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Conceptual Physics Design of a Compact Torus Fusion Reactor (CTOR)

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Conceptual Physics Design of a Compact Torus Fusion Reactor (CTOR)

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R. A. Krakowski

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CONCEPTUAL PHYSICS DESIGN OF A COMPACT TORUS FUSION REACTOR (CTOR)

by

R. L. Hagenson and R. A. Krakowski

ABSTRACT

The general approach to fusion power embodied by field-reversed plasmoid configurations is reviewed within the context of a power reactor. A simple analytic formulation is developed and applied to the field-reversed theta pinch as a core plasma for a thermonuclear reactor. These calculations and results are based on a minimum power constraint and will serve as a basis for more exact and detailed reactor modeling.

I. INTRODUCTION

The generic name "compact torus" (CT) has recently been applied to the general class of toroidal plasma configurations in which no magnetic coil or material walls extend through the torus. This closed-field, plasmoid configuration is not new, having been generated by a coaxial plasma gun over two decades ago.¹ Interest in this configuration as applied to a conceptual fusion reactor, however, began when the Spheromak² was proposed as a means to retain the developing physics base for tokamaks, while simultaneously shedding certain technological difficulties encountered when that concept is extended to a fusion power reactor. Since the Spheromak reactor proposal was first made, the fusion community has identified the general area and potential of compact toroids, the spheromak being one element of the CT class of plasma configurations. Fig. I-1 summarizes this CT class, as organized by a recent workshop and exchange on that topic.³

This study began with an attempt to assess generally the reactor potential of the CT configuration. It soon became evident that a scoping study of this level-of-effort, could not comprehensively treat the entire CT "family tree" depicted on Fig. I-1. In addition to a great diversity of plasmoid formation, heating and confinement schemes, the fundamental physics of particle/energy transport and stability/equilibrium are poorly known for most subsets of the CT class. Consequently, a choice and a focus had to be

Fig. I-1. Classification of Compact Torus (CT) configurations.

made. Because of a desire for reactor plasmas with maximum power density, the MHD-like branch of the CT family was selected for a more focused study. Furthermore, the $B_\theta \sim B_\phi$ section of the MHD-like branch was not considered in this study due to lack of reactor-relevant experimental results. The remaining $B_\phi \sim 0$ MHD-like elements of the CT family are classified here as Field-Reversed Configurations (FRC). Since reactor studies of the Field-Reversed Mirror (FRM) component of the FRC have been examined elsewhere,⁴⁻⁸ it was decided to focus this preliminary CT reactor study on the Field-Reversed Theta Pinch (FRTP) configuration of the FRC category. The existence of both experimental and theoretical activity in support of the FRTP approach played an important role in arriving at this decision. Studies of the FRTP approach to fusion power have been⁹ and are being¹⁰ made.

In order to facilitate the assessment of reactor potential for Alternative Fusion Concepts (AFC), a three-tiered structure has been established wherein a Level I study (Engineering Design Phase) is the most detailed, and a Level III study (Conceptual Physics Design Phase) is the most preliminary. This report is classified as Level III; only simple analytic models are used to generate a highly conceptual boundary in parameter space wherein a FRC reactor might operate. Even considering the Level III category, this study must be viewed as highly preliminary in view of the large

uncertainties and sparse knowledge associated with this very new but rapidly developing area of magnetic confinement physics. The primary intent of this report is to summarize the results of this interim study and to set the basis and direction for an analytically and conceptually more detailed examination of the FRC/FRØP as a fusion power reactor; this reactor embodiment is termed the Compact Torus Reactor (CTOR). This report is being issued to inform physics researchers of the basis and direction of the continuing FY-1980 reactor study in the hopes that their activities and focused thinking can have a maximum impact on a more detailed Level II (Conceptual Engineering Design Phase) study of the FRØP/FRC reactor study.

II. EXECUTIVE SUMMARY

Although the full spectrum of Compact Torus Reactors (CTOR) has been reviewed and summarized, the primary focus of this scoping study has been a system wherein a plasmoid formed by an external source (FRØP) is translated through a linear burn chamber. Simple analytic models were used to estimate the plasma response and overall engineering constraints, and a CTOR design point has been estimated on the basis of minimum power production. Table II-I summarizes the range of minimum-power operating points as determined by either fixing the duty factor, f_d , or the plasmoid injection rate, $1/\tau_I$. Unlike other CTOR system studies, no constraint was imposed on the ratio of plasma radius to ion gyroradius, $S = a/\rho_i$. The preliminary CTOR design point presented herein operates with all stabilizing/confining electrical conductors positioned outside a neutron-moderating/tritium-breeding blanket. This constraint, when coupled with the minimization of joule heating incurred within a room-temperature conducting shell, results in minimum thermal powers of ~ 1 Gwt for the FRØP/CTOR approach.

It should be emphasized that the results of the simple analytic models used herein are intended to guide a more detailed time-dependent analysis that is presently in progress. Important determinants of the CTOR viability appear to be the value of S , the joule losses in a conducting (stabilizing) shell, and the trapping efficiency and dynamical effects of the alpha-particle fusion products. These issues will be examined in more detail while maintaining the desirable feature of locating a plasmoid formation/heating system outside the reactor core.

TABLE II-I
TYPICAL CTOR PARAMETERS (MINIMUM POWER)

PARAMETER	Constant f_ℓ (0.1)	Constant τ_I
Total thermal power, P_{TH} (MWt)	880	1141
Burn chamber length, L (m)	42	85
Separatrix radius, r_s (m)	0.83	0.63
Plasmoid length, ℓ (m)	5.8	4.4
First-wall radius, r_w (m)	1.2	0.75
Conducting shell radius, r_c (m)	1.7	1.25
Shell skin time, τ_s (s)	0.6	0.2
Burn time, τ_B (s)	4.5	4.2
Injection time, τ_I (s)	6.2	$2.2(f_\ell = 0.1)$
Translational velocity, v (m/s)	9.4	20.4
Plasma density, $n(10^{21}/m^3)$	1.1	1.2
Compressed field, B_i (T)	3.0	3.1
Vacuum field, B_o (T)	2.3	2.3
Engineering power density, $P_{TH}/\pi r_c^2 L$ (MW/m ³)	2.4	2.7
First-wall temperature rise for copper, ΔT (K)	14.2	14.9
First-wall temperature rise for stainless steel, ΔT (K)	62.1	65.3
<u>ASSUMED OR FIXED PARAMETERS</u>		
Blanket thickness, Δb (m)	0.5	
Plasma temperature, T (keV)	10	
Fusion neutron wall loading, I_W (MW/m ²)	2.0	
Shell thickness, δ (m)	0.05	
Duty factor, $f_\ell = \tau_s/\tau_I$	0.1	
Lawson parameter for 22% burnup, $n\tau_B(10^{21}s/m^3)$	5.0	
Equilibrium/Stability constraints		
• r_c/r_s	2.0	
• ℓ/r_s	7.0	

III. THE GENERAL CLASS OF COMPACT TORI

The term Compact Torus (CT) is applied to a general class of toroidal plasma configurations in which no magnetic coils or material walls extend through the center of the torus. A typical CT configuration is shown in Fig. III-1, which illustrates the toroidal magnetic field, B_ϕ , the poloidal magnetic field, B_θ , and the location of the separatrix that divides open and closed magnetic field lines. A spectrum of conceptual CT systems result when B_ϕ is varied from 0 to $\sim B_\theta$. This class of toroidal plasma configurations is further enlarged when applied to a range of specific geometries. An excellent summary of past theoretical and experimental work on CT plasmas is presented in Ref. 11. Therefore, only an overview of this work is presented here.

A summary of CT plasma configurations that have been experimentally and/or theoretically investigated is given in Fig. I-1. Two major CT categories are shown in order to define the scope of this reactor study, which is limited to a field-reversed configuration (FRC) produced by a Field-Reversed Theta Pinch (FRTP). The major geometric parameters, used throughout this study to describe the CT plasma, are defined in Figs. III-1 and III-2. The CT has a length ℓ , with a separatrix radius r_s , effective major radius R and plasma half-width or minor radius a . The conducting shell radius, r_c , and first-wall radius, r_w , are also shown.

Fig. III-1. Schematic diagram of Compact Torus plasma configuration. For some CT configurations the toroidal field, B_ϕ , is zero.

Fig. III-2. Compact torus geometry showing radius of conducting shell, r_c , first wall, r_w , separatrix, r_s , and plasmod length, ℓ .

The FRØP has a stronger experimental basis¹¹ relative to other CT configurations. Recent and encouraging results¹² (confinement times $\sim 100 \mu s$, $T_i \sim 2T_e \sim 200 \text{ keV}$) are a consequence of establishing a large-radius, wall-stabilized plasma with $r_c/r_s \sim 2$. In fact, experimental evidence¹¹ indicates decreased confinement times as r_c/r_s increases and the plasma becomes over compressed. Experimental parameters of $r_c/r_s \sim 2$, $\ell/r_s \sim 7$ and $\beta \gtrsim 0.5$ (fraction of plasma energy divided by fraction of magnetic field energy contained inside separatrix), measured on the FRØP at the Los Alamos Scientific Laboratory,¹² along with analytic equilibrium constraints, are used to guide this reactor study. Unlike other studies,⁴⁻⁸ the constraint that $S = a/\rho_i \lesssim 5$ is not imposed.

CT configurations produced by theta-pinch sources contain little or no toroidal field, B_ϕ . The physics implications of adding varying amounts of toroidal field to the FRØP configuration are largely unknown. The low-beta ($\beta \sim 3\%$) Spheromak² has been theoretically investigated as a logical extension of Taylor's¹³ minimum-energy theorem. In this case, the current density within the plasmod, $j = \alpha B$ ($\alpha = \text{constant}$), is proportional to the field, and B_ϕ is of the order of B_θ . Spheromak plasmons would have an aspect ratio $R/a \sim 1.5-3.0$, $\ell/r_s \lesssim 1.7$ and require a conducting shell and/or feedback coils

for equilibrium and stability. Reactor-relevant experiments have yet to be performed with these configurations, and the Spheromak configuration is not addressed in this phase of the reactor study. Additionally, the right-hand branch of the CT family shown in Fig. I-1 is completely ignored by this study.

