ACACIA-INDIRECT: A SMALL SCALE NUCLEAR POWER PLANT FOR NEW MARKETS

D.F. DA CRUZ, J.B.M. DE HAAS and A.I. VAN HEEK
NRG, P.O. Box 25, NL-1755 ZG Petten, The Netherlands

ABSTRACT

A 60 MWth, 23 MWe pebble bed HTR plant with indirect Brayton cycle is proposed for the applications of heat and power cogeneration or distributed electricity generation. The reactor will be cooled by helium, whereas for the secondary cycle nitrogen is proposed as a heat carrier. Economic performance is being optimized by simplification of the nuclear part and by the exclusive use of commercially proven systems in the energy conversion part. Cogeneration and maximised electricity production will be the two applications discussed. The pebble bed reactor will be of the cartridge type, refuelled off-line only once every three years. Excess reactivity will be controlled by burnable poison in the reflector. Optimization of burnable poison distribution will be discussed for two core geometries, a cylindrical and an annular one. It is shown that in an annular core burnable poison can be distributed in such a way that the reactor will be able to operate for three years with a sufficiently small overreactivity margin.

1. Introduction

Until now, nuclear power has been successful in the market of large scale electricity generation. Other markets, like heat and power cogeneration or distributed electricity generation in developing countries are still waiting to be penetrated by the uranium based energy source.
For these applications, the power level required per location will be much smaller than for the existing nuclear plants. ACACIA-Indirect (AdvanCed Atomic Cogenerator for Industrial Applications), a 60 MWth, 23 MWe (max.) nuclear plant design with indirect Brayton cycle is proposed. The reactor will be of the pebble bed type, because of the high level of inherent safety that can be attained. Economic performance is being optimized by both simplification of the nuclear part and by the exclusive use of commercially proven systems in the energy conversion part. For the reactor, no on-line fuelling or defuelling systems are envisaged, as the pebble bed reactor will be of the cartridge type, refuelled off-line only once every three years. Excess reactivity will be controlled by B_4C as burnable poison in the reflector only, so no new fuel pebbles with burnable poison need to be developed.
Whereas the reactor will be cooled by helium, nitrogen is proposed as a heat carrier for the secondary cycle because of its similarity with air. In this way, a conventional air based gas turbine can be applied, while at the same time excluding the scenario of air ingress through heat exchanger leak.
Optimization of core geometry and burnable poison distribution will be discussed, as well as cogeneration and maximised electricity production as two plant applications.

2. Plant design

A 60 MWt helium cooled pebble bed reactor is coupled with a secondary nitrogen cycle through a He/N_2 heat exchanger. Two applications are analysed [1]: one for cogeneration of electricity and process steam, and one for electricity generation only. In the last case this is done by a combined cycle of a gas turbine and a steam turbine. Table 1 highlights the main features of the plant, and in figure 1 the component arrangement is depicted for the cogeneration plant. The reactor and energy conversion components are placed into four modules, one nuclear one and three non-nuclear ones. The reactor pack houses the reactor, the He/N_2 heat exchanger (nitrogen heater) and the helium blower. The hot nitrogen is transferred to the gas turbine pack, where it drives the gas turbine. The turbine also drives the two compressors of the intercooled cycle, and a generator delivering 18.8 MWe. After leaving the turbine, the gas, now cooled down to 516°C, flows to the adjacent heat cogeneration unit. Here it is directed through four heat exchangers in a row: the heat recovery steam generator, the recuperator, the feedwater heater and the precooler. By now, the gas has been cooled down to 28°C, and is sent back to the gas turbine pack for intercooled compression. Before being sent back to the nitrogen heater it is preheated in the recuperator to 299°C. For the combined cycle electric plant, the hot steam leaving the heat recovery steam generator is expanded in an additional steam turbine coupled with a second generator, giving an additional 5.2 MWe.

Table 1 Main features of ACACIA indirect cycle plant, in cogeneration mode and in electricity-only mode.

	Baseline cogeneration	Combined cycle
Reactor power (MWt) Core inlet/outlet temperatures (°C)	60 352/900	
Net electrical power output (MWe)	18.1	23.2
Gas turbine output (MWe)	18.8	18.8
Steam turbine output (MWe)	-	5.2
Process steam production (t/h, 425°C/ 4.14 MPa)	27.8	-
Net power generation efficiency (% max.)	30.1	38.7
Net total thermal efficiency (%)	70.0	38.7

