

MIT PEBBLE BED REACTOR PROJECT

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The conceptual design of the MIT modular pebble bed reactor is described. This reactor plant is a 250 Mwth, 120 Mwe indirect cycle plant that is designed to be deployed in the near term using demonstrated helium system components. The primary system is a conventional pebble bed reactor with a dynamic central column with an outlet temperature of 900 C providing helium to an intermediate helium to helium heat exchanger (IHX). The outlet of the IHX is input to a three shaft horizontal Brayton Cycle power conversion system. The design constraint used in sizing the plant is based on a factory modularity principle which allows the plant to be assembled "Lego" style instead of constructed piece by piece. This principle employs space frames which contain the power conversion system that permits the Lego-like modules to be shipped by truck or train to sites. This paper also describes the research that has been conducted at MIT since 1998 on fuel modeling, silver leakage from coated fuel particles, dynamic simulation, MCNP reactor physics modeling and air ingress analysis.

KEYWORDS : Pebble Bed Reactor, Intermediate Heat Exchanger, Modularity, High Temperature Gas Reactor, Safety, Research

1. INTRODUCTION

MIT has been developing a conceptual design for pebble bed reactors since approximately 1998, when a student design project concluded that in order to resurrect the nuclear power industry a new, innovative approach was needed, not only in reactor design but also in construction and operation. In their quest to identify the appropriate technology several key conclusions were reached. First was that the reactors did not have to be big to compete, particularly in developing nations, where 1600 MWe reactors are not suitable for most developing nations' electric grids. Second, new reactors should also be capable of meeting large power demands in a modular, build-out array. Third, they concluded that to meet the competition, new reactors had to have long operational cycles such as combined cycle natural gas plants which rarely shut down for maintenance, certainly not for routine refueling negatively affecting capacity factors.

This led to a deep evaluation of current technologies in terms of existing light water reactors and plans for evolutionary plants that were being considered at the time, including the AP-600, the advanced boiling water reactor (ABWR) and the standard PWR designs offered by Combustion Engineering which were currently being developed by Korea. The group also looked at high temperature gas reactors for completeness. The two variants of high temperature gas technology were the prismatic reactor, developed largely by General Atomics, and the pebble

bed reactor, which was originally developed in Germany by the Julich Research Institute [1] and promoted by Professor Larry Lidsky at MIT in the late 1980's. What became quite clear was that if the student design objectives were to be met mainly high efficiency, continuous operating units with greatly improved safety features the down selection rested largely with high temperature gas reactors. These reactors had the benefit of higher thermal efficiency, upwards of 45-50% and, with the pebble bed, online refueling, matching the general performance characteristics of combined cycle natural gas plants.

After a careful review of the existing challenges for nuclear power and the expectations of the public relative to new plants, the students chose the pebble bed reactor as their technology of choice for the following reasons:

- 1) It was naturally safe, namely, it is not physically possible to cause a meltdown and no credible accidents would result in significant fuel damage.
- 2) It was small. The students judged that 100 to 200 megawatts electric would be the size necessary for international deployment of this technology. While the students recognized the potential advantage of economies of scale, they concluded that economies of production, namely, smaller units with less investment and shorter construction time, would be preferable. These units would be built out in modules to meet demand which should be more economically attractive to many nations and utility companies.
- 3) On-line refueling was judged to be a major advantage,

avoiding refueling shutdowns. Pebble bed reactors are continually refueled by removing depleted pebbles and adding fresh fuel pebbles during operation.

- 4) The students decided that an intermediate cycle in which the nuclear reactor helium coolant is separated from the power conversion system was the best approach. This decision, made very early, is presently one of the major attractive features of the design since it gives flexibility in the design of the power conversion system and is “hydrogen ready”. The intermediate heat exchanger transfers the heat of the helium coolant in the reactor to another helium system to produce either electric power or very high grade heat to hydrogen production plants. The intermediate cycle is the cycle chosen for the Next Generation Nuclear Plant (NGNP) being planned for construction and demonstration for the Idaho National Laboratory as part of the advanced nuclear-hydrogen initiative.
- 5) The students also recognized the importance of public acceptance and chose the pebble bed reactor largely because it was a new technology from the standpoint of public awareness. Its inherent safety features could be easily explained without reliance on complicated human action or emergency core cooling systems.