CT plasmas may also be established and/or driven by high-energy particle beams, operating in principle as steady-state, non-translating plasmoids. MHD equilibrium in this case would be established by Ioffe bars, with stability being provided by finite-Larmor-radius effects and/or feedback stabilization. It is for this reason that the constraint $S \lesssim 5$ has been enforced⁴⁻⁸. The field-reversed mirror (FRM) would use neutral-particle beams to generate a plasma with $T_i \sim 70$ keV, resulting in sheath widths of approximately two ion gyroradii and the potential for finite-Larmor-radius stabilization. A conceptual plasmoid, with confinement predicted by classical ion-ion collisions and based on a Hill's vortex¹⁴, is the basis for the physics model used for the FRM reactor study.⁶⁻⁸ The FRM configuration has not been experimentally produced in the sense of creating and sustaining a beam-driven plasma, although a gun-produced plasmoid or FROP may provide a satisfactory target plasma.¹¹

The ASTRON device consists of a circulating 20-50 MeV electron ring that would be provided by a high-energy gun and represents an early CT embodiment.¹⁵ This electron-layer contains and heats a lower-temperature plasma (~ 100 keV) that is trapped on the closed magnetic field lines inside the electron ring. Difficulties associated with cyclotron radiation losses emanating from the high-energy electron rings forced a lowering of the electron temperatures below 20-50 MeV; the resulting fusion power densities project to be too low for an economic fusion power system, however. The Ion-Compressor concept¹⁶ is based upon the Astron and attempts to resolve some of these problems. Ions would be injected into a reversed-field configuration at ~ 20 -MeV energies, the temperature of the trapped ions would then be raised to 300 MeV by adiabatic compression, while the plasmoid is translated into a burner section. The high-energy plasma ring contains and heats a lower-energy plasma (~ 20 keV) in which the fusion reactions would proceed.

Only the FROP approach to the FRC has a substantial experimental background. This reactor study, therefore, focuses on the highly-elongated FROP configuration, using experimental results as a basis for the reactor design. In addition to the stronger experimental base, the high-beta

character and the desire to focus this preliminary study, the substantial experimental and theoretical effort being directed towards the FRÖP in itself presents an important rationale for this choice.

IV. REACTOR CONSIDERATIONS FOR THE COMPACT TORUS REACTOR (CTOR)

Accompanying a preliminary definition of major engineering components, required of the reactor, an overview of the CTOR system under consideration is presented herein. Many of the "standard" engineering components, (blankets, shields, magnets, etc.) will be common to other fusion devices, and the necessary technology can be carried over directly to the CTOR. Those systems that are unique to the CTOR will be defined and correspondingly will receive more attention. This preliminary design, however, focuses on the projected plasma performance and the development of overall operating scenarios for the CTOR. After reviewing past CT reactor designs, this section addresses the general issue of reactor operating scenario, CT equilibrium, compressional scaling laws, stability properties, and translational properties.

A. Previous CT Reactor Designs

A number of conceptual reactor designs based upon reversed-field configurations have been documented, although no detailed reactor design exists. The first considerations of using a reversed-field plasmoid to produce power were based upon the ASTRON¹⁷ concept shown schematically in Fig. IV-1. Electrons accelerated to relativistic energies (20-50 MeV) are injected at the end of a cylindrical vacuum chamber. The electrons gyrate about the central axis while traveling back and forth between the mirrors, generating an electron layer. The current carried by this layer reverses the externally applied field and produces closed magnetic field lines that are potentially capable of confining a thermonuclear plasma. Particle interactions between the electron-layer and deuterium/tritium atoms produces the thermonuclear plasma immediately after the closed lines are formed. More detailed analysis of this concept revealed, however, that the slowing-down time of fast electrons, because of synchrotron radiation, would be shorter than that required for an energy breakeven, except for electron energies less than 20-50 MeV. This constraint limits the plasma density and fusion power output to a value that would be too low for economic power production.

Fig. IV-1. The original ASTRON¹⁷ concept.

To avoid the synchrotron radiation problem, the injection of high-energy ions was proposed.¹⁸ Electron-ring energies near 300 MeV were found to give optimal confinement properties. Producing and sustaining these electron rings solely by particle accelerators was deemed unfeasible¹⁶ because of the difficulties in making an acceptable energy balance. Assuming a steady-state ion ring, the overall power gain, Q , is defined as $\epsilon_a \epsilon_t \eta (E_p/E_r) (n_{\tau r}/n_{\tau p})$, where ϵ_a , ϵ_t and η are accelerator, trapping and thermal efficiencies, respectively. Taking the ratio of plasma thermal energy to the ion-ring energy as $E_p/E_r \sim 1-2$ and the ratio of $n_{\tau r}/n_{\tau p} \sim 10-15$ for the same two species gives $Q \sim (10-30) \epsilon_a \epsilon_t \eta$. If the overall efficiency of energy deposition in the plasma versus electrical input to the accelerators is $\epsilon_a \epsilon_t \sim 0.07$ and if $\eta \approx 0.4$, the system would not achieve an energy breakeven. In order to compensate for the poor energy balance a much more efficient ring heating source would be required.

The ion-ring compressor was then proposed.¹⁶ Producing the ion-ring at somewhat lower energies (~ 30 MeV) by particle beams, the inefficiencies become less significant, since the bulk of the plasma energy is added to the ring by adiabatic compression. A schematic diagram of this device is shown in Fig. IV-2, and a summary of expected parameters is listed in Table IV-I.

Fig. IV-2. The ion-ring compressor reactor concept.¹⁶

In both the ASTRON and ion-ring devices, the azimuthal current is carried predominantly by the high-energy particles. As the pressure of the background particles is increased, a significant fraction of this field-reversing current is provided by plasma diamagnetic currents. The field-reversed mirror (FRM) relies solely on these plasma currents to provide field reversal without the use of a high-energy, circulating layer of particles. The difference between the ASTRON and FRM geometries can be described in terms of $S = a/\rho_i$, the number of ion-gyroradii enclosed by the plasma radius, a . A class of particles with $S < 1$ exists in an ASTRON device, while the FRM configuration would operate with $S \sim 5-10$. In the absence of a conducting shell, finite-larmor-radius stabilization is considered crucial to the FRM stability, and an upper limit on a/ρ_i is generally taken⁴⁻⁸ to be ~ 10 . In either case, Ioffe bars are required to provide a radial magnetic well for plasma stability. The quadrupole field produced by four Ioffe bars, located near the first wall, produces the required magnetic field configuration.

The FRM has been investigated⁶⁻⁸ as a possible way to increase the energy gain for a simple mirror fusion reactor. A sample field line configuration with $R/a \sim 2$ and $l/a \sim 14$, based on results from the particle code

TABLE IV-I

ESTIMATED PARAMETERS FOR ION-RING COMPRESSOR REACTOR¹⁶

<u>PARAMETER</u>	<u>BURN CHAMBER</u>	<u>COMPRESSION CHAMBER</u>
Deuteron energy (MeV)	300	30
Total fast-ion charge (C)	1.5	1.5
Major ring radius (m)	3	10
Radial ring thickness (m)	3	10
Axial ring length (m)	4.5	15
Plasma temperature (keV)	20	low
Plasma density ($10^{20}/\text{m}^3$)	0.63	0.1
Fusion power per ring (MW)	300	0
Total energy per ring (MJ)	540	50
Ring lifetime (s)	5	0.1
External axial magnetic field (T)	1.4	0.14
Magnetic field at ring radius (T)	0.67	0.20
Axial current (MA)	10	10
First-wall radius (m)	4.5	15
First-wall loading (MW/m^2)	2.3	0.1
Compression time (s)	--	0.2-0.5
Duty cycle	0.8-0.9	--
Ring energy gain, Q	3	--

SUPERLAYER,⁶ is used as the FRM model. All plasma quantities are integrated over an assumed isothermal plasma using a cubic density profile; a set of time-dependent zero-dimensional equations results. Including neutral-beam interactions, alpha-particle burnup, radiation losses (bremstrahlung and cyclotron), ion-electron equilibration, diffusion and thermal conduction, steady-state solutions are determined. The particle loss rate was taken as $\tau_p = A_p a^2 \tau_{ii} / \rho_i^2$, where A_p represents a profile-related constant of order of unity, and ρ_i is the ion gyroradius. This ad hoc scaling is proportional to the ion-ion collision time, which is hoped to represent a conservative or "worst-case" limit for the particle confinement. The ion heat conduction is taken to be small while the electron conduction time is expressed as $\tau_E = 0.2$

$a^2 \tau_{ei} / \rho_e^2$, where the constant, 0.2, is inferred from tokamak experiments, and the electron-ion collision time is used.

Fixing S at 5 and assuming 10% of the alpha-particle energy is deposited in the plasma, curves of Q versus neutral-beam energy are generated for an assumed steady state. A maximum Q is achieved for a neutral-beam energy of 200 keV; a summary of plasma parameters for the FRM are listed in Table IV-II. The calculated plasma parameters are used as input to a computer code which determines required reactor sizes and component costs. A minimum unit reactor cost (\$/kWe) is achieved for the plasma parameters given in Table IV-II; a summary of the FRM reactor design is given in Table IV-III.

No detailed reactor design of the FRM reactor has been made, although estimates of system maintenance and overall plant design are available.⁶ The helium-cooled FRM reactor proposes solid, lithium-containing compounds for tritium breeding. Cylindrical components are used to construct the first wall, blanket, shield and superconducting coils. Advantages of linearity and axial modularity are emphasized, with each 2.04-m long cell weighing ~ 550 to ne, being removable from the system as a single unit. The original FRM reactor design⁷ is shown schematically in Fig. IV-3 as a vertically-oriented device. Because of maintenance problems, the FRM reactor is presently being

TABLE IV-II
PLASMA PARAMETERS AT OPTIMAL Q FOR THE FRM REFERENCE REACTOR⁶

<u>PARAMETER</u>	<u>VALUE</u>
Plasma minor radius, $a(m)$	0.07
Aspect ratio, R/a	2
Length-to-radius ratio, L/a	14
$S = a/\rho_1$	5
Plasma beta	1.5
Plasma centerline density, $n_0(10^{20}/m^3)$	6.5
Electron temperature (keV)	32
Plasma temperature (keV)	96
Vacuum field (T)	4.1
Fusion power (MW/cell)	20
Fusion power/Injected power	5.5

TABLE IV-III
REFERENCE FRM REACTOR DESIGN PARAMETERS⁶

<u>PARAMETER</u>	<u>VALUE</u>
First-wall radius (m)	0.73
Cell length, l (m)	2.0
Number of cells	11
Superconducting field (T)	4.1
Axial magnetic well on axis (mirror coils)	1.0013
Radial magnetic well at plasma edge (Ioffe bars)	1.0001
Injected power to plasma (MWt)	40
Fusion power ^(a) (MWt)	220
Gross electric ^(b) (MWe)	136
Power to 200-keV neutral-beam injectors (MWe)	54
Power recirculated to copper coils (MWe)	8
Net electric power (MWe)	74
Recirculated power fraction	0.46
System efficiency	0.29
Direct capital cost (\$/kWe)	1210

-
- (a) Losing 16 MWt of the fusion neutron power in the room-temperature copper coils positioned inside the first wall and taking a blanket multiplication of 1.2 results in a total blanket power of 192 MWt.
- (b) The 84 MWt (injected plus 20% of fusion power) of charged particles pass through a 50% efficient single-stage direct-energy convertor. The remaining thermal energy, along with the blanket energy, is converted to electricity with a thermal efficiency of 0.4.

proposed in a horizontal orientation, with a vacuum shell surrounding the coil structure. Plan and elevation views of this system are given in Reference 6.

