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FR8901656

CEA-CONF --9696

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SPACE NUCLEAR POWER STUDIES IN FRANCE - A NEW CONCEPT OF PARTICLE BED REACTOR

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Communication présentée à : 23. Intersociety Energy Conversion Engineering Conference

Denver, CO (US)
31 Jul - 5 Aug 1988

23 rd Intersociety Energy Conversion Engineering Conference
July 31 - August 5, 1988 - DENVER (Colorado)

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91191 GIF-SUR-YVETTE CEDEX - FRANCE

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I - INTRODUCTION

A cooperative program about space nuclear turboelectric space power systems was initiated in 1982 by both the Centre National d'Etudes Spatiales (CNES) and the Commissariat à l'Energie Atomique (CEA) agencies of the French government, with a view to assessing the feasibility, the lead time and the cost for the development of nuclear space power systems relevant to the power range of 20 to 400 kWe. A reference 200 kWe turboelectric power system compatible with the ARIANE 5 launcher has been developed to support preliminary feasibility and cost studies. As reported in previous papers [1,2] , the basic design options of this system are a fast neutron spectrum lithium cooled reactor, a redundant Brayton conversion system and a heat pipe radiator.

The effort on conceptual studies recently shifted towards low power systems (20 kWe), which are most likely to meet the power needs of the first European space missions. In order to widely cover the range of possible technologies for the 20-kWe space power systems, and to assess the impact of the reactor concept (liquid metal versus gas cooled) and of the relevant operating temperature upon the system performances, a set of three reference turboelectric systems were selected for comparison [3] . Those considered for both extreme bounds of the explored range of maximum heat source temperature (970 K and 1470 K), use a liquid metal cooled reactor (sodium or Nak and lithium respectively) and the basic features of the 200 kWe system . In addition to both liquid metal cooled systems, a third system using a gas cooled epithermal particle bed reactor, to drive a direct cycle conversion system with a turbine inlet temperature of 1120 K is being investigated ; this system is intended to make full use of the heat resisting materials and of the techniques, which have been developed for the high temperature gas cooled reactors.

2 - SYSTEM DESCRIPTION

The lay out of the considered 20 Kwe direct cycle system is represented on figures 1 and 2, and its main characteristics are summarized in table 1.

The system basically consists of a gas cooled epithermal particle bed reactor, which is directly coupled with a Brayton converter, which includes a turbine, a compressor and an alternator mounted on the same shaft. The reactor is equipped with a neutron and gamma shield, in the solid angle, which contains the radiation sensitive components, like the electronics of the control system.

The heat sink of the conversion system consists of either a gas cooled radiator, made of finned pressure tubes connected in series with the recuperator and the compressor (fig.2), or of a heat pipe radiator made of circular finned heat pipes, which exchange heat with the working gas throught their finned evaporator section gathered in a longitudinal heat exchanger.

- 2.1 - REACTOR AND SHIELD

Design studies of gas cooled reactors have been restricted in a first step to epithermal reactors, as the use of hydride moderators (Z_r H and Li H) was not believed to be advisable for the aimed lifetime and reactor temperature conditions. However, purposely adapted coolant ducting schemas for an appropriate thermal conditioning of such moderators, may deserve further investigations.

The design of the considered epithermal reactor was dominated by the search for a compact critical core assembly with a routing scheme designed so as to keep a relative pressure drop below 3 % across the reactor, which is necessary to prevent an excessive degradation of the conversion cycle efficiency. These concerns led to a compact particle bed reactor cooled by perforated drains inserted in the bed as illustrated in figure 3 and 4. The low specific power of the reactor and the low fast fluence integrated over the lifetime are assumed to allow the use of fuel particles with large UC_2 kernels (1mm in diameter) and two thin coating layers (50 μ m PyC and 50 μ m SiC), which leads to a particularly favorable uranium filling factor in the bed (3.6 g/cm^3). The large porosity of this reactor concept makes 19 safety rods necessary to meet the aimed subcriticality margin in case of immersion.