2. MIT PEBBLE BED REACTOR (MPBR) PLANT DESIGN

The key reactor specifications for the modular pebble bed reactor as being developed by MIT are shown on Table 1.

The reference nuclear reactor design for the MPBR is based largely on the Pebble Bed Modular Reactor (PBMR) project in South Africa [2]. There are unique differences however since the MIT design utilizes an intermediate helium to helium heat exchanger and still maintains a dynamic column of graphite central reflector pebbles. Studies are currently underway to determine whether the additional complexity and cost associated with a central reflector, whether a solid central graphite column or a dynamic pebble column, is justified. The purpose of this central reflector column is to allow for higher power levels while still maintaining the effectiveness of external control rods in the outer reflector.

The decision on the use of an intermediate heat exchanger, given the extra cost, complexity and efficiency penalty, was based on several factors. The students decided that, for the initial core design and reactor operation, the intermediate cycle was preferable because it allowed for design flexibility in the secondary side; namely, it provided less complicated systems and allowed for more conventional systems for the power conversion cycle. In addition, the isolation from the primary system was a safety measure that would avoid contamination on the secondary side, reducing maintenance costs and also providing a barrier

Table 1. Nuclear Specifications for the MIT Pebble Bed Reactor

Thermal Power	250 MWth - 120 MWe
Target Thermal Efficiency	45 %
Core Height	10.0 m
Core Diameter	3.5 m
Pressure Vessel Height	16 m
Pressure Vessel Radius	5.6 m
Number of Fuel Pebbles	360,000
Microspheres/Fuel Pebble	11,000
Fuel	UO ₂
Fuel Pebble Diameter	60 mm
Fuel Pebble enrichment	8%
Uranium Mass/Fuel Pebble	7 g
Coolant	Helium
Helium mass flow rate	120 kg/s (100% power)
Helium entry/exit temperatures	520/900 C
Helium pressure	80 bar
Mean Power Density	3.54 MW/m ³
Number of Control Rods	6

against early initial fuel failures that could contaminate the entire system. For the future, the students also envisioned this reactor as being a heat source for many other applications such as hydrogen production and oil sands bitumen extraction for which an intermediate heat exchanger would be required.

An additional constraint was added in the design to take advantage of modularity in manufacturing one of the key differentiating features in the MIT design. This constraint required that all the components be able to be transported by truck or train, and with rare exception by barge, since it was desired to deploy this technology where access to navigable waterways would not always be possible. The modularity constraint was further developed in subsequent work which will be described below.

Having decided key performance criteria, a plant schematic was developed that would build on existing work performed in Germany and South Africa. The design selected was such that the size of the power conversion equipment did not require significant new research which would facilitate early deployment. A plant schematic showing key process variables is shown on Figure 1.

3. BALANCE OF PLANT

Due to the intermediate heat exchanger, flexibility in the design of the power conversion system was possible.

