A HIGH TEMPERATURE REACTOR FOR SHIP PROPULSION

BY

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ABSTRACT

The initial thermal hydraulic and physics design of a high temperature gas cooled reactor for ship propulsion is described. The choice of the thermodynamic cycle and thermal power is made to suit marine applications. Several configurations of a Helium cooled, graphite moderated reactor are then analysed using the WIMS and MONK codes from AEA Technology. Two geometries of fuel elements formed using micro-spheres in prismatic blocks, and various arrangements of control rods and poison rods are examined. Reactivity calculations through life are made and a pattern of rod insertion to flatten the flux is proposed and analysed. Thermal hydraulic calculations are made to find maximum fuel temperature under high power with optimized flow distribution. Maximum temperature after loss of flow and temperatures in the reactor vessel are also computed. The temperatures are significantly below the known limits for the type of fuel proposed. It is concluded that the reactor can provide the required power and lifetime between refuelling within likely space and weight constraints.

Introduction

There has recently been renewed discussion[1,2] of nuclear power for merchant ships. Reference has been made1 to the consolidated nuclear steam raising plant, a water cooled design for which much relevant data exists. A high temperature gas cooled reactor (HTR) coupled directly to a gas turbine has also been advocated[2], but information on such a system is lacking. Much experience[3] with the proposed fuel exists but it has not been shown that a compact reactor with a long refuelling interval and controllability for marine use can be designed. The present study aimed to produce a preliminary design of HTR suitable for marine use, which operates within the known temperature limits of the fuel.

Power requirements

The first part of the study determines the thermal power required from the core. Considerations of turbine maintenance and operator culture leads to the choice of steam turbine as the power conversion system. A cycle using super-heated steam at 550°C at the turbine inlet is analysed to find its efficiency. The gas circulators are assumed to be similar to those previously described[4]. An assessment of the power required for propulsion, hotel load and coolant circulation when the efficiency of the power cycle is taken into account leads to a requirement for 180 MW thermal from the reactor. The overall plant parameters are given in Table 1.

TABLE 1 - *Overall Plant Parameters*

Thermal power	180 MW
Primary coolant (Helium) flowrate	86 kg/s
Helium core inlet/outlet temperatures	350°C / 753°C
Helium pressure	45 bar
Steam pressure	40 bar

Core Design and Shielding

To design the core, two software packages from AEA Technology were employed. The first, MONK[5], is based on the Monte-Carlo method. This stochastic method is mainly used for calculations of criticality. Calculations of k-effective and burn-up were performed, requiring considerable computer time. The library used was either the JEF2.2 or the UKNDL compilations. The second package is WIMS[6], a deterministic code that solves the Boltzmann Transport Equation. Some modules are based on collision probabilities, others on the Sn method in 1 or 2 dimensions. The code was used in this study to perform rapid burn-up and k-infinity calculations on simple geometries, before using the Monte-Carlo code MONK on whole core models.

The use of prismatic graphite blocks was imposed at the start of the project. A previous study had considered a pebble bed design but concerns exist about the motion of the pebbles and recycling pebbles in the marine environment. Two ways of incorporating the basic fuel microspheres into element are therefore considered, alternate fuel rods and coolant holes in the hexagonal graphite blocks and hollow fuel rods within coolant passages in the graphite moderator blocks. Similar elements have been used in the Fort St Vrain and Dragon reactors[7] respectively. Using WIMS and MONK the effect of rod size and pitch on k-infinity at various burnups was explored. The WIMS model used a single element surrounded by annuli of graphite and helium. The MONK model had a single hexagonal graphite block in reflecting boundaries. The dragon type element was chosen for further analysis because it is more closely linked to the coolant for heat transfer. This should result in superior dynamic behaviour when confronted with the varying power demands of the marine application.

The size of the core was determined by setting a maximum power density of 3.0 MW/m3 which previous studies suggest will limit the temperature during loss of flow accidents[7]. Another constraint is the space available in a typical ship. This has been represented by a 10.0 m cube within which the core, pressure vessel and shielding are required to fit. Using the Dragon type hexagonal blocks this leads to a core of 169 blocks each holding 19 fuel elements with a radius of 3.3 m and a height of 3.0 m. This is shown in (FIG.1).

