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W. C. Condit, G. A. Carlson, R. S. Devoto, J. Doggett, W. Neef

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THE FIELD-REVERSED MIRROR AS A D-T POWER REACTOR

W. C. Condit, G. A. Carlson, R. S. Devoto, J. Doggett, W. Neef

LAWRENCE LIVERMORE LABORATORY*

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The Field-Reversed-Mirror is a plasma confinement scheme which uses the diamagnetic current of the D-T fuel plasma to convert the open field pattern of a conventional mirror machine into a closed-field pattern with plasma confinement properties which are expected to be considerably improved. If realized, this improvement in confinement will considerably improve the energy gain of the mirror reactor, and result in a reduction in the cost of producing energy. The Field Reversed Mirror device is described and compared with earlier field-reversed configurations, and the overall energy and particle balance relations are given. Based on this, preliminary engineering design calculations of the major components of an FRM reactor are presented. We find that the engineering design leads to simple structures for which reasonably accurate cost estimates are easy to make (circular coils, cylindrical vacuum tanks, etc.). A cost optimization has been performed, and the optimum DT reactor is found to have a fusion output of 23 MW/cell from a plasma radius 5 cm, length 15 cm, in a field of roughly 10 Tesla.

I. Introduction

In the past year a group at LLL has been studying a number of possibilities for enhancing the power gain factor, Q , to be expected from a mirror fusion reactor.⁽¹⁾ One of the most promising schemes for higher Q is the Field-Reversed Mirror (FRM) configuration. It offers the potential of a high Q fusion reactor with both modest cost and modest system sizes. We have begun a conceptual design process to see what such a system might look like, the magnetic fields and plasma parameters needed, and the optimum system size for lowest-cost net electric power generation. The motivation for this work was to find out, in a preliminary way, whether the FRM idea would lead to a viable fusion reactor

design; in other words, whether it was worth working on. We were pleased to find that the FRM reactor looks extremely attractive based on the physics we know today. The present report is intended to document our current knowledge and the reasons for our continuing interest.

A preliminary CTR reactor design always involves a number of physics assumptions. The present work is no exception, particularly in the areas of particle loss rates and hydromagnetic stability, where theoretical work is at a preliminary stage. In these areas, we have been as optimistic as current knowledge allows. We have assumed that observed stable configurations can be scaled to higher temperatures and B fields, and we have assumed that energy and parti-

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cle losses occur at classical ion transport rates (intermediate between the strictly classical electron diffusion rate⁽²⁾ and the extremely pessimistic diffusion rates such as arise from Bohm diffusion).

II. The Field-Reversed Mirror

The idea of a closed field-line geometry using a purely poloidal field, with field lines encircling an azimuthal current, was proposed early in the CTR program for the toroidal Z-pinch⁽³⁾ and the Astron thermonuclear reactor.⁽⁴⁾ The idea is shown schematically in Fig. 1. In the ion Astron

FIGURE 1. Schematic of Field-Reversed Mirror Reactor.

reactor design,⁽⁵⁻⁶⁾ the azimuthal current was carried predominantly by high energy beam protons - those with enough energy to encircle the axis of the device in roughly circular orbits. The D-T fuel ions were at a much lower average energy. In the course of the Astron work, it was noted that a significant fraction of the current could be contributed by the low energy, fuel ions, via the diamagnetic effect.⁽⁵⁻⁶⁾ The Field-Reversed-Mirror lies at a limit of this process: a field-reversed configuration, localized by a weak mirror field, in which the azimuthal current is provided

entirely by diamagnetic current. There is, of course, a continuous transition from the Astron to the FRM case. Reactor designs in the Astron limit were studied extensively in the early 1970's.⁽⁶⁾ They seemed very attractive, but of large unit size (about 5 to 6 gW). In this paper, we will study reactor parameter sets in the FRM limit, and will find that much smaller reactor units can be designed.