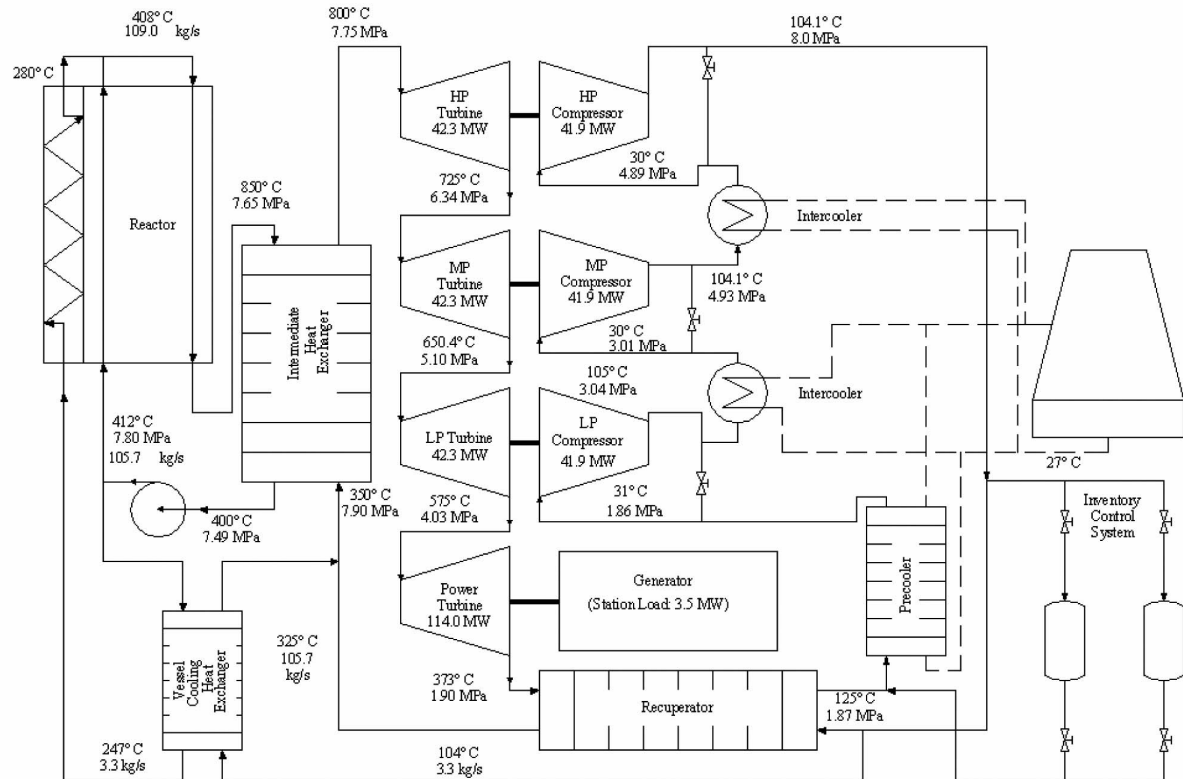


Fig. 1. Schematic of MIT Pebble Bed Thermal Hydraulic System

The MIT design moved away from large vertical power conversion vessels found in past designs of General Atomics to a horizontal arrangement found in more conventional plants, thus eliminating the need for magnetic bearings which complicated the designs with new unproven systems and allowed for conventional lubrication systems. This flexibility in design is shown on Figure 1 and is graphically illustrated in Figure 2 in terms of a plant layout. As mentioned, above one of the key design constraints was what could be shipped by truck or by train allowing for full economies of production. What can be seen is that instead of having only one heat exchanger or recuperator, six are specified due to the shipping constraint. The resulting design is a recuperated and intercooled power conversion cycle capable of thermal efficiencies in the range of 45%. The performance characteristics are shown on Table 2.

The resulting three shaft system is limited to a nominal demonstrated shaft horsepower. The overall power conversion system is a three shaft system - one low speed power shaft driving a generator and two separate turbo-compressor sets. The basis of this selection was to limit the shaft power of any one turbine to less than ~36 MW (to stay within existing turbomachinery designs). Additionally, by reducing the length of each individual turbocompressor set, it becomes easier to layout the

reactor plant as each shorter shaft can be positioned in adjacent modules horizontally or vertically.

Second, the intermediate heat exchanger (IHX) consists of six smaller modules each with its own containment vessel. This was done to limit the weight of each module to within the 200k lb truck limit. Additionally, by splitting up

Table 2. Key Plant Parameters MPBR

Thermal Power	250MW
Gross Electrical Power	132.5MW
Net Electrical Power	120.3MW
Plant Net Efficiency	48.1% (Not take into account cooling IHX and HPT. If considering, it is believed > 45%)
Helium Massflowrate	126.7kg/s
Core Outlet/Inlet T	900°C/520°C
Cycle Pressure ratio	2.96
Power conversion unit	Three-shaft Arrangement

