Conf-910968--24

UCRL- JC-108494
PREPRINT

Received by OSTI

NOV 01 1991

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This paper was prepared for presentation at
The 14th IEEE/NPSS Symposium
on Fusion Engineering
San Diego, California
9/30 - 10/3/91

September 30, 1991

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COMPACT FUSION ADVANCED RANKINE (CFARII) POWER CYCLE - OPERATING REGIMES

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UCRL-JC--108494

DE92 002171

Abstract

Performance (cost/kWe and efficiency) of generic Compact Fusion Advanced Rankine (CFARII) power conversion is investigated for various working fluids, operating temperatures and pressures, and thermal power levels. A general conclusion is that good CFARII performance is found for a remarkably broad range of materials, temperatures, pressures and power levels, which gives considerable flexibility to future design studies which may apply CFARII energy conversion to specific fusion energy sources such as ICF, MIFC, and Mini-PACER.

Introduction

A recent work¹ reported at the 1991 ICENES Conference in Monterey described the basic concept and numerical model for the Compact Fusion Advanced Rankine (CFARII) type of plasma magnetohydrodynamic (MHD) power conversion system (see Figure 1). That work evaluated the performance (cost and efficiency) for a particular reference case CFARII Balance-of-Plant (BoP), with plasma parameters similar to those proposed earlier by Velikhov², and found a very low cost (≤ 40 M\$ for a 1 GWe BoP) and high efficiency ($\geq 50\%$ gross cycle efficiency), sufficiently attractive to justify further work. Accordingly, this work surveys CFARII performance for several different working fluid materials, operating plasma temperature and pressures, and thermal power levels, to help guide the selection of suitable combinations of those choices in future studies which could apply CFARII power conversion to particular fusion sources (such as ICF³, MIFC⁴, and Mini-PACER⁵). The MHD generator design used here is similar to the reference case design in Reference 1, but has magnetic fields and dimensions changed for different plasma parameters as described in the following section.

CFARII Performance Evaluation

The numerical model used to evaluate the reference case CFARII design in Reference 1 was generalized to accept any working fluid species characterizable by specifying the following input parameters for any mixture of up to three primary elements:

- (1) the molar fractions m_{fi} of each element, assuming the gas species are completely dissociated above some minimum temperature T_x , taken also to be the minimum exhaust temperature at the exit end of the MHD generator;
- (2) the molar masses m_i (kg/mole) of each element;
- (3) the first ionization potentials I_i (in eV) of each element;
- (4) the mass density ρ_L (kg/m³) of the liquid phase of the mixture;
- (5) the total specific enthalpy h_s (MJ/kg) to take the mixture from solid state at 300°K to the dissociated gas phase at temperature T_x , including the heats of fusion, vaporization, and dissociation, if any;
- (6) the specific enthalpy rise per pass Δh_L (MJ/kg) for the condensate "raindrops" recirculating in the condenser (see Fig. 6 in Ref. 1).

Besides the three primary elements in each working fluid mix, the model includes a fourth species for the transpiration-coolant injected from the jet nozzle walls and

MHD generator electrodes. The molar fraction of this fourth species varies continuously from 0 at the start of the jet to 5-20% of the original mix flow rate, as the wall coolant mass flux mixes into the turbulence core flow. This wall coolant (an alkali metal such as cesium, potassium, or lithium) cools the walls by its heat of vaporization, thickens the conductive, laminar boundary layers, reduces momentum loss due to viscosity, and greatly reduces radiation loss, all at the expense of parasitically reducing the plasma jet kinetic energy when it mixes in (see Ref. 1). Lithium is the preferred wall coolant due to its low mass and high heat of vaporization, and is assumed to be the wall coolant in all cases here. Since all cases also assume lithium as one of the primary mix elements (for the purpose of allowing tritium breeding), there are actually only three elements in each mix, with one (lithium) varying in molar fraction as a function of distance down the channel in the model.

Implied but unspecified fusion targets are assumed to vaporize and singly ionize solid target shells of a working material, raising the material to an average plasma temperature $T_c \approx 1-3$ eV (12,000 to 36,000°K) at pressures $p_c \approx 40$ to 1000 bar in a suitable reactor cavity. Fusion yields of order 10 GJ absorbed in shells > 1 neutron mfp thickness would add a "superheat" plus "ionization" enthalpy h_g which is usually much larger than h_s . Since the "saturation" enthalpy h_s in this type of Rankine cycle is rejected out the condenser, the maximum possible MHD CFARII cycle efficiency η_{MHD} (assuming radiation losses in the plasma jet and MHD generator channels were small) would be

$$\eta_{MHD} \approx \frac{h_g}{h_g + h_s} \quad [\text{ideal}]. \quad (1)$$

Thus, materials which both easily ionize (adding available ionization energy in h_g) and easily vaporize (lower h_s) are generally desirable. Radiation losses are included in the model as described in Reference 1, and range from $< 5\%$ of h_g at $T_c < 1$ eV, $p_c > 200$ bar, to $> 50\%$ of h_g at $T_c > 3$ eV, $p_c < 200$ bar. Design features to minimize radiation loss are included in the model as described in Reference 1.

