180
11-6-79

DR. 251

ORNL-5582

ornl

OAK
RIDGE
NATIONAL
LABORATORY

UNION
CARBIDE

US/FRG Joint Report on the Pebble Bed High Temperature Reactor Resource Conservation Potential and Associated Fuel Cycle Costs

E. Teuchert
H. J. Rutten
B. A. Worley
D. R. Vondy

MASTER

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ORNL-5582
Distribution Category UC-77
Gas-Cooled Reactor Technology

Contract No. W-7405-eng-26

Engineering Physics Division

US/FRG JOINT REPORT ON THE PEBBLE BED HIGH TEMPERATURE REACTOR RESOURCE CONSERVATION POTENTIAL AND ASSOCIATED FUEL CYCLE COSTS

E. Teuchert*
H. J. Rütten*
B. A. Worley
D. R. Vondy

*Kernforschungsanlage Jülich Gmbh, FRG

Date Published - November 1979

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

TABLE OF CONTENTS

ABSTRACT

Independent analyses at ORNL and KFA have led to the general conclusion that the flexibility in design and operation of a high-temperature gas-cooled pebble-bed reactor (PBR) can result in favorable ore utilization and fuel costs in comparison with other reactor types, in particular, with light-water reactors (LWRs). Fuel reprocessing and recycle show considerable promise for reducing ore consumption, and even the PBR throwaway cycle is competitive with fuel recycle in an LWR. The best performance results from the use of highly enriched fuel. Proliferation-resistant measures can be taken using medium-enriched fuel at a modest ore penalty, while use of low-enriched fuel would incur further ore penalty. Breeding is possible but net generation of fuel at a significant rate would be expensive, becoming more feasible as ore costs increase substantially. The ^{233}U inventory for a breeder could be produced by prebreeders using ^{235}U fuel.

I. SYNOPSIS

I.1 BACKGROUND

In February, 1977 the governments of the United States (US) and the Federal Republic of Germany (FRG) signed an umbrella agreement providing for cooperation in the field of gas-cooled power reactor research and development. The work areas cover wide ranges of applied and base technologies: fuel development, fuel recycle, graphite behavior, process heat applications, etc. Specific tasks are formalized in writing in a number of project work statements consisting of technical milestones, scheduling, division of work between US and FRG contractors (principal investigating organizations), manpower effort, and estimated costs.

One important area of study was initiated in October, 1977 when a project work statement[1] was written devoted to the evaluation of the Pebble Bed Reactor (PBR). The task title is: "Thermal Gas Reactor Resource Conservation Potential and Associated Economic Performance," and the contractors are Oak Ridge National Laboratory (ORNL) and Kernforschungsanlage (KFA). The objective of this task "... is to assess on a consistent basis the potential of HTR's as economic systems for improved fuel utilization, and their interaction with other reactors." This joint report summarizes the results of the technical assessment.

I.2 INTRODUCTION

The pebble-bed reactor is a graphite-moderated, helium-cooled, high temperature reactor unique among gas-cooled reactors because of its spherical fuel elements and operation with continuous fueling. The concept is well supported in the Federal Republic of Germany: the Arbeitsgemeinschaft Versuchsreaktor (AVR) is a small 15 MWe pebble-bed reactor built at Jülich, West Germany in 1967; construction of a 300 MWe reactor, the Thorium High Temperature Reactor (THTR) is underway; and proposed designs have been developed for large reactor concepts for the purpose of generating electricity, the Hochtemperatur Reactor-Kernkraftwerke (HTR-K), and as a source of process heat, the Prototypanlage Nukleare Prozesswärme (PNP).

BLANK PAGE

Complementary to such dedicated tasks is the need to evaluate the role of the pebble-bed reactor in a large nuclear industry. The scope of this study has been directed toward an assessment of the potential of a 3000 MW_{th} PBR for use as a fuel burner (throwaway/stowaway), converter (fuel recycle with reprocessing), a prebreeder (a ^{233}U producer), and a breeder.

The analysis of the pebble-bed reactor was done initially at KFA with follow-on at ORNL, but the efforts have been carried out quite independently — conclusions concerning reactor performance and preferred fuel cycles were made from independent studies, and exact design details differ; furthermore, the analytical methods used were different, requiring substantial methods development by ORNL. The referenced work of the two organizations is documented[2-5] and the information is summarized in this report.

A short summary of key results and conclusions drawn from the joint study is given below. Section II contains a more detailed discussion of PBR performance for particular applications, and qualifications on the analysis are presented in section III.

I.3 SUMMARY AND CONCLUSIONS

The flexibility of design and operation using a pebble-bed reactor is projected to have a cost and ore impact favorable in comparison with other reactor types and light-water reactors (LWR's) in particular. Considering ore utilization, reprocessing with recycle of fuel is preferred over once-through stowaway cycles, and use of high-enriched fuel is preferred over medium- and low-enriched fuel for all applications. Net breeding with ^{233}U fuel produced from a prebreeder is possible.