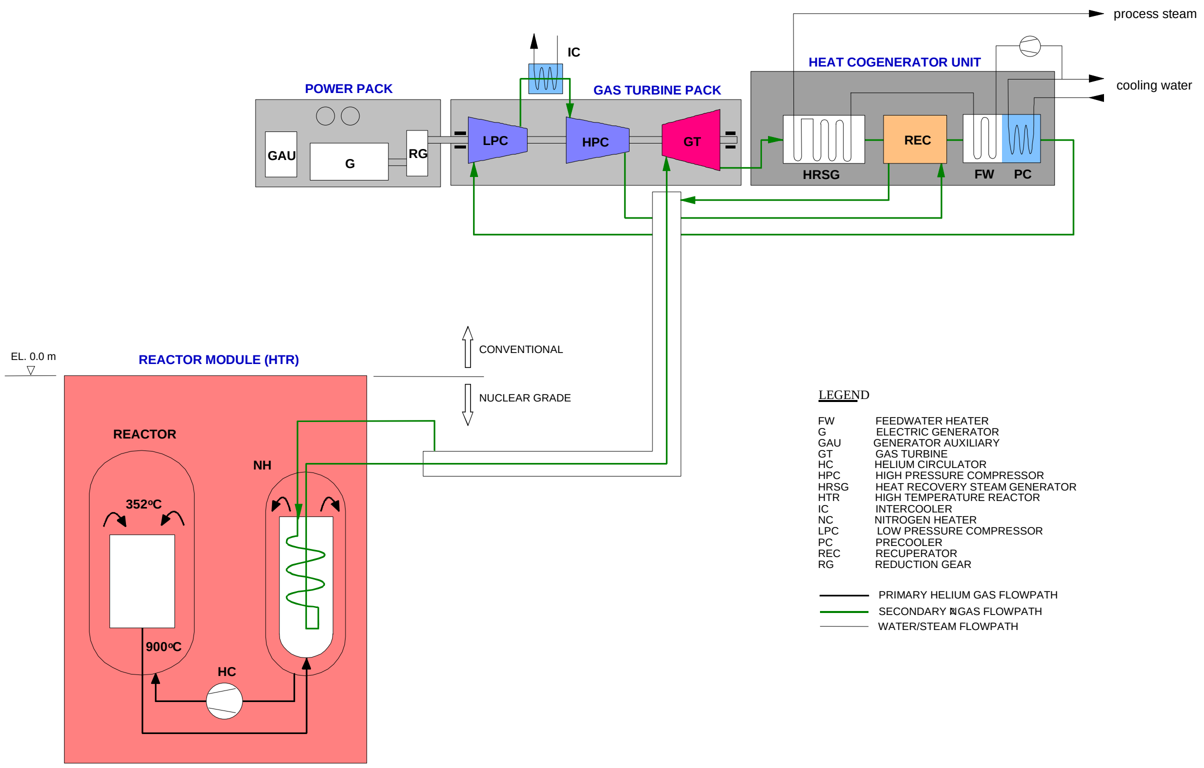

Fig.1 ACACIA cycle design for cogeneration of electrical power and process steam.

The core outlet temperature is set 900°C, which is below what has been or will be demonstrated by the fuels in AVR, HTR-10, HTTR, etc. No safety hazard of water or steam ingress into primary system exists, since all water and steam circulation is remotely located in the third loop. The nitrogen heater is essentially pressure balanced with a slightly higher secondary pressure to ensure that no fission products will enter the secondary system in case of leaking tubes. The reactor vessel will be kept below 370°C, so normal SA533 steel can be used. The nitrogen heater can be designed as compact as an HTR steam generator, by selecting a large temperature difference of 50°C between the primary and secondary inlet and outlet fluids, an optimal pressure balance inside and outside of the tubes and a minimal tube wall thickness.

Whereas for direct cycle systems a helium turbine needs to be developed and commercialized, a simplification goal in this study is adaptation to conventional or existing components and systems so that the available experience becomes sufficient enough to minimize any significant R&D requirements and deployment risks.
The past and current system and component technologies that support the present N_2 closed cycle are identified below:

- A number of past closed cycle air gas turbine generators were built for up to 30 MWe in Europe, the U.S. and Japan; Some of the plants were operated for up to 100,000 -150,000 hrs.
- More modern gas turbine technologies developed in conventional gas turbines such as dry gas shaft seal, high temperature blade materials, aerodynamic and rotor dynamic modeling will greatly improve the closed cycle experience of the past.
- Conventional gas-to-water coolers and heat recovery steam generator.
- Conventional or retrofitted steam turbine and auxiliaries.
- The present design study has identified little or no R&D requirements for the ECS of the HTR indirect cycle plant and that all major equipment can be obtained based on available experience or from off-the-shelf products (technology references will be provided as required).

3. Core design

The cartridge core is the ultimately simplified pebble bed core besides the recirculation, OTTO and PAP cores [2]. The core is loaded at once with fresh pebbles, and then operated for three years without refuelling or fuel shuffling. After this period the entire core is replaced. The associated loss of fuel utilization efficiency will be offset by a reduction of capital and O&M costs.