For simplicity, the model neglects doubly-ionized species in calculating Saha equilibrium ionization, which is a reasonable approximation below 3 eV at the high pressures considered here. Temperatures above 3 eV are not useful anyway because increased radiation losses prevent η_{MHD} increasing in proportion to h_g above that temperature. Ideal efficiencies at $T_c \approx 3$ eV range from 70 to 90% depending on the material (but as found in this report, radiation, entrance eddy, joule and friction losses typically reduce these ideal efficiencies down to 50 to 60%, respectively).

Working Fluids Evaluated

Table 1 lists the constituents and input data for four different working fluid mixtures evaluated here, and designated as "KLA", "FLB", "PLA", and "LKA". Mixtures are used instead of single elements for a variety of reasons, including: (1) the model for radiation transport loss assumes continuous opacity as a function of wavelength, and mixtures run a far lower risk of having occasional opacity windows than do single elements. (2) Lithium is a needed ingredient in all cases for fusion to have tritium breeding, but pure lithium by

Figure 1 General scheme for Compact Fusion Advanced Rankine (CFARII) MHD-power-conversion cycle

Table 1 Input Data on Four Working Fluid Mixtures Evaluated for CFARII Performance

Mixture "KLA"

Potassium, lithium, aluminum

Minimum temp. $T_x = 3400^{\circ}\text{K}$

Liquid mass density $\rho_L = 2000 \text{ kg/m}^3$

Average molar mass $m_o = 0.0315 \text{ kg/mole mix}$

Sat. Enthalpyp (to T_x) $h_s = 8 \text{ MJ/kg mix}$

Liquid enthalpy rise $\Delta h_L = 0.4 \text{ MJ/kg}$

Element	Molar Fraction	Ionization Energy (eV)
K	0.70	4.32
Li	0.20	5.36
Al	0.10	5.96

Mixture "FLB"

Flourine, lithium, beryllium (FLiBe salt)

Minimum temp. $T_x = 5000^{\circ}\text{K}$

Liquid mass density $\rho_L = 2000 \text{ kg/m}^3$

Average molar mass $m_o = 0.028 \text{ kg/mole (atoms)}$

Sat. Enthalpyp (to T_x) $h_s = 18 \text{ MJ/kg mix}$

Liquid enthalpy rise $\Delta h_L = 0.8 \text{ MJ/kg}$

Element	Molar Fraction	Ionization Energy (eV)
F	0.57	17.34
Li	0.29	5.36
Be	0.14	9.28

Mixture "PLA"

Lead, lithium, aluminum

Minimum temp. $T_x = 4600^{\circ}\text{K}$

Liquid mass density $\rho_L = 9600 \text{ kg/m}^3$

Average molar mass $m_o = 0.168 \text{ kg/mole (atoms)}$

Sat. Enthalpyp (to T_x) $h_s = 1.4 \text{ MJ/kg mix}$

Liquid enthalpy rise $\Delta h_L = 0.2 \text{ MJ/kg}$

Element	Molar Fraction	Ionization Energy (eV)
Pb	0.80	7.38
Li	0.15	5.36
Al	0.05	5.96

Mixture "LKA"

Lithium, potassium, aluminum

Minimum temp. $T_x = 4200^{\circ}\text{K}$

Liquid mass density $\rho_L = 560 \text{ kg/m}^3$

Average molar mass $m_o = 0.083 \text{ kg/mole (atoms)}$

Sat. Enthalpyp (to T_x) $h_s = 25 \text{ MJ/kg mix}$

Liquid enthalpy rise $\Delta h_L = 1.2 \text{ MJ/kg}$

Element	Molar Fraction	Ionization Energy (eV)
Li	0.95	5.36
K	0.03	4.32
Al	0.02	5.96

itself may not give optimum performance due to its very high heat of vaporization. The "LKA" mixture in Table 1 is chosen lithium-rich to represent the basic performance of pure lithium, but adds small amounts of other elements to cover opacity windows. (3) In some cases an added element may be desired to reduce lithium flammability, as in the cases of lead-lithium alloy (the "PLA" mix) and FLiBe ("FLB"). (4) In KLA, PLA and LKA mixes, some aluminum content is chosen to allow for the possibility of using strong, lightweight, breeding-compatible alloys of lithium-aluminum to form some needed fusion target shell structure in future reactor designs using CFARII.

