The Modular Pebble Bed Nuclear Reactor – The Preferred new Sustainable Energy Source for Electricity, Hydrogen and Potable Water Production?

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SUMMARY. High Temperature Gas Cooled (HTGC) nuclear power plant have the potential to become the preferred base load sustainable energy source for the new millennium. The great attraction of these helium cooled "Generation Four" nuclear plant can be summarised as follows:

- Factory assembly line production
- Modularity and ease of delivery to site
- High temperature Brayton Cycle ideally suited for cogeneration of electricity, potable water and hydrogen
- Capital and operating costs competitive with hydrocarbon plant
- Design is inherently "meltdown proof" and proliferation resistant.

This paper discusses, in part, work carried out for a Proposal Submitted in Response to the U.S.A. Department of Energy, Office of Nucleare Energy, Science and Technology, Nuclear Energy Research Imitative Solicitation Number DE-P503-2SF22467 (April 2002). This is a joint project of the Massachusetts Institute of Technology, Nu-Tec Inc. and Proto Power. It incorporates Patents and Intellectual Property. The Author is grateful to his colleagues in all three organisations for stimulating and critical comment and discussion.

Introduction

At the present time, some 438 nuclear power stations operating in 31 countries deliver around 16% of the world's electrical energy. The vast majority of these plants are Light Water moderated and cooled. The High Temperature Gas Cooled nuclear reactor concept was developed almost in parallel with the water reactors and prototype plants have operated successfully in many countries notably Germany, the United States and the United Kingdom. During the 1960s and 1970s, the Australian Atomic Energy Commission adopted as one of its major research projects, the development of a High Temperature Gas Cooled Reactor – with spherical "pebble bed" – type fuel elements. Unfortunately, the choice of Berryllia as the moderator proved to be an error and the project was finally abandoned.

Nuclear engineers and physicists in many countries all agree that the elegant simplicity of the graphite moderated pebble bed reactor is the basis for a most attractive design concept for a "Generation Four" nuclear power plant. In fact some, including this author, believe that such a design could well become the preferred base load energy source of the twenty-first century.

In order to develop and commercialise many areas of leading edge nuclear science and technology, the company Nu-Tec Inc. was established in the United States in October 2001 by a group of Australians. Nu-Tec is now involved in research, development, licencing, joint ventures and commercialisation in the fields of power generation, environmental remediation, plant surveillance, mining of fissile and precious metals, scanning systems for the detection of illicit movement of dangerous materials, and the medical agricultural and industrial uses of radiation.

Nu-Tec quickly established that for many outstanding technical reasons the Massachusetts Institute of Technology (MIT) design of the Modular Pebble Bed Reactor (MPBR) represents the pre-eminent technology in the field of all new power plant on offer. Nu-Tec will be working with MIT in the areas of MPBR dynamics, control and surveillance, and also plans to invest financially in the development of the prototype plant. The MIT pebble bed reactor is normally a 250 Mwth-110Mwe indirect cycle helium cooled and helium gas turbine powered plant using pebble bed technology developed in Germany. This project is similar to that being proposed by ESKOM in South Africa in its core design but radically different in the balance of plant. The indirect cycle was chosen to allow for more flexibility in process heat applications and easier layout configurations, and it supports the fundamental premise of modularity, factory fabrication and site assembly that will allow a plant of this size to be competitive with larger custom built plants.

The modular pebble bed reactor

A pebble bed reactor is illustrated in Figures 1&2. The reactor core contains approximately 360,000 uranium fuelled pebbles about the size of tennis balls. Each pebble contains 9 grams of low enriched uranium in tiny grains of sand-like microsphere coated particles within a hard silicon carbide shell. These microspheres are embedded in a graphite matrix material in the shape of spherical pebbles. The unique feature of pebble bed reactors is the online refuelling capability in which the pebbles are recirculated with checks on integrity and burnup. This system allows new fuel to be inserted during the operation and used fuel to be discharged and stored on site for the life of the plant.