I.3.1 KFA Results

The case for the pebble-bed high temperature reactor (HTR) is summarized in Figs. 1 and 2. Most notable is that:

-Ore requirements for recycle of bred fuel using high-enriched feed (Th/U-REFERENCE) could be made lower by a factor of three in comparison with LWR recycle.

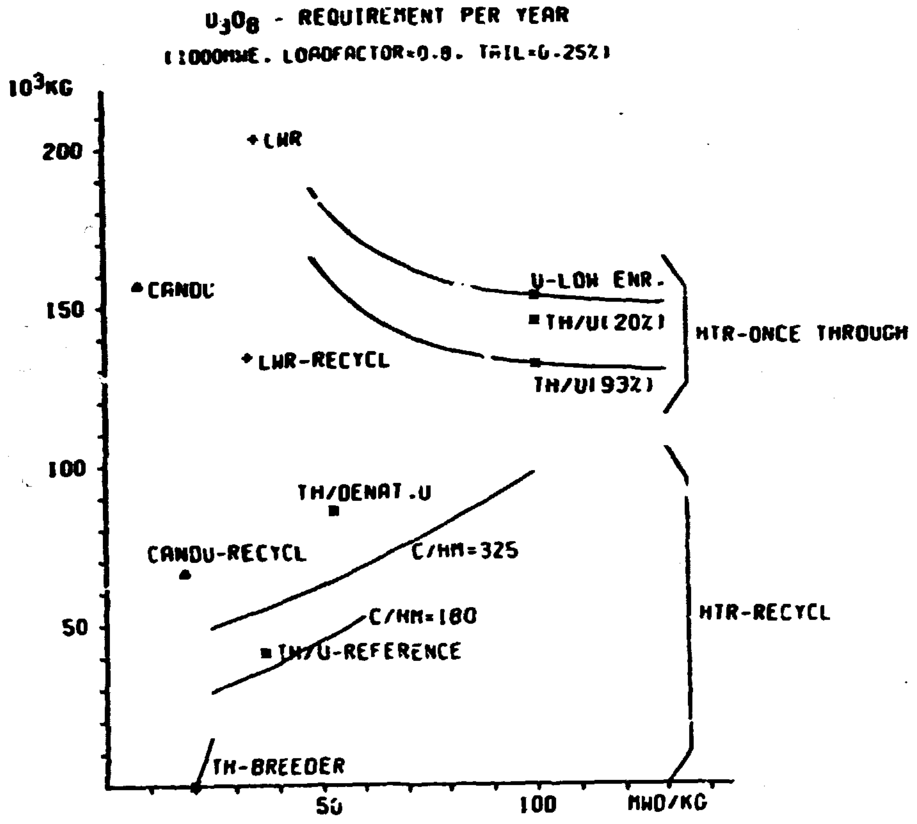
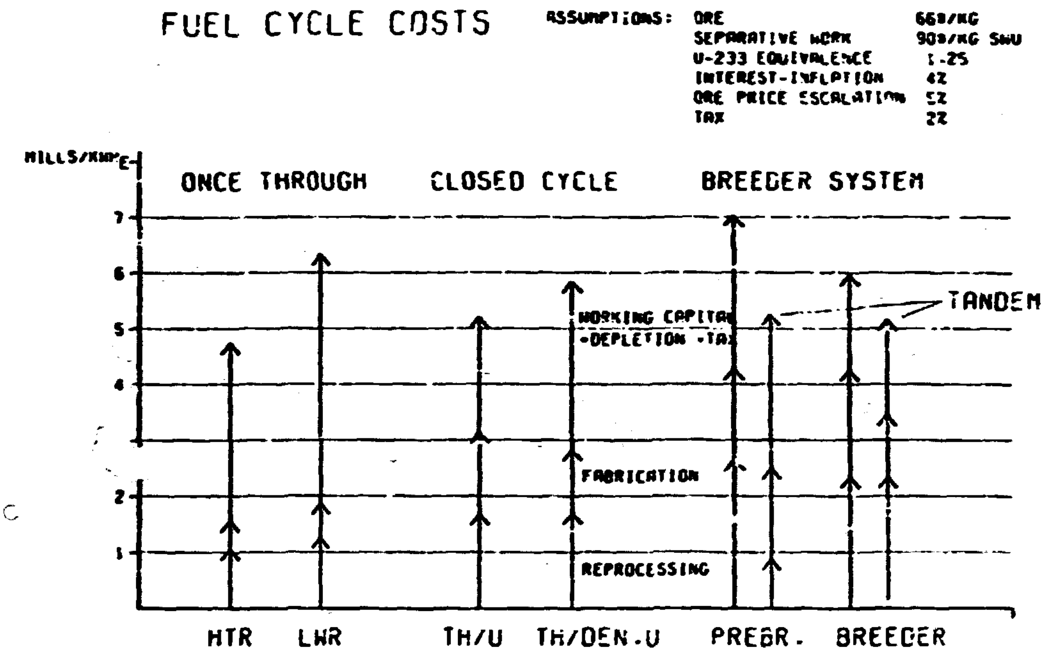