The FLB (FLiBe salt) case is included since a lot of experience and data with FLiBe is available from many previous fusion reactor designs. FLiBe is non-flammable, and could be cast into solid pipes and shells of salt to be used in fusion targets for CFARII cycles. In addition, it is a poor conductor of electricity, so it offers the possibility of being used as a protective liquid salt coating on ceramic insulators in the MHD generator side walls, eliminating the need for recirculating helium gas to accomplish this in Figure 2. Finally, FLiBe gives a good first example of potential CFARII performance for a much wider class of chemically-active working fluid compounds, including, for example, steam, uranium hexafluoride, and lithium hydride, to name a few, which could be studied in the future.

Cost Model

Table 2 lists the subsystem elements included in the CFARII Balance-of-Plant cost model used here, based on the design concepts described in Reference 1. Table 2 shows the costs and unit costs for the reference case in Ref. 1, which is repeated as one of the KLA mix calculations here (the point at $T_c = 13,300^\circ\text{K}$ and $p_c = 200$ atm), and also lists the cost scaling factors for each subsystem used in this survey. The cost scaling factors indicate the physical basis of estimating the costs here and in Reference 1, and also the exponents are indicated to include the effect of economy-of-scale on costs of different subelements. The unit costs assumed at the reference case size represent the conservative high-end of assumptions commonly used in other fusion reactor design studies, with the exception of the DC/AC inverters, whose unit costs assume a factor of 2-4 cost/kWe reduction from current gas thyatron-switch technology. The CFARII generator voltages (1 to 2 kV) are in a convenient range for many new switch technologies that promise considerably higher performance than thyatrons (for example, new solid state power transistors).

As Table 2 shows, the single largest CFARII cost element (next to the DC to AC inverters), is the MHD generator magnet cost, as is typical of many MHD generators designed and built. In the particular CFARII mode of using the MHD generator to extract energy by slowing down the plasma jet rather than by reducing pressure (so-called impulse mode of MHD generator operation), the MHD generator magnet cost is sensitive to the required magnetic field at the generator exit, which is typically several fold stronger than the field at the generator entrance, to compensate for the usually falling plasma temperature hence, conductivity, from the generator inlet to the generator outlet. Since the exit field $B_{\text{exit}}^2 \sim 1/\sigma_{\text{exit}}$, where

the exit plasma conductivity σ_{exit} is exponentially-dependent (very sensitive) on the lowest exit temperature, it was difficult for the numerical model to determine optimum generator parameters to minimize costs/kWe. The values of T_x fixed for each working fluid in Table 1 are roughly consistent with minimum cost/kWe, but not exactly so. For the purposes of this first survey, the absolute generator

magnet costs for minimum \$/kWe, are sensitive to T_x , so the numerical determination of costs with different T_x fixed for each species is uncertain to within $\pm 30\%$ on generator magnet costs, giving $\pm 6\%$ BoP cost/kWe uncertainty. Thus, the reader is advised to ignore differences of $\sim 10\%$ in cost/kWe reported in the next section, and look only at broader trends. The estimated numerical uncertainty in determining efficiency η_{MHD} is smaller, $\pm 2\%$.

In the model of Ref. 1, the plasma jet velocity (and convertible kinetic energy) increases with increasing jet expansion ratio p_c/p_{jet} (exit) until the momentum loss due to lithium wall coolant mass injection (proportional to the radiation loss) stops further jet velocity increases (limiting the maximum generator electrical output), or until some other constraint is applied. In this survey, either one of two constraints are applied to the jet expansion ratio: (1) the expansion ratio stops at maximum generator output, caused either by the jet velocity limit discussed above, or when the generator exhaust plasma temperature drops to the minimum set by T_x (to prevent precipitous increases in the generator exit magnetic field), whichever constraint applies first. This mode gives the maximum η_{MHD} subject to these combined constraints, and the unit capital cost/kWe is calculated at this maximum of η_{MHD} . (2) As the unit capital cost/kWe often reaches a minimum with jet expansion ratio before the maximum generator output is reached, the numerical calculation can be set to stop the jet expansion when the minimum cost/kWe is reached, and then η_{MHD} returned at this minimum is less than the maximum η_{MHD} . Both modes are used in different cases, and often the \$/kWe for maximum η_{MHD} can be 50% higher than the minimum \$/kWe, for only a few % points difference in η_{MHD} . Unless the reactor plant (non-BoP) costs are more than 10 times higher than the \$ (of BoP)/kWe calculated here, the minimum \$ (BoP)/kWe is a good indicator of desirable jet expansion ratio when CFARII is applied in the future to a complete plant design. If very high non-BoP costs are anticipated, then the \$ (BoP)/kWe for maximum η_{MHD} can be used.