It is projected that each pebble will pass through the reactor 10 times before discharge in a three year period on average. Due to the on-line refuelling capability, plant maintenance outages are projected to be required every 6 years. The conceptual layout upon which the modularity principles are applied is shown in Figure 1. The turbomachinery module and the intermediate heat exchanger are capable of being shipped in 21 modules for site assembly in a horizontal layout.

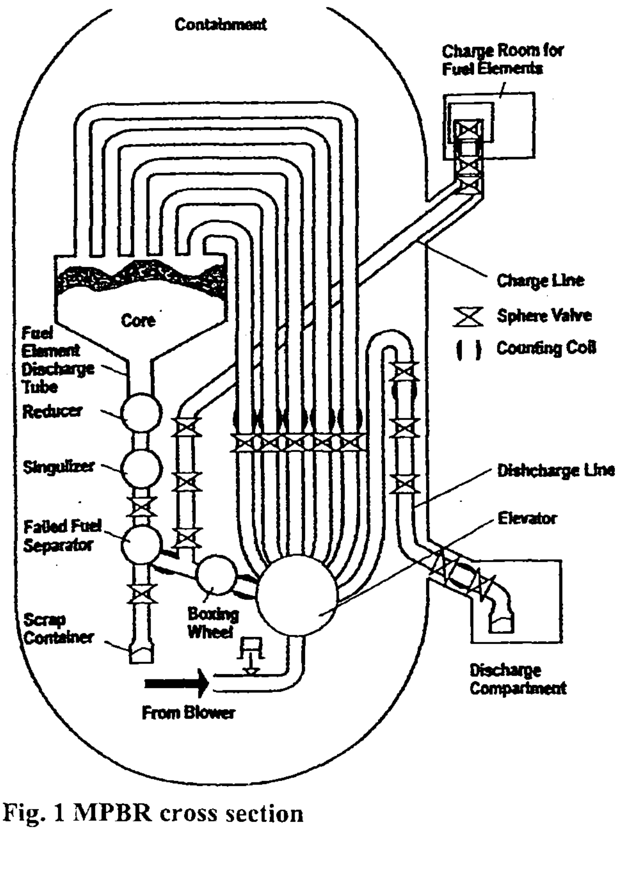


Fig. 1 MPBR cross section

The plant key parameters are shown on Table 1. The plant will be designed to emulate many of the attractive features of the combined cycle natural gas plants in its operation and automatic control.

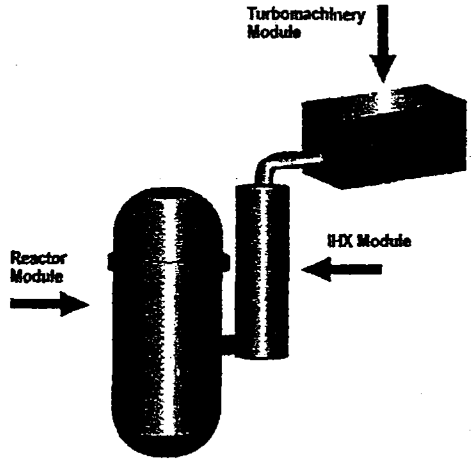


Fig. 2 Schematic of modularity

Table 1. Nuclear plant parameters

Thermal power	250MW
Core Height	10.0m
Core Diameter	3.5m
Pressure Vessel Height	16m
Pressure Vessel Diameter	5.6m
Number of Fuel Pebbles	360,000
Microspheres/Fuel Pebble	11,000
Fuel	UO_2
Fuel Pebble Diameter	60mm
Fuel Pebble Enrichment	8%
Uranium Maas/Fuel Pebble	7g
Coolant	Helium
Helium mass flow rate	120 kg/s (100% power)
Helium entry/exit temperatures	450°C/850°C
Helium Pressure	80 bar
Mean Power Density	3.45 MW/m3
Number of Control Rods	6
Number of Absorber Ball Systems	18