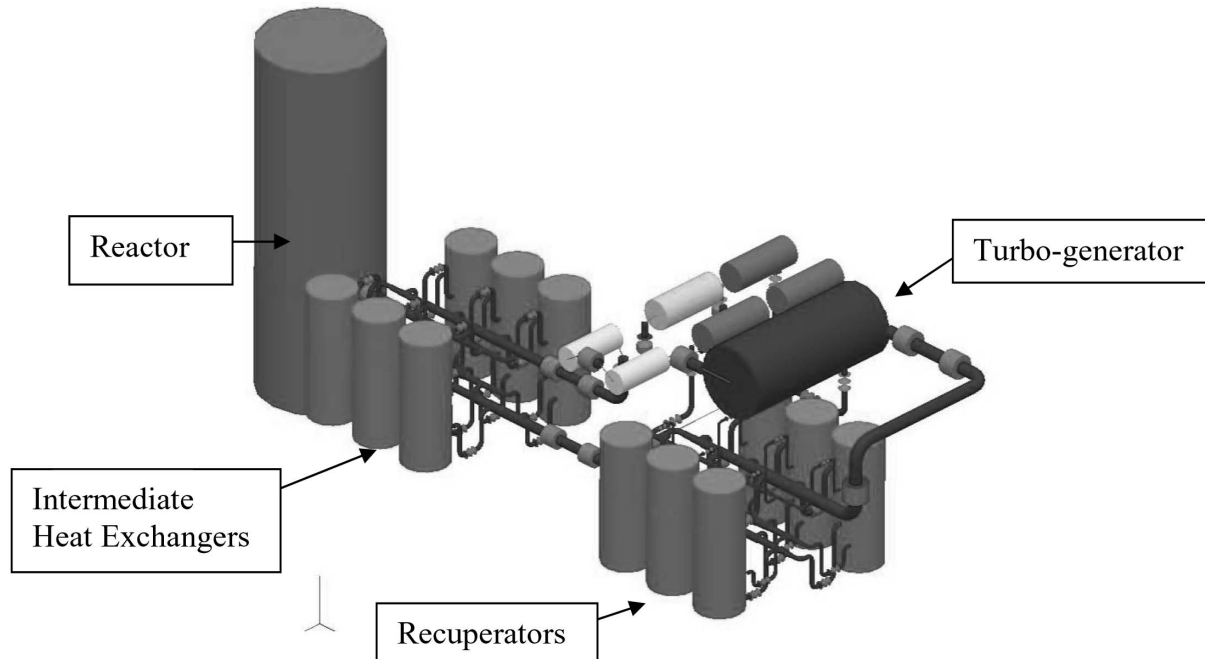


Fig. 2. New Proposed Layout of MIT Pebble Bed Reactor

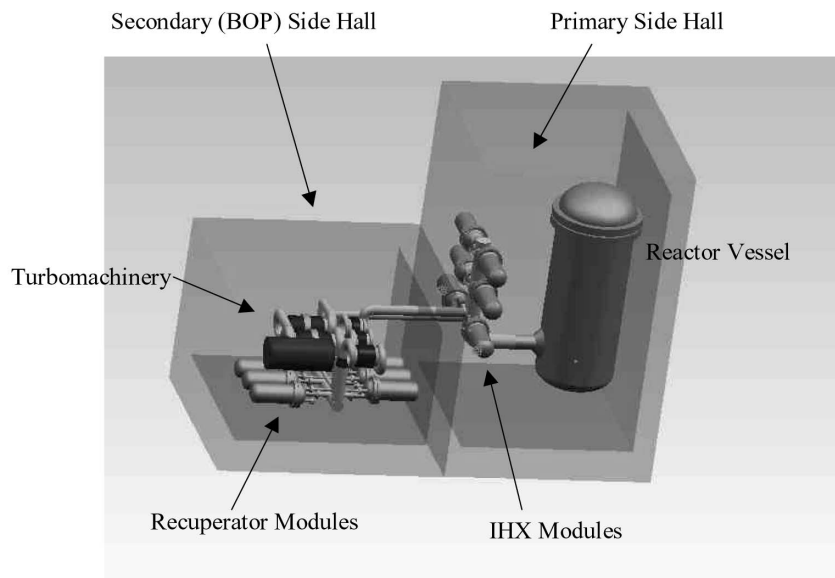


Fig. 3. Plant Layout in Reactor and Turbine Building

the IHX into smaller modules, they can be removed and replaced if there is damage or failure to a part of the IHX. As the IHX will in all probability be contaminated by

fission products or fuel pebble debris, the six module arrangement minimizes the cost of an IHX repair since the most likely damage would be confined to a

single module.