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The general shape of the core is an orthocylinder 38 centimeter in diameter. The fuel particles are placed in bulk inside a cylindrical vessel forming the core barrel. This particle bed assembly is contained in a pressure vessel. The ducting of the cooling gas between the reactor and the conversion system is effected by 4 cooling loops, which are connected with the lower region of the reactor vessel and symetrically run around the radiation shield.

12 rotating control drums of beryllium with B_4C absorbing segments are placed around the reactor vessel. The rotation of the control drums is achieved with 12 step by step electric motors placed behind the radiation shield.

The 19 B_4C in core safety rods are movable also by motors placed behind the shielding. These rods are withdrawn from the core when the reactor is in normal operation on safety orbit ; (>800 km). A following plug made of beryllium oxide replaces the absorber for normal operation.

The integrated dose specifications assumed for the design of the shadow shield are 10^{13} n/cm^2 (E > 1MeV) and 0.5 10^6 rad gamma photons at a distance of 20 meters from the reactor and a life time of 7 years.

A half cone angle of 15° is assumed and the shielding materials (liH and B_4C) are arranged so as to meet the dose criteria with the minimum shielding mass and with an operating temperature compatible with the technological limits of the materials. Temperature considerations lead to the use of 10 centimeters thick of B_4C , close to the reactor.

2.1.1. - NEUTRONIC CHARACTERISTICS

The reactor has been sized for a built-in reactivity of 6 % at beginning of life and for a subcriticality margin of 5 % in case of immersion.

The use of axial and radial reflectors, which respectively consist of 10cm thick BeO slabs at both lower and upper end of the active core, and of a 8cm thick annular beryllium assembly set around the reactor vessel, not only permits an efficient saving of the reactor mass for an aimed built in reactivity, but also effects an efficient flattening of the power distribution.

The axial peaking factor is less than 1.10, and the radial peaking factor ranges from 1.15 to 1.36 depending on the position of the rotating drums (respectively OUT and IN) ; this results in a radial peaking factor of about 1.22 in the critical configuration and to a dimensional peaking factor less than 1.35.

The thermal power required for a 20 Kwe turboelectric power system, amounts to 125 kWt only, which is far below the potential of the reactor in terms of coolability and burn-up limitations. The average burn-up at the end of a 7 years lifetime at nominal power, is 2330 Mwd/t (peaking at 3150 Mwd/t). This corresponds to the consumption of 0,25 % only of the initial fissile inventory (137 kg of uranium enriched at 93 % in uranium 235), which induces a reactivity loss of 0,3 % only.

The reactivity feed-back effects associated with a temperature rise from 20 to 850°C, has been evaluated at -1,25% which correspondonds to an isothermal feed back reactivity coefficient of about $- 1.5\ 10^{-5}/°C$. The major contribution to this negative feedback effect, is attributable to the increase of neutron leakage associated with the thermal expansion of the active core.

The neutronic analysis of the 12 drum system in synchronous rotation, indicated a residual worth of 0,6 % with all absorbing segments (2,5cm thick 90 % enriched B_4C in ^{10}B) in the outer position, and a total worth of 17 % between the extreme positions.

The above examined reactivity items (residual central worth, burn-up reactivity compensation and temperature feed-back effects) plus a 2 % contingency margin and a provision of 1 % to compensate for the residual negative reactivity worth of the safety rods, when with drawn from the core, call for a built-in reactivity of 5,2 % in the cold state at beginning of life, which is approximately achieved with active core height and diameter of 38 cm. In such conditions, the control drum systems assures a shutdown margin in excess of 10 %.

The porosity of the particle bed leads to a moderator to fuel ratio close to unity, in case of reactor immersion,which would cause a reactivity rise of 15 % in absence of safety rods. The neutronic analysis of this accidental situation proved 19 absorbing rods of B_4C (27mm in diameter and 90 % enriched) to be necessary to assume a subcriticality margin in excess of 5 %.

2.1.2. TECHNOLOGY PROBLEMS RELEVANT TO THE PROPOSED REACTOR CONCEPT

The use of perforated cooling drains in a particle bed reactor poses a number of technological problems, relative to the behavior of the fuel particle and to the achievable cooling efficiency, which need to be resolved.

