for adequate burnup measurement time using at least two parallel fuel measurement channels. [2]

The models used in this effort did not include control elements. This is not unreasonable for normal operation of a PBR. Semi-continuous refueling allows these reactors to operate with very little excess reactivity. Excess reactivity (a few percent $\Delta k/k$) 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.[3] 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.[4,5] Any diversion of neutrons from power production would be either prohibitively slow or easily detectable.

II. B. Analytical Tools

The INEEL code PEBBED[6] 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 considered as a candidate for construction in South Africa. This 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 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.

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.[7,8] 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.

For confirmation of passive safety, the thermal-hydraulics code MELCOR[9] is used in this design effort. 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.[10] The multi-fluid capabilities allow MELCOR to use other fluids such as helium as the primary coolant.

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 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 a constant outer wall temperature boundary condition.

III. RESULTS

A number of candidate designs for 300 and 600 MW_t reactors were analyzed. The original concept for the 268 MW_t *Pebble Bed Modular Reactor* (PBMR),[11] with its dynamic (pebble) inner reflector, was used as the base configuration to which modifications in fuel and core geometry were applied. Selected characteristics of the best candidates are shown in Table 1 and are discussed below.

TABLE I. Features of Top Candidate Systems

Design	**VHTR-300**	**VHTR-600**
IR/FA/OR Radius (cm)	40/175/251	110/225/301
Height(cm)	940	900
Power Density (W/cc)		
Mean	3.5	5.5
Peak	7.7	9.0
Peak Fuel Temperature (^{o}C)		
Normal	1023	1038
DLOFA (*PEBBED*)	1521	1455
DLOFA (*MELCOR*)	1473	N/A
Peak Vessel Fast Fluence after 60years (n/cm2)	2.8E19	2.8E19

At the time of this writing, the MELCOR calculations for the VHTR-600 had not been completed. A comparison of the VHTR-300 DLOFA values suggests that the one-dimensional PEBBED model is more conservative than the more sophisticated MELCOR model.

The geometry of the fuel pebbles was modified to obtain improved moderation. The details and results of this effort and more recent development will be presented in a future publication. The first core modification consisted of varying the size of the inner reflector until the core multiplication factor attained a maximum (see Figure 1).

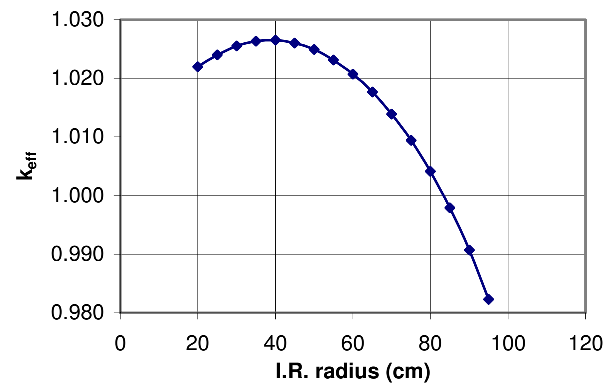

Figure 1: Asymptotic Core Eigenvalue vs. Radius of Inner Reflector – VHTR-300

Fixing the inner reflector radius at the peak value yields superior neutron economy but may not yield a core that is passively safe. The temperature calculation may indicate the need to compromise neutron economy in the interests of core safety. Fortunately for the 300 MW_t core, the D-LOFA fuel temperature remained under the 1600 °C limit and a highly efficient core design was generated. In the 600 MW_t case, the inner reflector dimensions that allowed a passively safe core did not bracket the core eigenvalue peak. Nonetheless, Table II indicates comparatively good fuel economy for both the 300 MW_t and 600 MW_t designs. The discharge burnup of fuel spheres was allowed to reach 94 megawatt-days per kilogram of heavy metal (MWd/kg_{hm}) or 10% fissions per initial heavy metal atom (FIMA), the limit to which German fuel was certified.

Small insertions of steam into the core cause a positive insertion of reactivity because of the superior moderating ability of hydrogen in the water molecules. The magnitude of the reactivity peaks at some value of the water density and eventually becomes negative as the neutron absorption dominates the improved thermalization (Figure 2).