A core study has been made as an investigation about the parameters needed to obtain a pebble core with an as flat as possible reactivity behaviour as function of the time between two fuel reloads. This flatness is needed to have a sufficiently small and constant excess reactivity to be controlled by control rods or gas flow. The idea is to use the pebble fuel composition as proposed for the PBMR plant, with 8.1% enrichment and 9 g of heavy metal per fuel element. Excess reactivity will be controlled by B_4C as burnable poison in the reflector. A parameter study regarding core geometry, poison location and concentration is discussed in this section.

The technique of using burnable poison in the reflector of a pebble bed reactor has been proposed in the paper by Van Dam [3]. Instead of a 1-D 2-groups diffusion approximation we used a 2-D 16-neutrongroups approach. The 16-groups nuclear data were condensed from 172-groups cell calculations, based on JEF2.2 data, in which the double heterogeneity of the pebbles was taken into account. For a 60 MW reactor two geometries were modelled in the WIMS/SNAP-code, a cylindrical and an annular one. The first has a pebble bed core with radius 1.45 m and height 6.50 m (average core power density 1.4 MW/m^3) leaving 0.5 m of void on top of the bed till the top reflector.
The cylindrical core is surrounded by a graphite side reflector of 1.0 m thickness and an effective top and bottom reflector of 2.0 m, based on the earlier direct cycle ACACIA design with PAP fuelling [4]. In the side reflector zones were applied to which burnable boron could be added. Results of these calculations for different initial boron concentrations (1, 50, 75 and 100 ppm of natural boron) and as function of the number of full power days can be seen in fig. 1.

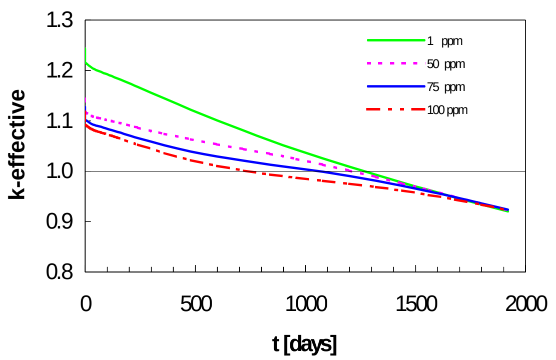

Fig 1. Reactivity as function of the number of full power days for different boron concentrations in the side reflector.

From this figure it can be seen that for a cylindrical core the excess reactivity can be suppressed but will keep a to steep descending tendency during cartridge lifetime, while reducing the lifetime too much. Another disadvantage of poison in the side reflector will be the partial suppression of the control rod worth in the reflector because of the lowered thermal flux importance by the poison in this region.

To obtain an annular core an inner reflector of solid graphite, with radius 0.6 m was placed in the centre of the core. To maintain the same averaged power density the core was elongated to 7.5 meter. In fig. 2 the borated regions in the inner and outer (side) reflectors are indicated by the dashed lines. The effect of poisoning respectively the bottom, inner and outer reflector has been examined.

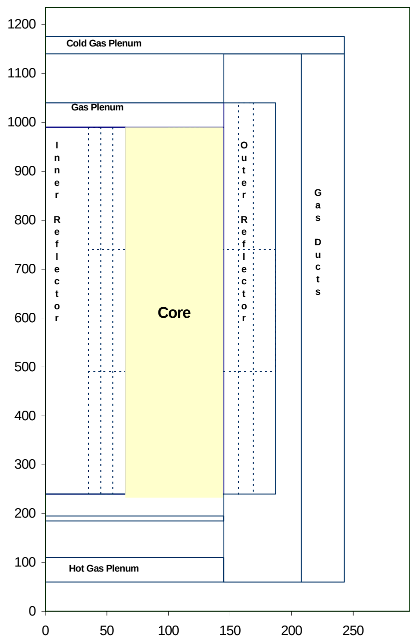

Fig 2. Sketch of the ACACIA model with annular core.

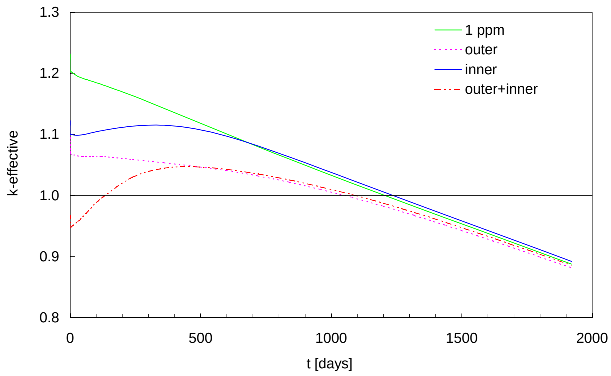

Fig 3. Reactivity effect for 50 ppm boron in the different reflector regions.

