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A CONCEPTUAL D-^{3}He TOKAMAK REACTOR*

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Abstract

The potential for highly efficient conversion of fusion power to electricity provides one motivation for investigating D-^{3}He fusion reactors. This stems from: (1) the large fraction of D-^{3}He power produced in the forms of charged particles and synchrotron radiation, which are amenable to direct conversion, and (2) the low neutron fluence and lack of tritium breeding constraints, which increase design flexibility. The design team for a conceptual D-^{3}He tokamak reactor, ARIES-III, has investigated numerous energy conversion options at a scoping level in attempting to realize high efficiency. The energy conversion systems have been studied in the context of their use on one or more of three versions of a D-^{3}He tokamak: a first stability regime device, a second stability regime device, and a spherical torus. The set of energy conversion options investigated includes bootstrap current conversion, compression-expansion cycles, direct electrodynamic conversion, electrostatic direct conversion, internal electric generator, liquid metal heat engine blanket, liquid metal MHD, plasma MHD, radiation boiler, scrape-off layer thermoelectric, synchrotron radiation conversion by rectennas, synchrotron radiation conversion by thermal cycles, thermionic/AMTEC/thermal systems, and traveling wave conversion. The original set of options is briefly discussed, and those selected for further study are described in more detail. The four selected are liquid metal MHD, plasma MHD, rectenna conversion, and direct electrodynamic conversion. Thermionic energy conversion is being considered, and some options may require a thermal cycle in parallel or series.

Overview

This study aims to identify attractive, high-efficiency energy conversion schemes for a D-^{3}He tokamak reactor. The loss channels for a D-^{3}He plasma are through charged particles, neutrons, and radiation (synchrotron and bremsstrahlung), with only a few percent of the energy loss in neutrons. In contrast to D-T fusion reactors, this gives high leverage to energy conversion methods which apply to charged particles or radiation. The ideas investigated here focus on efficiently converting such energy to electricity or on converting thermal energy in ways which make effective use of fusion reactor characteristics, such as high magnetic fields.

The energy conversion methods investigated are given in Table 1, which also indicates whether the concept was chosen for further study and the applicability of the concept to the three tokamak versions under consideration for ARIES-III: a high-field reactor (HFR), a second stability reactor (SSR), and a spherical torus (ST). Options not selected for further pursuit within the ARIES project will be described briefly, and those selected will be discussed more extensively. Selection criteria included cost, efficiency, technical feasibility, and how well a concept made use of fusion-specific features. An option not being selected for further pursuit within the ARIES-III study does not necessarily imply that it is unsuitable for alternate fusion reactor configurations; a D-^{3}He tokamak has some unique characteristics and constraints which had a strong impact on the winnowing process.

Options Studied Only in the Initial Phase

Some early ideas were revisited, including conversion of the bootstrap current[1] or travelling waves[2] using an external antenna system to damp out either part of the bootstrap current, a naturally growing instability, or an artificially stimulated instability. The key difficulty is effectively coupling to the antennas, and no efficient solution was found. Similarly, the projected scrape-off layer thermoelectric efficiency was low.

Two ideas attempted to take advantage of the high in situ tokamak magnetic fields. The internal electric generator (IEG) would put a generator within a toroidal field coil. The difficulties in effectively

Table 1. Energy conversion options investigated for the ARIES-III, D-³He tokamak reactor.