The drains are regularly distributed within cross section of the core, so that the distance between inlet and outlet drains is only 18 millimeters. The perforations on the drains are disposed so as to adapt the coolant flow to the local power distribution (axialy and radialy). Detailed thermal studies would be necessary to verify that the temperature distribution is compatible with the particle and material structure thermal characteristics.

Another problem to be solved is the nature of the material of the pressure vessel, which supports a gas pressure of 0,80 MPa at 512°C with an integrated dose over 7 years of approximaty 4.10^{20} n/cm^2 ($E > 1$ MeV). The exit pipes are at 850°C with a more reduce dose.

The now considered material for the pressure system is a superalloy like Hastelloy X or XR. An experimental program of irradiation of different metal alloys samples is engaged.

The characteristics of the considered fuel particles (large kernel with 2 coating layers) call for a specific development ; the corresponding effort, however, is believed to be limited, as the CEA has accumulated a good experience on particle fuel development for HTGR'S.

- 2.3 ENERGY CONVERSION SYSTEM

The conversion of the thermal energy into electricity is realized by a single Brayton machine. The coolant gas is a mixture of Helium and Xenon with a specific mass of 40 grams per mole.

The machine is equipped with gas bearings, which allows a long lifetime duration without lubrication. The machine is completely enclosed with its recuperator, inside a vessel filled with the primary coolant gas at the compressor entry characteristics.

A gas cooled radiator is considered at this stage of the study, but the potential advantages of heat pipes radiator is intended to be investigated.

The radiator is disposed symetrically around the axis of the spacecraft, and is an integral part of the holding structure, which transmits the forces between the reactor and the launcher. The other parts of this structure are a tubular treillis between the shielding and the radiator, supporting the pipes and the Brayton machine, and a thin tube, 4.6 meter in diameter made of beryllium joining the radiator to the launcher.

The overall dimensions and the dimensionning are compatible with the caracteristics of the ARIANE 5 launcher see (figure 2).

3 - SYSTEM OPERATING CONDITIONS

A preliminary version of the general system optimization and design code : DIOGENE [3] was used to compute operating conditions (illustrated in fig.5) that minimize the system total mass. However, a design model of the reactor being not available for incorporation in DIOGENE, the optimization was carried out assuming a reactor relative pressure drop low enough (3 %) to prevent an excessive degradation of the conversion cycle efficiency ; and an average (0.38 MPa) compressor inlet pressure was choosen so as to realise the optimum trade-off between the pressure losses (especially in the reactor), the single stage turbine and compressor efficiencies (not to low specific speed), the alternator losses, and the reactor structures mass.

These optimized operating conditions result in a relatively low overall efficiency (16 %) because the main subsystems masses are only slightly (radiator, radiation shield,reactor) if not (power conditioning, APUS, instrumentation, ...) sensitive to the efficiency.

In comparison, mass minimization criterions lead, for either the low or the high temperature version of the liquid metal cooled 20 Kwe systems, to recommend a higher overall efficiency (∿18 %), because both systems require a primary heat excnager (whose mass is sensitive to the efficiency) and poor efficiency electromagnetic pumps (which increase the electrical power to be produced by the conversion system).

4 - CONCLUSIONS

An original concept of a gas cooled particle bed reactor cooled by porous drains has been purposely developed to best meet the requirements of core compacity and coolability with a moderate pumping power, which are crucial for an application as heat source of a space power system using a direct Brayton conversion.

