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A fusion-fission hybrid reactor driven by high-density pinch plasmas

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Abstract A conceptual design for a 200 MW hybrid fusion-fission reactor to be used as a heat source for district heating has been developed. The fission, heat-generating blanket is based on the CANDU reactor technology, while the fusion fast neutrons are provided by a high-density, pinch plasma. The basic assumption regarding the fusion neutron source is that in a pinch plasma (high-density Z-pinch and plasma focus configurations have been considered) a fusion power level of 10 MW can be achieved. An outstanding feature of the design is that no active components are necessary within the reactor containment area, all the hybrid system control being ensured by the fusion component of the reactor.

Key words CANDU • high-density pinch • hybrid reactor • plasma focus

Introduction

The feasibility of a fusion reactor based on a high-density pinch device is rather uncertain. Such a fusion device could however be used to trigger a subcritical fission assembly and generate enough heat to make the resulting hybrid fusion-fission system economically interesting. The hybrid nuclear reactors described in this paper are envisaged as new thermal sources for central heating and represent subcritical nuclear assemblies whose design is based on the CANDU technology for the fission component and on dense magnetised plasma systems for the fusion component [3, 6]. The use of such nuclear power systems for the production of thermal energy and the possibility of their siting close to the end users are encouraged by the intrinsic nuclear safety of these assemblies backed by the advantages of the operation at reduced temperatures and pressures with respect to those of the CANDU reactor.

Principle of operation

The proposed hybrid reactor concept uses a fusion neutron source (fast neutrons with the energy of 14.1 MeV) to initiate nuclear fission reactions within a surrounding blanket made up of CANDU fuel (depleted or natural uranium). The reactor is a subcritical nuclear assembly operating in a pulse regime at a frequency of 1 Hz. This assembly does not need control, command and safety systems since the nuclear fission reaction is terminated once the fusion neutron source is stopped. The fusion neutron source is a

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dense magnetised plasma neutron generator (e.g., a dense Z-pinch or a plasma focus device) capable of generating a neutron yield in the range $(0.5–5)\times10^{18}$ neutrons/pulse at a frequency of 1 Hz. In a first design of the reactor the fusion source needs 10 MW electrical energy for a 200 MW thermal power delivered by the reactor.

The principle of operation of a hybrid fusion-fission reactor for district heating is schematically presented in Fig. 1. The vacuum chamber within which the fusion plasma is generated is surrounded by a fission blanket made up of CANDU type fission fuel elements. The fuel elements could be provided both by the fuel element production plant and by the CANDU reactor after fuel discharge. After their use within the hybrid reactor the fuel elements could be stored or be transferred to the fuel reprocessing plant. The fission blanket is cooled by light water in a natural convection circuit that transfers the generated heat by means of an intermediary heat exchanger to a secondary thermal circuit (district heating circuit) that includes the end user (household or industrial).

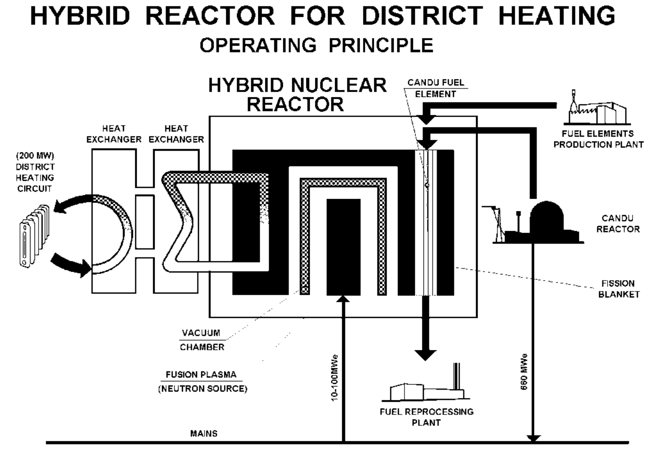

Fig. 1. The principle of operation of a hybrid fusion-fission reactor for district heating.

The fission component of the hybrid reactor

A preliminary blanket concept of the fission part of the reactor is presented in Figs. 2 and 3. The configuration in Fig. 2 was used for neutron transport calculations [3]: the ANISN code was used for the fusion neutron transport and the WIMS code for the fission neutrons and burning calculations.