The recuperator is split up into six modules similar to the IHX. This enables each recuperator module to be closely located to a corresponding IHX module, limiting the amount of piping required between the two. The separate recuperator modules also permit easy maintenance and ease of replacement, like the IHX modules.

Figure 3 shows how this plant may be configured in the reactor and turbine building.

4. MODULARITY

The future of new nuclear power plant construction will depend in large part on the ability of designers to reduce capital and maintenance costs. The initial concept for the MPBR was to build all the parts in distributed factories and ship them to the construction site, where they would be assembled in a simple, bolt together, plug and play fashion, loaded with fuel and powered up.

The primary concept that defines the innovation of this proposed MPBR modularity approach is the minimization, and where possible, elimination, of the new capital facilities, on-site construction, and labor required to construct a nuclear power plant. This approach is defined by a new way to examine how components are built and assembled [3]. In the past nuclear power plant construction has been performed almost completely on site, as most of the components are far too large to transport assembled. Each plant was effectively a “new” plant, in that it shared little, even in “factory” plants with its brethren. These plants were putting all the utilities’ “eggs in one basket”, as any major component failure would eliminate all 1000 Mwe of generating capacity until the part could be replaced. Given the complexity and assembly techniques used, such a repair could take a substantial amount of time, and require parts that weren’t off-the-shelf available.

The MPBR will be built in a “virtual” factory in which individual component manufacturers would be asked to provide all components, piping connections, electric power connections and electronics for the volume occupied by the component in a space designated by a “space frame” (Figure 4). These space frames would then be assembled at the plant site using a simple, bolt together, plug and play style assembly process. This should dramatically reduce construction time and costly field work.

The value of this approach is that it improves overall quality, reduces site field work and rework, and speeds the construction of the plant further reducing the time to operation. The advantage true modularity provides is that it emphasizes the economies of production, not necessarily relying on the economies of scale to reduce costs. The other advantage of modularity is that it can reduce maintenance costs and down time since the modules, if properly designed, allow for a replacement rather than a repair strategy.

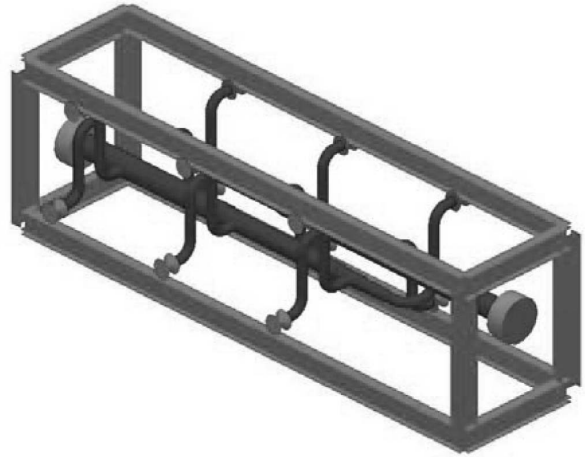


Fig. 4. Sample Space Frame Module

An early consideration in the design of the MIT pebble bed reactor was whether there would be interest in nations that already had a significant nuclear infrastructure. Would these smaller plants be of any interest to these utilities in the United States, for example. The conclusion reached was that the key determinant was economics and need for power at 1200 Mwe all at once. This conclusion was supported by the initial active interest of Exelon, one of the largest US nuclear utilities in the development of the PBMR in South Africa for US application¹.

Should there be a need for a 1,200 MWe plant, 10 modules could be built at the same site. This modularity concept is being followed in China by the Chinergy company that plans to build up to 19 pebble bed modules in a build out strategy that when complete, will have a site capable of 3,700 Mwe. Figure 5 illustrates the Chinese view of their pebble bed power station that will use the HTR-PM technology based on a steam cycle.

The MIT concept calls for a single control room operating all 10 units through an advanced control system employing many of the multi-plant lessons of modern gas fired power plants in terms on modularity and automatic operation. Construction plans and schedules were developed to refine the cost estimates and schedule expectations. The preliminary schedule called for getting the first unit on line in slightly over two years with additional modules coming on line every three months should they be needed as power

¹ Exelon eventually dropped out of the development of the PBMR since their position had changed regarding whether their company should be in the reactor development business or simply in the business of buying electric power stations and selling electricity.