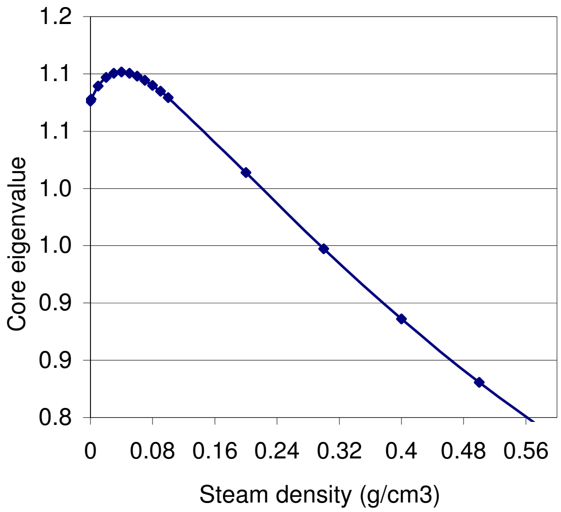

Figure 2: Core Multiplication Factor vs. Steam Density

The initial positive reactivity inserted by a small amount of steam will cause a power excursion that may or may not be counteracted in time by thermal feedback (Figure 3). The actual thermal excursion will depend upon the rate and magnitude of steam flow and the heat capacity of the core.

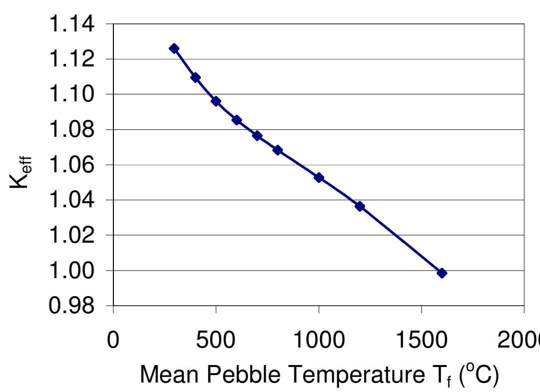

Figure 3: Core Multiplication Factor vs. Average Fuel Temperature

Further analysis with a proper transient accident analysis code is required to fully examine this effect. However, a comparison with an established design (the PBMR) indicates that the risk from steam ingress is manageable. To be neutronically valid, the discharge burnups of the VHTR designs were adjusted to yield the same core multiplication factor as the PBMR. For a 0.001 g/cm^3 steam ingress into the core, the PEBBED calculates a reactivity insertion of \$0.30. Table 2 compares the steam ingress values for the three cases. The VHTR-300 is more susceptible to a steam ingress event than the PBMR, as indicated by the higher ingress reactivity while the VHTR-600 is clearly less susceptible. The reason for this will be given in a forthcoming paper.

TABLE II. Comparison of Steam Ingress Reactivity and Fuel Utilization

Design	**PBMR**	**VHTR**	**VHTR**
Thermal Power (MW)	268	300	600
Pumping Power (MW)	2.9	6.4	26.5
0.001g/cm^3 Steam Ingress Reactivity (\$)	0.30	0.42	0.13
Discharge Burnup (MWd/Kg$_{hm}$)	80	94	87.2
Fuel Utilization (particles/ net MWd)	21000	18100	20000

Finally, PEBBED calculations of the fuel requirements for the VHTR can be compared to the basic PBMR design. The 268 MW$_t$ PBMR requires about 21000 particles (about 1.4 pebbles) for every net MWd of energy produced (thermal power minus pumping power). The modified pebble and core design of the VHTR-300 exhibits about 14% better fuel economy than the PBMR. The VHTR-600 uses about 5% less fuel than the PBMR per net MWd.

At all power levels, major preliminary design objectives are achieved. Further optimization and design changes may yield improved results for secondary objectives vessel such as pressure vessel fluence values and pumping power. To achieve a 60 year vessel life, fluence levels must be reduced by an order of magnitude. Acceptable fluence levels may be obtained by increasing the width of the outer reflector (at the cost of a larger pressure vessel) and through the use of a borated shield. More accurate treatment (a transport calculation) of the shielding is required to assess how much the design must be modified to reduce the fluence. Pumping power can be reduced by changing the core geometry. Preliminary calculations suggest that the pumping power requirement for the 600 MW$_t$ design can be reduced to under 20 MW for further savings.