Fig. 1. Uranium Ore Demand of Various Fuel Cycles

- Ore utilization in comparison with LWRs is such that even the HTR throwaway cycle compares favorably with LWR recycle.
- The Th/Denatured Uranium fuel with recycle is projected to require forty percent less ore than LWR recycle. This denatured cycle is considered attractive from non-proliferation aspects since no weapons-grade enriched uranium appears anywhere in the cycle, and the plutonium content of the reprocessed elements is extremely low and unfavorable for production of a nuclear explosive.
- Net breeding of fissile fuel is possible with a thorium cycle at very low burnups.
- For Th/U recycle, the ore requirement decreases as the fuel exposure decreases so that high utilization may be realized at a small cost penalty.



*Costs include a credit for disloaded fuel.

Fig. 2. Break Down of Life Time Averaged Fuel Cycle Costs

-The possibility of conserving ore by moving toward low burnup with recycle may be a distinct advantage of continuous fueling due to refueling downtime in a fixed-fueled reactor.

-Fuel cycle costs compare favorably with an LWR. Among the closed HTR cycles the fuel costs are similar; the dominant argument for the assessment of the HTR is not the fuel cycle costs but the potential for uranium saving and, if necessary, the feasibility of a proliferation-resistant closed thorium cycle.

A quantitative index is needed when considering long-term uranium ore requirements on a national basis. As an example, the relative ore requirement for implementing various reactor types to meet an assumed nuclear energy growth for FRG is shown in Fig. 3. The minimum ore requirement is achieved by the Th/U HTR cycle for some 70 years, which is primarily the buildup phase of nuclear power. In the long term the Prebreeder/Breeder system is superior, requiring only a first and final investment of 2045 tonnes of U_3O_8 for one 1000 MWe Breeder cycle. The proliferation resistant Th/Denatured Uranium cycle clearly brings some penalty in the U_3O_8 requirement.

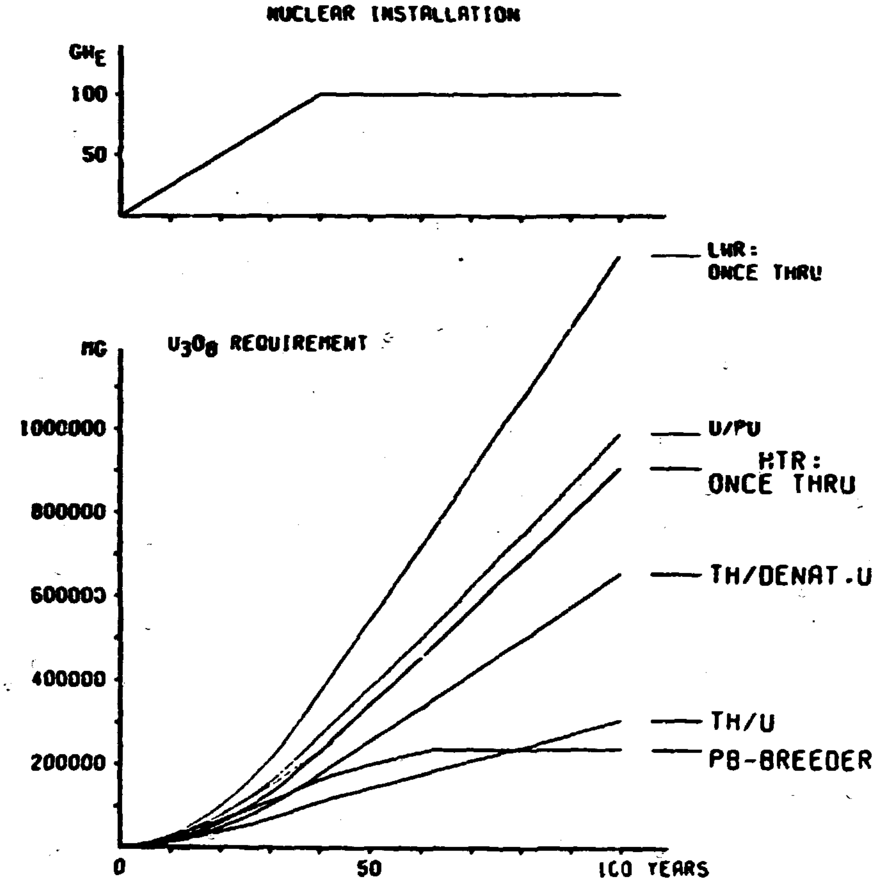


Fig. 3. Uranium Ore Requirement for Given Sequence of Reactor Installments

1.3.2 ORNL Results

The various applications of the pebble-bed reactor are compared in terms of ore requirement and fuel cycle cost in Table 1. The "level of technology" indicates a relative measure of expected pioneering from current conceptual designs (i.e., possible burnup limits, use of radial and axial blankets, recycle of fuel elements without reprocessing, etc.). The projected performance confirms support of recycle and use of high-enriched fuel. In terms of ore utilization, the competitive position of the PBR versus other reactor types is summarized in Table 2.