The quantitative distinction between an Astron geometry and an FRM geometry is best made on the number of gyroradii included in the minor radius of the plasma. If the characteristic gyroradius ρ_i is a small fraction of the minor radius a , one has the FRM. In this case the characteristic ρ_i is based on the mean ion energy. On the other hand, if the characteristic ion (or electron) gyroradius based on the injection energy satisfies ρ_i (or ρ_e) $\sim a$, one has the Astron case. In this latter limit, stable E-layers have recently been observed.⁽⁸⁾ Experimental work by a group at the Kurchatov Institute⁽⁸⁾ has also shown that field reversal at $(a/\rho_i) \sim 5$ in toroids with "greatly diffused" current sheaths is also apparently stable - the plasma survives for a hundred or more sound transit times across the major radius.

A theoretical framework for analyzing the stability of field-reversed layers has been developed.⁽⁹⁾ It casts the stability criterion in the form of an energy principle with five terms, three of which are familiar from zero gyroradius stability theory. These three terms on balance indicate instability, and the effect of the new terms, which can be seen to have a stabilizing influence in certain limits, is under study. Examples of layers which are stable have not, as of this writing, been found. This is thought to be due to failure to search out the relevant parameter space for

the "new" terms; it may, however, be due to omissions in the theory (which does not consider line-tying of the open field lines). Therefore, we rely on the above-mentioned experimental results.⁽⁹⁾ Since the ratio $S = a/\lambda_i$ was about 5 for stable plasmas in the Russian work (see Appendix C of Ref. 1 for a more detailed analysis), we have assumed $S = 5$ in our work. The Russian workers made no attempt to sustain their field-reversed configuration with neutral beam injection, but we will assume, for purposes of evaluation, that this can be done. We will further assume the FRM current layer can be established in situ at full magnetic field. One possible means for accomplishing this is a high-voltage pulsed ion diode of the type currently under development at several laboratories.⁽¹⁰⁾

III. Computation of Plasma Parameters

In order to evaluate the field-reversed mirror, it is necessary to compute the expected plasma parameters. To do so, we have formed a simple model with a number of free parameters which can be adjusted to fit experimental measurements or other, more detailed, theoretical calculations. We consider only conditions in the toroidal reversed field layer since the surrounding plasma is assumed to be confined only by weak mirrors; ions which diffuse into this region will be quickly lost. Basic to the model are equations for the central ion number density n_i and the mean ion and electron energies $\bar{E}_i$ and $\bar{E}_e$. We assume an isothermal plasma and only one average ion of mass $A_i = 2.5$ AMU, and allow for the expected density gradient by an imposed density profile of cubic shape. We take particle and energy losses to be diffusive in nature and neglect the α -particles. Except for very high-energy beams, the

gyroradius (at 3.5 MeV) will exceed the plasma dimensions; they will thus be lost essentially without energy deposition in the plasma. With these assumptions the appropriate zero-dimensional equations are

$$\frac{dn_i}{dt} = 0 = \dot{n}_0 - \frac{n_i}{\tau_p} \quad (1)$$

$$\begin{aligned} \frac{d(n_e \bar{E}_e)}{dt} = 0 &= \dot{Q}_{ie} - \frac{n_e \bar{E}_e}{\tau_E} \\ &- \frac{5}{3} \frac{n_e \bar{E}_e}{p} - \dot{Q}_s - \dot{Q}_B \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{d(n_i \bar{E}_i)}{dt} &= \dot{n}_0 \bar{E}_{IN} - \frac{n_i \bar{E}_i}{\tau_{Ei}} \\ &- \frac{5}{3} \frac{n_i \bar{E}_i}{p} - \dot{Q}_{ie} \end{aligned} \quad (3)$$

$$\dot{n}_0 = n_i \quad (4)$$

$\dot{n}_0$ is the rate of increase of central density due to beam deposition, $\bar{E}_{IN}$ is the beam energy (assumed the same for D and T), and p , τ_E and τ_{Ei} are, respectively, the particle, electron energy and ion energy confinement times. $\dot{Q}_{ie}$ is the ion-electron energy transfer rate per unit volume, for the assumed Maxwellian distribution function of ions and electrons given by⁽¹¹⁾

$$\dot{Q}_{ie} = \frac{n_i (\bar{E}_i - \bar{E}_e)}{\tau_E} \cdot (W/m^3), \quad (5)$$

$$T_E = \frac{5.396 \cdot 10^{18} A_i E_e^{3/2}}{n_e Z^2 (n_i)^{3/2}} \quad (6)$$

$$\left[1 + \frac{E_i}{1836 A_i E_e} \right]^{3/2} \quad (6)$$

with E in keV and n in m^{-3} . n has been taken as the typical value of 20 for these calculations. The cyclotron and bremsstrahlung loss terms are computed from standard expressions.^(12,13) For the synchrotron losses, the wall reflectivity has been taken as 0.8.