Option	Further Study?	Applicability
Bootstrap current conversion	no	HFR, SSR, ST
Compression-expansion cycles	no	ST
Direct electrodynamic conversion (DEC)	yes	ST
Electrostatic direct conversion	no	HFR, SSR, ST
Internal electric generator (IEG)	no	HFR, SSR, ST
Liquid metal heat engine blanket	no	HFR, SSR, ST
Liquid metal MHD (LMMHD)	yes	HFR, SSR, ST
Plasma MHD (PMHD)	yes	HFR, SSR(?)
Radiation boiler	no	HFR, SSR, ST
Scrape-off layer thermoelectric	no	HFR, SSR, ST
Synchrotron conversion by rectennas	yes	HFR, SSR(?)
Synchrotron conversion by thermal cycles	no	HFR, SSR(?)
Thermionic-AMTEC -thermal cycle	no	HFR, SSR, ST
Traveling wave conversion	no	HFR, SSR, ST

driving such a generator with a hot working fluid and the low leverage to be gained in replacing the already efficient generator caused this option to be abandoned. The liquid metal heat engine blanket, based on ideas developed primarily at LANL[4], uses a set of closely spaced radial plates inside a liquid metal blanket. The radial temperature gradient drives oscillations, whose energy would be extracted by MHD conversion. The predicted efficiency was low, ~30%.

A large fraction of the fusion power in a D-³He tokamak will appear as bremsstrahlung radiation. Therefore, the early idea[5] of achieving a high working-fluid temperature by using a low-Z first wall, relatively transparent to bremsstrahlung, and absorbing the radiation on a high-Z material behind that wall was revisited. The difficulty in finding a material suitable from both transparency and structural considerations led to this option being abandoned.

In a tokamak, the experimentally demonstrated technique of electrostatic direct conversion[3] requires a bundle divertor, with a consequent negative impact on stability and difficulty in bucking the very high fields at the toroidal field coils (except in an ST). Because it converts the Maxwellian, scrape-off layer plasma, a multi-stage direct converter is needed for high efficiency.

Two concepts, thermal conversion of synchrotron radiation and thermionic conversion, were retained in partial form by investigating their features in the context of other options. Absorbing synchrotron radiation in a molecular gas, in order to achieve a high working-fluid temperature, showed some merit. However, the various features of the method overlapped the rectenna and MHD conversion options, so this method was not separately pursued. The concept of using thermionic, AMTEC (thermoelectric), and thermal conversion systems in series was examined, but the high cost of the AMTEC system led to the retention of thermionic conversion as a topping cycle for the MHD options and the abandonment of AMTEC.

For the ST, where the external magnetic field is low, compression-expansion cycles appear attractive. These are analogous to the standard Otto thermal cycle, but gains in efficiency because of the high temperature of plasmas[1]. Preliminary analysis was favorable, including operational questions such as the effect on magnets and transport. However, lacking resources to continue investigating two options for an ST, work on this option was halted in favor of DEC.

Options Selected for Further Study

Liquid Metal MHD Conversion (LMMHD)

The source energy in LMMHD is converted to DC electricity by: (1) Thermal energy to kinetic energy of a liquid metal (LM), and (2) LM kinetic energy to electricity as the LM traverses a perpendicular magnetic field. In (1), the LM is mixed with a thermodynamic working fluid (TWF)—a volatile liquid or a gas. As the TWF expands, it accelerates the LM. Approaches to LMMHD design differ in the combination of TWF and LM they use and in the way these fluids are coupled and separated[6-8]. A unique feature is that the expansion of the TWF is nearly isothermal.

The Ericsson LMMHD cycle, shown in Figure 1, appears most promising for ARIES-III[7,8,9]. It is the LMMHD counterpart of a gas turbine cycle, with multiple reheating and intercooling stages. The LMMHD cycle is free of rotating machinery, can be hermetically sealed and, hence, directly coupled with the reactor coolant, and is free of reheating and intercooling heat exchangers. The upper cycle temperature strongly depends on the first wall and blanket design details, as well as on the design of a topping cycle, if used. It appears likely that the LMMHD cycle can be designed to have a high temperature of at least T_h=1200 C. Three design approaches are under consideration: (1) Cool the first wall and blanket with He at inlet temperature T_i=900 C and outlet temperature T_o=1500 C, heating the LM TWF by direct He contact; (2) Divert the synchrotron radiation out of the fusion core and dump it into the LM using a simple heat exchanger. Use He TWF to remove the remaining fusion power. Here, T_o=1200 C could suffice; and (3) Mist cooling. Add LM droplets to the He, thus significantly reducing T_o-T_i and T_h-T_o, while avoiding adverse MHD effects[9].