Table 1. Performance Summary for the Pebble Bed Reactor Concept at a Net Plant Efficiency of 0.4[a]

Service and Technology Level	Nominal Carbon to Heavy Metal (Atomic)	Nominal Fueled Pebble Residence (Full power yrs)	Average Conversion Ratio	Peak Pebble Power (kW)	Fueled Pebble Exposure (MW_{th} D/kgm HM)	Fissile Inventory (kgm/Installed MW_e) Plant	Fissile Inventory (kgm/Installed MW_e) System	External Fissile Feed (kgm/MW_e-Yr)	Fissile Commitment (kgm/Installed MW_e)	Ore Requirement (kgm U_3O_8/Installed MW_e) Consumption	Ore Requirement (kgm U_3O_8/Installed MW_e) Commitment	Fuel Cost (mill/kW_e-Hr) Low Indirect	Fuel Cost (mill/kW_e-Hr) Reference
Burner, Low Enriched Uranium													
Reference Technology	575	2.0	.54	2.[illegible]	130.	0.9	1.3	.05	20.5	4,360	4,650	5.6	6.2
Burner, Medium Enriched (denatured) Uranium Fuel													
Low Technology	450	2.5	.54	2.2	130.	1.0	1.3	.80	19.4	4,120	4,420	5.4	6.1
Reference	450	2.6	.55	5.1	205.	0.9	1.2	.76	18.2	3,890	4,170	5.0	5.7
High Technology	450	2.9	.55	5.9	220.	0.8	1.1	.69	16.6	3,550	3,780	4.6	5.3
Burner, Fully Enriched Uranium													
Low Technology	250	3.9	.55	2.1	90.	1.3	1.5	.71	17.9	3,700	4,000	5.2	5.9
Reference	250	4.0	.58	5.0	225.	1.3	1.5	.66	16.8	3,400	3,800	4.7	5.6
High Technology	250	4.2	.57	5.8	250.	1.4	1.6	.60	15.1	3,100	3,500	4.4	5.2
Converter, Fully Enriched Uranium, Recycle													
Low Cost													
Low Technology	250	3.8	.63	2.1	95.	1.3	2.0	.45	11.4	2,220	2,620	4.5	5.6
Reference	250	4.0	.65	5.0	225.	1.3	2.0	.42	10.8	2,150	2,550	4.2	5.3
High Technology	250	4.2	.67	5.8	250.	1.4	2.1	.40	10.4	1,980	2,430	4.0	5.1
Low Ore													
Low Technology	175	2.0	.75	2.2	36.	1.6	2.7	.41	10.8	1,750	2,450	5.7	6.9
Reference	175	2.0	.78	3.3	90.	1.6	2.7	.36	9.7	1,500	2,200	5.3	6.5
High Technology	175	2.0	.80	3.6	100.	1.7	2.8	.32	8.7	1,330	2,080	5.1	6.4
Prebreeder, Fully Enriched Uranium[b]													
Low Cost	175	2.5	.70	2.9	110.	2.0	2.8	.60	16.3	3,110	3,780	4.6	5.8
Reference	175	1.5	.73	2.9	74.	1.9	3.0	.70	18.8	3,630	4,330	5.1	6.3
High Performance	175	3.0	.71	4.1	135.	2.2	2.8	.70	18.6	3,630	4,280	4.8	5.9
Near Breeder, Breeder, U^{233} Fuel													
Low Cost	2[illegible]	4.2	.710	5.0	220.	1.1	1.6	.26	7.6			4.0	5.1
Intermediate	175	1.5	.890	3.0	50.	1.1	2.3	.11	4.7			5.5	6.8
High Conversion	110	2.0	.990	3.3	40.	3.0	5.6	.030	8.3			5.6	8.0
Break even	90	1.5	1.023	2.8	26.	3.8	8.1	—	8.1			7.9	11.3
Breeder	80	1.5	1.036	2.7	24.	4.6	9.8	—	9.8			9.0	13.0

---

[a] Burner and converter load factor 0.75; prebreeder, near breeder, breeder are high technology, load factor 0.85; ore enrichment tails .002, 30 year plant life.

[b] Breeder fuel generation for these cases in kgm/MW_e-Yr (net); 0.28, 0.36, 0.38.