The major advantages of a 20 Kwe power system based on these options, relate :

- To the simplicity afforded by the direct conversion
- To the use of well established and readily available materials and technologies.
- To the improved reliability to be expected from both previous advantages.
- To the excellent heat resistance of the fuel particles

TABLE 1 PARTICLE BED REACTOR CHARACTERISTICS FOR A 20 kwe POWER SYSTEM

Thermal Power (kw)	125
Gas inlet temperature (k)	785.3
Gas peak temperature (k)	1123
Gas outlet temperature (k)	1093
Gas inlet pressure (kPa)	805
Gas relative pressure drop (%)	3.0
Gas flow rate (g/s)	784
Radiator surface (m^2)	53,4

Structural material : Hastelloy XR

Coolant gas : 40g/mole Helium-Xénon mixture

TABLE 2 MASS SUMMARY (Kg)

Reactor	437
Radiation shield	370
Brayton Rotating unit and recuperator	150
Main radiator	281
Power conditionning unit	242
Auxilliary Power Units	289
Instrumentation	75
Supporting structures	100
Interface structures	232
TOTAL MASS	2177

giving a good margin in reference to cooling accidents behavior.

The preliminary conceptual studies of a 20 Kwe nuclear Brayton power system, using the considered gas cooled particle bed reactor, lead to a mass of 800 kg for the reactor equipped with its radiation shield, and to a relative pressure drop of 3 % across the reactor, with an acceptable number of drains (about 300) and with a moderate pressure level in the heat source (0,8 MPa).

These encouraging performances result in a total system mass of 2170 kg for 20 kWe, which compares well with that of equivalent systems equipped with fast spectrum liquid metal cooled reactors operating at the same heat source temperature (850°C).

The preliminary investigations of this reactor concept are obviously by far insuffícent to establish its feasibility, and more detailed design and operating studies will be needed to resolve the relevant critical issues. Among those, which have been already identified are, the reactivity control of the porous bed in case of immersion, the capability of the porous drains to achieve an efficient cooling of the particle bed and of its containment structures, and the compatibility of the fast fluence integrated in the pressure vessel, with the performances of the existing superalloys.

The proposed reactor concept is believed to match consistently and adequately with a direct cycle Brayton conversion system. Furthermore, the use of cooling drains is expected to provide some flexibility for the scalability to higher power levels, as the gas pressure drop across the reactor can be controlled not only by the rise of the absolute pressure but also by increasing the density of the cooling drains, with little impact on the critical core size.

This will be part of the continuation of the joint CNES-CEA program on space power systems, to more in depth assess the feasibility of the drain cooled particle reactor to compare its performances with a direct Brayton conversion, to those of alternative systems with liquid metal cooled, fast spectrum reactors.

ACKNOLEWDGMENTS

This work is being performed within the frame of the joint CNES - CEA study program ERATO at The Institute of Technological Research and Industrial Development (IRDI) of the COmmissariat à l'Energie Atomique (CEA).

All the authors belong to the Department of Mechanical and Thermal studies - Saclay.