The magnetic field is related to the plasma pressure via the total β . We take as given, either from experiment or from an equilibrium code, and require B_0 along with the solution to the other equations from

$$B_0 = \left[\frac{2.68 \cdot 10^{22}}{r} (n_e E_e + n_i E_i) \right]^{1/2}$$

(Tesla) (7)

For the present calculations we have assumed $r = 1.5$, a value observed in 2X11B (apparently without field reversal, however).⁽¹⁴⁾

For given confinement times, a very large family of solutions to Eqs. (1) - (10) depending on both n_0 and $E_{||0}$ is possible. However, as discussed earlier, diffuse density profiles are expected, so we choose the characteristic beam attenuation length of the plasma to yield a cubic profile. The fraction of neutral beam which penetrates a distance x into the plasma is given by

$$f(x) = \exp \left[- \int_0^x \langle \sigma_i + n_i \sigma_e \rangle dx \right] \quad (8)$$

where $\langle \sigma_i \rangle$ is the sum of the cross sections for ionization and charge-transfer⁽¹⁵⁾ averaged over the ion and electron Maxwellian velocity distributions, for radial beam injection, the distance x is measured along the plasma radius. For isothermal plasmas with density profiles of the form $n = n_0 [1 - (x/a)^2]^{1/2}$, where a is the radial distance from the minor axis, Eq. (8) becomes

$$f(x) = \exp \left[- \frac{r}{2} (1 + \frac{n_i}{n_e}) \left(\frac{x}{a} \right)^2 \right] \quad (9)$$

Results for the current HRF design⁽¹⁶⁾ suggest that a cubic profile is close to be expected for radial injection at $r/a = 1.75$. It is clear that we can obtain this value by adjusting B_0 to yield the desired $f(x)$ through its dependence on n_i . Note that β depends also on $i_{||}$, $f_{||0}$ and i_{p0} , albeit only very weakly, on the latter.

To complete the description, we need expressions for the particle and energy confinement times. The classical result of $\tau_p = \epsilon_0 a^2 / e n_i \lambda_e^2$ where λ_e is the electron gyroradius and ϵ_0 is the electron-ion scattering time has seldom been observed in experiments. We have therefore made the more conservative assumption of

$$\tau_p = a^2 / i_{||} f(j) / i_i^2$$

$$\tau_{Ee} = \tau_{Ei} = a^2 / i_{||} / i_i^2 \quad (10)$$

where i_i is the ion gyroradius and $i_{||}$ is given by⁽¹⁷⁾

$$f_{ii} = 3.58 \cdot 10^{14} \frac{n_i^{1/2} E_i^{3/2}}{n_i n_i^{1/2}} \quad (11)$$

f_{ii} is a factor which accounts for the effect of the cubic density profile. In Eq. (11) the mean number density n_i (n_i) for the plasma is used.

We have also considered Bohm diffusion as a loss mechanism. This amounts to estimating the diffusion coefficient as $D = e^2 c^2 / B_0^2$. At the high temperatures and modest magnetic fields and densities we are considering for the FRM reactor, Bohm diffusion is $\neq 1$, orders of magnitude faster than classical diffusion and, since $\frac{e^2 c^2}{B_0^2} \gg \frac{1}{n_i}$, it is well over 5 orders faster than the ion loss rates we used in the energy balance calculations. It is clear that any loss rate approaching the Bohm rate will be fatal to the FRM. Also, since the size of the plasma appears to be limited to a small number of gyroradii, one cannot avoid the problem by going to a large plasma minor diameter.