Table 2. Estimates of Ore Consumption for Several Reactor Concepts

Reactor Type	Data Source	Initial Inventory (kg/MW$_e$)	Fissile Makeup (kg ^{235}U/MW$_e$ yr)	Ore Consumption[a] (kg U_3O_8/MW$_e$ for 30 yr at 0.70)
				Low Cost (Low Ore)
Throwaway Cycle				
PWR (U)	ORNL-3686[b]	2.06	1.16	5,480 (4,990)
	CE			5,090 (4,330)[c]
HWR (U)	ORNL-3686	0.59	1.29	5,400
HTGR (U)	GA			3,900
HTGR (Th)	GA			3,730
	ORNL			3,790 (3,470)
PBR (Th)	KFA		0.66	3,200
	ORNL	1.00	0.68	3,400 (3,100)
Fuel Reprocessing and Recycle				
PRW (U)	ORNL-3686	2.06	0.78	3,490[d]
	CE			3,220
SCCR (Th)	ORNL-3686	3.34	0.66	2,810
HWR (Th)	ORNL-3686	1.44	0.39	1,170
HTGR (Th)	ORNL-3686	2.60	0.45	1,930
	GA			2,360 (1,940)
	ORNL	1.44	0.48	2,300 (1,900)
PBR (Th)	KFA			2,040 (1,000)
	ORNL	1.00	0.45	2,150 (1,500)

[a] Ore enrichment tails 0.002.

[b] Calculations done in 1964.

[c] A 15 percent reduction from the apparent economic optimum is allowed here.

[d] Not calculated; 85 percent discharge fissile credit; requires highly enriched makeup.

I.3.1.3 Summary

KFA and ORNL generally agree upon the superior ore utilization capability of the PBR concept in comparison with the LWR. Once reprocessing capability is established, fuel breeding with ^{233}U would be possible. The short-term fuel-cycle cost of the breeder is high, but as ore costs rise, breeding becomes increasingly attractive with depletion of the ore resource.

II. REACTOR APPLICATIONS — ORE REQUIREMENTS AND ECONOMIC FEASIBILITY

II.1 INTRODUCTION

Calculations were performed for a 3000 MW_{th}, 1200 MW_e reactor with an average core power density of $5W_{th}$/cc and a reactor lifetime of 30 years. The choice of 5 W_{th}/cc is based upon a reduced ore requirement in comparison with higher power densities. Capital cost and fuel temperature limits also influence the choice of power density. The reactor height is chosen as 5.5 and 5.0 meters (KFA and ORNL respectively). A tradeoff between lower fissile requirements at an increased height and a lower peak power density at a decreased height contributes to the chosen height.

The primary methods of analysis used at KFA and ORNL differ in approach. The KFA calculations follow the reactor history from its start while ORNL calculations treat a point in time to determine steady-state conditions directly.

The reported analyses (references 2-5) cover a wide range of designs. Radial blankets were considered as well as a wide range of other parameters. The results reflect independent choices of data and design details, and the conclusions put forth in this section will draw from a wide range of calculations too numerous to be accorded a large degree of detail. In order to make some direct comparisons, an effort has been made to choose similar cases which reflect technically feasible designs and nearly optimal fuel cycles.

II.2 THROWAWAY CYCLES

The pebble-bed reactor must operate with fresh fuel until reprocessing becomes commercially available, and the discharged fuel must be stored, either temporarily or permanently. The performance of the throwaway cycle is characterized by the obvious desire to reach high fuel burnups since all discharged fuel is considered lost to the system.

Table 3. High-Enriched Uranium Feed; Equilibrium Results

CASE	KFA M093	KFA 22005	ORNL MR326	ORNL MR238A
Average Carbon/Heavy Metal	325	220	325	250
Average Burnup (MW_{th}-d/kg HM)	100	101	98	92
Conversion Ratio	0.594	0.647	0.584	0.630
Fissile Inventory (kg/GW_e)	917	1527	1068	1254
^{235}U Feed Rate (kg/GW_e-d)	1.810	1.746	1.905	1.794
Fissile Discharge Rate (kg/GW_e-d)	0.552	0.638	0.562	0.592
Thirty Year Ore Requirements (kg/MW_e)[a]	4045	3901	4257	4009

[a] Make-Up Ore Requirements; does not include initial inventory and out-of-core fuel; calculation is for a load factor of 0.80 and diffusion plant tails enrichment of .25%.

II.2.1 High-Enriched Feed

Results for several cycles using high-enriched uranium and thorium are identified in Table 3. Note the reduction in the daily ^{235}U feed requirement for the lower carbon to heavy metal (C/HM) ratio, offset somewhat by the higher fissile inventory. If credit were allowed for the discharged fissile fuel, the lower C/HM is favored even more because the higher conversion ratio indicates better net fuel usage.

A large fraction of the thorium-oxide could be placed into a separate fertile pebble with a lower heavy metal loading in the fueled pebble (enriched uranium with some thorium). This separation would allow variation in the loadings and the ratio of fueled to fertile pebbles, providing flexibility in satisfying performance criteria. First, the fertile pebbles can be passed along the outer section of the core and used as a blanket in order to reduce damage to the graphite reflector and decrease neutron leakage. Secondly, the isolation of the primary fissile feed into one pebble type permits selective recovery of the bred ^{235}U from the fertile pebble only, limiting reprocessing costs to only a fraction of the total pebbles discharged. At the head-in, the fact that the fertile pebbles will have a high heavy metal loading and no fissile fuel should reduce overall fabrication costs.