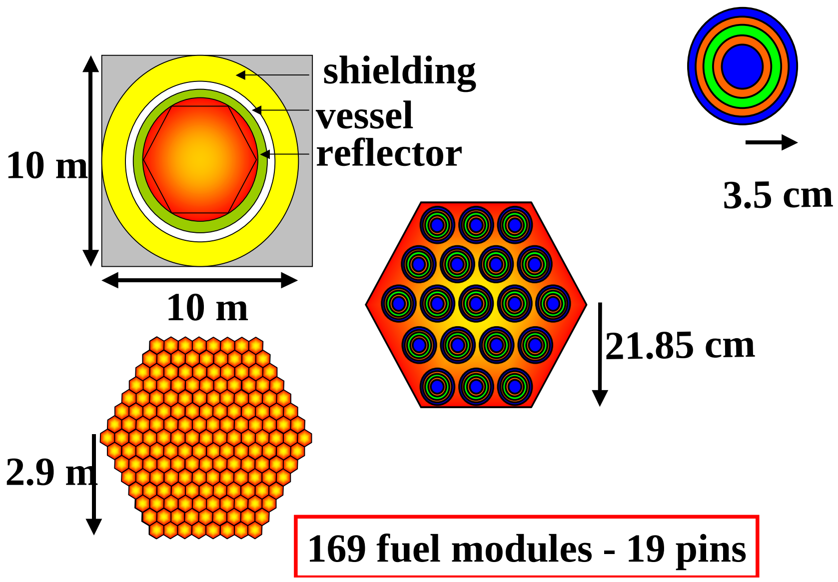

FIG.1 - OVERALL CORE CONFIGURATION

The use of burnable poisons to produce an even reactivity over a long core life was studied using WIMS for infinite array calculations and MONK for whole core calculations. Using WIMS a design of poison rod was developed which gives k-infinity close to 1.15 over a life of 30000 MWd/T. The poison pins are placed in the central hole of each graphite block and have a concentration of gadolinium which increases in four steps from 1% at the outer radius of 3.5 cm to 4% at the inner radius of 1.5 cm. This design was then analysed in a whole core model using MONK and produces k-effective close to 1.1 over the core life.

Three patterns of control rods were analysed using MONK before choosing an arrangement of seven rings of six hexagons each containing a large circular section rod and 12 standard fuel channels. One of these rings is at the centre and one at each corner of the core. The control rod material is Hafnium with a diameter of 12.0 cm. A calculation of the power profile across the core, showed the desired influence of these rods. Four rod configurations based on three rod groups were analysed. Group-1 rods are the six rods in the core centre and Group-2 rods are the remaining four rods in each outer ring. Group-3 rods are the two rods in each outer ring which lie on a radial line to the corners of the core. This grouping can be modelled using 1/12th of the core which can be seen in (FIG.2).