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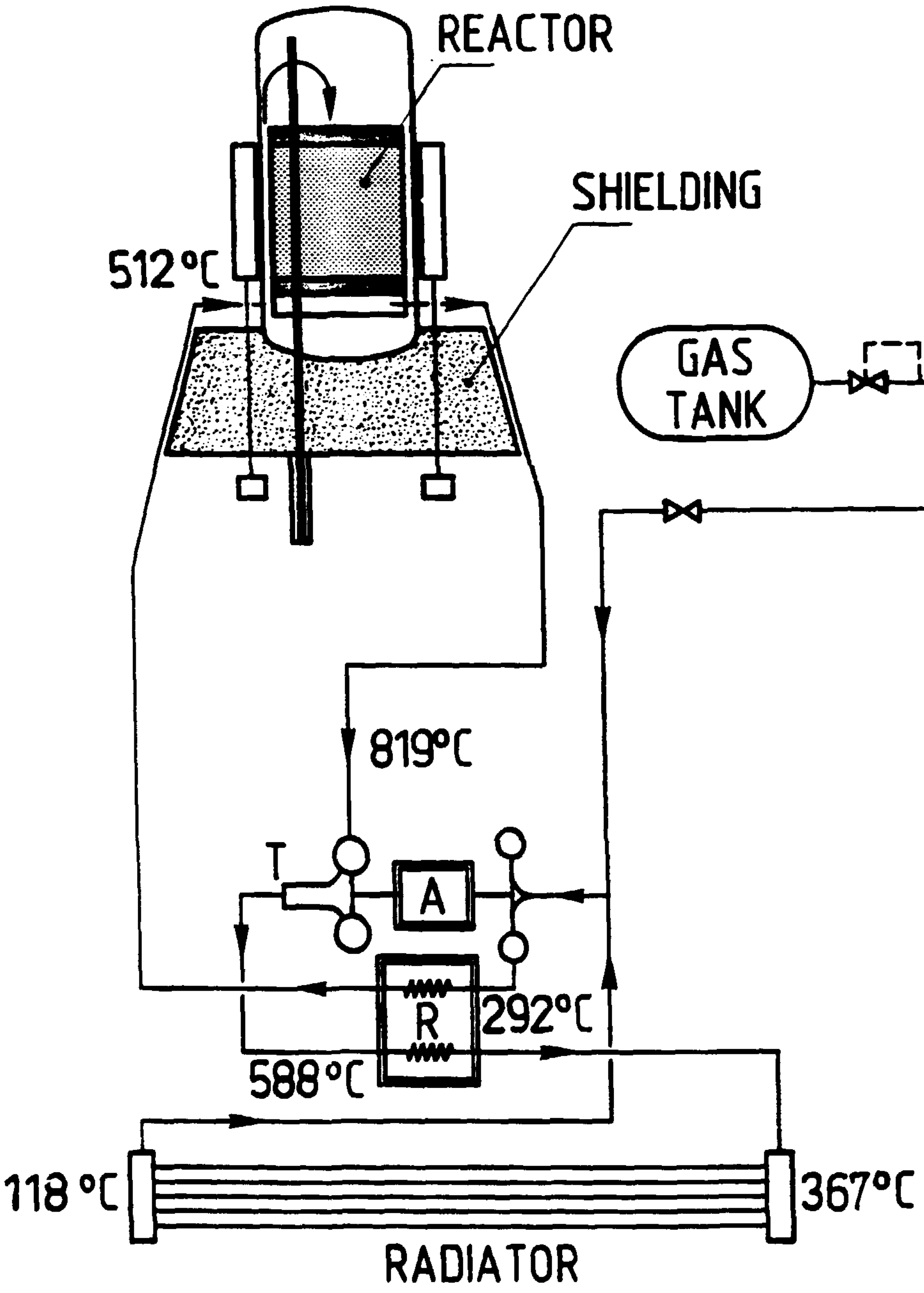