Results of CFARII Performance Survey

The results of this CFARII performance survey are presented in Figures 3-7. Figures 3 and 4 compare the performance of the four working fluid mixtures for efficiency η_{MHD} at minimum \$/kWe (Fig. 3) and minimum \$/kWe (Fig. 4) at the same pressure $p_c = 200$ bar and thermal power $P_{\text{jet}} = 2$ GW. Figures 5 and 6 explore the variation of maximum efficiency and \$/kWe at maximum efficiency, respectively, with reactor stagnation pressure, for the KLA working fluid. Figure 7 explores the economy-of-scale effect with P_{jet} on η_{MHD} and \$/kWe at minimum \$/kWe, also for the KLA working fluid.

Comparing the performance of the four working fluids, the major observation one can make from Figs. 3 and 4 is: all species require plasma operating temperatures T_c above some minimum around 1 eV ($12,000^\circ\text{K}$) to get good efficiency and low \$/kWe. This is because of the basic η_{MHD} scaling as Equation 1, with h_s constant and h_g increasing with temperature, and because generator (magnet) costs scale inversely with conductivity, and conductivity increases with temperature. All fluids' η_{MHD} and minimum \$/kWe exhibit a tendency to saturate with T_c above 2 eV, due to increasing radiation losses with T_c largely canceling the benefits of higher h_g and conductivity. The spread of η_{MHD} and \$/kWe between the different working fluids narrow above 2 eV, where the performance of all species become remarkably similar, despite the differences in material parameters given in Table 1.

Figure 2 Elevation and Plan views of a constant pressure, constant voltage, Faraday MHD generator operated in an "impulse" mode, slowing down the plasma jet

Table 2 Subsystem Elements in the CFARII Balance-of-Plant Cost Model. Showing costs and Unit Costs for the Reference Case Described in Reference 1, and the Scaling Fctors used for other Cases in this work

SUBSYSTEM	QUANTITY	UNIT DIRECT COST	COST M\$	COST-SCALING FACTOR
JET (2.55 M\$)				
Channel Wall	1744 kg	1000 \$/kg	1.74	(jet wall area) ^{0.9}
Nozzle Magnets	911 kg	400 \$/kg	0.35	(jet magnet stored energy) ^{0.8}
Li Coolant System	89.3 kW	5000 \$/kW	0.45	(jet wall coolant pump power) ^{0.67}
MHD Generator (10.08 M\$)				
Generator Tank	2333 kg	200 \$/kg	0.47	(generator volume x pc pressure) ^{0.9}
Generator Magnet	32,700 kg	200 \$/kg	6.54	(generator magnet stored energy) ^{0.8}
Electrodes	4240 kg	500 \$/kg	2.12	(electrode mass) ^{0.9}
LM Coolant System	143 kW	5000 \$/kW	0.72	(electrode coolant pump power) ^{0.67}
He Coolant System	22.8 kg/sec	10,000 \$/kg/s	0.23	(side wall He coolant flow) ^{0.67}
Condensor (3.73 M\$)				
Tank (inc. shower)	21,000 kg	40 \$/kg	0.84	(condensor volume x pc pressure) ^{0.9}
LM Pump	78 kW	5000 \$/kW	0.39	(condensate recirculation pump power) ^{0.67}
Heat Pipes (inc. Fins)	25,000 kg	100 \$/kg	2.5	(condensor heat rejection power) ^{0.67}
T ₂ Cryopanels	10 m ²	10 ⁵ \$/m ²	1.0	(tritium flow x condensor pressure) ^{0.67}
MHD Return Pump	830 kW	5000 \$/kW	4.15	(return pump power) ^{0.67}
DC/AC Inverters	1,056,000 kWe	10 \$/kWe	10.56	(gross electric output) ^{0.8}
BPS Building	736 m ³	1000 \$/m ³	0.74	(building volume) ^{0.8}

38.2 M\$ total reference case BoP cost

Figure 3 MHD gross cycle efficiencies η_{MHD} (%) at minimum \$/kWe as a function of stagnation temperature T_c (deg. K), for KLA, FLB, PLA, and LKA working fluids as defined in Table 1. Pressure $p_c = 200$ bar, thermal power $P_{jet} = 2$ GW.