The structure of the hybrid reactor is presented in Fig. 3. The uranium radial blanket consists of 256 vertical pressure channels (item 9, Fig. 3), each housing 8 fuel bundles (item 10) of the standard CANDU type (0.5 m long, 0.1 m diameter). The equilibrium core is to be fuelled with depleted uranium oxide (0.3% U235) fuel bundles, otherwise identical with the standard natural uranium fuel bundles. The infinite neutron multiplication factor of an equilibrium core at an average core burnup of about 7 MWd/kg is 0.82, the average energy multiplication factor is about 20 (values as

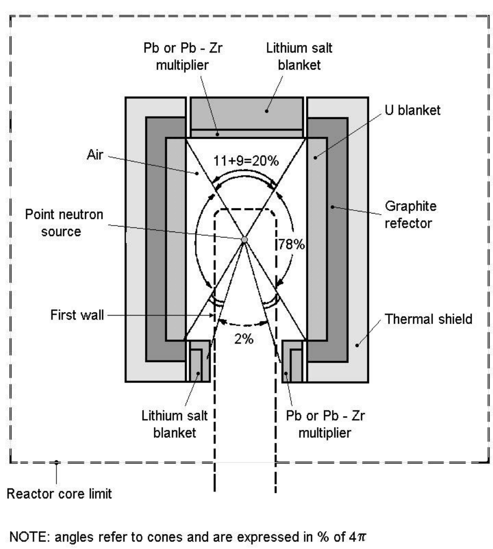

Fig. 2. Configuration used for calculations of the preliminary blanket concept for the fission part of the hybrid reactor.

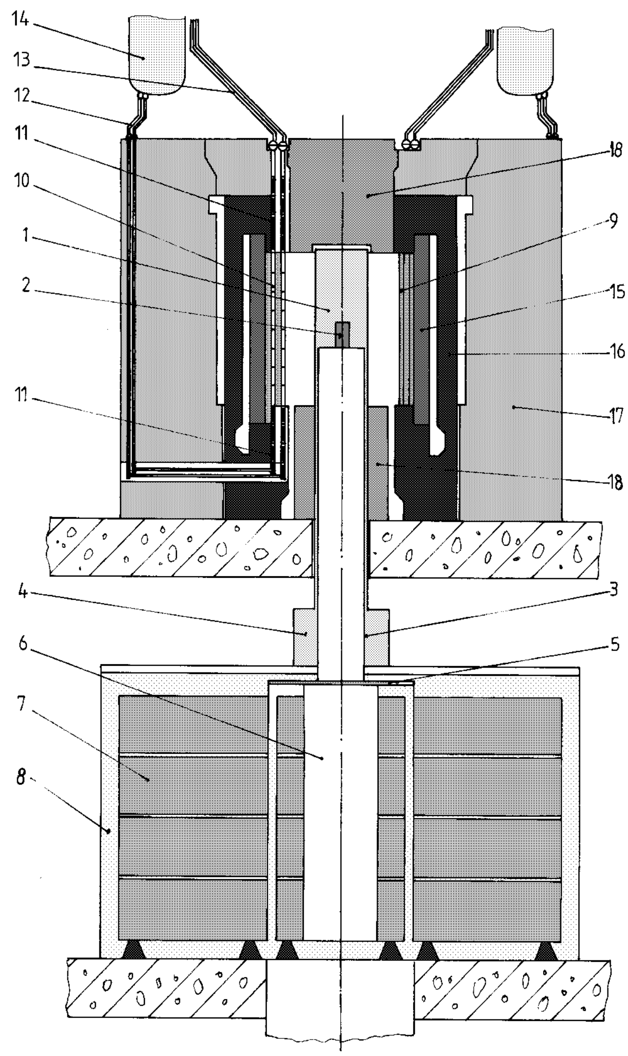

Fig. 3. Structure of the hybrid reactor: 1 – discharge chamber; 2 – pinch plasma head; 3 – coaxial transmission line; 4 – pumping, fuelling and cooling manifold; 5 – parallel-plate collector; 6 – parallel-plate transmission line; 7 – energy storage condenser module; 8 – oil tank; 9 – pressure tube; 10 – fuel bundle; 11 – shield bundle; 12 – lower feeder duct; 13 – upper feeder duct; 14 – primary heat exchanger; 15 – radial reflector; 16 – radial thermal shield; 17 – radial biological shield; 18 – axial blanket assemblies.

Table 1. Fission blanket performance data.