The above equations have been combined in a computer code which enables all quantities to be evaluated as a function of the neutral-beam energy E_{ib} . Calculations have been made for a torus of circular cross section and one with a highly elongated cross section. The latter yields higher values of Q and appears possible from both experiments⁽⁷⁾ and theory (Ref. 1, Appendix E). Similarly, a torus with aspect ratio near unity is indicated; we have taken the major radius $R = 2a$. Results for this case are plotted in Fig. 2 for

$S = a/v_i = 5$ and a length/radius ratio $L/a = 3$. We note quite favorable Q values (for D-T and a fusion energy of 17.6 MeV) of 4-6 for beam energies of 150-300 keV. At the higher beam energies, the required magnetic field is quite high, but it appears that for a small penalty in Q we

FIGURE 2. Mean ion and electron energies (E_i , E_e), magnetic field (B_0) and Q vs. neutral-beam energy for $a/v_i = 5$, $R/a = 2$, $L/a = 3$.

can lower the beam energy and thus the required B_0 to values attainable with inexpensive superconductors. The best combination of parameters is dictated by economic considerations which is the subject of the next section.

IV. Reactor Parameters and Cost Estimates

In this section we first describe the overall configuration of an FRM power reactor. Then we will describe the details of our parametric analysis and cost estimates which we are using to optimize the design for minimum power cost. The parametric analysis and cost estimate are still in an early stage of development; so the results reported here should be considered preliminary.

We assume that an FRM reactor would consist of a number of plasma layers (10) on a common axis (see Fig. 3), held apart by weak magnetic mirrors in the essentially uniform field of a long superconducting solenoid. The magnetic mirrors are produced by water-cooled copper coils placed

FIGURE 3. Layout of Multi-cell FOM Reactor.

between the plasma and blanket. Also, copper ioffe-bar conductors are placed at this location to form a magnetic well.

The neutron moderating blanket and the shield for the superconducting coil are cylindrical shells. We are considering both a high and low energy multiplication blanket. The high multiplication blanket contains beryllium and achieves an average M (blanket thermal energy per fusion neutron/14.1 MeV) of 1.7 through n, Zn reactions. The low multiplication blanket

achieves an M of 1.2 due to exothermic neutron captures. Tritium is bred in solid lithium-containing compounds. The blanket is cooled by helium. Hot and cold manifolds pass axially through the reactor, and individual axial segments of the blanket are cooled by parallel flow circuits. The exit helium is used to generate steam for a steam power cycle which has an efficiency of 40%.

As we will show, the optimum magnetic field strength for the superconducting sol-

enoid appears to be about 10 Tesla, thus permitting the use of niobium-titanium superconductor. The superconducting solenoid is restrained by a simple hoop structure. Outside the coil and coil structure is a cylindrical vacuum vessel.

Neutral beam injectors are arranged along the length of the reactor, aimed radially inward. As we will show, injection energies of 200 keV are desirable, thus necessitating the use of negative ion type neutral beam injectors for high injection efficiency (80%).

At each end of the reactor, a single-stage direct converter converts about 50% of the energy of the plasma end leakage directly into electricity. The remaining energy is removed by helium coolant and added to the steam power cycle. The direct converter chambers contain the primary vacuum pumping system for the reactor, consisting of 4K helium-cooled condensation panels.

The entire reactor, including the injectors and direct converters, is assumed to be oriented vertically and enclosed in a reinforced concrete containment building. Depending on the desired electrical output of the power plant, more than one reactor may be placed in the same building.

Now we will describe the step-by-step procedure used in the parametric analysis to design a particular reactor. The primary independent physics parameter has been taken to be the injection energy. The physics model of Section III then yields the required magnetic field strength, the size of the plasma layer, the plasma energy and density, the fusion power and the plasma Q (fusion power divided by injected neutral beam power). Some of these results are shown in Fig. 2. The fusion power is shown in Fig. 5. For each value of injection energy the engineering design begins with the coupled problem of the internal

FIGURE 5. Power cost and fusion power vs. injection energy for optimum cell lengths.

