Direct Energy Conversion in Fission Reactors: A U.S. NERI project

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Abstract

In principle, the energy released by a fission can be converted directly into electricity by using the charged fission fragments. The first theoretical treatment of direct energy conversion (DEC) appeared in the literature in 1957. Experiments were conducted over the next ten years, which identified a number of problem areas. Research declined by the late 1960's due to technical challenges that limited performance. Under the Nuclear Energy Research Initiative we are determining if these technical challenges can be overcome with todays technology.

We present the basic principles of DEC reactors, review previous research, discuss problem areas in detail, and identify technological developments of the last 30 years that can overcome these obstacles. As an example, the fission electric cell must be insulated to avoid electrons crossing the cell. This insulation could be provided by a magnetic field as attempted in the early experiments. However, from work on magnetically insulated ion diodes we know how to significantly improve the field geometry. Finally, a prognosis for future development of DEC reactors will be presented

I. Introduction

Direct energy conversion has been pursued since the earliest days of power reactor development with significant research being conducted during the 1950s and 1960s. The basic concept behind direct conversion was to create a fission electric cell. The cathode of the cell contains the fissionable material. Nearly 80% of the fission energy goes into two fragments with an average energy of approximately 80 MeV. Each fragment has a positive charge of approximately 20 electron charges and thus could be stopped if the anode was raised to a potential of about 4 MV. With no current drawn through the fission cell the anode will be charged up to this voltage by the fission fragments. When current is drawn through the cell the anode voltage must be less than 4 MV to allow a sufficient fraction of the fission fragments to carry current to the anode. However, large quantities of low energy electrons (~ 100 eV) are also generated during fission. These electrons must be insulated from the anode or their negative charge will cancel out the positive charge of the fission fragments. It has been proposed to use a grid at negative potential to return the electrons to the cathode[1]. However, experiments using such a grid resulted in the anode charging to a negative potential[2]. This indicates that electrons were reaching the anode. It is quite probable that the grid itself becomes a source of electrons. In contrast, the anode charged to positive potential of about 13 kV when an axial magnetic field was applied to a cylindrical cell[2]. This voltage is still much too small to indicate efficient operation of a fission electric cell. It was believed that end effects allowed some electrons to reach the anode and that this limited the anode voltage. The expected cell voltage was calculated as a function of the magnetic field strength (driving current) assuming a planar gap. Data indicated that the anode voltage was substantially below this curve. There are two reasons for this discrepancy. The first is the use of a planar geometry for a cylindrical system. The second is the assumption of uniform magnetic field strength. Using parameters from the experiment, we have calculated the magnetic field using the code ATHETA[3]. We find that the magnetic field lines are not axial, which leads much less insulation than estimated by the experimentors. The degree of magnetic insulation is conveniently parameterized by the parameter V_{crit}, which is the maximum voltage that can be applied between the electrodes before electrons will be driven across the magnetic field to reach a particular point on the anode. V_{crit} can be calculated using the principle of conservation of energy and canonical angular momentum[4]. This results in the following expression

$$\frac{\Delta\psi}{r_a} = \frac{mc}{e}\sqrt{\left(1+\frac{eV_{crit}}{mc^2}\right)^2 - 1} \tag{1}$$

where $\psi(\mathbf{r}) = rA_\theta(\mathbf{r})$ is the magnetic stream function, $\Delta\psi = \psi(r_a) - \psi(r_c)$, is the difference between ψ at the anode and the cathode, $\mathbf{r_a}$ is the anode radius, **m** and **-e** are the mass and charge of an electron, respectively, and **c** is the speed of light in vacuum. The fission events produce electrons that have typical energies of only 100 eV. Ignoring the initial electron energy, we have calculated the critical voltage for electrons leaving the cathode at the midplane to reach the anode as a function of position on the anode. The results show a large variation in V_{crit} across the anode collector is due to the curvature of the magnetic field lines. The strength of the B field along the axis corresponds well to the experimental field[2] for 60 A of current in the field coils. The minimum value of V_{crit} is approximately 15 kV, which corresponds well to the observed cell operating voltage of 13.5 kV. We find good agreement between our calculated values of the minimum V_{crit} at different field coil currents and the JPL experimental operating voltages. The cell operated at voltage slightly below V_{crit}, which is consistent with the behavior of magnetically insulated ion diodes. Thus it appears likely that the low operating voltage was due to a poor magnetic field design.