Reference plant design

The current reference plant design along with all of the relevant design temperatures, flow rates and losses and efficiencies is illustrated in Figure 3. The reference plants is a 4-shaft, inter-cooled, recuperated system. The power turbine consist of two blade sets on the same shaft but operated in parallel to comply with the 70,000 HP restriction. The intermediate heat exchanger is of the compact

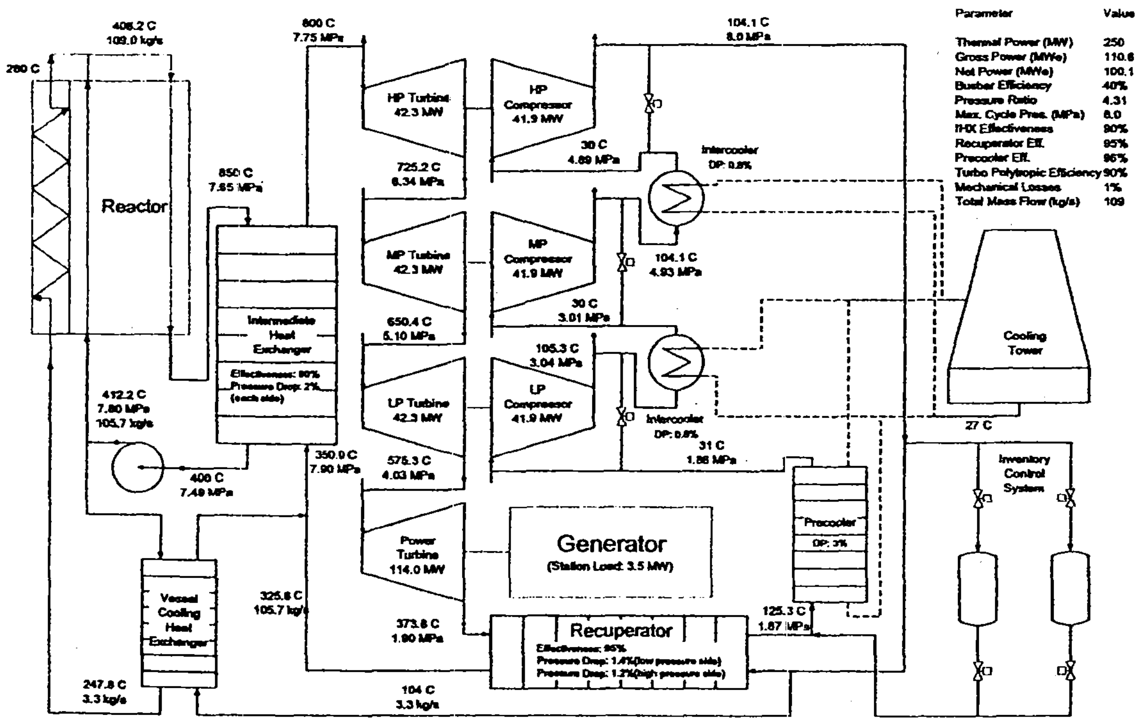


Fig 3. Reference plant design

plate-fin design. The plant uses bypass control on the compressor section as part of the control system instead of on the turbine side to limit the temperature of the control valves. The complete control system includes the capability for inventory control. The turbo compressor sets use 5 stage axial configurations for the compressors. Vane control is used to extend the high efficiency region of operation. No blade or disk cooling is needed. Turbine blades will be single crystal P & W 1498 alloy. The primary pressure boundary complies with ASME Section III, subsection NB and makes use of 316 stainless steel (S31603) or Iconel alloy 625 (NO6625). The overall efficiency of the plant is 45% and includes allowances for station loads and reactor vessel cooling. The design is currently being reviewed and may evolve into a simpler design prior to the start of this Nuclear Energy Research Initiative project.