Major engineering concerns focus on the severe insulation and lifetime problems associated with the mirror coils, which are located immediately inside the first wall, and the Ioffe bars, which are located near the first wall. The development of negative-ion-beam neutral-particle injectors would require a major effort. Startup of the FRM presents an uncertainty that is only qualitatively discussed.⁶ Slow buildup of this FRC by neutral-atom beams, intense pulsed ion-neutral-atom sources, reversed-field theta-pinch, rotating

Fig. IV-3. Layout of multicell field-reversed mirror reactor.⁷

electron or ion-beam, conical theta-pinch guns, coaxial plasma guns and remote magnetic compression of field-reversed plasma rings are methods that have been considered for startup. Coupling of the initial or starting plasma to the reactor burn has not been investigated. Noting that $\tau_{ii} \sim T_i^{3/2}$ and $\tau_{ei} \sim T_e^{3/2}$, it follows that $\tau_p \sim a^2 \tau_{ii} / \rho_i^2 \sim T_i^{1/2}$ and similarly $\tau_{Ee} \sim T_e^{1/2}$; these scalings imply substantially higher powers may be required for startup than is needed for sustenance of the burn. The maintenance of stability and equilibrium throughout this startup phase represents an additional concern.

Conceptual design studies for a rRM pilot plant have also been performed.⁸ This system has as a primary objective net power production using near-term technology. Only one FRM cell is used to produce 22 MW of fusion power and requires 4.4 MW of neutral-atom beam injection power. Parametrically increasing $S = a/\rho_i$ from 5 to 7 increases the fusion power from 22 to 42 MW with 3.2 MW of injected power being required. The target plasmoid is assumed to be formed by a coaxial plasma gun and is subsequently heated, fueled and sustained by 200-keV (negative ion) neutral beam injectors with an

assumed efficiency of 50%. A pair of superconducting coils provide the solenoidal field and small axial well, while the radial magnetic well is provided by four superconducting saddle coils. With $S = 5$, 90% of the 11.6-MWe gross electrical power must be recirculated, yielding a net power of 1.2 MWe. For the case where $S = 7$, 46% of the 19.8-MWe gross power is recirculated, giving a net power of 10.7 MWe. The problems associated with locating magnet coils near the first wall have been avoided in this latest design⁸; superconducting coils are positioned outside the blanket and shield. The unknowns associated with plasma startup, equilibrium, stability and neutral-beam construction and utilization, however, have not been suppressed.

The Moving-Ring Field-Reversed Mirror Reactor (MRFRMR)⁴⁻⁵ exhibits many similarities to the FRM reactor and uses the same plasma physics model. The major difference between the two concepts rests with the means by which a plasmoid is utilized in the burn chamber. The FRM reactor uses high-energy neutral beams for refueling and sustaining a confined plasma ring in a fixed magnetic wall. The MRFRMR reactor, on the other hand, proposes magnetically compressing the plasmoids to the initial burn temperature and transporting them down the burner section of the reactor by means of mirror coils, as is

Fig. IV-4. Moving-Ring FRM Reactor.⁴

shown in Fig. IV-4. Little external energy is added to the ring during this translation, although relatively cold plasma may be used to refuel the plasmoid during its transit. In the preliminary design⁴ the plasmoids are not ignited, and thermal quenching of the burn because of the cold-plasma refueling determines the ring lifetime; the magnetic diffusion time (tens of seconds) is considerably longer than the plasma burn time (~ 0.3 s). An electrically conducting first wall provides wall stabilization, centers the moving plasmoid within the burn section and eliminates the need for multipole fields (Ioffe bars) to provide radial stabilization.

The basic physics assumptions invoked by the MRFRMR design are similar to those used for the FRM reactor. A multi-species, non-thermal relativistic Fokker-Planck code calculates the time dependence of an isothermal plasma on the basis of an assumed cubic radial density profile. The particle confinement time is required to be three times longer than that assumed for the FRM in order to achieve the same overall plasma Q-value. Electron and ion heat conduction are neglected because of the assumed rapid particle loss along the open field lines outside the separatrix. The fraction of alpha particles retained by the plasma is again assumed to be 0.1. A summary of key plasma parameters for the reference MRFRMR is listed in Table IV-IV. Systems with and without cold fuel addition were investigated, using the fueled plasmoid as the reference case. Adding fuel causes a significant decrease in plasma temperature from 75 keV to ~ 8 keV at the end of the burn, although the power is maintained at a nearly constant 10.6 MWt because of the doubling of the ion-density during the 0.32-s burn. Without fuel addition a nearly constant ion temperature is maintained, although the fusion power varies from 10.6 to 4 MWt during the same burn period. Plasma refueling by pellet injection is assumed, using a CO₂ laser with a pulse energy of a few hundred joules, pulse width ~ 0.5 μ s, repetition rate of 10 Hz and spot of focus 0.5-mm diameter over a distance of 30 mm. For an input laser power of 15 kWe, pellet velocities of $\sim 10^5$ m/s could be achieved.

Plasma startup is qualitatively addressed by the MRFRMR design study. Using one of the aforementioned plasma initiation techniques discussed for the FRM reactor, the plasmoids would be compressed to the initial burn temperatures, as illustrated by Fig. IV-4. Specific parameters are not given, although a substantial final ion temperature (~ 75 keV) would be required. Using analytical equilibrium results given in Sec. IV.D for a separatrix

TABLE IV-IV

KEY PLASMA PARAMETERS FOR THE MOVING RING FRM REACTOR (MRFRMR)⁴⁻⁵

<u>PARAMETER</u>	<u>VALUE</u>
Initial plasma major radius (m)	0.096
Final plasma major radius (m)	0.066
Plasmoid aspect ratio	2
Ratic of length to minor radius	6
Initial value of $S = a/\rho_i$	5
Peak plasma beta, β	1.5
Initial ion temperature (keV)	37.5
Initial ion density ($10^{20}/\text{m}^3$)	4.8
Initial electron temperature (keV)	37
Initial electron density ($10^{20}/\text{m}^3$)	9.6
Vacuum field (T)	6.5
Burn time(s)	0.32
Fueling injection energies for D/T/e (keV)	3.3/4.9/0.9
Average particle injection rate per species ($10^{20}/\text{s}$)	0.2
Energies per plasmoid (MJ)	
• Fusion energy	3.38
• Initial plasma energy	0.41
• Refueling energy	0.008
• Expansion/compression work on plasma	0.181

radius, r_s , equal to the conducting shell radius, r_c , the quantity $\text{Tr}_s^{8/5}$ is a constant. A linear radial compression of ~ 15 would then be required if the starting plasma is ~ 1 keV. These conditions correspond to a starting plasma radius of ~ 1.5 m before compression.

Having achieved the desired temperature, the plasmoid would translate through the device by a set of mirror coils that are positioned internally to the first wall. The electrical and mechanical integrity of these coils, which would be subjected to an intense radiation environment, is not addressed in detail. A 20-mm thick aluminum conducting shell in conjunction with the mirror coils provides necessary stabilization against the precessional mode. The residence time of the MRFRMR plasmoid does not exceed 20% of the classical L/R decay time for currents induced in an infinitely long conducting shell.

For a 20-mm thick shell this residence time is ~ 0.015 s and the plasmoid speed is taken as $2(0.29 \text{ m})/0.015 \text{ s} \sim 40 \text{ m/s}$, where twice the maximum axial length is used. At this speed the resistive drag on the plasmoid at the beginning of the burn amounts to $\sim 3 \text{ kJ/m}$, while the smaller end-of-burn configuration presents a resistive loss of only $\sim 0.3 \text{ kJ/m}$. The equations derived in Sec. IV.F. substantially over-estimates the resistive drag loss if applied to the MRFRMR design. These equations require $l/r_c \gg 1$ (axial uniformity), whereas for the MRFRMR $l/r_c \leq 1$. Using the aforementioned plasmoid speed and taking the burn time of 0.32 s, the length of the reactor would be 12.5 m. Establishing a magnetic well that is stable against the precessional mode leads to the reactor parameters listed in Table IV-V. The helium-cooled blanket is constructed of annular cylindrical components containing solid lithium compounds for tritium breeding. Several blanket

TABLE IV-V
MOVING-RING FIELD-REVERSED MIRROR REACTOR PARAMETERS⁴⁻⁵

<u>PARAMETER</u>	<u>VALUE</u>
First-wall radius (m)	0.325
First-wall (conducting shell) thickness ^(a) (m)	0.02
Cell length (m)	1.05
Mirror coil centerline radius ^(b) (m)	0.255
Mirror coils axial spacing (m)	0.35
Mirror coil dimension (mm x mm)	40 x 40
Plasmoid speed (m/s)	40
Reactor burn section length (m)	12.5
Li ₇ Pb ₂ breeding blanket thickness (m)	0.4
Stainless steel/B ₄ C shield thickness (m)	0.97
First-wall average neutron loading ^(c) (MW/m ²)	3.85
First-wall peak neutron loading (MW/m ²)	6.2
Gross electric power (MWe)	7.4-8.2
Net electric power (MWe)	1.25-4.75

(a) Aluminum shell operating at reactor blanket temperatures.

(b) Water-cooled copper coil.

(c) Assumes one plasmoid per cell length at any given time.

configurations are explored, including low-activation systems. A range of electrical outputs are given, since a detailed energy balance has yet to be performed.

The high recirculating powers computed for the earlier MRFMR design⁴ has lead to investigations of alternative burn cycles that could result in higher plasma Q-values. The most sensitive plasma parameters appear to be $S = a/\rho_1$ and the fraction of alpha-particle power retained in the plasma. Increasing S from 5 to 10-15 allows the plasma to ignite, resulting in substantially higher Q-values. Increasing S also dramatically increases the fraction of alpha-particle energy retained in the plasma. These results, have been incorporated into the MRFMR plasma model and a commercial prototype reactor design study based on the use of ignited plasmoids is presently in progress.⁵

The sensitivity of the reactor design on $S = a/\rho_1$ has led theta-pinch experiments¹⁹ to investigate the particle/energy transport as a function of this parameter. In contrast to past assumptions that an upper bound on S of 3-5 may exist, the maximum stable times are found at the highest values of S (~ 10) achievable by the device. Experimentally stable times ($\geq 50 \mu s$) are ~ 100 times greater than characteristic MHD e-folding times. This experimental finding implies that values of S in excess of 10 may be realistic and are, therefore adopted by the reactor designs proposed in the report.