IV. CONCLUSION

The conceptual design of a Very High Temperature Reactor is achieved with the PEBBED and MELCOR codes. A direct search on the core geometry is performed to yield a core with the desired core multiplication factor and peak fuel temperatures (normal and accident). The method and tools yield possible candidates for small or medium-sized VHTRs. Further design optimization should focus on reducing the flux impinging on the reactor pressure vessel so that a 60-year lifetime can be achieved, and reducing pumping power in the larger reactor. Also, the impact of control rods must also be included in subsequent optimization to ensure sufficient controllability and shutdown margin. Efforts are underway to implement a modern optimization algorithm to automate the variable selection and evaluation process.

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REFERENCES

[1] "*A Technology Roadmap for Generation IV Nuclear Energy Systems*", Issued by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, December 2002.

[2] HAWARI, A. I., BINGJING SU, JIANWEI CHEN, ZHONGXIANG ZHAO "*Investigation of On-Line Burnup Monitoring of Pebble Bed Reactor Fuel Using Passive Gamma-Ray and Neutron Detection Methods*," , Transactions of the Winter 2001 Annual Meeting of ANS, Reno, NV, Trans. ANS **85**, pp. 98-99, Nov. 2001.

[3] YAN, X. L. and L. LIDSKY, "*Design Study for an MHTGR Gas Turbine Power Plant Power Plant*," *Proceedings of the 53rd American Power Conference*, Chicago, IL, April, 1991.

[4] OUGOUAG, A. M., H. D. GOUGAR, and W. K. TERRY, "*Examination of the Potential for Diversion or Clandestine Dual Use of a Pebble-Bed Reactor to Produce Plutonium*," *Proceedings of HTR 2002, 1st International Topical Meeting on High- temperature Reactor Technology (HTR)*, Petten, Netherlands, April 22-24, 2002.

[5] OUGOUAG, A. M., M. MODRO, W. K. TERRY and H. D. GOUGAR, "*Rational Basis for a Systematic Identification of Critical Components and Safeguards Measures for a Pebble-Bed Reactor*", *Trans. Am. Nucl. Soc*., 87, 2002.

[6] TERRY, W. K., H. D. GOUGAR, AND A. M. OUGOUAG, "*Direct Deterministic Method for Neutronics Analysis and Computation of Asymptotic Burnup Distribution in a Recirculating Pebble-Bed Reactor*," Annals of Nuclear Energy **29** (2002) 1345 –1364.

[7] GRUEN, G. E., "*Passive Cooling Model for Pebble Bed Reactor*," Internal Technical Report SE-A-85-004, Reactor Analysis Branch, Idaho National Engineering Laboratory, February 1985.

[8] SAVAGE, M. G., "*A One-Dimensional Modeling of Radiant Heat Removal During Pressurized Heatup Transients in Modular Pebble-Bed and Prismatic High Temperature Gas-Cooled Reactors*," ORNL-TM-9215, Engineering and Mathematics Division, Oak Ridge National Laboratory, 1984.

[9] GAUNTT, R. O. , R. K COLE, S. H. HODGE, S. B. RODRIGUEZ, R. L. SANDERS, R. C. SMITH, D. S. STUART, R. M. SUMMERS, AND M. F. YOUNG, "*MELCOR Computer Code Manuals*," NUREG/CR-6119, Vol 1, Rev. 1, SAND97-2397-2398, 1997.

[10] MERRILL,B. J., R. L. MOORE, S. T. POLKINGHORNE, AND D. A. PETTI, *Fusion Engineering and Design,* **51-52,** 555-563 (2000).

[11] NICHOLLS, D., "*The Pebble-bed Modular Reactor*," *Nuclear News*, Vol. 44, **10,** American Nuclear Society, Lagrange Park, IL, September 2001.