Fig. 5. Rongcheng Pebble Bed Power Station Graphic (Illustration courtesy of Chinergy)

demands warrant. A unique feature of this modularity approach is that it allows one to generate income during construction of a 1,200 Mwe plant as opposed to paying interest during construction due to the considerably longer time period needed to build the larger plant.

5. MODULARITY PRINCIPLES IN DESIGN

The MPBR project is highly dependent on the ability to package the reactor, its intermediate heat exchanger (IHX), and the remaining balance of the plant in such a way to allow the MPBR plant to be transported via low cost means (truck or train as opposed to barge), easily assembled with minimal tooling and re-working, and operated in a small footprint commensurate with conventional power plants. All components other than the reactor vessel and its associated mechanical support systems are designed to be transportable by heavy lift tractor/trailer truck. Given that heavy lift trucks are used to transport the balance of plant components to the plant location, the following limitations must be met. First, the maximum dimensions of any one module are 8' wide, 12' tall, and up to 60' long. Second, the maximum weight of a single module must be less than ~200,000lb. Finally, the modules must be contained in a steel space frame to support the components within and to align those components with the components in other modules. The assembly on site of the modules must be limited to stacking the space-frames to align the various flanges and bolting the piping together. The new proposed layout is shown on Figure 6.

This layout seeks to maximize the modularity of the design by concentrating manifolds and plumbing in

individual modules while restricting each module to a single type of major component keeping turbomachinery in separate modules from heat exchangers whenever possible to minimize parasitic effects during maintenance. While this type-specific module isolation increases the total number of modules in the system, it limits the amount of functioning components that have to be removed during replacement of a single component. Overall, this layout requires the use of 27 modules (not including command and control or power processing), each of which is truck transportable.

The balance of plant fits in a footprint roughly 80 ft x 70 ft, a comparable size to 100 MWe gas turbine facilities,

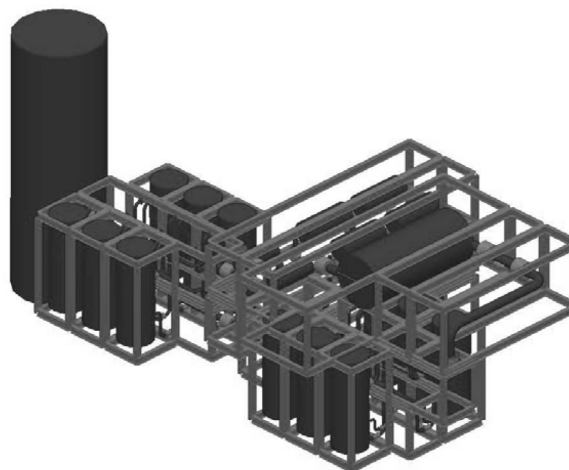


Fig. 6. MIT Modular Space Frame Power Plant Layout

and far smaller than conventional nuclear plants. With reactor vessels, such a plant could easily be made to fit within a 125 ft x 80 ft footprint, for a power density of roughly 10 kW/ft². For a conventional 1 GWe plant, this power density would require a facility footprint of ~100,000 ft². Given that conventional reactor containment buildings (not including the turbine shed and control facilities) consume nearly 40,000 sq ft on their own, this power density is equal to, if not greater than, conventional facilities, including advanced gas turbine systems.

The concept is that instead of constructing a nuclear power station one would need to assemble it using prefabricated, in a factory, C-type vans that would be literally stacked and bolted together, constructing the power conversion system. This “Lego” system (Figure 7) of construction would surely shorten construction time. Extensions of this modularity concept to the reactor vessel and the fuel handling system are planned in the future.



Fig. 7. “Lego” Type Construction Principles

6. MIT RESEARCH ACTIVITIES ON PEBBLE BED REACTORS

In addition to the conceptual design work described above, significant other work has been performed at MIT. This work involved the development of a fuel performance code that was benchmarked against National Production Reactor tests as well as German fuel tests [4]. This model incorporates transient behavior of the pebbles going through the reactor core in its prediction of fuel failure [5]. In addition, MCNP was for the first time applied to a reactor physics prediction of pebble bed reactor performance, with excellent predictions of initial criticality for the HTR-10 reactor in China as well as being benchmarked against the PBMR VSOP core code analysis [6].