Two reactor concepts^{10,20} have also been proposed based directly on the FROP system. A multiple-cell device²⁰ has been proposed to "end stopper" a linear theta pinch. A multiple-mirror geometry would be stabilized by internal plasma cells consisting of reversed-field configurations. Using a long FROP, multiple cells are produced by weak mirror coils that in turn induce resistive tearing. The FROP multiple mirror appears to offer advantages over a simple multiple-mirror device because the effective ion mean-free-path is reduced from a collision mean-free-path (5-10 m) to the intercell distance (0.05-0.1 m). Also, a significant fraction of the fusion yield would arise from plasma trapped on open field lines. A reactor length of ~ 200 m is projected²⁰ for a plasma with a ~ 20 -mm radius, requiring a 10-T magnetic field to achieve a Lawson parameter of $\sim 10^{21}$ s/m³ at $T = 8$ keV with a total plasma energy of 18 MJ. The reduced size is significant when compared to lengths in excess of 10 km projected for conventional linear theta pinches.²¹

The TRACT reactor concept (Triggered Reconnection, Adiabatically Compressed Torus)¹⁰ is based on the use of a single FROP cell. A superconducting bias field maintains a 7-T field during the 0.5-s plasma burn. During the startup a normal coil positioned near the first wall is used to cancel the superconducting field and establishes a reverse-bias field inside the plasma chamber. A rapid decrease in the normal coil current causes a radial shock and reverses the magnetic field while a cusp field at each end delays field-line reconnection until the vertical flux peaks. Reversal of the cusp current subsequently triggers the reconnection, resulting in a rapid axial compression and strong plasma heating. As the current in the first-wall normal coil is reduced to zero, the plasma is adiabatically compressed by the raising superconducting magnet field. The reactor parameters for TRACT are summarized in Table IV-VI. This reactor design and plasma burn are similar (on a per unit length basis) to the Reference Theta-Pinch Reactor (RTPR) concept,²² with the toroidal configuration being replaced by a compact torus of much smaller axial length in a cylindrical reactor. Both the multiple-mirror²⁰ and TRACT¹⁰ concepts initiate and burn the plasma in the same chamber. The potential engineering difficulties of handling high-voltages in a radiation environment are introduced; the required voltage, however, may be substantially reduced compared to the RTPR design²² as a result of additional heating caused by the axial shock. These pulsed reactor systems must also address first-wall thermal fatigue problems in conjunction with voltage requirements.

Lastly, the LINUS^{23,24} reactor concept proposes the compression of a reversed-field plasmoid configuration by a rotating liquid-metal (Li or LiPb) liner. This system has advantages of compactness and high power density, while possessing a renewable first wall that also functions as a neutron moderating and tritium breeding medium. A helium reservoir is used to drive the lithium liner and to compress the plasma to ignition. This concept is significantly different from those investigated in this report and is, therefore, not explored here in detail.

B. CTOR Operating Scenario

The development of a reactor embodiment on the basis of a concept that is as embryonic as the FROP/FRC has certain advantages; specifically, the choice of the CTOR operating scenario can be dictated at the present level of understanding by engineering technology considerations that are only mildly constrained by known physics limitations. This situation to varying degree is

TABLE IV-VI
TRACT REACTOR PARAMETERS¹⁰

<u>PARAMETER</u>	<u>VALUE</u>
Length (m)	5.0
First-wall radius (m)	0.5
Magnetic field (T)	7.0
Plasma temperature (keV)	15
Plasma average density ($10^{20}/\text{m}^3$)	20
Plasma separatrix radius (m)	0.34
Plasma length (m)	2.12
Assumed confinement time (s)	0.5
Shock heating energy (MJ)	8
Adiabatic compression energy (MJ)	80
Electric field at first wall (kV/m)	< 50
Peak thermal power (MWt)	367
Burn time (s)	0.5
Repetition rate (1/s)	1
Peak first-wall neutron loading (MWt/m ²)	15
Recirculating power fraction ^(a)	0.11
Net electric power ^a (MWe)	90

-
- (a) A total output energy of 278 MJ/pulse would be converted with an efficiency of 0.36 to electricity; 1.9 MJ/pulse is recirculated for joule heating, 4.2 MJ for switching losses, 4.5 MJ for plasma preparation and 1 MJ for coolant pumping losses.

reflected by the reactor studies that have been summarized in the preceding section. In this spirit, therefore, the CTOR burn chamber is specified to function only as a heat recovery unit; all plasmoid formation and heating functions should occur in accessible, external and near-room-temperature systems. Furthermore, all electrical systems required for equilibrium/stability that are associated with the burn chamber are specified to be either steady-state (i.e., superconducting) or passive (i.e., a simple conducting shell). Enforcing this specific mode of operation generally leads to a drifting plasmoid that is driven at a velocity which is compatible with the constraints imposed by: a) flux-diffusion or electrical skin times of a

passive conducting shell, b) first-wall thermal cycling and c) total system power output.

A schematic cross-sectional view of the proposed CTOR is shown in Fig. IV-5. The plasmoid is produced in a region that is separate from the high-temperature reactor core and would subsequently be translated to the linear burner chamber. Plasma formation and heating (startup) may be performed by a theta-pinch source, as is done in present experiments,¹² or startup may be initiated more slowly and in larger dimensions, allowing significant ohmic heating to occur before external heating sources drive the plasma to ignition. Compressional and/or beam heating are considered as viable alternatives for driving the plasma to ignition prior to translation through the burner section. The compressor section, (Fig. IV-5) would be tapered to assure a nearly constant ratio of conductor-to-separatrix radii, $r_c/r_s < 2$, as the plasmoid is compressed and translated to the burn chamber; mirror coils of increasing magnet field strength would compress and translate the plasma. Although neutral-atom beams can also be considered as a heating source, significant constraints must be imposed on the plasmoid source and size in order to minimize the required injected power.⁶⁻⁸

Fig. IV-5. Schematic view of the Compact Torus Reactor (CTOR) based on a translating Field-Reversed Theta Pinch.

After translation into the reactor core, the burn is assumed to proceed at a nearly optimal temperature of ~ 10 keV. Ideally, the heated plasmoid would retain sufficient alpha-particle energy to achieve ignition and to maintain its temperature near the optimum value of ~ 10 keV, although the actual alpha-particle confinement properties of the CT plasmoid are largely unknown. Non-ignition will undesirably require the plasma to be heated from external sources as the plasmoid moves through the burn chamber. At the other extreme, excess alpha-particle heating will lead to expansion of the plasmoid. In either case, the power output of the plasmoid may vary, and this variation must be taken into account by the translation mechanism (i.e., mirror coils) in order that a nearly constant power density along the length, L , of the burn chamber is maintained.

Translation or drifting of the plasmoids through the burn chamber provides a means of continuously purging the reactor core of fuel ash, of producing a nearly steady-state engineering system using batch-burn (unrefueled) techniques and of decoupling the conceivably complex plasma source (formation and heating) from the burn chamber. Movement of the plasmoid through the burn chamber and inside a flux-conserving shell forces the local magnetic field to increase as magnetic flux is compressed to a smaller volume between the separatrix and the shell. Part of the plasma pressure would be supported by the conducting shell, and the resultant ohmic dissipation within this shell would be extracted from the translational energy of the plasma. This loss may be significant and has forced this design to locate a room-temperature conducting shell of radius r_c outside the blanket region of thickness Δb rather than positioning the shell at the first-wall radius, r_w . This approach is quantitatively discussed in Sec. IV.F.

An analytic expression for the CT equilibrium is derived in Sec. IV.C. The subsequent parametric evaluation of this concept accounts for the dimensional characteristics of these plasmoids inside a conducting shell. Equilibrium considerations also lead to scaling relationships that can be used to define the trajectories of temperatures, densities and overall geometries as compressional heating is imposed.

C. Compact Tori Equilibrium

Before even a global plasma energy balance can be formulated and evaluated, a three-dimensional equilibrium for the CT plasma must be defined. An analytic equilibrium expression is determined from an axial force balance

that in turn is used in conjunction with radial pressure balance. An approximate equilibrium expression as proposed by R. Linford²⁵ is given here. Three regions are identified in the vicinity of the CT plasma, as is shown in Fig. IV-6. Region I includes the closed field plasmoid, but the regions near the separatrix are excluded; Region II contains the complex transition between regions of closed and open field lines; and Region III includes all open field lines located far away from the separatrix. Regions I and III are considered to be sufficiently long to ensure that changes in the plasma length do not alter the magnetic field/plasma configuration. The energy contained in Region II then remains unchanged when the plasma column undergoes axial motion.

Assuming a sharp-boundary plasma, the axial force exerted by the plasma and magnetic field trapped inside the plasma column is given by

$$F_p = \frac{B_I^2}{2\mu_0} \pi (r_o^2 - r_i^2) , \quad (IV-1)$$

Fig. IV-6. Schematic diagram of model used to generate the CT equilibrium expressions.

where the pressure exerted by the plasma column must equal that provided by the vacuum field in Region I, $B_I^2/2\mu_0$. This force must be counterbalanced by the vacuum fields and is given as

$$F_B \approx \frac{\partial}{\partial z} \left\{ \frac{B_I^2}{2\mu_0} \pi [r_c^2 - (r_o^2 - r_i^2)]z + W_{BII} + \frac{B_{III}^2}{2\mu_0} \pi r_c^2 (z_1 - z - \Delta z) \right\}, \quad (IV-2)$$

where the energy associated with the assumed "invariant" Region II is designated as W_{BII} , and B_{III} is the magnetic field in Region III. Performing the differentiation, the opposing force becomes

$$F_B \approx \frac{B_I^2}{2\mu_0} \pi [r_c^2 - (r_o^2 - r_i^2)] - \frac{B_{III}^2}{2\mu_0} \pi r_c^2. \quad (IV-3)$$

Imposing flux conservation between the conducting wall at radius r_c and the separatrix at radius r_s leads to

$$B_I \pi (r_c^2 - r_s^2) = B_{III} \pi r_c^2. \quad (IV-4)$$

Flux conservation inside the separatrix results in

$$r_i^2 = r_s^2 - r_o^2, \quad (IV-5)$$

and the force exerted by the vacuum fields becomes

$$F_B = \frac{B_I^2}{2\mu_0} \pi [r_o^2 + 3r_1^2 - (r_1^2 + r_o^2)^2/r_c^2] . \quad (IV-6)$$

Equating the two forces given by Eqs. (IV-1) and (IV-6) leads to-

$$2r_1r_c = r_1^2 + r_o^2 , \quad (IV-7)$$

and using Eq. (IV-5) gives the following relationship between the separatrix radius, r_s , and the conductor radius, r_c

$$r_s^2 = 2r_1r_c . \quad (IV-8)$$

Simplifications of these equilibrium equations are found if the separatrix is located at the conducting shell ($r_c = r_s$), which from Eqs. (IV-7) and (IV-8) yields

$$r_o/r_1 = \sqrt{3} . \quad (IV-9)$$

Defining an effective major radius, R , for the CT plasmoid, and a thickness or "minor diameter", $2a$, of the plasma column (Fig. III-1) gives

$$r_o = R + a \quad (IV-10A)$$

$$r_1 = R - a . \quad (IV-10B)$$

For the case where $r_c = r_s$ Eq. (IV-9) becomes

$$R/a = 2 + \sqrt{3} . \quad (IV-11)$$

For highly elongated plasmoids with the separatrix located near the conducting shell, the aspect ratio of the toroidal plasma is predicted to lie in the range 3 to 4.