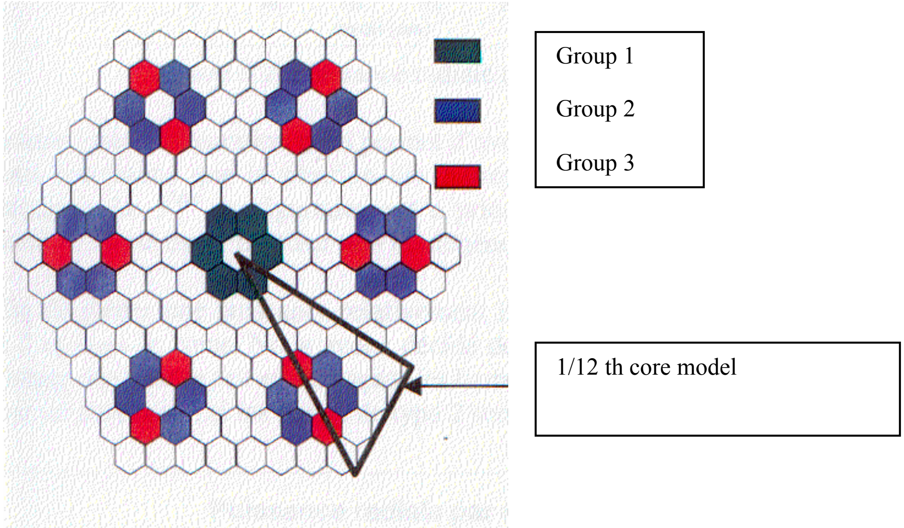

FIG.2 - CORE PLAN AND ROD GROUPS

The final configuration has Group-1 inserted 2.0 m into the 3.0 m high core, Group-3 are fully inserted and the core is controlled by Group-2 rods which are inserted 1.0 m at the start of life. This gives a radial power profile a peak to average value of 1.08 and an average power per assembly of 1.06 MW at full power. Axial power profiles are calculated by the same MONK analysis. This calculates the power in 50 cm axial sections of each hexagonal column in the core. The maximum power in such a section is twice the average power and is found in the region under the central control rods. The k-effective value with all rods withdrawn is 1.117 and with each group alone fully inserted it is 1.0998, 1.0725 and 1.0625. For all rods inserted k-effective = 0.916 and maximum value for any two rods withdrawn is 0.951.

Calculation of the temperature coefficients of reactivity for the fuel and for the moderator were made at the beginning and end of life, showing that a single value closely describes the behaviour between 30°C and 1300°C with a second value between 1300°C and 1700°C.

The effect of poisons following reduction of power from full power is explored by performing a burn up calculation at a constant temperature of 900°C. A reduction in reactivity of 1400 pcm occurs after 3-4 days which can be compensated by withdrawing Group-2 rods. A similar calculation for a reactor scram and temperature fall to 30°C shows recovery of reactivity but confirms that the reactor can still be kept sub-critical even if two rods fail to drop. The principal features of the core are summarized in Table 2.

TABLE 2 - *Principal Features of the Core*

Radius of fuel micro sphere	0.457 mm
Spacing between micro spheres	1.0 mm
Number of micro spheres per element	771300
Radius of fuel element	R_i : 1.875 cm / R_o : 2.50 cm
Radius of Helium channel	R_i : 1.325 cm / R_o : 3.50 cm
Pitch of elements	8.0 cm
Volume % of fuel in element	9.36 %
Number of fuel elements	2790
Number of hexagonal assemblages	169
Assemblage size - centre to flat	21.85 cm
Core size - centre to flat	2.9014 m
Reflector radius	3.8 m
Core height	3.0 m
Power density	2.51 MW/m^3
Number / diam. of control rods (Hf)	42 / 12.0 cm
Number / diam. burnable poison rods (Gd_2O_3)	127 / 7.0 cm

Calculations of the performance, size and disposition of the secondary machinery and of the reactor shielding were also made. These may be the subject of a separate paper.

Thermal Hydraulics

The thermal hydraulics of the reactor was examined to ensure that the maximum fuel temperature in operation is below 1100°C and after a depressurisation accident is less than 1600°C. Programs were written in the general scientific computing package MATLAB[8] to calculate the temperature in the fuel matrix, at the centre of a micro-sphere, in the pressure vessel in the steady state and also for the transient following loss of convective cooling.

The steady state calculation analysed a representative fuel element for each of the 169 prismatic blocks in the core. A numerical integration in the axial direction for the coolant temperature is performed using the power profiles generated by MONK. This is linked to analytical expressions for the radial temperature differences which involves finding the power split to the internal and external coolant channels of the hollow fuel elements. The temperature rise through a micro-sphere is added to the maximum temperature in the fuel matrix. With equal flow rates in all channels the maximum temperature is above 1100°C. The program is developed to optimize the flow distribution so that the temperature is below 1100°C everywhere without an excessive number of different rates. Eleven flow groups are found giving the maximum fuel temperatures shown in (FIG.3).