Figure 4 Minimum unit direct costs (\$/kWe) as a function of stagnation temperature T_c (deg. K), for KLA, FLB, PLA, and LKA working fluids. Pressure $p_c = 200$ bar, thermal power $P_{jet} = 2$ GW.

Figure 5 Maximum gross cycle efficiency η_{MHD} (%) of KLA working fluid as a function of reactor stagnation temperature T_c (deg. K), for reactor stagnation pressures p_c of 1000 bar, 200 bar, and 40 bar.

Figure 6 Unit direct cost (\$/kWe) at maximum efficiency as a function of reactor stagnation temperature T_c (deg. K), for KLA and reactor stagnation pressures p_c of 1000 bar, 200 bar, and 40 bar.

Figure 7 MHD gross cycle efficiency η_{MHD} (%) and unit direct costs (\$/kWe) for KLA working fluid, minimum \$/kWe, reactor stagnation temperature $T_c = 20,000^\circ K$, and pressure $p_c = 200$ bar, as a function of reactor thermal power P_{jet} (GW).

Figure 5 shows that the maximum η_{MHD} improves with pressure p_c , although not strongly so, given the 16-fold range in pressures evaluated. The highest η_{MHD} found, 67% cycle efficiency for KLA at 20,000K and 1000 bar, would present a significant challenge to future reactor designs due to the high pressure required. One might prefer to settle for a more modest $\eta_{MHD} = 40\%$ at 40 bar, considering the difficulty of inserting suitable target shells into a reactor chamber at these pressures through some pressure lock mechanism. The effect of pressure on the \$/kWe at maximum η_{MHD} shown in Figure 6 is less, and less clear, than the effect on η_{MHD} itself.

One can compare the difference between η_{MHD} at minimum \$/kWe and η_{MHD} (max), and the corresponding \$/kWe, by comparing the curve labeled KLA in Fig. 3 with the curve labeled 200 bar in Fig. 5, and by comparing the KLA curve in Fig. 4 with the 200 bar curve in Fig. 6. This comparison shows that \$/kWe for maximum η_{MHD} is about double that of minimum \$/kWe, for only 3-5% higher η_{MHD} than for minimum \$(BoP)/kWe. Thus, values of minimum \$/kWe are preferred unless the rest of the reactor plant were more than an order of magnitude more expensive than the BoP costs.

Figure 7 shows an expected \$/kWe economy-of-scale, with the minimum \$/kWe decreasing with thermal power level approximately as $(P_{jet})^{-0.2}$, similar to unit cost scaling with power found in many present nuclear plants. The lack of sensitivity of efficiency η_{MHD} with thermal power P_{jet} , in spite of the decline of fractional radiation loss with size, is because fractional entrance eddy losses (see Eq. 14 in Ref. 1) increase with size, canceling the benefit of lower fractional radiation losses. On the other hand, the near constancy of η_{MHD} down to 100 MW_{th} size allows low power, low cost demonstration tests to perform almost as well as full scale reactor systems, which could facilitate CFARII development.

Conclusions

Overall, adequate CFARII efficiency and low BoP costs [contributing less than 1-2 mills/(kWe·hr) to the cost of electricity] is found for a wide variety of materials, temperatures, pressures and thermal power levels. Thus, in future designs that would apply CFARII power conversion to particular reactor designs, there is considerable flexibility to choose combinations of materials and operating conditions to accommodate other reactor design constraints, and therefore, a greater chance of finding a combination that meets all engineering and physics constraints while still achieving attractive efficiency and low cost. Inevitably, CFARII cost estimates will rise as more detail is considered in future designs, but would still be attractive (vis-a-vis conventional BoP costs of 800\$/kWe) even if CFARII costs increased 2 or 3 fold. The economic robustness of CFARII is directly related to its extremely high mass power density (≥ 10 MWe/ton of BoP mass for the reference case in Ref. 1), and the high efficiency $\eta_{MHD} \geq 50\%$ of CFARII relative to previous MHD generator design and experiments is due to the higher temperatures of 1 to 3 eV made possible by direct coupling of nuclear energy release to the working fluid material. Future work will be able to optimize the temperature regime by varying the thickness of the target material shells for a given fusion yield, trading off the fraction of fusion yield captured in the shell with the CFARII performance as a function of plasma temperature.

Acknowledgments

The author wishes to acknowledge several valuable discussions with Professor Mike Hoffman of U.C. Davis concerning this work. Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.

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