The fraction of the cross-sectional area within the conducting shell that is occupied by the plasma is generally given by

$$f_p = 4[(r_o/r_i)^2 - 1]/[1 + (r_o/r_i)^2]^2 \quad . \quad (\text{IV-12})$$

For the case where $r_s = r_c$ and $r_o/r_i = \sqrt{3}$, therefore, $f_p = 0.5$, and half the bore is filled with plasma.

D. Adiabatic Compressional Heating

Using the equilibrium results from the previous section and applying the adiabatic law results in the scaling relationships that describe the thermodynamic response of the plasma to geometric changes. The vacuum magnetic field pressure can be expressed as

$$P = B_o^2/2\mu_o = \phi_i^2/(2\mu_o\pi^2r_i^4) \quad , \quad (\text{IV-13})$$

where the flux, ϕ_i , inside the radius r_i is assumed constant with time. Substituting Eq. (IV-13) into the adiabatic relationship

$$PV^\gamma = \text{Constant} \quad , \quad (\text{IV-14})$$

gives

$$[2r_i(r_c - r_i)\ell]^\gamma/r_i^4 = C_1 \quad , \quad (\text{IV-15})$$

where the plasma volume

$$V_p = \pi(r_o^2 - r_i^2)\ell \quad , \quad (\text{IV-16})$$

has been used, and C_1 is a constant. Equation (IV-15) can be re-arranged into the following form in conjunction with Eq. (IV-8)

$$\ell/\ell_0 = (\rho_0/\rho)^{4/\gamma} (r_s/r_{so})^{2[2/\gamma-1]} [1-1/2\rho_0^2]/[1-1/2\rho^2] \quad , \quad (\text{IV-17})$$

where $\rho = r_c/r_s$, and the subscript "o" indicates an initial or reference state. For the case of a plasmoid compressed by a radially-inward moving liner^{23,24} with $\rho = \text{constant}$, Eq. (IV-17) becomes for $\gamma = 5/3$

$$\ell/\ell_0 = (r_s/r_{so})^{2/5} \quad . \quad (\text{IV-18})$$

This relationship between plasmoid length and radius is appropriate if the flux between the conducting shell and the separatrix is conserved, which for realistic liner compressions may not be completely true.²⁴ On the other hand, taking r_c as a constant, Eq. (IV-17) reduces to

$$\ell/\ell_0 = (r_s/r_{so})^{14/5} [1-1/2\rho_0^2]/[1-r_s^2/2\rho_0^2 r_{so}^2] \quad . \quad (\text{IV-19})$$

The two extreme cases represented by Eqs. (IV-18) and (IV-19) are depicted in Fig. IV-7 for a range of initial values of conduction-to-separatrix ratios, ρ_0 . Good agreement is shown between the analytic curves and results from a two-dimensional simulation.²⁵ Deviations of the two results occur as the plasmoid becomes spherical and violates the analytic assumption $\ell \gg r_s$. The plasmoid exhibits considerably less length compression if the conducting shell is maintained near the plasma than for the case when the conducting shell radius is fixed as compression of the separatrix occurs. The insensitivity of the trajectory of ℓ/ℓ_0 versus r_s/r_{so} to values of ρ_0 for the flux-compression case (r_c is constant) allows Eq. (IV-19) to be simplified

$$\ell/\ell_0 \approx (r_s/r_{so})^{14/5} \quad , \quad (\text{IV-20})$$

where the bracketed terms in Eq. (IV-19) have been taken to be of order one.

Fig. IV-7. Length versus radius relationships for CT plasmoids compressed by flux conserving shells that either move with the separatrix radius (liners) or are stationary (FROP).

Using the adiabatic relationships (Eq. IV-14), Eqs. (IV-18) and (IV-20), a set of adiabatic invariants can be constructed, which are listed in Table IV-VII. Only for the case where $r_c/r_s = \text{constant}$ is the conducting shell radius forced to vary as the plasmoid changes dimensions, whereas r_c is constant for the other two cases. The variation in plasmoid length with the separatrix radius is large for $r_s < r_c = \text{constant}$, resulting in correspondingly large increases in temperature and density with decreasing separatrix radius, r_s . For compression by radially-moving liners, where $r_s = r_c$, only a modest length variation is envisaged during the compression, with the density and temperature variations being much closer to those expected for a purely cylindrical plasma. A graphic illustration of this behavior is shown in Fig. IV-8, where the efficiency, η_{AC} , is defined as the ratio of the plasma cross-sectional area to the total cross-sectional area inside the radius r_c , assuming a plasma configuration with $\beta \approx 1$. For a purely cylindrical plasma,

TABLE IV-VII
ADIABATIC INVARIANTS^(a) FOR TEMPERATURE, DENSITY AND PLASMOID LENGTH

<u>COMPACT TORI</u>		<u>CYLINDRICAL PLASMA</u>
$r_c/r_s = \text{Constant}$	$r_s < r_c$ ^(b)	$l = \text{Constant}$
	$r_c = \text{Constant}$	
$Tr_s^{8/5}$	$Tr_s^{16/5}$	$Tr^{4/3}$
$nr_s^{12/5}$	$nr_s^{24/5}$	nr^2
$l r_s^{-2/5}$	$l r_s^{-14/5}$	l

- (a) Listed quantities are constant to changes in plasma dimensions assuming no heat gain or loss from the plasma.
- (b) These quantities are approximately constant, subject to the simplification of Eq.(IV-19) to Eq. (IV-20) and r_c being fixed.

Fig. IV-8. Dependence of adiabatic compression efficiency on a range of assumed equilibrium constraints.

which initially completely fills a chamber formed by the conductor at radius r_c , r/r_0 begins at unity with the temperature varying as $T/T_0 \propto (r/r_0)^{-4/3}$ (Table IV-VII). For the CT configuration, however, the plasma initially fills half the plasma chamber inside the conducting radius, r_c , as given by Eq. (IV-12). For the case where $r_s = r_c$, the efficiency of compression does not change, because the relative volume of plasma to magnetic field inside the conducting shell is constant. A compression that allows the separatrix to move away from the conducting shell is less efficient because of the increased volume of magnetic field that must be introduced as the plasma is forced away from a stationary conductor.

Expectedly, the magnetic field energy necessary to perform a given compression can be minimized if the shell radius is reduced as the plasmoid is compressed. This prediction represents a distinct advantage of moving shell or liner compressions. Using a tapered compressor section, the ratio r_c/r_s can also be preserved. These approaches not only minimize the required magnetic energy but the stabilizing effect of the conducting shell is also preserved. Experimental values¹¹⁻¹² of $r_c/r_s \approx 2.0$ are taken as a design criteria imposed here on the reactor scaling.

E. Stability Properties

Although an accelerated theoretical effort is in place to understand the stability properties of low-beta spheromak configurations,^{2,26} comparable support for the high-beta FRC configuration that can be applied to a reactor analysis is at a much lower level. Earlier studies of the FRM version of the FRC⁴⁻⁸ have stressed the need for finite-Larmor-radius (FLR) stabilization, and consequently these reactor studies have directly constrained the ratio, $S = a/\rho_i$ of plasma radius to ion Larmor radius to be $\sim 4-5$. The constraint that $S < 5$, although conceivably valid for plasmoids with lengths, l , roughly equal to the separatrix radius, r_s , and without toroidal field, has a dramatic impact upon the ultimate plasma parameters; generally, FRM/FRC systems with $S < 5$ must operate at high fields ($> 5-6$ T) and plasma temperature (70-100 keV) in order to achieve a modest-Q performance.⁴⁻⁸ Furthermore, since values in excess of $S \sim 10$ are generally required before the level of alpha-particle retention is sufficient for a self-sustained ignition, FRC plasmoids with $S \lesssim 5$ generally must be driven.

The FROP/FRC configuration considered here has been constrained to $\ell/r_s \approx 7$. Therefore, FLR stabilization may not be required for these elongated configurations, even in the absence of toroidal field within the separatrix radius. Stabilization for these FROP/FRC plasmoids, therefore, must be provided by an electrically conducting shell that should be situated at a radius r_c that is relatively close to the separatrix radius, r_s . Existing FROP experimental evidence¹¹ indicates decreased confinement times as r_c/r_s increases beyond ~ 2 . Given the correctness of the assumptions of wall stabilization ($r_c/r_s \lesssim 2$), elongated plasmoid equilibrium ($\ell/r_s \approx 7$) and a relatively unconstrained value of S ($< 20-30$, rather than < 5), the FROP/FRC reactor embodiment naturally develops to one of a translating, high-beta and ignited FRC that must move continually at a velocity that is compatible with its length and the electrical skin time, τ_s , of an electrically conducting shell (i.e., $v \sim \ell/\tau_s$).

In summary, the equilibrium shape, properties and constraints of a high-beta FRC configuration (i.e., FROP versus FRM), as applied to thermonuclear reactor conditions, can have a significant influence on the resulting reactor embodiment. FRM configurations that assume FLR stabilization are at best marginally ignited, must be externally heated and, therefore, would burn in a stationary and driven mode within a burn chamber. The high S -value, elongated FROP/FRC, on the other hand, must be translated in order to assure that compressed flux does not diffuse through a passive but conducting stabilizing shell. Because of the higher values of S that might be claimed for the FROP/FRC reactor plasmoid, a non-driven and unrefuelled (batch-burn) operation emerges. It should be emphasized, however, that the stability requirements of FRC configurations without toroidal field, as inferred by plasmoid S -value and/or shape, represents a major uncertainty for any reactor projection, and, therefore, deserves more theoretical emphasis; relevant experimental evidence is not expected to clarify this important issue for at least a few years.