An additional problem with this design is that even if the magnetic insulation was designed properly, the cell efficiency would be quite low. The efficiency of fission electric cells has been calculated in planar, cylindrical, and spherical geometry[5]. In these calculations it was assumed that a thin film of fissionable material was coated onto a substrate. Thus a maximum of half of the fission fragments would enter the cell. Assuming a thickness 0.2 times the range of the fission fragment, the maximum cell efficiency was 5.5%, 11%, and 18% for planar, cylindrical, and spherical geometries, respectively. The low efficiency for the planar and cylindrical case is due to the isotropic distribution of the fragments' initial velocities. Fragments that are not directed toward the anode will be turned back to the cathode by the electric field in both planar and cylindrical geometry. The energy of these returned fragments will only result in heating the cathode. In spherical geometry with an inner cath-

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ode the initial direction of the fragment does not matter since all directions are toward the anode, at least in the limit of a very small cathode. The efficiency also increases as the thickness of the fissionable coating is decreased, because fewer fragments are absorbed in the cathode. Since electricity can be generated at 30% efficiency using a thermal cycle, these efficiencies are too low to be interesting for commercial power plants. We investigate two approaches that could produce efficiencies greater than 30%, at least in priciple. The first of these concepts is a magnetically insulated quasi-spherical fission electric cell, which is described in the next section. The second concept involved a magnetic collimator to direct the fission fragments in one direction. These fragments can then be collected and converted into electricity efficiently by a venertian-blind convertor. This concept is presented in section III. We are also considering two MHD conversion concepts. The first involves the enhancement of the conductivity of the MHD working fluid through the direct deposition of fission fragments. This is described in section IV. The second involves a liquid fuel reactor that periodically goes prompt critical, which drives the conducting fuel through an MHD covertor. This concept is discussed in section V.

II. Magnetically insulated quasi-spherical fission electric cell

A. magnetic insulation and basic geometry

A schematic of a magnetically insulated quasi-spherical fission electric cell is shown in Fig. 1. The magnetic field has been designed so that V_{crit} is uniform along the anode surface, which is essentially spherical except for the apertures at each end. These apertures are required for magnetic insulation, since the anode can not intercept the same field line as the cathode, see eq. (1). Fragments can escape through the apertures. Thus the cell structure should be repeated periodically to obtain the highest operating efficiency, since escaping fragments then enter another cell and have a significant probability of being collected on the anode. We can estimate the minimum aperture size from eq. 1. Assuming that $r_a \sim r_c$ and V_{crit} =4 MV, B = 10 Tesla, the aperture can be as small as 1.3 mm. The field coils could be constructed from superconductive material for steady state operation, since the magnetic field is substantially below the quenching field of most superconductors.

V_{crit} does not strictly have to be uniform along the anode. However, designs with uniform V_{crit} will require less magnetic field strength than for nonuniform insulation. An additional advantage is that the electrons will tend to form a sheath along a surface of constant V_{crit}, which will form a virtual-cathode. The electric field between the anode and the virtual-cathode will be radial as long as the virtual cathode is essentially spherical. Thus a nonuniformly insulated anode will not have as high an efficiency. We have shown a hollow spherical cathode, which could be constructed from a thin foil of fissionable material, possibly supported by a wire structure. These cathode assemblies would supported by a wire down the axis of the cell. In this configuration a fragment initially traveling in the negative r direction can still exit the cathode if the foil is sufficiently thin. A wire support structure would not significantly lower the fraction of fragments that escape, since it would only occlude a small fraction of the solid angle. Other configurations might be desirable, e.g., a thin disk which could have twice the film thickness for the same efficiency, but with only one half of the mass.