Fig.1 DIAGRAM OF THE REACTOR SYSTEM

T. TURBINE
C. COMPRESSOR
R. RECUPERATOR

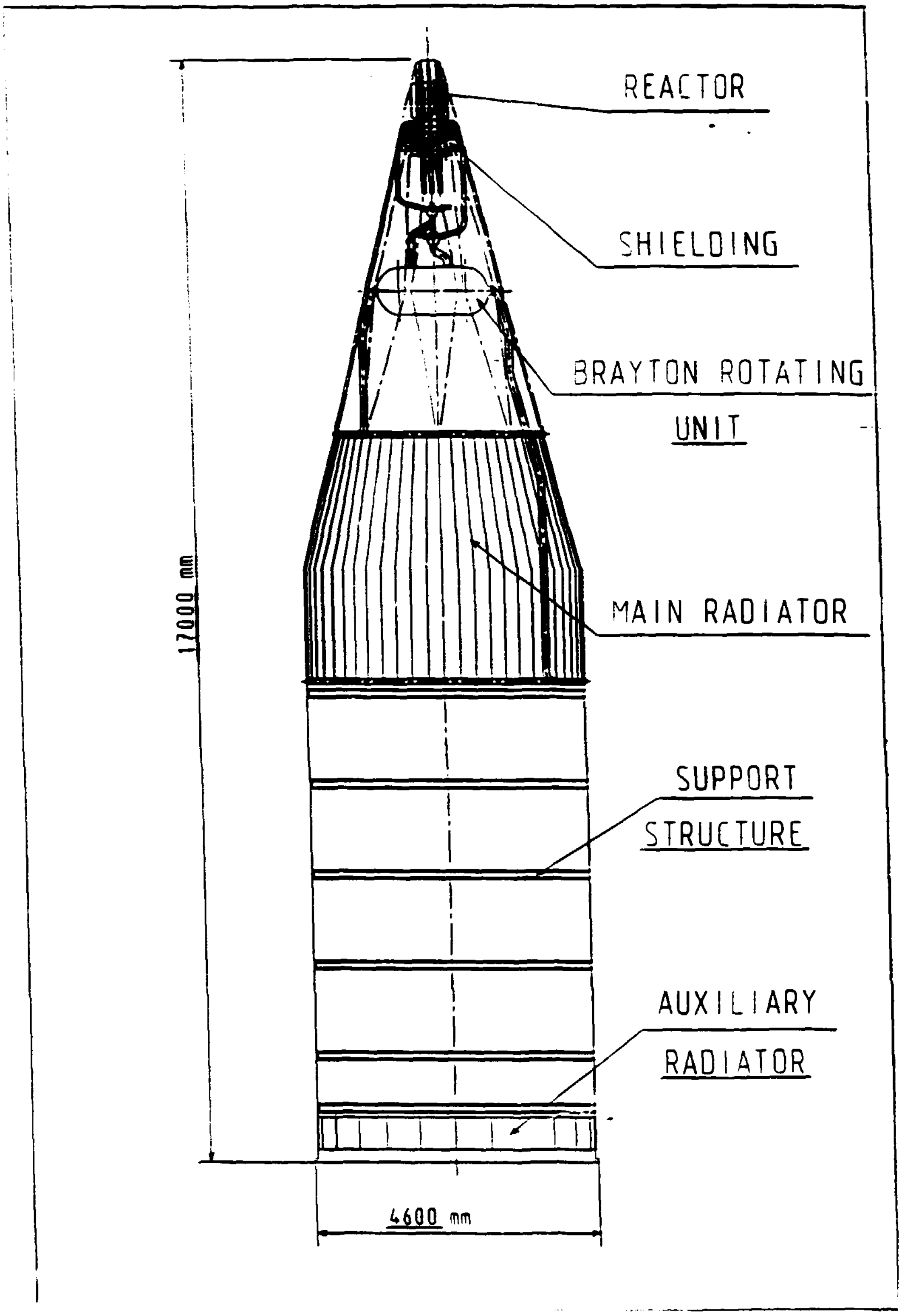


Fig. 2 SPACESCRAFT GENERAL ARRANGEMENT