Boron in the bottom reflector did not give a significant effect because of the small absorbing area compared to the reflector surface. This did not show as a tool to tailor the reactivity curve.

To compare the influence on the reactivity due to boron in the outer or inner reflector, calculations have been done for 50 ppm boron in the borated regions of the inner or outer and both reflectors. The results are given in fig 3. The references case for 1 ppm or natural boron impurity has been given as well. It can be seen that the influence of the inner reflector is stronger especially in the begin of the lifetime, this is due to the "flux trapping" in the inner core resulting in a high thermal flux importance but also in a faster depletion of the boron in the region.

The required effect of reflector poisoning was found for the annular core with inner reflector poisoning only. From the results given in fig 4 it can be seen that increasing the boron content leads to a flattening the reactivity curve, until there is so much boron that the reactivity increase due to the boron depletion can not keep pace with the decrease by the fuel depletion. For a boron concentration of about 150 ppm the reactivity curve is almost flat until about 1000 full power days. It can also be seen that the period where $k_{eff}>1$ increases as well with the boron concentration.

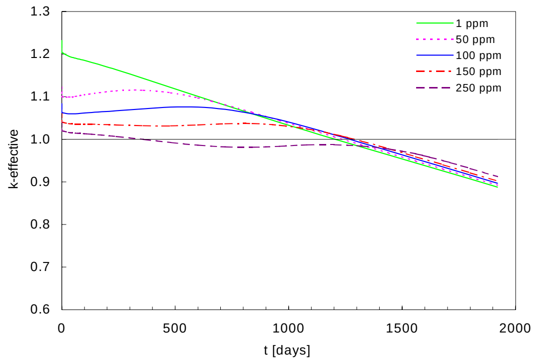

Fig 4. Reactivity as function of boron concentration in the inner reflector.

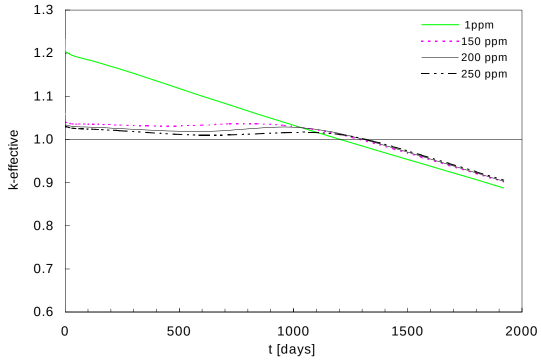

Fig 5. Reactivity as function of different boron contents in the middle section of the inner reflector.

The possibility of axial zoning of the burnable poison in the inner reflector has been investigated as well, see fig. 5. The inner reflector was divided into three zones; the two outer zones were given a concentration of 150 ppm whereas the middle zone was given up to 250 ppm. A further overall lowering of the reactivity curve can be observed. This figure together with fig. 4 shows that there are tools to obtain an almost flat reactivity curve with a core lifetime of about 3 years. In this stage flatness is more important than the absolute difference from k_{eff} =1 because this can be solved by geometrical means.

In the continuation nuclear data will be generated with boron concentrations within the bandwith obtained with this study. These nuclear data will be used in the full 3-D reactor code PANTHERMIX with thermal-hydraulic feedback for the calculation of neutron fluence, power and temperature fields.

4. Conclusion and Prospects

A pebble bed HTR plant for small scale markets with an indirect Brayton cycle and cartridge core has been designed. As the secondary medium is nitrogen, all energy conversion system components are conventional and existing, so R&D requirements and deployment risks are minimized.

The cartridge core will be entirely reloaded once every three years. Core geometry will be annular with with burnable poison in the inner reflector. Poison concentration and location have been chosen in such a way that core overreactivity remains sufficiently small and constant over an operating period of three years.

Thermal-hydraulic and transient analysis is planned to be done for both the core and the entire plant system with the Panthermix code package. A model has been made, and as a start, the lifetime of the unpoisoned core has been calculated. With 1255 days this is 2% different from the corresponding WIMS/SNAP result.

5. References

[1] Longmark Power International Inc., HTR^{icc}, Indirect Cycle Cogeneration, Contract of NRG, 2001.

[2] E. Teuchert, H. Gerwin and K.A. Haas, Simplification of the Pebble Bed High Temperature Reactor, International Specialist's Meeting on Potential of Small Nuclear Reactors for Clean and Safe Energy Sources, Tokyo, October 23-25, 1991.

[3] H. van Dam, Long-term Control of Excess Reactivity by Burnable Poison in Reflector Regions, Annals of Nuclear Energy 27, 63-69, April 2000.

[4] E.C. Verkerk, Dynamics of the Pebble-Bed Nuclear Reactor in the Direct Brayton Cycle, PhD Thesis, Delft University of Technology, 2000.