dimensions (radius and length) of the reactor cell and the design of the copper coils. First we specify a trial length L for the reactor cell. Then, adding the neutron flux contribution from each plasma layer, the first wall radius R_w is set so that the peak first wall neutron wall loading, ϕ_w , is a preselected value. For the cases discussed in this paper we have set $\phi_w = 4 \text{ MW/m}^2$, based on typical results from the Yin Yang mirror reactor study.⁽¹⁹⁾ For simplicity, we assume that the mirror coils, loffe bars, and blanket first wall are all at the first wall radius. This is a good approximation since the copper coils are always small in cross-section. There is a lower limit placed on the first wall radius: it is not allowed to be less than the radial extent of the plasma toroid plus two alpha particle gyro radii. At this point in the calculation we check to verify that the cell length L satisfies the criterion $L \sim 1.2 R_w$. Below this spacing the

axial mirror ratio (coil to center) of a pair of coils is less than unity. The optimum distance from an economic point of view always turns out to be somewhat greater than this minimum spacing, because as this spacing is approached, very large mirror currents are required to maintain the mirror ratio greater than unity. (See Figure 4.) With the mirror coils defined

FIGURE 4. Projected cost of electrical power vs. cell length.

in length and radius, the axial mirror ratio may be varied by changing the mirror coil current. (Recall that a large uniform solenoidal field is established by the superconducting coil.)

Just how much axial mirror ratio is necessary is not obvious. Indeed, it is conceivable that the plasma layers could be stable in a uniform field. However, for this study, we have required a small axial mirror ratio of 1.0001; this ratio is defined to include the fields from all coils and all plasma layers except the one in the cell under consideration i.e. it is the "vacuum" mirror ratio seen by the

plasma layer. For the current in the Ioffe bars we require a small radial well of 1.0001 at the plasma major radius. An approximate formula of Taylor⁽²⁰⁾ is used for this calculation; more accurate coil calculations may show the well to be somewhat different. Although the above choices of mirror ratios are somewhat arbitrary, the resultant mirror coils and Ioffe bars contribute a negligible amount to the overall reactor cost and higher currents could be specified.

Now we must determine the cross-sectional area of the copper mirror coils and Ioffe bars. An economic trade-off exists: large cross-section coils will minimize the resistive power loss in the coils, but maximize the neutron attenuation in the coils. We perform an optimization to minimize the sum of the resistive loss in the coils and the potential for electrical power production which is "lost" because of neutron attenuation in the copper. The latter quantity is approximated by multiplying the neutron heating of the copper by M and by the thermal efficiency of the steam power cycle. Within this optimization is another optimization such that, for a given total resistive loss in the coils, the loss is apportioned between the mirror coils and Ioffe bars so as to minimize neutron interception. This completes the design of the reactor cell and copper coils for a single trial cell length.

In general, larger trial cell lengths result in smaller first wall radii (because of the criterion on neutron wall loading) and smaller copper coil losses. The calculation of all costs determines the optimum cell length for the injection energy being considered. Because the first wall radius is a weak function of cell length and the copper coil losses tend to

be quite small, we have found to date that small cell lengths rather close to the minimum allowed are best.

The remainder of the reactor is designed from the first wall outward. The thickness of the cylindrical shell blanket is set at 1 meter. The design thickness for the superconducting coil shield involves an economic trade-off. Thicker shields reduce the neutron heating of the coil and thus the cost of cryogenic refrigeration, but they increase the size and cost of the coil, coil structure, vacuum vessel, and the containment building. We calculate an optimum shield thickness for each case. However, because of the exponential attenuation of neutrons in the shield, we have found that the optimum shield thickness is always in the narrow range of 70 to 80 cm. The superconducting solenoid is placed outside the shield. The thickness of the coil restraining structure (a single stainless steel cylindrical shell) is calculated based on a 60,000 psi design stress. The main vacuum tank surrounding the coil structure was assumed to be aluminum, and was designed to ASME code as a long cylindrical vessel. (This neglects the stiffening effect of the ends and any webbing, and thus overestimates the weight.) The containment building is sized to hold the reactor, complete with its injectors and direct converters. We have not yet designed the components of the reactor in much detail, but they are in most cases simple (circular coils, cylindrical tanks, etc.) and we feel that adequate preliminary cost estimates can be made. We have calculated direct capital costs using 1975-76 prices except where noted, and have not included indirect cost factors for construction facilities, engineering, interest during construction, contingency, etc. Table I gives the basis for our preliminary

cost estimates. For a number of components, the estimates were borrowed from other reactor studies conducted at LLL, and are not based directly on the concurrently developed FRM design shown in Fig. 3. In future work we will be able to improve our cost estimates for these components. Although all of the estimates are subject to change and additional cost categories may be added, we believe our present results to be reasonably accurate.