MIT developed a code which replicated the dynamic

simulation of the reactor and power conversion system [7]. The power conversion system was unique at the time since it was the first that suggested a three shaft system with two independent compressor systems as well as a power turbine generator set each optimized for its function. The linkage between these three shaft systems was a challenge that many felt was too difficult to overcome.

The development work at MIT continued with the testing of the silicon carbide to identify the source of Silver Ag 110m leakage in the coated fuel particles [8]. Significant research was performed that led to the conclusion that it was not diffusion through the silicon carbide but rather leakage through nanocracks developed as a result of thermal stresses. As is known, Ag (110) is the primary source of contamination, even for good fuel, in high temperature gas reactors.

The research program continued with the development of the modularity concept [9], which would revolutionize the building of reactors. The feasibility of this modular concept was witnessed by several visits to the United States submarine manufacturing facilities in Newport News, VA and Qonset Point, RI General Dynamics facility, where submarines are routinely assembled in a form very similar to that being proposed.

One of the most recent research projects performed by the MIT team was to assess the safety of the pebble bed reactors. It is well known that the pebble bed reactors, due to their basic design—mainly low power density—cannot melt down. They can, however, suffer from air and water ingress accidents. Given the MIT design was isolated from water systems, the focus was largely on air ingress events. MIT developed a computational fluid dynamics capability to model not only the thermal hydraulics but also the chemical reactions associated with air and graphite reactions using Japanese benchmark tests [10]. This methodology was then applied to the most recent NACOK tests in which an open chimney and a hot and cold return duct were tested in March 2004 [11].

This work showed that the CFD tools and methodology developed by the MIT team were able to predict the experimental results in blind benchmarks with quite good accuracy. The key parameters monitored were temperature, concentrations of CO, CO₂, O and graphite corrosion. The analytical modeling was able to identify key technical parameters that are required to appropriately predict the performance in actual real reactors. It is hoped that this work will be extended to allow for analysis of reactors using a FLUENT analysis technique as well as expanding this work to more simplified systems analysis codes such as MELCOR with a validated benchmark.

7. FUTURE APPLICATIONS

At the present time, the pebble bed reactor concept is

being considered and applied to oil sands applications as a heat source for steam assisted gravity drainage systems in the Canadian oil sands. These fields, if developed to their full potential, have been estimated to be as large as those of Saudi Arabia. [12]. The Next Generation Nuclear Plant (NGNP) is expected to be built at the Idaho National Laboratory to demonstrate production of both electricity and hydrogen using high temperature gas reactor technologies. It has not been decided whether the South African based pebble bed reactor or the General Atomics or AREVA based prismatic reactor will be used as the nuclear heat source. The NGNP technology requirements which are driven largely by the high temperatures (950 C) required for the thermo-chemical production of hydrogen will push the nuclear and materials envelope. The location in Idaho will challenge the delivery of components currently being considered for both designs. The MIT work on the modular pebble bed design and its intermediate cycle modularity approach may ultimately play a significant role in the actual implementation of the final design.

8. CONCLUSIONS

In conclusion, the concepts and ideas being developed through the MIT pebble bed reactor effort await the next step which is a more detailed conceptual design to allow for the demonstration of its economic viability, particularly the modularity approach, which offers potentially large advantages in terms of shorter construction times, lower costs of power and more reliable power net output compared to ultra large power stations. In the vernacular of the MIT project, it is hoped that future plants will be assembled rather than constructed piece by piece in the field. This should also improve the quality of the assembled components since they would be built in a factory environment.

High temperature gas reactors are viewed as the true next generation of reactor technology that, if economic, could be deployed in developing as well developed nations. At present the PBMR project in South Africa and China's HTR-PM project are leading the world in the development and deployment of pebble bed reactors. Pebble bed reactors have left the paper design stage to become the

only high temperature gas reactors that are being built. It is hoped that the US Next Generation Nuclear Plant project will add a new hydrogen dimension to the capabilities of pebble bed reactors and high temperature gas reactors in general. All these initiatives are important to the future energy supply of this world.

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