The LMMHD technology potentially offers 50% to 61% efficiency using a single system featuring direct cycle, relatively low operating pressures, as well as simple and robust stationary components. The relatively large efficiency range reflects the uncertainty in the expected performance of system components. The TWF and LM are assumed to be He and Li, and the expansion ratio is 2.5.

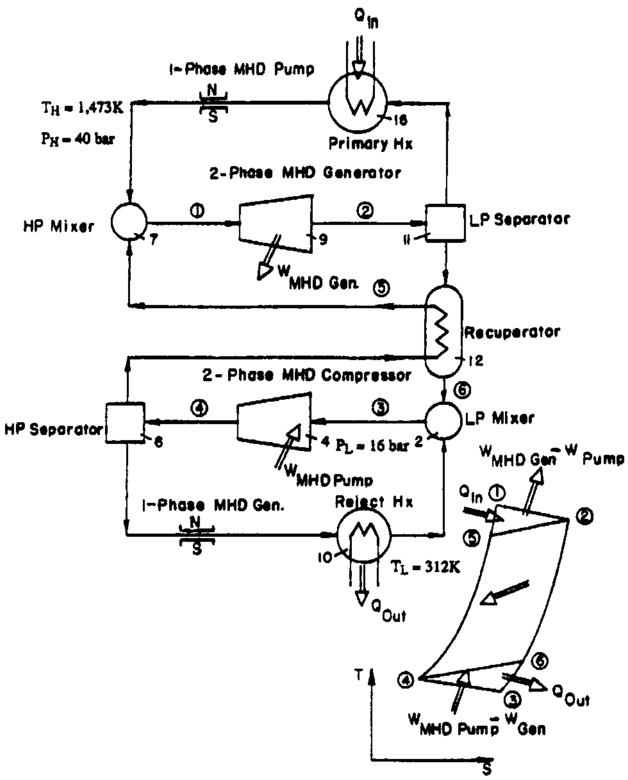

Figure 1. Schematic of an all LMMHD Ericsson Cycle

Plasma MHD Conversion (PMHD)

In PMHD, the electrical conductivity of the working fluid is obtained by thermal ionization. Since appreciable ionization of common gases requires temperatures of ~5000 K, a small amount of seed material (~0.1 atom percent) such as cesium or potassium is added, giving sufficient electrical conductivity at about 3000 K. Fairly extensive theoretical and experimental work in PMHD exists[10,11,12], and ARIES-III would use closed-cycle MHD (CC-MHD).

For ARIES-III, He working fluid seeded with Cs or K has been chosen. The CFAR[12] concept for a DT reactor uses Hg; however, Hg vapor toxicity poses unacceptable safety concerns in a D-^{3}He fusion reactor—where safety and environmental advantages are a key reason for investigating the fuel cycle. The bottoming cycle is a supercritical Rankine steam cycle with multiple reheat. The power conversion flow diagram is shown in Figure 2. The stagnation temperature of the working fluid is ~2000 K. The use of synchrotron radiation to further heat the working fluid while keeping the chamber wall at much lower temperature makes this option fusion-specific.

The predicted thermodynamic efficiency of the combined PMHD/Rankine steam cycle is ~64%. The component cycle efficiencies are ~30% for the topping PMHD and ~49%[13] for the bottoming Rankine steam cycle. The MHD duct is simple and reliable, without any moving parts, and the high conversion efficiency leads to a smaller reactor thermal output, compact balance of plant, and an expected decrease in cost of electricity. Issues include the high temperature blanket, transport of synchrotron radiation, efficiency of heating the working fluid by synchrotron radiation, the synchrotron radiation window, and the possibility of activation of the seed materials by fusion neutrons.

