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TOKAMAK FUSION REACTOR

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REACTOR APPLICATIONS OF THE COMPACT FUSION ADVANCED RANKINE (CFAR) CYCLE

FOR A D-T TOKAMAK FUSION REACTOR

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1. INTRODUCTION

In collaboration with the Japanese researchers, we have been investigating the feasibility of compact, high-temperature Rankine cycles using MHD (magnetohydrodynamic) generators for fusion energy conversion, as originally proposed by Logan [1]. Earlier work on potassium Rankine cycles for fusion using conventional turbines and electric generators (e.g., Refs. 2 and 3), showed considerable promise. However, several problem areas were encountered including the following: (1.) molybdenum or niobium alloys proposed to cope with the high temperatures of the boiling potassium resulted in a large waste disposal problem, (2.) even with the use of refractory alloy structures, the maximum temperature of the blanket was limited to temperatures less than about 1600 K by the turbine blade limitations, (3.) the low density of the potassium vapor required very large outlet ducts, and (4.) the MHD effects on the liquid inflow across the magnetic fields caused large pressure drops and stresses in the inlet ducts. We have overcome these problems by (1.) use of a low-activity vanadium alloy, (2.) the use of MHD disk generators which can operate at temperatures above 3000 K, (3.) use of mercury which has higher vapor pressures than potassium, and (4.) use of a technique which flashes the liquid at the inlet to the blanket into a mist flow. This latter technique is a variation of the concept of using a helium carrier gas to carry potassium as droplets into the blanket proposed in Ref. [3].

In this paper, a preliminary design of a blanket concept with the above features is described, and the results of performance calculations for this concept with and without the benefit of a microwave superheater are presented.

2. REACTOR PARAMETERS

Table 1 shows a set of self-consistent tokamak reactor parameters which were chosen to maximize the synchrotron radiation produced by the plasma. The reactor utilizes the synchrotron radiation for current drive [4] and also for additional superheating of the mercury vapor. The neutron wall loading which results is 4.6 MW/sq.m. Two cross-sectional views of one of the twelve sectors of the reactor, each with its own MHD disk generator and condenser are given in Figures 1 and 2. These scale drawings illustrate the compact size of the power conversion components which all fit inside the reactor vault except for the final natural draft, heat rejection heat exchanger which is "wrapped" around the outside of the vault.

3. REFERENCE CYCLE AND BLANKET CONCEPT

The CFAR cycle is shown in Figure 3 and some key cycle and blanket parameters are given in Table 2. The cycle is implemented with the components shown in Figure 4. Each of the twelve blanket sectors contains 40 blanket modules, each with a nominal frontal area of one square meter. A typical outboard module in the equatorial plane of the reactor is shown in Figure 5, and all the discussion which follows will be for this typical module unless otherwise stated. Using these figures, the cycle and blanket concept will now be described step by step, starting at state 1:

1-2: The liquid mercury (seeded with less than 1 mole-% of potassium) is pumped from the condenser pressure of 3800 Pa (0.55 psia) to 636,000 Pa (92 psia).

2-3-4: The liquid mercury is preheated to the saturation temperature using heat rejected from other parts of the cycle (a form of internal regeneration).

4-5: The liquid mercury is flashed through a specially designed orifice to the boiling pressure of 327,000 Pa (48 psia); this produces a mist flow with a quality of 2.3% and a void fraction of about 96% at state 5 at the entrance to the blanket modules (see Figs. 4 and 5).

5-6: The mist flow cools the vanadium-alloy module side walls as it flows toward the

first wall, absorbing about 1% of the neutron internal heat generated and increasing in quality to about 4.1%. The temperature remains at the saturation temperature of 703 K.

6-7: The mist flow turns the corner into the first wall channels and the droplets are forced to the walls of the channels by swirl inserts at position 6, creating an annular liquid film flow with a vapor core flow. (This two-phase flow pattern is very stable for mercury according to Ref. [5], and the parallel magnetic field should enhance its stability.) The modules are designed such that the two-phase mercury then flows parallel to the main toroidal field to minimize the MHD effects on the liquid film flow. The flow removes the plasma and neutron heating of the first and second walls and increases its quality to about 21.5% at state 7.

7-7B: The two-phase mercury then flows into a plenum and is directed into the flow channels between the plates of the low temperature breeder zone by a suitable arrangement of vanes and distributor baffles which are designed to produce an "annular" two-phase mercury flow with the liquid flowing on the walls of these channels.

7B-8: The low temperature breeder zone has been designed as an array of parallel plates to reduce the strength of the electrical eddy currents and the resultant MHD retarding body forces on the liquid film flow as was done in the flattened heat pipe design concept of Ref. [6]. 45% of the neutron internal heat generation is absorbed by the evaporating mercury in this zone, and the reference flow rate is chosen to produce a quality of 100% at the exit position 8.