There is an additional incentive for using separate pebbles: After an initial pass through the reactor the burnup in the fertile pebble is low, warranting immediate recycle to the reactor in order to fission the bred ^{235}U. Calculations by ORNL indicate immediate recycle of fertile pebbles could decrease daily ^{235}U requirements by as much as 9% at equilibrium, thus reducing fuel cost and ore consumption. The savings are somewhat less, about 5%, when averaged over the reactor lifetime.

Design considerations must be carefully weighed, however, before a firm decision can be made regarding the desirability of two pebble types versus one. For a given reactor power rating, the use of two pebble types reduces the number of fueled pebbles in the reactor. Since the majority of the power is produced in the fueled pebbles, the average and peak power per pebble will increase substantially; and as a consequence, the temperatures and burnup of the fueled pebble would be higher at fixed power density and fixed coolant conditions.

II.2.2 Medium- and Low-Enriched Fuel

The performance of fuel cycles using medium-enriched uranium (MEU) and low-enriched uranium (LEU) feed are compared in Table 4. The MEU can be mixed with thorium, and the enhanced neutron economy afforded by the bred ^{233}U is reflected in the lower daily fissile requirements of the medium-enriched cycle compared to the low-enriched cases with no thorium. The reduction in ore consumption of MEU vs LEU is not quite proportional to the reduction in daily fissile feed for a fixed tails enrichment, the savings being 6% (KFA) and 11% (ORNL). In addition, the use of MEU fuel is projected to be more proliferation resistant than the use of LEU.

Cost and ore considerations indicate that these cycles have an optimum C/HM ratio substantially higher than the high-enriched throwaway cycles. The analysis performed by KFA and ORNL show best performance for MEU at a C/HM near 450, but the optimum may be even higher for LEU.

Table 4. Medium- and Low-Enriched Uranium Feed; Equilibrium Results

CASE	KFA		ORNL	
	M02C	LEU	TDRRB	TD602
Average Carbon/Heavy Metal	458	366	450	575
Average Burnup (MW_{th}-d/kg HM)	100	100	137	131
Uranium Enrichment, $^{235}U/U$	.198	.085	.190	.123
Conversion Ratio	.575	.556	.551	.543
Fissile Inventory (kg/GW_e)	706	1022	913	940
^{235}U Feed Rate (kg/GW_e-d)	1.951	2.102	2.076	2.339
Fissile Discharge Rate (kg/GW_e-d)	.526	.570	.527	.731
Thirty Year Ore Requirements (kg/MW_e)[a]	4317	4572	4591	5135

[a] Makeup Ore Requirements; does not include initial inventory and out-of-core fuel, calculation is for a load factor of 0.80 and diffusion plant tails enrichment of 0.25%.

II.3 FUEL RECYCLE

The closed U/Th fuel cycle has a greatly reduced ore requirement in comparison with the throwaway cycles for the HTR. The bred ^{233}U, being a much better fuel in thermal reactors than ^{235}U, can best be utilized in low-burnup, high-conversion, closed cycles. Once reprocessing facilities become available and the once-through cycle with fuel stowaway has been demonstrated, recycling in a self-supporting closed cycle provides optimal near-term utilization of the pebble bed reactor. The reference closed cycles are summaried in Table 5 in which the reported results reflect reactor operation near equilibrium.

Differences in the ore requirements between cases 180/32 (KFA) and JC15 (ORNL) are a direct result of the respective predictions of neutron economy (KFA projects a 0.85 conversion ratio, ORNL only 0.79).

The difference in conversion ratio is, of course, a direct result of differences in neutron accounting. Relative nuclide reaction rates play a major role and there is a contribution from the difference in recycle material. Small contributions come from the estimates of the effectiveness of reflectors and parasitic absorptions. The ORNL estimates

Table 5. Closed Fuel Cycles: Close to Equilibrium Results[a]

CASE	KFA			ORNL	
	Th/U	180/32	Th/Denat. U[b]	JE13	JC15
Average Carbon/Heavy Metal	220	180	442	250	175
Average Burnup (MW_{th}-d/kg HM)	36	32	53	93	55
Conversion Ratio	0.639	0.650	0.656	0.661	0.766
Fissile Inventory (kg/GW_e)	1272	1665	602	1452	1722
^{235}U Makeup Feed (kg/GW_e-d)	0.533	0.478	1.374	1.126	0.760
^{233}U Recycled Feed (kg/GW_e-d)	1.546	1.655	0.654	0.466	1.501
^{235}U Recycled Feed (kg/GW_e-d)	0.344	0.452	0.179	0.127	0.536
Fissile Discharge Rate (kg/GW_e-d)	1.932	2.308	1.050	0.656	2.124
Thirty Year U.O. Consumption (kg/MW_e)[c]	1187	1068	2.936	2516	1698
Thirty Year U.O. Commitment (kg/MW_e)[d]	1742	1769	3256	2979	2403