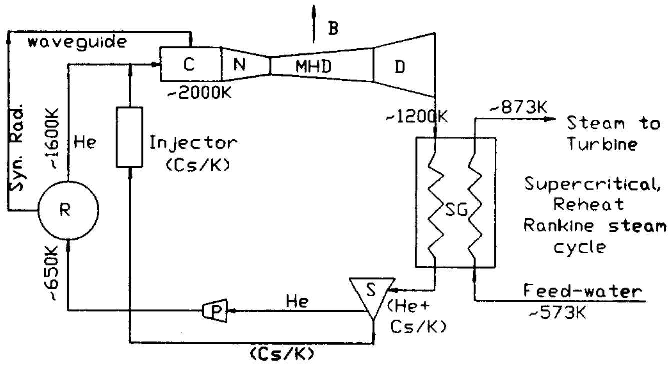

Figure 2. Schematic of PMHD System. R=reactor core, C=chamber, N=nozzle, D=diffuser, SG=steam generator, S=separator, P=pump/compressor, B=magnetic field

Thermionic Conversion

Thermionic energy conversion is a well-advanced technology utilizing thermally stimulated electron emission (thermionic emission). The cathode (emitter) and anode (collector) are separated by a small interelectrode space. To obtain good efficiency and heat flux capability, the emitter should operate at ~2000 K, while the collector should operate at ~1000 K. Typical emitter/collector materials are tungsten/molybdenum. Operating systems have achieved efficiencies (η) of ~10% and heat fluxes of ~0.1 MW/m^2, and projections give η ~20% and heat fluxes of ~0.25 MW/m^2.

The conversion would occur out of pile and, therefore, the thermionic converters would not be subject to radiation and magnetic fields. The thermionic converters would be configured as two concentric tubes of ~1 m in length. One module would consist of a close-packed array of ~900 converters, handling ~80 MW of thermal energy. The key technical issue for ARIES-III is the high emitter temperature. One possible combination of blanket structure and coolant would be titanium carbide and helium, which would exhibit attractive activation characteristics.

Direct Electrodynamic Conversion (DEC)

A direct electrodynamic converter (DEC) would consist of a chamber above the core plasma into which the scrape-off layer plasma would be diverted. It could also function as a divertor. As shown in Figure 3, the DEC plates would be biased so that particle drifts would separate ions from electrons. Ions would be collected on the top plate, while electrons would be collected on the end plate[14].

A DEC would operate in a low-recycle divertor regime, and the scrape-off layer plasma temperature would be 2-5 keV. The mode of operation would be similar to that of an in situ MHD disk generator. Details of the particle drifts and distribution functions within the DEC are being pursued, but a preliminary estimate of the efficiency is 50%.

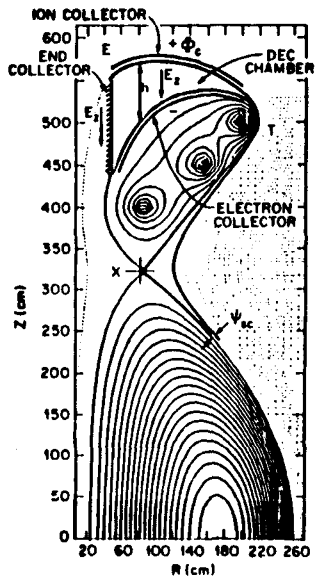

Figure 3. Schematic of a Spherical Torus with DEC

Synchrotron Radiation Conversion by Rectennas

The concept of directly converting synchrotron radiation to electricity at ~80% efficiency using rectennas (rectifying antennas) was originated by Grant Logan[15]. This method appears attractive for D-^{3}He fusion reactors[16]. Overmoded waveguides would channel synchrotron radiation out of the tokamak and convert it in a separate chamber. Rectennas, not yet developed at frequencies of interest, require integrated circuit technology within the state of the art. Big production runs of large-scale integrated circuits indicate rectenna costs are reasonable. A high fraction of the fusion power must be generated as synchrotron radiation, placing more stringent requirements on energy confinement, as reaching high synchrotron radiation fractions requires higher magnetic fields and higher plasma temperatures. It may be necessary to enhance transport of the ash above that of fuel ions to avoid choking the fusion burn.