8-9: Saturated mercury vapor enters the first of two high-temperature pebble beds at state 8. Packed beds like those proposed for the MARS Synfuel blanket [7] were chosen for these zones because they are ideally suited for high temperature operation; in addition, the high pressure drops associated with such high-temperature, low-density flows have only a small effect on the thermal efficiency of Rankine cycles, unlike the strong detrimental effect they can have on Brayton (gas-turbine) cycles. The mercury vapor is superheated from 703 K at the inlet to 2071 K

at the exit state 9 of this BeO pebble bed. (The BeO pebbles contain 20% lithium aluminate for tritium breeding.)

9-10: The flow is further superheated in a ZrC pebble bed to 2950 K at state 10, where it exits the blanket through insulated ducts in the shield to the microwave superheater (MWSH).

10-11: Synchrotron radiation from the fusion plasma is transported in wave guides to twelve specially designed microwave cavities just outside the shields of each of twelve blanket sectors, as shown on Figs. 1 and 2. The microwave radiation then passes through the walls of the porous ceramic tubes of the microwave superheater (MWSH); this further superheats the seeded mercury vapor to about 3258 K at state 11. (See Ref. [8] for further details.) In order to keep the walls of the ceramic tubes at about 1000 K so that they will be transparent to the microwaves, it is estimated that about 15 % of the mercury vapor will be required for transpiration cooling of the porous tube walls. The potassium seed is separated from this portion of the liquid mercury flow in the cooler/separator in process 15-16 as shown on Fig. 4. This 15% of the liquid mercury is then pumped, flashed, evaporated and superheated from state 1 to state 10 in modules which are otherwise identical to the rest of the modules used to heat the seeded mercury flow, as shown on Fig. 4.

10-8TR: The unseeded mercury vapor is cooled from 2950 K at state 10 to 900 K at state 8TR for use in transpiration cooling of the ceramic MWSH tubes by passing it through regenerator/heat exchangers which heat the liquid mercury flows from state 3 to state 4, as shown on Fig. 4. Since the heat content of the 15% unseeded mercury vapor flow is usually insufficient to heat all the liquid flow from state 2 to state 4, the heating of the liquid from state 2 to state 3 is done using part of the waste heat from the vapor precooler from state 13 to state 13N.

11-12: The highly superheated flow at about 3258 K is expanded in a supersonic nozzle and enters the twelve MHD disk generators (one for each sector of the blanket). The flow expands over a reference pressure ratio of 70 down to a Mach number of about unity and a temperature of 1354 K at the generator exit state 12.

About 85 MW of DC electric power is produced by each MHD generator; this DC power is inverted to AC and sent to the electric grid. No other power generators or turbines are required. (For further details of the MHD generator performance, see Ref. 9.)

12-13: The flow is diffused to subsonic velocities in a nearly-adiabatic diffuser duct leading to the mercury precooler/desuperheaters and condensers. The pressure drop across the diffuser is not critical, since very large fractional pressure drops can be tolerated in the low pressure components with negligible impact on the cycle efficiency.

13-14: The front part of a compact finned-tube, cross-flow heat exchanger is the mercury vapor precooler/desuperheater. The initial heat rejection from state 13 to 13N is used to preheat the liquid mercury from state 2 to 3, as mentioned above. The next part of the heat rejection is used to heat the liquid mercury from state 16 to 1 after the tritium and potassium seed separation processes. Any remaining vapor heat rejection required to bring the vapor down to the condensing temperature at state 14 is to boiling freon (which is used as the heat-rejection coolant in the desuperheater and condenser).

14-1: The back part of the cross-flow heat exchanger is the mercury condenser where the bulk of the heat rejection to boiling freon takes place. The freon evaporates as it flows through the condenser tubes and then is transported outside the reactor vault to a natural draft heat exchanger, which is built around the outside of the reactor vault for compactness. The heat is then rejected to the atmosphere, recondensing the freon.

From the above discussion, it can be seen that the cycle is a unique type of regenerative Rankine cycle, where every effort has been made to minimize the main heat-transport piping required, keep the power conversion system compact and minimize the waste heat rejected to the atmosphere in order to obtain an acceptable cycle efficiency, while avoiding the use of any bottoming cycles or additional power conversion components.

As shown on Table 2, the reference cycle efficiency is 35% when the microwave superheater is used. If the microwave superheater is eliminated and the synchrotron radiation is assumed to be absorbed in the first wall, then the cycle efficiency decreases to about 32%. This illustrates the fact that CFAR cycles for D-T reactors can give excellent performance even without microwave superheating. More benefit of microwave superheating is expected with advance fuel reactors such as D-He3 reactors, where a large portion of the fusion energy release can be converted to synchrotron radiation for use in superheating. Application of this advanced Rankine cycle to D-He3 reactors will be considered in future work.

4. SOME OTHER ISSUES

We are looking into the issues of materials compatibility and high-temperature capabilities (10), tritium inventory, afterheat and safety, and costs. These will have to be reported upon in a future paper, due to lack of space.