[a] Load factor=0.8; tails enrichment=.25

[b] Medium-enriched feed

[c] Ore requirements of daily feed after initial inventory

[d] Estimated fissile committment=consumption + out-of-core inventory of fabricated feed (0.5 years) and fissile discharge (1.5 years) + initial inventory

of the fission product absorption fractions are 5 to 10 percent higher than the KFA estimates. In a more fundamental sense, however, the large degree of independence of analysis between KFA and ORNL leads to a difference in the estimates of performance that arises from the use of different base data and from independent modeling of somewhat different reactor core and pebble designs. In general, for all reactor applications, ORNL projects lower performance than KFA. The difference represents an uncertainty in the performance to be expected.

The effect of moderating ratio (C/HM) upon total ore utilization is small. As the carbon-to-heavy metal ratio increases, the daily fissile feed rate increases, but both the in-core and out-of-core fissile inventory decrease, resulting in only a slight variation in gross ore commitment. This tendency is exemplified by comparing the ore consumption and commitment of cases Th/U and 180/32. From parametric studies the optimum C/HM appears to be near 200.

Of much greater importance is the influence of the exposure of the discharged fuel upon ore utilization and fuel cost By reducing the exposure the buildup of fission products is suppressed and the conversion ratio is increased (because of the greater overall usage of ^{233}U as opposed to ^{235}U); however, fuel cost and out-of-core inventory are adversely affected. The relative dependence of the fissile feed requirement, total fissile commitment, and fuel cost upon exposure, as estimated by ORNL, is shown below.

Exposure (MW_{th}-d/kg HM)	Daily Fissile Consumption	Total Fissile Commitment	Fuel Cycle Cost Interest Rate 0.05	Fuel Cycle Cost Interest Rate 0.10
97	1.00	1.00	1.00	1.00
51	0.76	0.89	1.12	1.11
36	0.68	0.86	1.26	1.23
20	0.60	0.83	1.67	1.57

Note that decreasing the exposure incurs a modest cost penalty and the reduction in the ore commitment is less than that of the ore consumption.

The fuel cycle denoted by case "Th/denat.U" proposed by KFA has excellent proliferation-resistant aspects using medium-enriched uranium and thorium feed within a closed system. Mixed-oxide elements are passed through the reactor and reprocessed. The content of the elements remains denatured upon discharge so the recycled fuel is denatured even after reprocessing. Elements of a third type containing denatured uranium (no thorium) are supplied to the core to maintain criticality and are then stored since reprocessing them would be uneconomical. Thus no weapons-grade enriched uranium appears anywhere in the cycle. In addition the fissile Pu content is low and mixed with a considerable amount of nonfissile Pu. The ore requirements, however, are high in comparison with the high-enriched uranium closed cycles.

II.4 BREEDER AND PREBREEDER

Operation with continuous fueling, the flexibility provided by use of different feed element types, and closing of the thorium cycle are characteristic features of the pebble-bed HTR which provide the capability to produce more fuel than is consumed. Unfortunately, the net production of fuel at a significant rate is likely uneconomical until ore cost increases substantially.

In order to achieve breeding, operation and design aspects must be considered, each of which competes against low cost and/or total ore utilization.

-A short residence time (low burnup) is required in order to limit the buildup of fission products; as the residence time decreases, the fabrication and reprocessing costs increase as does the system inventory and associated indirect charges.

-Operation at a lower carbon-to-heavy metal ratio (80-110) is required (the low flux level reduces leakage and losses by Xe capture); a lower C/HM increases fissile inventory and associated indirect charges.

-Large blankets decrease leakage and enhance breeding prospects, but blankets may be costly and may degrade the heat removal efficiency; axial blanketing at the inlet may prove impractical.

-Of the fissile fuels, ^{233}U has the highest value of η in a thermal reactor; thus, the feed to the breeder should be ^{233}U in as pure a form (low ^{235}U and ^{236}U content) as possible — an expensive fuel.

-Low fissile loss in reprocessing is of special importance; limiting the loss incurs additional cost.

The purpose of a prebreeder is to use ^{235}U feed in the thorium fuel cycle in order to produce a ^{233}U product with a content of the higher uranium isotopes sufficiently low such that the discharged material could serve adequately as fuel for a thermal breeder or near breeder. Primary considerations are:

- Decreasing the fuel residence time in the prebreeder appears desirable in order to decrease in-core consumption of bred ^{233}U, but there is a cost penalty in going to a lower residence time.
- A breeder or near-breeder that has a very low fuel makeup requirement basically needs only be supplied inventory from prebreeders using ^{235}U from ore. There exists an optimum set of operating and design conditions for a two-reactor system that may be sensitive to the data assumptions. An important parameter is the ratio of breeder fuel produced per unit ore consumed.