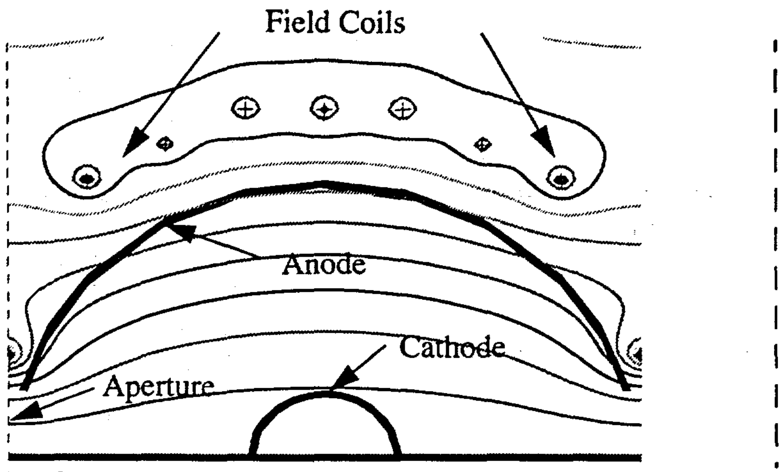

Figure 1. A schematic of a magnetically insulated quasi-spherical fission electric cell

B. Efficiency calculations

Our approach to calculating the efficiency of a spherical fission electric cell involves both analytic and Monte Carlo modeling. We shall assume that ^{235}U is used as the fissionable material. The average energy released in a fission event is 202 MeV with approximately 166 MeV going into the kinetic energy of the fragments[6]. The fragment mass has a double humped distribution which is given approximately by the sum of two gaussians with mean atomic numbers $A_L = 95$ for the low mass group and $A_H = 138$ for the high mass group. The width of the distribution $\Delta A = 8.7$ is approximately the same for both groups and P is a normalization constant. We use this function and Monte Carlo methods to determine the mass of the fragment. We then determine the initial energy from conservation of momentum. We assume that the fragment is born with a random initial direction at some random position within the cathode which is in the form of a spherical shell. We then calculate the total distance, Δ, through cathode material that the fragment must traverse to exit the cathode structure. The fragment range is given approximately[7] by the formula $\lambda = \lambda_0 E_0^{2/3}$, where $\lambda_0 = 0.536$ mg/cm^2/(MeV)$^{2/3}$. The energy of the fragment is given approximately by the expression[7] $E=E_0(1-\rho\Delta/\lambda)^2$. We can now obtain the charge of the fragment as it exits the cathode from the formula[8]

$$q_F = Z\left\{1 + \left(\frac{0.066Z^{0.9}E}{Z}\right)^{\frac{1}{2k}}\right\}^{-k} , \qquad (2)$$

where q_F is in units of electron charges, k=0.6, where E is in MeV. It is now simple mechanics to determine the maximum cell voltage, V_x, that will allow the fragment to reach the anode. We set up an array of cell voltages V_i and a corresponding array E_i that represents the total energy that would be extracted from the fragment, while in transit from the cathode to the anode. We increment E_i by $V_i q_F$ for each fragment with V_X greater than E_i. If V_X is less than V_i, the fragment would not reach the anode so no energy is added. We also sum the initial energy of each fragment, E_0, to obtain E_{TOT}. The efficiencies for each cell voltage, V_i, are then given by $\eta_i = E_i/E_{TOT}$.

C. Model results

The efficiency of the fission electric cell will be a strong function of the areal thickness of the fissionable cathode, Γ. The efficiency is plotted as a function of the cell voltage in Fig. 2 for various values of Γ, for a fixed ratio $r_A/r_C=4$. As seen from the figure, high efficiencies are possible, but only with low values of Γ. The double humped behavior, which is most pronounced in the small Γ curve, is due to the bimodal mass distribution of the fission fragments. As can be seen from Fig. 2, the efficiency increases as the areal density of the cathode is made smaller. Calculations also indicate that the efficiency increases as the ratio r_A/r_C is increased. In both cases the mass of the fissionable cathode is made smaller with respect to the volume occupied by the fission electric cell. A critical mass will have to be made by assembling a large number of these fission electric cells. It is clearly desirable to have the reactor of a manageable size. We want the optimum efficiency for a given effective fissionable material (fuel) density, ρ_U, which we define to be the total mass of fissionable material divided by the volume of the reactor. The mass of fissionable material within one cell is $M_{fc} = 4\pi r_C^2 \Gamma f_U$, where f_U is the mass fraction of ^{235}U within the cathode (other fissionable materials could be used).