Thermal power, MW	200–330
Active core internal radius, m	1.5
Active core external radius, m	2.0
Core height, m	4
Channel number	256
Channel lattice pitch, m	0.15
Heavy element core charge, kg U	38000
Light water inlet temperature, °C	80
Light water outlet temperature, °C	180
Light water pressure (*), MPa	1
Maximum mass flow, kg/m^{2}s	850
Average channel power, MW	0.8
Maximum channel power, MW	1.3
Average specific power of FE, kW/kg	5.25
Maximum specific power of FE, kW/kg	13
Peak temperature increase during pulsing, °C	45
Maximum temperature in the fuel, °C	800

(*) at the upper end of the heat exchangers; (FE = fuel element)

high as 45 were obtained in calculations) and the average spent fuel fissile content for a discharge burnup equal to 14 MWd/kg is about 0.6%. The initial core should consist of both depleted and natural uranium fuel bundles in order to assure this multiplication factor of the fresh core.

The primary circuit is operated in natural convection with light water, which is allowed to boil. The channels are distributed to 3 loops, each loop being provided with a once-through heat exchanger. The heat exchanger elevation is high enough to provide a chimney for natural draft. The void at the exit of the most powered channel is about 0.3, corresponding to a quality factor of about 0.001. The intermediate circuit (that prevents radioactive water infiltration in the urban heating network) is operated with motor pumps. A cooling tower is connected to this circuit in order to provide a necessary heat sink for the post-fission heat in case of unavailability of the flow in the urban heating network.

The uranium blanket is surrounded by a graphite reflector tank (15) (a tank containing an aqueous lithium sulphate solution was also considered – see axial blanket), a thermal shield (16) and a biological shield (17). This shield will allow access during maintenance. The performance data of the uranium blanket is given in Table 1. The upper and lower axial blankets (18) consist of tanks containing an aqueous lithium salt solution wetting a lead pebble bed.

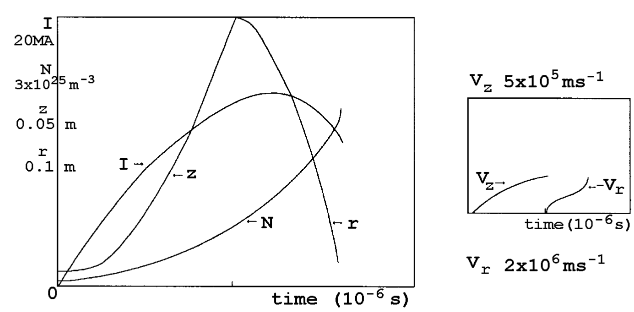

Fig. 4. The evolution of the main system parameters for a plasma focus load obtained with a "slug" type numerical code: I: discharge current; N: particle density in the plasma sheath; z and V_z: axial position and velocity of the plasma sheath; r and V_r: radial position and velocity of the plasma sheath (all numbers represent full-scale values for each parameter).

Table 2. Parameters of the pinch fusion device.

Neutron (14.1 MeV) yield per pulse	(0.5–5)×10^{18}
Repetition rate of the neutron pulses	1–10 Hz
Average (fusion) nuclear power	10 MW
Peak input (driver) power	10–100 MW
Tritium charge	0.1 kg

The lithium sulphate solution was chosen to reduce the water radiolysis and lead to enhance the fast neutron multiplication. The total tritium production (in the axial blankets and the radial reflector) amounts to about 0.3–0.4 of the tritium consumption.

The cooling of this blanket is provided by the natural convection driven flow of this aqueous solution, the circuit including the radial blanket reflector and high elevation heat exchangers.

The fusion component of the hybrid reactor

A pinch fusion device was considered to act as the neutron source in the hybrid reactor for district heating. The fusion device should have the parameters presented in Table 2.

Two components of the fusion neutron source [5] were analysed, the pulse power supply and the discharge (vacuum) chamber, both having important effects on the hybrid reactor concept as far as the reactor configuration and overall energy efficiency are concerned.

The vacuum chamber containing the pinch electrodes is cylindrical with access at the lower part for a circular coaxial line for energy transmission, for the cooling circuit and for the gas filling and vacuum pumping. The cooling for the fusion vacuum chamber uses liquid lithium in a configuration [1] that also provides protection of the first wall against radiations and particles emitted by the plasma.