The \$/kWe cost of the reactor is calculated by dividing the total direct capital cost by the net electric power of the plant. Figure 5 shows this cost as a function of injection energy for cases of optimum cell length. Curves are shown for two values of blanket energy multiplication, $M = 1.2$ and 1.7 . We see that the minimum costs occur for injection energies near 250 keV. The minimum cost is \$950/kWe for $M = 1.2$ and \$730/kWe for $M = 1.7$. Also shown on Figure 5 are the fusion power and the net electric power per reactor cell.

Figure 5 shows that the cost variation is quite small over a range of injection energy from 200 to 300 keV. At lower energies the cost increases primarily because of lower Q's and the resulting high recirculating power fractions. At higher energies the cost increases because the more slowly increasing Q no longer compensates for the higher magnetic field strengths which are required. For the $M = 1.7$ case, the magnet and magnet structure accounts for 16% of the total cost at the optimum energy, but 38% of the total at 400 keV.

Table II gives reactor parameters for a near-optimum design with $M = 1.7$. We chose the slightly off-optimum case with 200 keV injection energy because the required superconductor field strength is lower, making possible the use of niobium-titanium

TABLE I. Basis for Cost Estimate

1) Superconductor:	Present prices reduced by Powell 3.5 factor for mass production. (21)
2) Winding	1/2 of Yin-Yang winding cost per A-m. (22)
3) Structure	Stainless steel at \$11/kg.
4) Power supply	Proportional to coil energy, normalized to Ref. (23).
5) Refrigeration system	Proportional to coil neutron heating, normalized to Ref. (22).
6) Blanket (with beryllium)	\$280k/m ³ . (22)
7) Blanket heat transfer loop	\$37 kW handled. (22)
8) Shield	80 stainless steel at \$11/kg.
9) Vacuum tank	Aluminum at \$22/kg.
10) Vacuum pumping system	1/2 of vacuum tank cost.
11) Neutral beam injectors	\$200/kW injected.
12) Diagnostics and control	\$100k/cell.
13) Tritium handling systems	Normalized to Ref. (22).
14) Direct converters	\$100/kW of charged particles. (22)
15) Direct converter heat transfer loop	\$35/kW handled. (22)
16) Main containment building	Proportional to volume, normalized to Ref. (22).
17) Thermal conversion system	\$28/kW handled. (22)
18) Turbine building	\$5/kW handled. (22)

TABLE II. Typical FRM Reactor Design

Beam Energy = 200 keV

Plasma minor radius $a = 0.031$ m	Wall Radius = 0.61 m
Plasma major radius $R_p = 0.062$ m	Cell Length = 1.1 m
Plasma length = 0.19 m	Injected current = 17 A/cell
$a/v_i = 5$	Injected power = 3.5 MW/cell
Vacuum Field = 8.2 Tesla	
Ion Energy = 77 keV	Mirror coil current = 46 KA
Electron energy = 29 keV	loffe bar current = 10 KA
Peak Density = 3.6×10^{21} ions/m ³	Mirror coil cross section = 13 cm^2
Fusion Q = 5.3	loffe bar cross section = 14 cm^2
Fusion Power = 18.5 MW/cell	resistive power = 0.28 MW/cell
Plasma $\beta = 1.5$	neutron heating = 0.36 MW/cell
Blanket thickness = 1 m	$P_{\text{net}} = 10.2 \text{ MWe/cell}$
Blanket M = 1.7	Total cost = \$745/kWe
Shield thickness = 0.8 m	
Superconducting solenoid radius = 2.4 m	

superconductor. The optimum design occurs for 250 keV injection. The power output (23 MW/cell) and B field (110 kilo Gauss) are slightly higher than the case in Table II, and the plasma dimensions are slightly smaller. The power cost for this high field case is only about 2% lower than the cost in Table II.

The reactor costs shown in Fig. 4 are extremely attractive. This was perhaps to be expected a priori for a system with high β and simple magnetic field configuration. We are taking a detailed engineering design of a reactor with the parameters given in Table II, and are at present working to reduce the number of physical extrapolations and assumptions needed. We feel confident that, at questions such as the start-up and maintenance of an FRM configuration can be answered with reasonable technology, the end product will be a very useful form of CTR reactor.

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