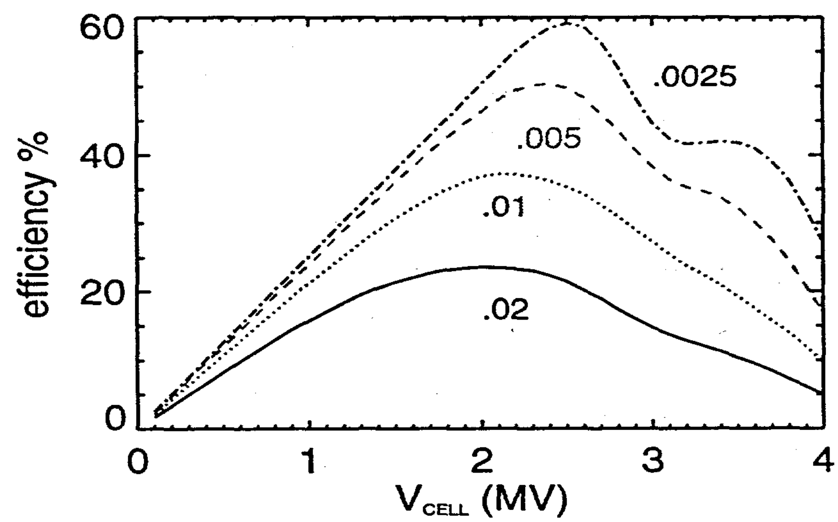

Figure 2. Efficiency as a function of cell voltage. The curves are labelled with Γ in kg/m^2.

The effective volume of a cell must include the space between adjacent cells. We envision the cells strung together with each cathode supported by a rod. Many of these strings will then be arranged into a bundle. We have assumed that the strings must be separated from each other by the distance $r_s = f_s r_A$ to accommodate the field coils and coolant ducts. The magnetic field will exert a considerable force on the field coils. This force will be minimized by choosing $f_s \approx \sqrt{2}$. These strings of fission electric cells can then be arranged as fuel rods in a hexagonal close packed configuration. The volume occupied by each cell is then $V = 4\sqrt{3} r_A^3 f_s^2$. The size of the aperture will be approximately the same as the radius of the cathode. Thus using the magnetic insulation condition, (1), we obtain the following expression for the fission density

$$\rho_U = \frac{\pi}{\sqrt{3}}\Gamma\left(\frac{r_C}{r_A}\right)^3 \frac{f_U B c}{2 f_s^2 V_{crit}} = \frac{\rho_{scale} B}{F_{SUV}}, \text{ where } F_{suv} = \frac{f_s^2}{2 f_U}\left(\frac{V_{crit}}{4 \times 10^6}\right) \approx 1. \quad (3)$$

The optimum cell parameters are plotted as a function of the scaled fission density in Fig. 3