F. Translation Properties

If the FROP/FRC reactor plasmoid is to be stabilized by a passive conducting shell during a reactor burn, the electrical skin time for the shell, τ_s , must be greater than the burn time, τ_b , if a stationary plasma is used. Otherwise, in addition to FLR stabilization ($S < 5$), active coils and associated circuitry must be placed within the burn chamber (i.e., the FRM

approach). The translating FRØP approach on the other hand, requires only a passively conducting shell with a skin time that is comparable with the plasmoid residence time.

As the FRØP plasmoid is translated into the burn chamber, the flux, ϕ_c , contained inside the conducting shell is conserved and compressed between the separatrix and the conducting shell, as is illustrated in Fig. IV-6. Conservation of ϕ_c is provided by the superconducting coils generating a vacuum field, B_o (Fig. IV-5), and upon compression leads to an internal field B_i . The flux conservation is given by

$$B_i [(r_c + \delta)^2 - r_s^2] = B_o (r_c + \delta)^2 \quad , \quad (IV-21A)$$

where δ is the shell thickness. Taking $\delta/r_c \ll 1$, Eq. (IV-21A) becomes

$$B_i \approx B_o / (1 - r_s^2/r_c^2) \quad . \quad (IV-21B)$$

The flux that would ultimately diffuse through the shell at long times equals $B_o \pi r_s^2$. A characteristic time, τ_s , for this flux penetration into the conducting shell can be estimated from the expression

$$d\phi/dt \approx \frac{B_o \pi r_s^2 (r_w^2 - r_s^2)}{\tau_s (r_c^2 - r_s^2)} = I_c R \quad . \quad (IV-22)$$

Equation (IV-22) includes the possibility of placing the (vacuum) first wall inside the conducting shell (i.e., $r_w < r_c$). For this case the amount of flux that is allowed to leave the system before the plasmoid would contact a surface is reduced by the ratio $(r_w^2 - r_s^2)/(r_c^2 - r_s^2)$. The current induced in the shell is given by

$$I_c = (B_i - B_o) \ell / \mu_o \quad , \quad (IV-23)$$

where ℓ is the length of the plasmoid. The resistance of the shell is given by

$$R = \eta 2\pi r_c / \delta \ell \quad , \quad (IV-24)$$

where η (ohm-m) is the resistivity of the conducting shell. Substituting Eqs. (IV-21B), (IV-23) and (IV-24) into Eq. (IV-22) gives the following expression for the resistive diffusion time of the conducting shell

$$\tau_s = \frac{\mu_0}{2\eta} \frac{\delta}{r_c} (r_w^2 - r_s^2) \quad . \quad (IV-25)$$

Typical value of the electrical skin time are summarized in Table IV-VIII for two sample cases. The maximum thickness of a first-wall shell is taken to be 0.05 m, as dictated by neutronics considerations; the skin time for this case is computed from Eq. (IV-25) to be ~ 0.3 s. Re-location of the conducting shell outside the neutron-moderating and tritium breeding blanket allows the use of a nearly room-temperature shell of a somewhat greater thickness (0.1 m). The shell thickness for the case where $r_c > r_w$ cannot be arbitrarily increased and in cross-sectional area must be significantly smaller than the crucial area where flux is being displaced; otherwise the conducting shell represents a significant energy sink for magnetic field and its effectiveness is thereby reduced. As seen from Table IV-VIII, positioning the shell outside

TABLE IV-VIII
COMPARISON OF FIRST-WALL VERSUS ROOM-TEMPERATURE CONDUCTING SHELL
LOCATED OUTSIDE THE BLANKET REGION

CASE	r_s (m)	r_w (m)	r_c (m)	η_{Cu} (Ω -m)	δ (m)	τ_s (s)	P_d/P_η
$r_w = r_c$	0.7	1.0	1.0	$5.0(10)^{-8}$	0.05	0.3	4.3
$r_w < r_c$	0.7	1.0	1.4	$2.0(10)^{-8}$	0.1	1.1	59.

the blanket allows a factor of four increase in the estimated skin time, presuming that $r_c/r_s \approx 2$ is adequate from the stability/equilibrium viewpoint.

The power dissipated in the conducting shell is directly related to the electrical skin depth and is given by

$$P_\eta(W) = I_C^2 R = \frac{(B_1 - B_0)^2}{\mu_0^2} \eta \frac{2\pi r_c \ell}{\delta} \quad . \quad (\text{IV-26A})$$

When combined with Eq.(IV-21), Eq. (IV-26A) reduces to

$$P_\eta(W) = \frac{\eta}{\mu_0^2} \frac{2\pi \ell}{\delta} \frac{r_s^4}{r_c^3} B_1^2 \quad . \quad (\text{IV-26B})$$

The relative magnitude of this electrical loss is better appreciated if it is compared to the alpha-particle power, as given by

$$P_\alpha(W) = n^2 \langle \sigma v \rangle E_\alpha \pi r_s^2 \ell / 8 \quad , \quad (\text{IV-27})$$

where the ($\beta \approx 1$) plasma occupies one-half of the volume inside the separatrix, and $E_\alpha = 5.63(10)^{-13}$ J/fusion (3.5 Mev/alpha-particle). Using pressure balance and forming the ratio P_η/P_α gives for $\beta \approx 1$

$$P_\alpha/P_\eta = 8.6(10)^{16} \frac{\delta}{\eta} \frac{r_c^3}{r_s^2} \frac{\langle \sigma v \rangle}{T^2} B_1^2 \quad . \quad (\text{IV-28})$$

The quantity $\langle \sigma v \rangle / T^2 \approx 10^{-24}$ s/m² keV² is nearly constant over the temperature range (10-20 keV) of interest. Taking $B_1 \sim 5$ T for illustrative purposes, the power ratio, P_α/P_η , is also listed in Table IV-VIII. Substantial electrical dissipation can be associated with the presence of a conducting shell that is

positioned near the first wall; this ohmic dissipation is greatly reduced if the shell is moved outside the blanket region, where it can be thick and operate at or near room temperature.

Another difficulty associated with locating the conducting shell at the first wall is the availability of translational power required for a moving ring reactor. This power is associated with the translation and cannot realistically be provided by the initial translational velocity, which according to the sample comparison given in Table IV-VIII would have to be of the same order as the plasma thermal velocity ($v \sim 10^6$ m/s). The plasmoids must, therefore, be driven through the system using mirror coils or by relying on the direct conversion of alpha-particle power to translational power as the plasmoid moves through the reactor chamber of ever-enlarging radial dimension. Operating active mirror coils at or near the first wall or externally driving a first-wall conducting shell is considered unattractive because of severe thermal and neutron loadings.

Generation of the required translational power from the alpha-particle heating requires the expansion of the plasma during the burn translation. The thermodynamic work available in plasma expansion from an initial volume, V_i , to final volume, V_f , is

$$\Delta W_{PV} = \int_{V_i}^{V_f} p dV = \int_{V_i}^{V_f} (pV) dV/V \quad . \quad (IV-29)$$

Assuming the plasma temperature remains essentially constant during this alpha-particle driven expansion, $pV = 2NkT$ is a constant, where N is the total number of plasma particles. Equation (IV-29) is readily integrated to yield

$$\Delta W_{PV} = 3NkT \ln(V_f/V_i)^{2/3} \quad . \quad (IV-30)$$

For an equivalent conversion of all of the plasma internal energy, $\Delta W \sim 3NkT$, the volume ratio V_f/V_i must equal approximately 4.5. This substantial dimensional change alters the plasma density by 4.5 and lowers the fusion power density by roughly a factor of ~ 20 . A characteristic energy loss time associated with ohmic dissipation is defined as the ratio of plasma energy to ohmic power

$$\tau_L \sim \frac{\mu_0}{8} \frac{\delta}{\eta} \frac{r_c^3}{r_s^2} , \quad (IV-31)$$

where pressure balance ($\beta = 1$) and Eq. (IV-21b) has been used. Using the properties given in Table IV-VIII for a hot (first-wall) conducting shell gives $\tau_L \sim 0.3$ s. Therefore, the plasma must undergo large dimensional changes in a relatively short time in order to provide the necessary translational power from alpha-particle heating. This unattractive option provides further impetus to locate the shell outside of the blanket region, a conclusion that is further reinforced when the nonlinear time dependence of alpha-particle production and the largely unknown confinement properties of alpha-particles in the CT geometry are considered.

The reactor estimates presented herein, therefore, are based on a conducting shell positioned outside the first-wall/blanket region with r_c/r_s taken as ~ 2.0 . The translation power is provided by moving mirror fields produced by driving currents in the conducting shell. In order to provide the necessary stabilization, the plasmoid must have a velocity, v , given by $\ell/v < \tau_s$, where τ_s is defined by Eq (IV-25) and ℓ is the total plasmoid length. The CTOR power level and physical size is estimated on the basis of these constraints.

It should be emphasized that the decision to locate the conducting shell at a radius $r_c = r_w + \Delta b$ is based on a highly simplified and heuristic model (Eq. (IV-25)). Extending a calculational result obtained originally for image currents induced in a thin first-wall shell,²⁷ the moving ring FRM/FRC reactor concept^{4,5} has induced ohmic losses and wall-drag forces that are negligible. This important issue for shell-stabilized, translating FRC systems must be resolved by a more detailed and pertinent numerical analysis. Nevertheless, at this stage of the FRQP/FRC reactor study, the conducting shell is assumed to be located outside the thermal blanket, and the systems is optimized on the basis of this assumption.

V. DESIGN POINT ESTIMATE

A. Parametric Evaluation

An optimal burn sequence is considered here in which the plasma is brought to ignition by adiabatic compression from an initial temperature of ~ 1 keV; the ignited burn would ideally be sustained at ~ 10 keV by alpha-particle heating. Transport losses are assumed to prevent the plasma from overheating, although the magnitude and mechanism of particle/energy transport in the CT is not known at this time. All burn cycles investigated are presumed to be unrefueled or "batch", in which the initial fuel charge is partially burned as the plasmoid moves at velocity $v = \ell/\tau_s$ through the linear burn section (Fig. IV-5). This operating mode leads to straightforward fueling and ash-removal techniques that appear attractive compared to more complex schemes required to sustain indefinitely a steady-state burning plasma. A comprehensive numerical burn simulation has not yet been applied to describe the burn and magnetic field (conducting shell) dynamics. Instead, a simple but valuable analytic model is used that simply specifies the reactor performance in terms of the neutron wall loading, I_w (W/m²). The desired plasma performance is established by selecting a desirable value of $n\tau_B$, where the burn time, τ_B , for a reactor of length L is given by L/v . The reactor thermal power, P_{TH} , and length are then evaluated parametrically in terms of plasmoid size, r_s and ℓ , for a given plasma temperature, T , plasmoid performance, $n\tau_B$, and system performance I_w .