The 'heart' of the MPBR is illustrated in Figure 4. In a pebble bed modular reactor, uranium fuel contained inside graphite 'pebbles' slowly flows, gumball-style, through a helium-cooled reactor linked with graphite. The lining and plain graphite pebbles moving through the centre reflect and slow the uranium's neutrons to sustain the energy-producing fission process. Helium heated by the energetic fuel pebbles expands to spin a turbine (not shown), which generates electricity. As pebbles flow out of the reactor bottom, automated systems discard broken pebbles and send plain graphite balls back to the top, propelled by a pressure differential. Intact fuel balls are checked for power levels. Reusable fuel is sent back to the reactor, a trip that is will make, on average, ten times in three years. Spent fuel is discarded into a container and replaced with fresh fuel.

In the reactor core, 330,000 billiard-ball sized graphite fuel pebbles (top) each contain 15,000 sand-sized (about one-millimeter) fuel kernels (bottom).

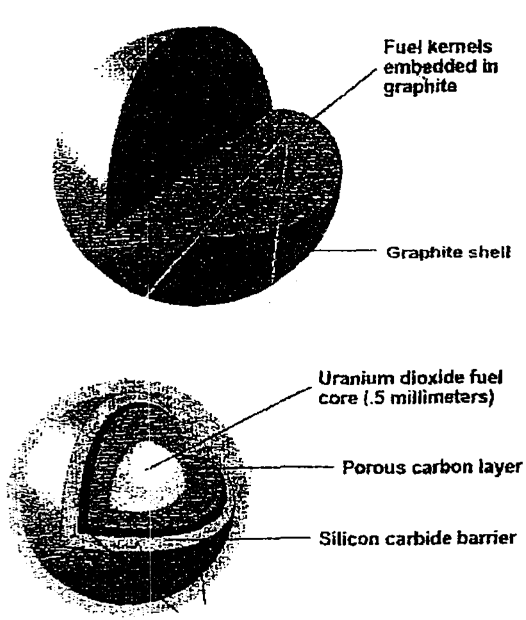


Figure 4. The fuel pebble

The MPBR and water reactors

The Modular Pebble Bed Reactor has some significant advantages over existing nuclear plant. These are summarised in Table 2.

Table 2. Technical advantages of the MPBR

ITEM	MPBR	LWR
Moderator	Graphite	Water
Coolant	Helium	Water
Core coolant exit	850°C	310°C
Core Structural material	Graphite	Steel, aluminium
Fuel clad	Graphite & Silicom	Zircalloy
Fuel	UCO	UO2
Fuel damage temperature	>2000°C	126°C
Power density, w/cc	6.6	58 – 105
Linear heart rate, KW/ft	1.6	19

These parameters indicate that the MPBR, unlike the LWR is:

- Safe under all transient malfunction conditions.
- Proliferation resistant.
- Suitable for hydrogen production and desalination, and
- Attractive economically, with an estimated capital cost around US$1,000 per k/W, and with a primary energy only generating operational cost of around US2 cents per KWh and typically, potable water production at under $US1 per cubic meter.

Furthermore, a factory produced MPBR module of 110 MW (e) can be delivered to site rapidly, and the construction can be carried out with relative ease. Plant can be scaled up to 1 GW(e) or beyond, or if required, manufactured in a basic unit of 10 MW(e) as required.

The MPBR "expert" surveillance system and "smart" sensors

The function of the centralised System Surveillance Office will be to implement, by artificial intelligence, control decision in cases of plant malfunction or improper operation. Furthermore, the computer stored database in the System Surveillance Office will be used to initiate planned maintenance and parts replacement strategies for key components of the MPBR.

Space limitation must preclude a full discussion of the hardware and software to be incorporated into the MPBR *expert* surveillance system. However, a simple example is given below indicating the use of Harwell type, enriched boron, uncompensated RC7EB ionisation chambers to monitor the core of the reactor plant. The twelve chambers are located in quadrature at three segments across the reactor core but external to it.