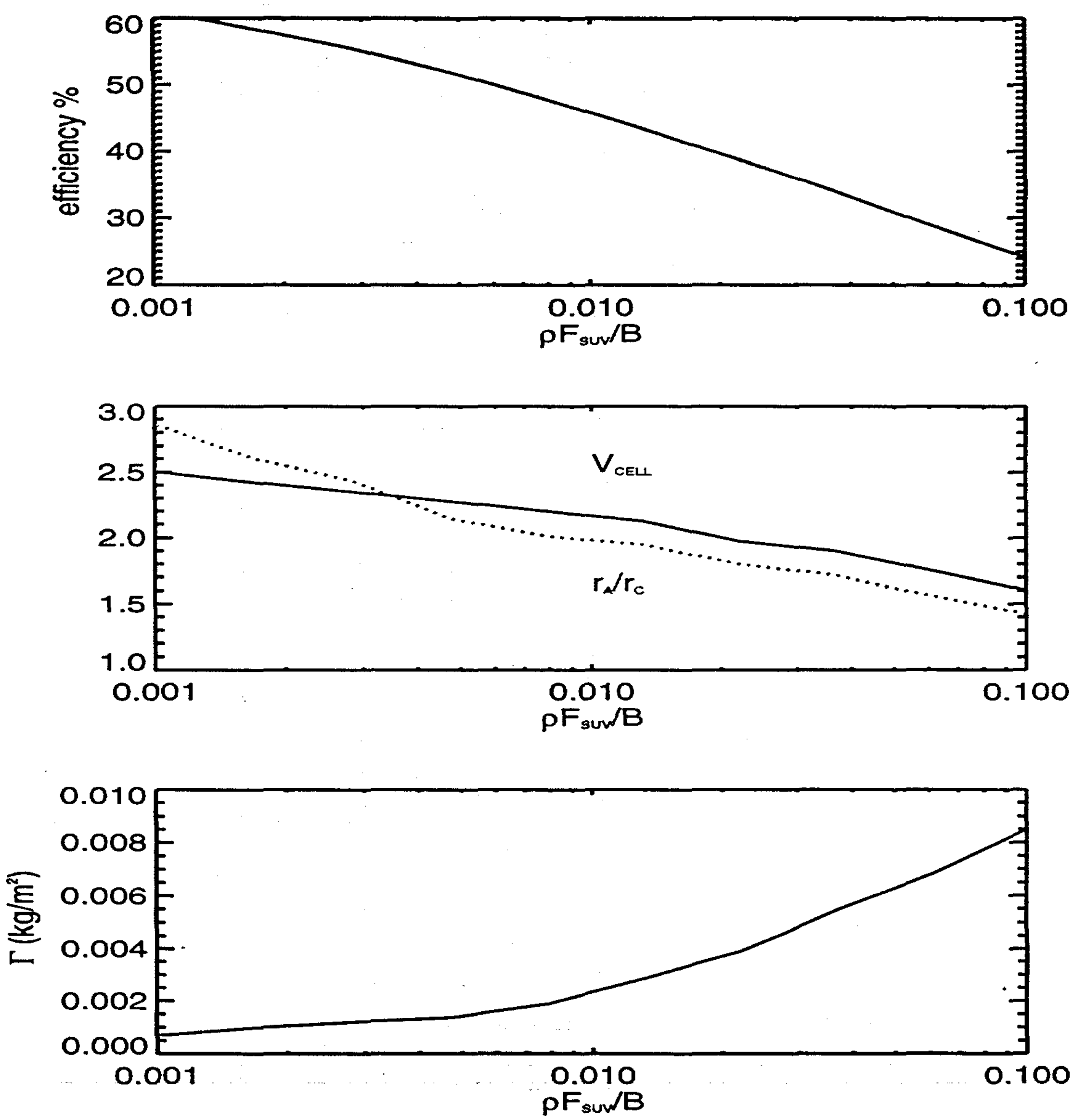

Figure 3. Efficiency, Cell voltage, ratio of anode/cathode radius, and areal density parameter as a function of the fuel density parameter.

As an example let's assume that we want a reactor that directly converts > 30% of the fission energy into electricity. Since 20% of the fission energy does not appear as fragment kinetic energy the cell efficiency must be > 37.5%, thus $\rho_U \sim 0.26$ assuming F_{suv}=1 and B=10 T. The cathode radius is found from eq. (1). Assuming V_{crit}=4 MV the cathode radius is approximately 2.7 mm and the anode radius is about 4.8 mm. The cell voltage is approximately 2 MV, and the areal density parameter should be approximately 0.0043 kg/m^2. The areal density parameter will be the most difficult engineering problem. Assuming UO_2 fuel at 10 g/cm^3 the thickness would be 0.4 microns.