Key results obtained for reference cycles are given below.

	KFA		ORNL	
	Prebreeder	Breeder	Prebreeder	Breeder
C/HM	179	110	175	110
Burnup (MW_{th}-d/kg HM)	17	20	27	21
Conversion Ratio	0.74	1.00	0.73	0.99
Thirty Year U_3O_8 Commitment (kg/MWe Installed)	6621	--	4619	--
Net Fissile Feed to Breeder (kg/MWe Installed)	15.88	--	9.07	--

Note the decrease in fissile commitment to the prebreeder as the burnup increases but a decrease in the quantity of breeder fissile feed produced at higher burnup. The economic optimum operation would occur for a prebreeder residence time at which the cost of the total power output of the system is minimized. This cost can be considerably decreased if the external ^{235}U feed to the prebreeder can be reduced by recycling the fissile fuel pebbles through the reactor a second time without reprocessing. Thus, a low burnup could be achieved in the discharged fertile pebbles while increasing the burnup of the discharged fissile feed and thereby decreasing the external ^{235}U feed rate. A penalty is incurred in that the power density of the fissile pebbles would increase, which might limit the recycle fraction.

II.5 SUMMARY

Both KFA and ORNL feel the PBR can operate with a much lower ore requirement and fuel cycle cost than LWR's. However, ORNL projects lower performance of the PBR than does KFA for each reactor application.

The ore commitment and fuel cycle cost of the reactor applications relative to HEU throwaway can be estimated from the results, as indicated in Table 6. Note the potential for improved ore utilization using high-enriched feed and recycle of fuel. The high indirect charges projected by ORNL account for the relatively high breeder cost in comparison with KFA.

Table 6. Relative Ore Commitment and Fuel Cycle Costs

	THROWAWAY[*]			RECYCLE			
	HEU	MEU	LEU	HEU	MEU	Prebreeder	Breeder
Cost							
KFA	1.00	1.04	1.02	0.91	1.02	1.23	1.05
ORNL	1.00	1.02	1.10	0.95 (1.16)[†]	--	1.12	1.42
Ore Commitment							
KFA	1.00	1.07	1.13	0.46	0.79	1.64	--
ORNL	1.00	1.10	1.22	0.67 (0.58)	--	1.14	--

[*] Full stowaway, no credit for discharged fuel.

[†] Low ore requirement results are shown in parentheses at a cost penalty.

III. QUALIFICATIONS REGARDING THE ANALYSIS

There are many uncertainties in projecting the performance of a nuclear reactor concept under development. The preferred fuel cycle depends on uranium ore availability, costs, design details and operating requirements. A specific plant design and mode of operation must be shown to satisfy performance criteria, particularly in the assessment of heat removal, control, and performance of the fuel elements and other materials. Blanketing of the core may or may not prove to be practical, and the core design is affected by the requirements for reactor control and handling of the fueled pebbles. Cost data should improve with time and other economic aspects are subject to review. Licensing requirements must be established and satisfied. Still we believe that a reasonable projection has been made of the ore conservation potential to be expected with the pebble bed reactor concept.

Benchmark calculations remain to be done for well-defined reactor applications in order to permit assessment of the details of the differences in projected performance obtained by ORNL and KFA. Continuing analysis effort is planned.

ACKNOWLEDGMENTS

The effort in the FRG was directed by R. Schulten in cooperation with L. Wolf. H. J. Rütten, H. Werner, K. A. Haas, and K. Petersen contributed to the technical analysis and calculations. The work was carried out at Kernforschungsanlage Jülich GmbH for the Federal Ministry of Research and Technology.

In the US the work was performed under D. E. Bartine of the Engineering Physics Division and P. R. Kasten, director of the Gas-Cooled Reactor Programs. The effort was carried out at the Oak Ridge National Laboratory, operated by the Union Carbide Corporation for the US Department of Energy.

REFERENCES

1. "Thermal Gas Reactor Resource Conservation Potential and Associated Economic Performance," Project Work Statement, US/FRG Thermal Gas Reactors Program (October 1977).

2. E. Teuchert, "Once Through Cycles in the Pebble-Bed HTR," Jül-1470, Kernforschungsanlage Jülich GmbH (December 1977).

3. H. J. Rutten, C. E. Lee, E. Teuchert, "The Pebble-Bed HTR as a Net-breeding Reactor System," Jül-1521, Kernforschungsanlage Jülich GmbH (July 1978).

4. E. Teuchert, H. J. Rutten, H. Werner, K. A. Haas, R. Schulten, "Closed Thorium Cycles in the Pebble-Bed HTR," Jül-1569, Kernforschungsanlage Jülich GmbH (January 1979).

5. D. R. Vondy and B. A. Worley, "Pebble Bed Reactor Core Physics and Fuel Cycle Analysis," USDOE report ORNL-5484 (in publication 1979).