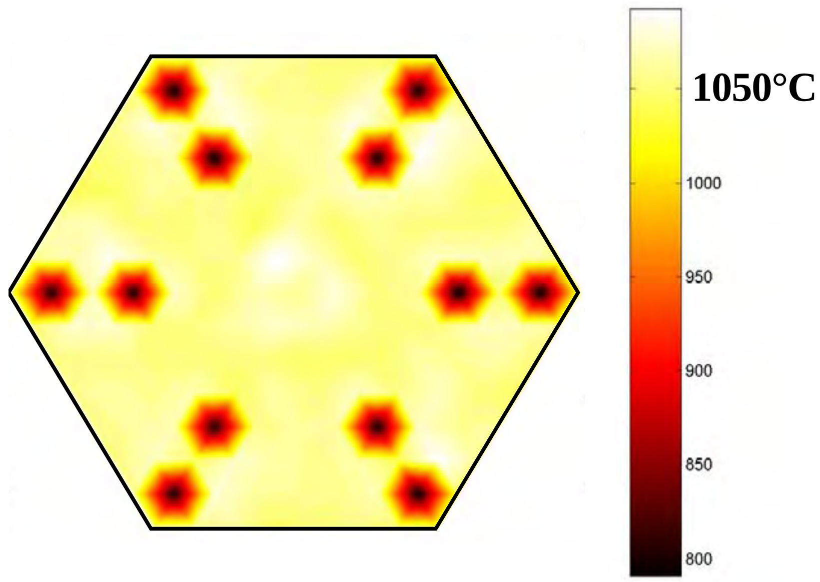

FIG.3 - MAXIMUM FUEL TEMPERATURES IN THE CORE

Further additions to the program allow the temperature in the steel pressure vessel to be calculated. This is externally cooled by natural circulation and on the inside separated from the core by Helium returning from the cold leg and flowing upwards before entering the core. A maximum temperature of 388°C is found at full power with little variation in the axial direction. This is below the limit of 500°C for phase transition.

The transient calculation uses a finite volume solution of the conduction equation with implicit time integration. A 10cm axial slice at the hottest level in the core is modelled. This is divided into six radial regions representing the core, reflector, first thermal shield, Helium layer, second thermal shield and pressure vessel. These are represented by a 25x42 (r,θ) grid of cells. Initial core temperatures shown in (FIG.3) are applied with corresponding values in the outer regions. A representative decay heat input is applied and an outer temperature of 50°C. The calculation is continued until the maximum temperature condition which occurs after 17 hours is found. At this point the maximum temperature is 1253°C, well within the limit of 1600°C proposed at the start of the study.

Conclusions

The advantages of high temperature Helium cooled reactors can be realized in a design which is adapted to the marine propulsion application. A design of sufficient power yet with low power density will fit within the space likely to be available. A long interval between refuelling with an enrichment of 5% can be obtained by using burnable poisons. Calculations confirming this for a scheme using Gadolinium oxide rods have been made. Maximum fuel temperatures at full power can be kept below 1100°C by distributing the Helium flow in a manner which has been calculated. The maximum temperature after a loss of coolant flow can be limited to 1300°C for the design proposed.

References

1. D J Palmer & J Tuttle, “The Economic and Political Feasibility of a Large High Speed Nuclear Merchant Vessel in the 21st Century”, The Nuclear Engineer Vol 42, no 4, Aug 2001, p 121.
2. G A K Crommelin & H van Dam, “The NEREUS approach to broaden applications of nuclear technology”, ICENES 2000, Sept 2000, p217.
3. H Nickel, K Hofmann, W Wacholz and I Weisbrodt “The helium-cooled high temperature reactor in the Federal Republic of Germany: safety features, integrity concept, outlook for design codes and licensing procedures” Nuclear Engineering and Design 127 (1991) p181.
4. P Buhrer, Ch Duttke, J Engel and D Glass, “Research program and test loop for the prototype of a HTR coolant gas circulator with magnetic bearings”, Nuclear Engineering and Design 137 (1992) p83.
5. MONK Users Manual, AEA Technology, 2000.
6. WIMS Users Manual, AEA Technology, 2000.
7. J L Head and A N Kinkead “Graphite fuel element structures for high temperature gas cooled reactors”, Nuclear Engineering and Design 18 (1972) p115.
8. “Using MATLAB Version 6” The MathWorks Inc. 2000.