D. Specific power density and issues of criticality

The power density is limited by the rate the heat can be removed from the fissioning cathode. Since the cathode must be very thin to obtain high efficiencies, thermal conduction will not be an effective way to remove heat. Therefore the dominant cooling mechanism will be radiation. The cooling of the anode will not have the same limitations, since there is no constraint on the thickness of the anode. We define the specific power density, P_s, to be the total fission power per mass of fissile material. The cathode temperature must be lower than its melting temperature. The melting point of pure uranium is approximately 1400 K. If we assume Γ=0.0043 kg/m^2, which would yield a direct energy conversion efficiency of approximately 30% for B=10 Tesla, we obtain P_s=52 MW/kg for $f_U = 1$. The maximum power density would then be approximately 12 MW/m^3(ρ_U = 0.26 kg/m^3), which is quite low as we expected due to the low density of fissile material.

The low density of fissile material could make the issue of achieving criticality rather difficult. We make a very simple estimate of the critical mass that will be needed. Carbon is an excellent neutron moderator. It also has high strength and good electrical and thermal conductivity. If we fill all the available space exterior to the anode with carbon, the ratio of carbon atoms to uranium atoms is approximately 1.4×10^5. The minimum critical mass of uranium mixed with graphite[9] is approximately 40 kg at this C/^{235}U ratio assuming the neutrons are reflected at the outside of a spherical assembly. In reality other materials will have to be used. In particular the field coils need to be constructed of a material that is superconducting at high magnetic field strengths, e.g., Niobium. Such materials could absorb neutrons and thus increase the mass of fissile material that will be required. This needs further exploration. Operation at one half of the power density imposed by radiative cooling of the cathode would allow a 1 GW electric reactor with a fuel inventory of approximately 80 kg. The reactor volume would be 310 m^3 or a sphere of approximately 4.2 m radius.

III. Fission Fragment Magnetic Collimator Reactor

Efficient direct conversion of fission fragment kinetic energy into electrical energy requires stopping the fragments in a retarding electric field with nearly all the fission fragments to traveling against the potential gradient. Since fission fragments are emitted isotropically from the fissioning nucleus,the field must be arranged to be along the line of flight of all the fragments. In the last section, we considered a spherical cell, which accomplishes this task. An alternative approach is to redirect the fission fragments before collection with a solenoidal field. When a fragment is created inside a solenoidal magnetic field there is always some component of its velocity parallel to the axis of the solenoid, so it migrates toward one end or the other. As it approaches the end, it enters into weaker and weaker magnetic fields. As it does so, it must cross some field lines that have a radial component. This radial component slows down the circular velocity of the particle and steers it more along the axial direction without loss of kinetic energy. Eventually the particle is moving almost entirely parallel to the solenoidal axis as it exits the solenoid. This is the principal behind a magnetic nozzle in a plasma rocket such as NASA/JSC's VASIMR engine[10,11]. This effect also occurs for particles lost from mirror fusion machines. Fragment trajectories within a solenoidal field have been calculate using the TRICOMP code[12]. These calculations indicate that the fragments are partially collimated as they exit the solenoidal field. The paths do not straighten out completely, but fan outward. Therefore a fragment collector, which is a segment of a sphere at a particular distance from the solenoid centerplane, should result in most of the paths impinging nearly at normal insidence. This could be a venetian blind collector[13], which has been demonstrated efficient conversion. The farther from the centerline that the fragments are born, the more the paths bend as they exit the solenoid. This suggests that the solenoid needs to be larger than the reactor core. The core can be formed from an array of thin walled tubes composed of fissile material, which are almost aligned with the strong magnetic field. Calculations indicate that a small misalignment (pitch angle) will allow the fragments to exit the core with a small probability of striking any of the tubes. The tubes could be cooled by flowing helium down the center or simply by radiation.