The pulse power supply [4] was chosen to be a capacitor bank using a modified Marx configuration with the following main parameters: 2 MV discharge voltage (starting from a 100 kV charging voltage), total energy 9.6 MJ, internal inductance 50 nH. The short circuit parameters for such a power supply (20 MA peak current, 770 ns current rise-time

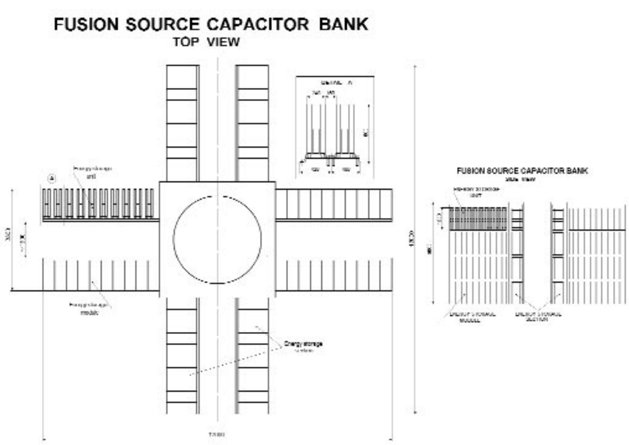

Fig. 5. The capacitor bank of the pulse power supply for the hybrid reactor.

and 4×10^{13} A/s initial value of the current derivative) provide a wide range for the optimisation of the coupling to the plasma load. For the particular case of a plasma focus load the evolution of the main system parameters were obtained with a "slug" type numerical code [2] and one example is presented in Fig. 4.

The capacitor bank of the pulse power supply (Fig. 5) has a module structure in which a number of 64000 capacitors (100 kV, 1.5 kJ) are divided in 320 energy storage units, each unit (200 kV, 30 kJ) having one high voltage switch. A number of 10 energy storage units makes up one energy storage module (2 MV, 300 kJ), the 32 modules being grouped in four energy storage sections. The last ones are coupled to the pinch plasma head by means of a coaxial transmission line and four parallel-plate transmission lines.

Conclusions

A high-density pinch device could be used to trigger a subcritical fission assembly and generate enough heat to make the resulting hybrid fusion-fission system economically interesting. A conceptual design for a 200 MW hybrid fusion-fission reactor has been developed to be used as a heat source for district heating. The fission, heat-generating blanket is based on the CANDU reactor technology, while the fusion fast neutrons are provided by a high-density pinch plasma. The reactor has a vertical cylindrical configuration, with the neutron source on the axis being surrounded by radial (fission) and axial (tritium breeding) blankets. The axial blanket is expected to produce a part of the needed tritium, the balance being supplied by the tritium produced in CANDU reactors. The radial blanket consists of pressure tubes housing standard CANDU fuel bundles.

The basic assumption regarding the fusion neutron source is that in a pinch plasma (high-density Z-pinch and plasma focus configurations have been considered) a fusion power level of 10 MW can be achieved. In the first conceptual design a repetition rate in the range 1–10 Hz is chosen for the neutron generator as an optimum value determined by technological problems raised by high energies per pulse, on the one hand, and high repetition rates, on the other hand.

An outstanding feature of the design is that no active components (pumps, valves, etc.) are necessary within the reactor containment area, all the hybrid system control being ensured by the fusion component of the reactor.

References

1. Bernard A, Cloth P, Conrads H et al. (1977) The dense plasma focus - a high intensity neutron source. Nucl Instrum Meth 145:191–218
2. Cengher M, Zoita V (1997) Computer optimisation of heavy gas filling for a plasma focus device. Romanian Reports in Physics 49:355–366
3. Lungu S, Zoita V (1993) Pinch-plasma driven fusion-fission hybrid reactor for district heating. In: 7th Int Conference on Emerging Nuclear Energy Systems. Makuhari-Chiba, Japan, paper CP-01
4. Zoita V (1985) New type drivers for the plasma focus. In: 4th Int Workshop on Plasma Focus and Z-pinch Research. Warsaw, Poland, pp 244–248
5. Zoita V (1989) Plasma focus neutron generator for a fusion-fission hybrid reactor. In: 7th National Conference on Plasma Physics and Technology. Iassy, Romania, pp 26–28
6. Zoita V, Lungu S (1997) Dense pinch driven fusion-fission hybrid reactor. In: IAEA Technical Committee Meeting on Innovative Approaches to Fusion Energy. Pleasanton, USA, pp 156–157