5. SUMMARY AND CONCLUSIONS

We have made a preliminary design of a D-T fusion reactor blanket and MHD power conversion system based on the CFAR concept, and found that the performance and costs for the reference cycle are very attractive. While much remains to be done, the potential advantages of liquid metal Rankine cycles for fusion applications are much clearer now. These include low pressures and mass flow rates, a nearly isothermal module shell which minimizes problems of thermal distortion and stresses, and an insensitivity to pressure losses in the blanket so that the two-phase MHD pressure drops in the boiling part of the blanket and the ordinary vapor pressure drops in the pebble-bed superheating zones are acceptable (the direct result of pumping a liquid rather than having to compress a gas). There are no moving parts in the high-temperature MHD power generators, no steam bottoming plant is required, only small vapor precoolers and condensers are needed because of the high heat rejection temperatures, and only a relatively small natural-draft heat exchanger is required to

reject the heat to the atmosphere. The net result is a very compact fusion reactor and power conversion system which fit entirely inside an 18 meter radius reactor vault. Although we have not yet performed a detailed cost analysis, preliminary cost estimates [11] indicate low capital costs and a very attractive cost of electricity.

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TABLE 1

REFERENCE DT REACTOR PARAMETERS WITH CFAR ENERGY CONVERSION

Fusion Power	2750 MW
Alpha Power	550 MW
Synchrotron Radiation	380 MW
Bremsstrahlung Radiation	31 MW
Transport Loss	139 MW ($\tau_E = 2\tau_{KG}$)
Major Radius	6.0 M
Minor Radius	1.2 M
Elongation	2.4
Triangularity	0.4
Edge Safety Factor	2.8
Toroidal Field	10 T
Toroidal Current	20 MA (3 MA Bootstrap)
Troyon Coefficient	0.030
Ave. Plasma Temperature	43 KeV
Ave. Plasma Density	$1.1 \times 10^{20} \text{ m}^{-3}$
Ave. Plasma Beta	0.05
Ave. Neutron Wall Load	4.6 MW/m^2
Ave. First Wall Heat Flux	0.16 MW/m^2 (0.23 MW/m^2)
Ave. Divertor Heat Flux	2.1 MW/m^2
First Wall Area	480 m^2
Synchrotron Waveguide Area	60 m^2
Synchrotron Poynting Flux	6.4 MW/m^2
Synchrotron Current Drive	12 MA
Synchrotron Current Drive Efficiency $\text{NIR}/P_{\text{SYNC}}$	$0.24 \text{ AW}^{-1} \text{ m}^{-2}$

TABLE 2

REFERENCE PARAMETERS FOR HIGH TEMPERATURE BLANKET FOR D-T FUSION REACTOR

INTERNAL HEAT GENERATION FOR $\Gamma_N = 4.6 \text{ MW/m}^2$

Vanadium First Wall	27 MW/m^3
Liquid Hg Behind First Wall	69 MW/m^3
Beryllium Nearest First Wall	31 MW/m^3
Flibe Nearest First Wall	60 MW/m^3

TRITIUM BREEDING RATIO (1-D) 1.07

BLANKET MULTIPLICATION (1-D) 1.30

NEUTRON AND GAMMA HEATING DISTRIBUTIONS:

Inflow (process 5-6)	1%
First Wall Zone (process 6-7B)	5%
Low Temp. Breeder (process 7B-8)	45%
BeO Pebble Bed (process 8-9)	28%
ZrC Pebble Bed (process 9-10)	18%
Shield	3%
	100%

High Temperature Heat Fraction (28 + 18) = 46%

REFERENCE CYCLE PARAMETERS	WITH 361 MW NET MICROWAVE SUPERHEATING ($F_{TR} = 15\%$)	
	WITHOUT MICROWAVE SUPERHEATING	
Boiling Temp. $T_5 = T_8$	703 K	703 K
Condensation Temp $T_1 \approx T_{14}$	488 K	488 K
Blanket Outlet Temp T_{10}	2581 K	2950 K
Microwave Superheater T_{t11}	2581 K	3258 K
MHD Generator Press. Ratio P_{t11}/P_{t12}	70	70
MHD Generator Efficiency	71%	73%
Rankine Cycle Efficiency, η_{th}	32%	35%
CFAR Plant Efficiency	27%	30%
NET Electric Output	943 MWe	1020 MWe

FIGURE TITLES

Figure 1. Cross-sectional side view of the D-T tokamak reactor with the compact fusion advanced Rankine (CFAR) power conversion system.

Figure 2. Equatorial plan view of one sector of the D-T tokamak reactor with the CFAR power conversion system.

Figure 3. The CFAR cycle temperature-entropy diagram showing the various states referred to in the text and on Figures 4 and 5.

Figure 4. Block diagram of the CFAR power conversion system showing the components with the inlet and exit states of the mercury flow indicated.

Figure 5. Three sectional views of a typical outboard module in the equatorial plane of the reactor showing the double-walled vanadium-alloy module shell and the internal blanket configuration (not to scale).

(a.) Top View of Typical Module

(b.) Front-View (Section B-8)

(c.) Side View of Module