A typical "smart' sensor

The autocorrelation power spectral density of this fluctuating signal which can be directly associated with the core physics and the transfer function of say a Modular Pebble Bed Reactor is given in an equation of the form

$$W(j\omega) = \frac{2\bar{I}^2}{\bar{C}} H(\omega) \left[\rho + 2\varepsilon D_\nu \sum_{p=1}^{7} \frac{A_p S_p G(S_p)}{\omega^2 + S_p^2} \right]$$

Where

$\bar{C}$ is average count rate of detector

$\bar{I}$ is average chamber current = $\bar{q}.\bar{C}$

q is charge produced by an absorbed neutron

$H(\omega)$ is normalised frequency response of detector

ρ is $\overline{q^2}/\bar{q}^2$ statistical factor of the ionisation chamber

ε is the detector efficiency = $\bar{C}/\bar{F}$

$\bar{F}$ is the mean fission rate

D_ν is $\overline{\nu(\nu-1)}/\bar{\nu}^2 = 0.795 \pm 0.007$ for U^{235}

$G(S)$ is the reactor transfer function with residues A_p and poles $-S_p$

The above equation was first derived in a publication by Diven B.C. (1956).

With such an ion chamber placed in quadrature around the reactor core, the analysis of signal coherences by stochastic algorithms permits reactor operating staff to assess the state of the plant and gain insight into important plant parameters such as relativity worth of control rods and – possibly – covertly introduced neutron absorbers. The theoretical background to such systems can be found in books by Uhrig R.E. (1970) and Williams M.M.R. (1974)

Non-neutronic instrumentation such as thermocouples accelerometers, pressure and velocity sensors can also give rise to fluctuating signals. The frequency spectrum of such signals also contains valuable physical information for surveillance purposes as observed by Siefritz W. and Stegeman D. (1967).

The table below gives a typical list of stochastic Measured Parameters which can be computed on-line by a combination of hard-ware and soft-ware and produce a diagnostic guide to optimal nuclear plant operation and maintenance as observed in a paper published by Kemeny L.G. (1978).

The user friendly multi-dimensional display of such Measured Parameters in the reactor plant control room and the telemetering of this data is a basic function of the surveillance system. It provides immense advantages in the potential for automatic shut-down based on pre-set regulatory parameters as observed by Kemeny L.G. (1984).

Table 3. Computation of stochastic variates

Statistical Techniques	Measured Parameter
Analysis of variance	System power level and stability
Autocorrelation of time series	System time constants
Auto-spectra of time series	System gain and stability
Cross-correlation of time series	System impulse responses, time delays and propagation velocities
Cross-spectra and quad-spectra of time series	Analysis of feedback effects and frequency relationship between them
System phase lags	Transfer function and stability information
System coherence function	Signal transmission quality of reactor including information on noise sources in core

To utilise this type of ion chamber as a *smart* sensor for *expert* systems and stochastic modelling, it is necessary to calibrate all instrumentation channels for both mean current and fluctuating current characteristics and its "filter" properties. This is done with carefully chosen d.c. power supplies and noise generators. Because of long neutron generation times in graphite moderated systems, accuracy necessitates long recording times for parameter identification.

Operation of the "expert" system

The MPBR surveillance and the systematic stochastic logging of the integrity of its key components will be carried out by an Artificial Intelligence algorithm operating within a dedicated computer as proposed by Kemeny L.G. (1998)

The algorithms will consult key stochastic variates at hourly intervals and compare them with pre-set values contained in a stored data base. Typical variates to be examined include:-

- Ion Chambers.. The zero crossing position of Cross-correlation Functions to establish a reactor core criticality and pebble flow reactivity effects.
- Accelerometers... The variance and probability distributions associated with the vibration of the Helium Turbine will be used to protect the coolant circuit.
- Thermocouples... The cross-power spectral densities of inlet and outlet thermocouples will monitor the integrity of single phase flow and sensitivity establish air or water ingress regimes.