We have explored various design tradeoffs to maximize total extraction efficiency within the limitations on the magnetic field strength (<10 tesla) , the fuel layer thickness (<10 microns) and the requirement of criticality. High efficiencies could only be obtained with tubes thin enough to allow the fragments to pass through them. These tubes could be cooled by a flow of helium down the center. The minimum fuel needed for criticality is very sensitive to materials and configuration, but based on similar constraints in the reactor-pumped laser program, there must be at least several kilograms of highly enriched U-235. To keep the extraction efficiency high, the core length should be kept small so that the fragments can escape before hitting a tube, but the aspect ratio of the core must be kept close to unity to minimize the fuel needed for criticality. The amount of fuel available is limited by the fuel layer thickness which must be minimized to reduce energy loss during the fragment's escape from the layer. A condition which maximizes the number of tubes in the reactor, and thus the amount of fuel, is that the tube spacing (in a hexagonal pattern) should be close enough to just barely allow the fragment to migrate out of the core without hitting the adjacent tube. We estimate that hollow thin-walled tubes of fuel (2 microns thick) results in 12 kg of fuel within a 12-m diameter, 15-m long core at a magnetic field of 4 Tesla. The resulting extraction efficiency should be approximately 35%. Further work is needed to determine if this configuration would achieve criticality.

IV. Pulsed MHD reactor

Turbostar[14] is a direct energy conversion concept proposed for inertial fusion energy, where the kinetic energy of an inertial fusion event was to be directly harnessed using turbines. This concept is extended to a prompt critical pulsed nuclear reactor with MHD chosen over turbines to minimize moving parts. Consider a chamber filled with an electrically conducting liquid fissile fuel that is prompt critical. The resulting high temperatures will cause the liquid to expand and generate gas bubbles. The resulting pressure rise can force the electrically conductive liquid fuel through a MHD channel generating electrical power. This liquid fuel could be an aqueous solution, a molten salt or a liquid metal. As the liquid is reassembled into the primary chamber, the reactivity is maintained at a low level by a set a neutron absorbing plates that separated the chamber from neutron reflectors. The plates rotate until holes in the plates align with the reflector and neutrons are reflected back into the core causing another prompt critical excursion. The cycle is repeated to generate energy. An alternative method is to rapidly remove a control rod using gas flow as is done in a TRIGA reactor.

Initial analysis indicates that an aqueous fueled reactor will be large. At high uranium concentrations the critical volume is quite small but the reactor will disassemble too quickly for a significant amount of energy to be deposited in the fuel. For at low uranium concentrations the critical volume is large and the power can be significant.

V. Summary

We have reviewed the basic mechanism of direct electrical conversion of fission energy. High efficiencies can only be obtained if the electric field opposes the direction of nearly all of the fission fragments. We present the concept of a magnetically insulated quasi-spherical fission electric cell. This concept is an advance over previous fission electric cells in two ways. First, the basic geometry is nearly spherical, which allows the cell to operate at high efficiency. Second, the anode is magnetically insulated in a manner that keeps V_{crit} nearly constant over the anode. High efficiency can only be achieved with very thin (or low density) free standing cathodes (fissile material). This allows the fission fragments to escape from the cathode regardless of the initial velocity direction of the fragment. We have presented Monte Carlo calculation of the efficiencies of quasi-spherical fission electric cells. We find that the efficiency of converting fragment energy into electricity can be quite high (>60%), but only for very thin cathodes, which result in a very low density of fissile material. A conversion efficiency of 37.5% requires a cathode foil thickness of 0.0043 kg/m^2, which for solid density uranium is 0.21 μm. This is indeed a very thin foil, but wires could be used to support the films with little penalty in efficiency. Still it needs to be determined if such thin foil cathodes can be constructed. The average density of fissile material within the entire reactor core assuming a magnetic field strength of 10 Tesla is 0.26 kg/m^3. We estimate that as little a 40 kg of ^{235}U would be needed to achieve critical mass if only carbon and ^{235}U are present within the reactor core. Other materials will be required, which may absorb neutrons and raise the fissile mass needed for criticality. In particular, the field coils need to be constructed of some material that has good superconducting properties, e.g. Niobium. This needs to be investigated. The use of the waste heat in a thermal cycle could raise the overall efficiency to 50% or better. It should also be noted that electricity could be generated at high efficiencies in a single cell if the cathode was constructed of an unstable material that emits alpha particles. High conversion efficiencies may also be possible by using a solenoidal field to collimate the fission fragments and then collect these fragments with a venetian blind collector. We have also looked at two MHD concepts that could produce efficiencies higher than the standard steam cycle. Considerable work is needed to determine if any of these schemes could produce a practical reactor.

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