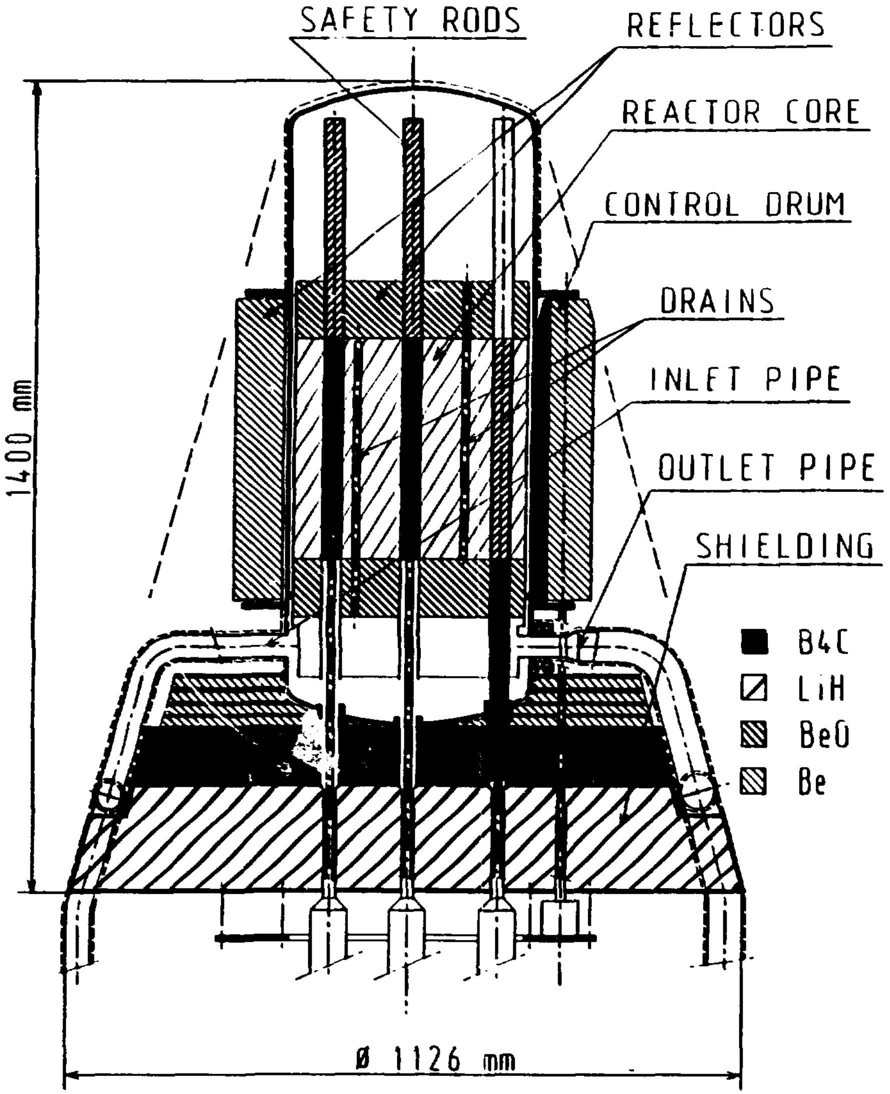


Fig. 3 REACTOR ASSEMBLY

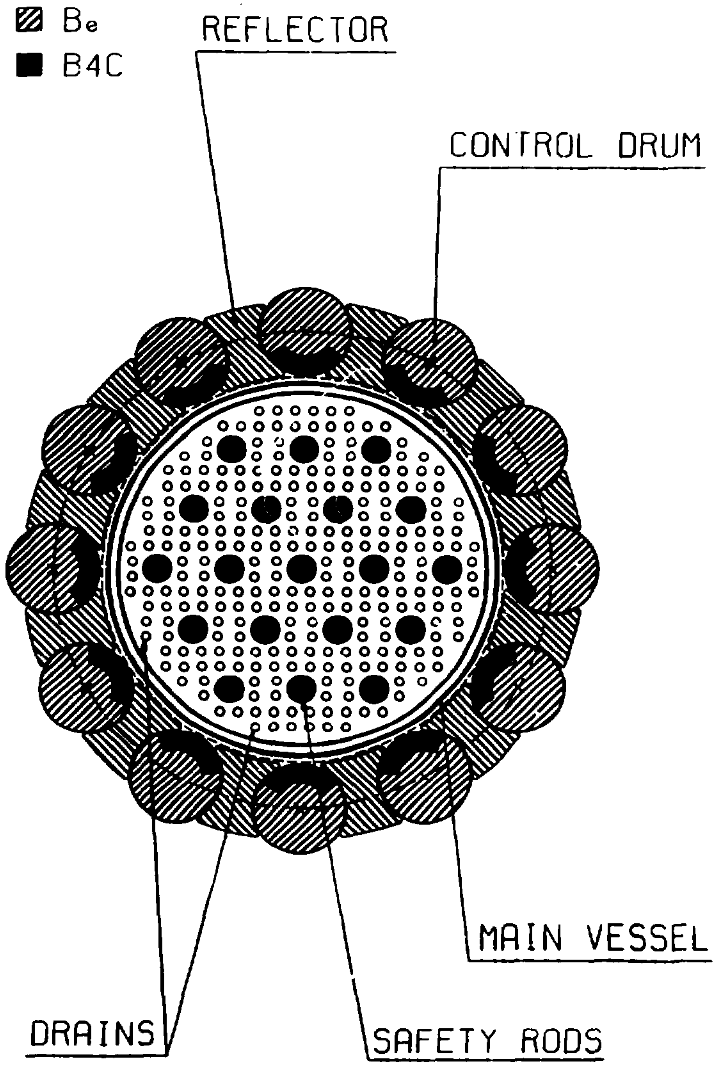
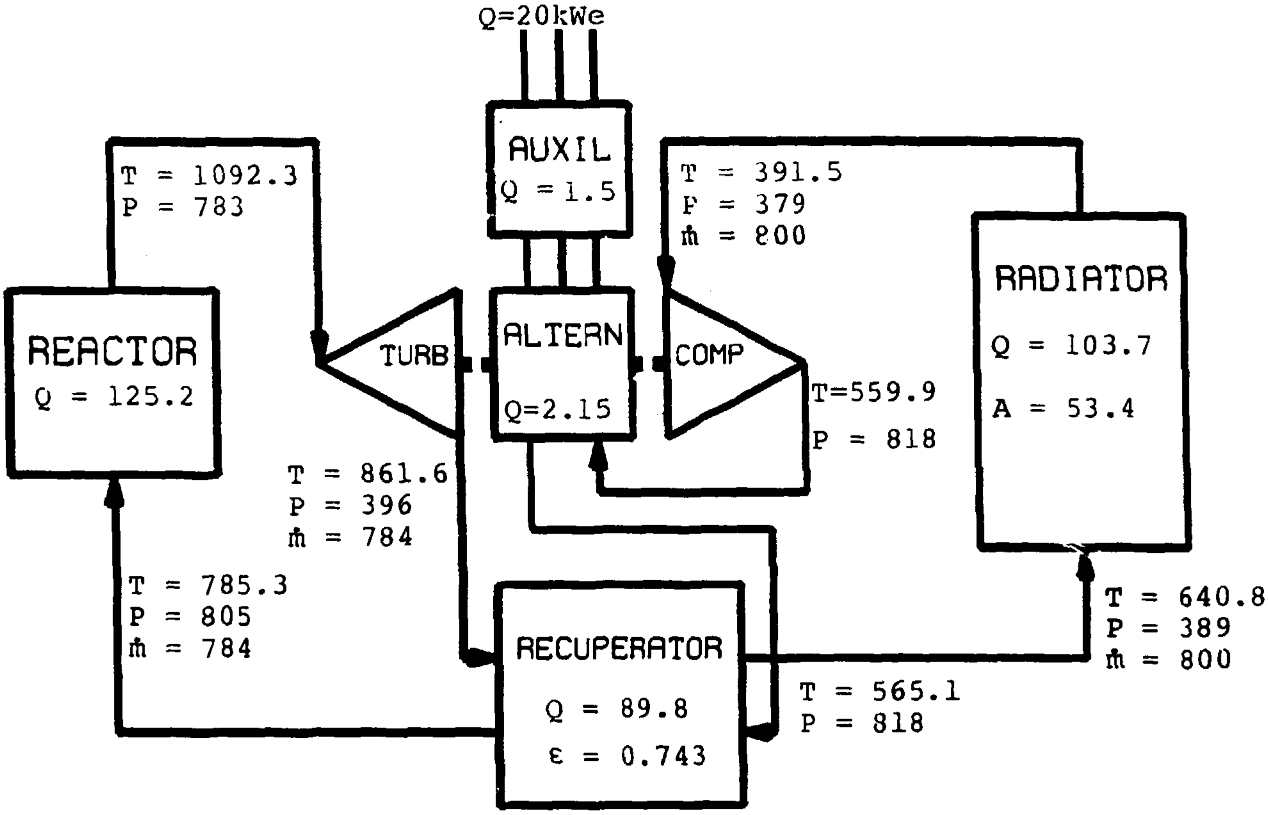


Fig.4 CORE CROSS SECTION



T : Temperature (K)

P : Pressure (kPa)

$\dot{m}$ = Flow rate (g/s)

Q : Power (kW

A : Area (m^2)

Fig. 5 - System Design Point Heat Balance and Statepoint.