Conclusions

This introductory paper describes work carried out for a Proposal Submitted in Response to the U.S.A.

Department of Energy, Office of Nuclear Energy, Science and Technology, Nuclear Energy Research Imitative Solicitation Number DE-P503-2SF22467 (April 17, 2002).

The Author is greatly encouraged by the renaissance of interest in nuclear power technology world wide and in particular the renewed enthusiasm for High Temperature Gas Cooled nuclear plant within the United States of America. With many other scientists and engineers, he believes that this design and technology could well emerge as the preferred energy source of the twenty-first century.

Acknowledgement

This Paper describes a joint project of the Massachusetts Institute of Technology, Nu-Tec Inc. and Proto Power. It incorporates Patents and Intellectual Property. The Author is grateful to his colleagues in all three organizations for stimulating and critical comment and discussion.

References

Diven B.C. (1956) et al Phys Rev (101) 1012

Kemeny L.G. (1978) Stochastic identification and parameter estimation of nuclear power systems and nuclear fuel channels, Proc 4th *International Conf On Identification and System Parameter Estimation* (Amsterdam, North Holland), 869-90.

Kemeny L.G. (1984). A nuclear power plant surveillance system and anomaly detector using digital on-line noise signal recording and analysis. *Conference on Measurement Instrumentation and Digital Technology*, 30-31 October 1984, Melbourne (*Institution of Engineers, Australia*), 1:91-96

Kemeny L.G. (1998), Stochastic Pattern Recognition Techniques and Artificial Intelligence for Nuclear Power Plant Surveillance and Anomaly Detection. *Proceedings of Fortieth Anniversary Conference, Australian Institute of Nuclear Science and Engineering*, 2 and 3 December 1998, Lucas Heights, Sydney, Australia, 73-80.

Seinfritz W. and Stegeman D. (1967), Nukleonik, (9) 169-179

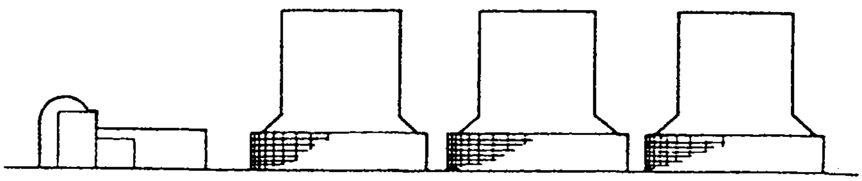
Uhrig R.E. (1970), Random Noise Techniques in Nuclear Reactor Systems the Ronald Press Company, New York.

Williams M.M.R. (1974), Random Processes in Nuclear Reactors Pergamon Press, Oxford.

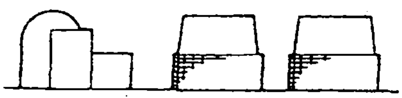
Appendix

Simplified Comparison of Reactor Coolants

	Coolant			
	Water	Helium		Sodium
Reactor type	PWR	HTGR	GCFR	LMFBR
Average temperature (°C)	300	550	450	450
Average pressure (MPa)	15	5	10	0.5
Coolant temperature rise ΔT (°C)	30	420	300	165
Density ρ (g/cm^3)	0.70	0.003	0.0068	0.80
Specific heat C_p (J/g·°C)	5.3	5.2	5.2	1.25
Flow velocity V (m/s)	4.5	50	80	6
Heat transport per unit core frontal area $\rho u\ C_p\ \Delta T$ (W/cm^2)	50 000	33 000	84 000	100 000
Rod surface heat transfer coefficient h (W/cm^2·°C)	3	0.25	1.5	10
Average film drop ΔT (°C)	20	120	100	20
Heat transfer per unit rod surface area $h\Delta T$ (W/cm^2)	60	30	150	200



STEAM CYCLE
LOW EFFICIENCY (LIGHT WATER REACTOR)



DIRECT GAS CYCLE
HIGH EFFICIENCY (HTGR-GT PLANT)