The spectrum of synchrotron radiation will be approximately 1.5 to 30 THz. The chamber walls must be highly reflective, so that most of the synchrotron radiation is lost out the waveguide. Proper waveguide positioning causes preferential absorption of synchrotron radiation, calculated to drive a large fraction of the total plasma current. Internal waveguide losses are calculated to be less than 5%. The key circuit components not presently available at the high frequencies of interest are diodes. However, Schottky diodes have been progressing rapidly in frequency as have vacuum microelectronics. Experimental programs exist in two regimes that bracket the range of interest for ARIES-III: 90-240 GHz and 1-28 THz[17].

Synchrotron radiation conversion by rectennas is intrinsically a D-^{3}He mode of operation because of the leverage gained by a high synchrotron radiation to fusion power ratio. The expected benefits in power plant simplicity, reliability, and cost must balance the more difficult physics requirements and the need to demonstrate rectenna technology at THz frequencies.

Conclusions

A wide slate of energy conversion candidates for the D-^{3}He tokamak reactor design ARIES-III has been narrowed down to four: liquid metal MHD, plasma MHD, rectenna conversion of synchrotron radiation, and direct electrodynamic conversion. The rectenna and DEC options are specific to fusion, but apply only to the high-field reactor and the spherical torus, respectively. LMMHD would apply to any ARIES-III version and is the only option not necessarily coupled to another energy conversion system. The PMHD option considered here requires synchrotron radiation superheat, and thus is best suited to a high-field reactor. If a second stability reactor can be operated in a high synchrotron radiation fraction regime, it might be suitable for PMHD or rectenna conversion.

References

[1] G.H. Miley, *Fusion Energy Conversion* (ANS, 1976).

[2] D.G. Samaras, *Applications of Ion Flow Dynamics* (Prentice-Hall, NJ, 1962).

[3] W.L. Barr and R.W. Moir, Nucl. Technol./Fusion 3, 98 (1983).

[4] G.W. Swift et al., J. Acoust. Soc. Am. 78, 767 (1985).

[5] R.T. Taussig and A. Hertzberg, in C.K. Choi, ed., *Proceedings of the Review Meeting on Advanced-Fuel Fusion*, EPRI Report ER-536-SR, p. 179 (1977).

[6] M. Petrick and H. Branover, *Progress in Astronautics and Aeronautics, Vol. 100*, p. 371 (1985).

[7] L. Blumenau et al., Fusion Technology 10 914, (1986).

[8] E. Greenspan et al., *Progress in Astronautics and Aeronautics, Vol. 111*, p. 129 (1988).

[9] E. Greenspan, IEEE 13th Symposium on Fusion Engineering (Knoxville, 1989).

[10] W.D. Jackson, in V.A. Kirilin and A.E. Sheyndlin, ed., *MHD Energy Conversion—Physicotechnical Problems* (VAAP, 1983) (English trans., AIAA, 1986).

[11] R.F. Grundy, ed., *Magnetohydrodynamic Energy for Electric Power Generation* (Noyes Data Corp, 1978).

[12] K. Yoshikawa et al., IEEE 13th Symposium on Fusion Engineering (Knoxville, 1989).

[13] M.Z. Hasan, IEEE 13th Symposium on Fusion Engineering (Knoxville, 1989).

[14] Y-K.M. Peng, Bull. APS 33, 2044 (1988).

[15] B.G. Logan, Fusion Power Associates Annual Meeting (Washington, DC, 1986).

[16] G.A. Emmert et al., IEEE 13th Symposium on Fusion Engineering (Knoxville, 1989).

[17] J.L. Christian, Jr. and R.J. Acosta, "Candidate Technologies for Beamed Space Power Application," NASA Lewis Report draft (1989).

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