The 14.1-MeV neutron wall loading is given by

$$I_w(\text{W/m}^2) = 0.25 f_\ell n^2 \langle \sigma v \rangle E_N \pi r_s^2 (0.87) / 2\pi r_w, \quad (\text{V-1})$$

where $E_N = 2.26(10)^{-12}$ J/fusion (14.1 MeV/n). The factor of 0.87 used in Eq.(V-1) is the fractional cross-sectional area inside the separatrix radius, r_s , that is filled with plasma at $\beta = 1$. This fraction is determined by Eq. (IV-12) on the basis of experimentally typical values of $r_c/r_s \approx 2.0$. The "duty factor", f_ℓ , is the fraction of the reactor length that contains plasma at any given time. For example, a 50-m long burn chamber reactor containing one 5-m long plasmoid, would operate with $f_\ell = 0.1$. Given that $v = \ell/\tau_s$, it is easily shown for a plasmoid injection rate equal to $1/\tau_I$ that,

$$f_{\ell} = \tau_S / \tau_I \quad . \quad (V-2)$$

The total burn time, τ_B , can be expressed in terms of the electrical skin depth, τ_S (Eq. (IV-25)), as

$$\tau_B = \tau_S (L/\ell) \quad . \quad (V-3)$$

Writing Eq. (V-1) in terms of the Lawson-like parameter $n\tau_B$ and using Eq. (V-2) gives

$$I_W (W/m^2) = 0.11 f_{\ell} (n\tau_B)^2 \langle \sigma v \rangle E_N (r_S \ell)^2 / (r_W L^2 \tau_S^2) \quad . \quad (V-4)$$

Positioning the conducting shell outside of the blanket of thickness $\Delta b \approx 0.5\text{-m}$ then requires

$$r_C = r_W + \Delta b \quad . \quad (V-5)$$

Using this relation in conjunction with the experimental plasmoid dimensions

$$r_C / r_S \approx 2.0$$

$$\ell / r_S \approx 7.0 \quad , \quad (V-6)$$

defines the required reactor length, L , for a specified $n\tau_B$, f_{ℓ} , $\langle \sigma v \rangle$, and neutron wall loading, I_W .

The total thermal power is simply given by

$$P_{TH}(W) = 2\pi r_W L I_W M \quad , \quad (V-7)$$

where M is the total fusion release, including blanket energy multiplication,

relative to the 14.1-MeV primary fusion neutron; typically, for a blanket multiplication of 1.16, $M = 1.42$. Recovery of the plasma translational and internal energy is not included in these estimates.

Operating the plasma at 10 keV gives $\langle\sigma v\rangle = 1.12(10)^{-22} \text{ m}^3/\text{s}$, and desiring a relatively high DT fuel burnup ($f_B = 0.22$) requires that $n\tau_B = 5(10)^{21} \text{ s/m}^3$. Use of a room-temperature copper shell fixes η at $2(10)^{-8} \Omega \text{ m}$, although the shell thickness, δ , must be determined. The cross-sectional area of the shell must be significantly less than the area between the separatrix and the first wall, as discussed in Sec. IV.F. Taking $\delta = 0.05$, the shell section would represent 24% of the cross-sectional area encompassed by the first wall and separatrix radii for $r_s = 0.85$, $r_w = 1.2 \text{ m}$ and $\Delta b = 0.5 \text{ m}$. A more exact definition of these parameters must await time-dependent calculations of flux diffusion into the shell as the plasmoid moves along the reactor burn chamber at a velocity v . The remaining parameters left unspecified are the first-wall loading, I_w , and the fraction of reactor length, f_ℓ , filled with plasma. Economic fusion systems are generally assumed to operate with $I_w \gtrsim 2\text{--}4 \text{ MW/m}^2$, and f_ℓ , therefore, remains to be determined.

Equation (V-4) for the wall loading can be re-expressed solely in terms of geometric variables

$$\begin{aligned} \frac{9.09 I_w}{f_\ell (n\tau_B)^2 \langle\sigma v\rangle E_N} &= \frac{r_s^2}{r_w} \frac{1}{\tau_B^2} \\ &= \frac{r_s^4}{2r_s - \Delta b} \frac{(\ell/r_s)^2}{L^2 \tau_s^2} \end{aligned} \quad (V-8)$$

Combining Eqs. (V-8), (V-7), (V-6) and (IV-25) gives the following expression for P_{TH} in terms of a variable $x = \Delta b/r_c = \Delta b/2r_s$, where $r_c/r_s = 2$

$$\begin{aligned} P_{TH}(W) &= 8.78 M L_w^{1/2} \langle\sigma v\rangle^{1/2} (\eta/\delta) \Delta b^{3/2} (n\tau_B) f_\ell^{1/2} f(x) \\ f(x) &= \frac{(1-x)^{1/2}}{x^{3/2} [(1-x)^2 - 1/4]} \end{aligned} \quad (V-9)$$

If the injection rate, $1/\tau_I$, rather than the duty factor, $f_\ell = \tau_S/\tau_I$, is treated parametrically, the following expression for P_{TH} results

$$P_{TH}(W) = 6.91(10)^{-3} M_{I_W}^{1/2} \langle \sigma v \rangle^{1/2} (\eta/\delta)^{1/2} \Delta b^2 (n\tau_B) \tau_I^{-1/2} f(x)$$

$$f(x) = \frac{(1-x)^{1/2}}{x^2 [(1-x)^2 - 1/4]^{1/2}} \quad (V-10)$$

Both Eqs. (V-9) and (V-10) show a similarly weak scaling with I_W , a direct scaling with $n\tau_B$, but a strong dependence on blanket thickness, Δb . Likewise, both expressions give a minimum power, P_{TH} , for an optimum value of x or plasmoid size. Specifically, Eq. (V-9) minimizes at $x = 0.3$ ($r_s = .83$ m for $\Delta b = 0.5$ m), and Eq. (V-10) minimizes for $x = 0.4$ ($r_s = 0.61$ m for $\Delta b = 0.5$ m). The dependence of P_{TH} on r_s , as given by Eq. (V-9), for the indicated "reference" parameters with $f_\ell = 0.1$ is depicted on Fig. V-1. For $T = 10$ keV, $M = 1.42$ and $\eta = 2(10)^{-8} \Omega m$, the minimum power given by Eq. (V-9) is

$$P_{TH}(W) = 5.54(10)^{-17} I_W^{1/2} \Delta b^{3/2} f_\ell^{1/2} (n\tau_B)/\delta, \quad (V-11)$$

whereas the equivalent expression for Eq. (V-10) is given by

$$P_{TH}(W) = 2.12(10)^{-16} I_W^{1/2} \Delta b^2 (n\tau_B)/(\tau_I \delta)^{1/2}. \quad (V-12)$$

The case depicted on Fig. V-1 minimizes at $P_{TH} = 880$ MWt, whereas for identical conditions ($\tau_I = 6$ s) Eq. (V-12) predicts a minimum power of 685 MWt. Table V-I gives a summary of all key parameters for the minimum-power design predicted by Eqs. (V-9) and (V-10).

Referring only to the $f_\ell = 0.1$ case (Eq. (V-9)) and Fig. V-1, a minimum reactor power equal to 880 MWt occurs for $L = 40$ m, $r_s = 0.83$ m, $r_w = 1.2$ m, and $r_c = 1.7$ m. This prediction is simply based on geometric effects and should be generally valid. As seen from Fig. V-1, the reactor power decreases as r_s is reduced, which is primarily a consequence of the decrease in the

Fig. V-1. Dependence of P_{TH} , L , and τ_s on plasmoid size for the case where f_l is fixed at 0.1 (Eq. (V-9)), $r_c/r_s = 2$, and $l/r_s = 7$). Values of other fixed parameters are indicated.

plasma cross-sectional area. As r_s decreases below 0.83 m, the effective skin time, τ_s , dramatically decreases, causing the required plasmoid velocity to increase. In order to satisfy the Lawson-like criterion, the reactor becomes much longer and the total power correspondingly rises as r_s is further increased.

The dependence of P_{TH} and the corresponding values of L , τ_B , and B_1 are depicted on Fig. V-2 as a function of the parametrically varied duty factor, $f_l \equiv \tau_s/\tau_I$; for power minimizations obtained by holding either f_l or τ_I constant. The reactor power decreases monotonically with decreases in f_l as a result of the shortening of the reactor length required to give the desired $n\tau_B$, and, hence, overall energy balance. To specify in a more constrained fashion the desirable value of f_l (i.e., τ_I), and hence the corresponding minimum power and burn time, a first-wall thermal cycle constraint is imposed.

TABLE V-I
TYPICAL CTOR PARAMETERS (MINIMUM POWER)

PARAMETER	Constant f_ℓ (0.1)	Constant τ_I
Total thermal power, P_{TH} (MWt)	880	1141
Burn chamber length, L (m)	42	85
Separatrix radius, r_s (m)	0.83	0.63
Plasmoid length, ℓ (m)	5.8	4.4
First-wall radius, r_w (m)	1.2	0.75
Conducting shell radius, r_c (m)	1.7	1.25
Shell skin time, τ_s (s)	0.6	0.2
Burn time, τ_B (s)	4.5	4.2
Injection time, τ_I (s)	6.2	2.2($f_\ell = 0.1$)
Translational velocity, v (m/s)	9.4	20.4
Plasma density, $n(10^{21}/m^3)$	1.1	1.2
Compressed field, B_i (T)	3.0	3.1
Vacuum field, B_o (T)	2.3	2.3
Engineering power density, $P_{TH}/\pi r_c^2 L$ (MW/m ³)	2.4	2.7
First-wall temperature rise for copper, ΔT (K)	14.2	14.9
First-wall temperature rise for stainless steel, ΔT (K)	62.1	65.3
<u>ASSUMED OR FIXED PARAMETERS</u>		
Blanket thickness, Δb (m)		0.5
Plasma temperature, T (keV)		10
Fusion neutron wall loading, I_w (MW/m ²)		2.0
Shell thickness, δ (m)		0.05
Duty factor, $f_\ell = \tau_s/\tau_I$		0.1
Lawson parameter for 22% burnup, $n\tau_B(10^{21}s/m^3)$		5.0
Equilibrium/Stability constraints		
• r_c/r_s		2.0
• ℓ/r_s		7.0

Fig. V-2. Dependence of P_{TH} , L , τ_B , and ΔT on f_l for both f_l and τ_I constrained cases.

B. First-Wall Thermal Cycle

Because of the "natural" divertor action of the open-field lines, particle losses and thermal conduction should be directed towards the ends of the linear burn chamber rather than impinging on the first wall. Therefore, only Bremsstrahlung radiation would be expected to contribute to the thermal wall loading. The Bremsstrahlung power density impinging the first-wall structure of radius r_w is given by

$$P_{BR}(W/m^2) = 5.35 (10)^{-37} n_e^2 Z_{eff} T_e^{1/2} \pi r_s^2 (0.87)/2\pi r_w, \quad (V-13)$$

where the origin of the factor 0.87 is explained in conjunction with Eq. (V-1). Writing Eq. (V-13) in terms of $n\tau_B$ gives for $T_e = T$

$$P_{BR} = 2.33(10)^{-37} (n\tau_B)^2 Z_{eff} T^{1/2} r_s^2 / \tau_B^2 r_w. \quad (V-14)$$

The temperature at the surface rise of a "thermally-thick" wall is approximately given by

$$\Delta T = \frac{2P_{BR}}{k} \left[\frac{k\tau_s}{c_p \rho \pi} \right]^{1/2}, \quad (V-15)$$

where k is the thermal conductivity, c_p the specific heat, the density is ρ and the first-wall exposure time is taken as τ_s . The use of Eq. (V-15) represents one of a number of approximations, the validity of which depend crucially on the relative values of τ_s , τ_I and the first-wall thermal time constant, τ_D

$$\tau_D = \Delta / (4c_p \rho / \pi k)^{1/2}, \quad (V-16)$$

where Δ is the thickness of the first-wall. For instance, if $\tau_D \ll \tau_s$ and the injection rate $1/\tau_I$ is sufficiently small (i.e., $\tau_s \ll \tau_I$), the first-wall

would heat adiabatically, and Eq. (V-15) would have to be multiplied by $\sqrt{\tau_s/\tau_D}$.

Using Eq. (V-15) to estimate ΔT for a thermally-thick first wall, the following expression results

$$\frac{\Delta T \sqrt{c_p k \rho}}{2.63(10)^{-37} (n\tau_B)^2 T^{1/2}} = \frac{r_s^4 (\ell/r_s)^2}{2r_s - \Delta b L^2 \tau_s^{3/2}} \quad (V-17)$$

Combining Eq. (V-17) with Eq. (V-8) gives the following explicit expression for ΔT

$$\Delta T(K) = 8.33(10)^{-28} (I_w/f_\ell) \frac{(\delta \Delta b)^{1/2}}{(\langle \sigma v \rangle / T^{1/2}) (c_p \rho k \eta)^{1/2}} f(x)$$

$$f(x) = \left[\frac{(1-x)^2 - 1/4}{x} \right]^{1/2} \quad (V-18)$$

The thermal constraint as embodied in Eq. (V-18) can be used to determine the injection rate vis a vis $f_\ell = \tau_s/\tau_I$ for a given wall loading. Equation (V-18) is plotted on Figs. V-1 and V-2 for a first-wall with thermophysical properties of copper ($\rho = 8880 \text{ kg/m}^3$, $k = 324 \text{ W/m K}$, $c_p = 393 \text{ J/kg K}$) or stainless steel ($\rho = 7800 \text{ kg/m}^3$, $k = 16.9 \text{ W/m K}$, $c_p = 546 \text{ J/kg K}$). For the fixed parameters and minimum-power case summarized in Table V-I, $\Delta T(\text{Cu}) = 14.2 \text{ K}$ and $\Delta T(\text{SS}) = 62.1 \text{ K}$. By using Fig. V-2, the enforcement of lower (higher) ΔT constraints will lead to higher (lower) values of f_ℓ and P_{TH} . These tradeoffs are not numerically presented here, but Fig. V-2 can readily be used to quantify such estimates. As for the constraint imposed by the conducting shell and τ_s , more exact numerical evaluation of the thermal cycle constraint is warranted, particularly with respect to the relationship between τ_s , τ_I , τ_D , and the total thermal power, P_{TH} .

VI. CONCLUSIONS AND RECOMMENDATIONS

A parametric evaluation of sample design points for a reactor concept based on the field-reversed theta-pinch (FRTP) has been performed analytically. Imposing approximate but realistic engineering constraints, minimal power systems of ~ 800 MWt with a first-wall radius of ~ 1 m and reactor lengths of ~ 40 m were found. A moving plasmoid system would allow a plasma burn in which the eddy (stabilization) currents could be maintained for times longer than the classical L/R time of the shell. The plasma dimensions were determined by analytical equilibrium expressions and experimental indications that $r_c/r_s \approx 2.0$ and $l/r_s \approx 7.0$. Locating the conducting shell outside the blanket, requiring a plasmoid velocity greater than l/τ_s (τ_s = conducting shell L/R time) and establishing the duty factor, $f_d \approx \tau_s/\tau_I$, (τ_I = plasmoid injection time) by wall surface heating constraints, a minimum-power system was found. Other approaches which treat the injection time as a constant give a somewhat different minimum, but the basic quantitative conclusions remain unchanged. This characteristic minimum size results from the placement of the conducting shell outside the blanket; even smaller systems are possible for first-wall conducting shells.²⁸

The conceptual reactor design investigated herein is based directly upon experimental results and the use of near-term technology. Plasma initiation is proposed by means of a FRTP or possibly a much slower, low-voltage startup. The compressor region requires ~ 50 MJ and could be driven by a conventional rotating machine. Unlike past compact-tori designs, all coils (including the conducting shell) are located outside the blanket region, thereby avoiding the neutron/radiation environment. Pulsed-burn plasmoids are used to simplify operation and to avoid the difficulties associated with refueling. Even with a pulsed burn, the overall engineering system appears essentially steady state because of the continuous flow of compact tori through a linear burn chamber. The moving plasmoid with an open field line configuration offers a natural divertor for the burn region. Coupling the above advantages with the linear geometry may lead to a potentially attractive system.

A more definitive assessment must await a detailed engineering design based upon a realistic plasma simulation. This more profound analysis requires the development of an overall operating scenario that includes plasma initiation, compression and burn dynamics while simultaneously accounting for plasma energy gains and losses along with dimensional changes determined by

equilibrium conditions. Because of the absence of reactor-like experimental results, the effects of varying amounts of alpha-particle trapping, the magnitude of $S = a/\rho_1$ and energy/particle confinement time scalings must also be parametrically investigated. An overall energy balance must then be calculated including plasma initiation and joule losses in the compressor and mirror coils/conducting shell.

It is emphasized that the major focus of the translating approach to the FROP reactor embodiment has been the desire to achieve stability/equilibrium through a passive conduction shell that could be located close to the plasma ($r_c/r_s \leq 2$) but nevertheless would be positioned outside the high-temperature blanket structure. The possible need for a moving mirror-field drive in part may negate some of the advantage of a passive shell system, and more detailed study of this version of the FROP concept may reveal additional complexities that would warrant more serious consideration of stationary, FRM-like systems that retain the FROP approach to plasmoid formation. In this spirit, therefore, the following study program will be pursued. This program focuses more onto the translating plasmoid approach, while maintaining the option of electing a stationary plasmoid system. This report concludes with an annotated outline of future work on the translating FROP reactor.

A. Plasmoid Formation (Initiation, Heating, Translation to Burn Chamber)

1. Plasmoid Initiation

- Quantify the pre-plasma conditions needed to form the initial (unheated) plasmoid by means of a FROP.
- Investigate the physics potential of a technologically easier inductive startup that would use rotating machines (≥ 5 -10 ms, i.e., a tokamak-like startup, with no high-voltage shock heating).

2. Plasmoid Heating (to ignition)

- Simulate the time-dependent trajectory of plasma heating in an external system compression in a tapered compressor section. This startup simulation would include all losses, equilibrium/stability constraints, coupling efficiencies of power to the plasma and major technology constraints.
- Investigate the use of other auxiliary, external heating sources. Focus onto possible advantages of other heating approaches (ohmic heating, neutral beams, rf, combinations), particularly as related to initial plasmoid size and heating efficiencies.

B. Thermonuclear Burn Dynamics

- Investigate means by which the formed and nearly ignited plasmoid would be induced to translate into and down a high-temperature burn chamber.
- Model the ignited and translating plasmoid by a time-dependent point model that realistically accounts for all plasmoid energy losses and alpha-particle heating.
- Model all burn trajectories with appropriate particle/energy transport and stability/equilibrium self-consistently enforced. The changing size, shape and density changes will be reflected in both the time dependent burn and the net thermonuclear yield per plasmoid.
- Model the time-dependent response of both the conducting shell and the driving mirror fields.

C. Engineering System Energy Balance

- Perform a complete system energy balance based upon losses and gains quantified from Tasks A and B described above. Include resistive losses incurred in conducting shell and driver coils.
- Estimate recirculating power needs of startup, compression to ignition, mirror translation coils, along with eddy-current losses in the coil and blanket structure.
- Quantify the amount and kinds of energy recovery from the discarded plasmoid.
- In conjunction with Tasks A and B, identify a Q_E -optimized operating point or range of operating points as characterized by technological realism for all subsystems.

D. Evaluate and Impose Major/Crucial Engineering Constraints

- The technology of plasmoid source (formation, heating, ejection) is to be evaluated with an emphasis being placed on feasibility, reliability, etc..
- The first-wall/blanket temperature and mechanical stresses must be optimized in terms of burn chamber lifetime as well as the optimal use of the heat recovery in terms of high average power density with a reasonable degree of thermal cycle and axial variations.
- The axial non-uniformity of the burn chamber response will be minimized in terms of the constraints imposed by Tasks A, B, and C.

Generally, the translating FRÖP approach shows a strong indication of a high-Q and modest-size system. The major uncertainties associated with this prognosis are embodied in the tasks described above. If the use of a moving mirror field proves to be equal in complexity as systems needed for a stationary plasmoid (FRM-like) approach, this option will be studied at a level of detail previously described for the translating FRÖP. In this case, the issue associated with the magnitude of $S = a/\rho_1$ will receive a greater focus, as will the need for a greater amount of active in- or near-blanket feedback control. Lastly, if the stationary plasmoid approach is pursued further, the feasibility of a partially or fully wall-supported system should be investigated, wherein the ignited plasmoid would be translated into a structural "can" and allowed to undergo a decaying burn with the hope of finding a net energy yield. These options will not be pursued, however, until the potential of the translating, shell-stabilized (high $S = a/\rho_1$) FRÖP system has been fully explored vis a vis the study tasks summarized above.

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