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A REVIEW OF ALTERNATIVE CONCEPTS FOR MAGNETIC FUSION*

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ABSTRACT

Although the Tokamak represents the mainstay of the world's quest for magnetic fusion power, with the tandem mirror serving as a primary backup concept in the US fusion program, a wide range of alternative fusion concepts (AFC's) have been and are being pursued. This review presents a summary of past and present reactor projections of a majority of AFC's. Whenever possible, quantitative results are given.

I. INTRODUCTION

Although the strength of the world-wide fusion effort rests with the rapid and successful advances in Tokamak physics, reactor studies have illuminated certain problems associated with large size, low power density, magnetics and beam technologies, materials limitations and remote maintenance, and the attendant uncertainities of economics and reliabilit[illegible] These results, therefore, have prompted a careful re-examination of the physics requirements and general approach taken by tokamak reactor designers as well as prudent evaluation of the potential of less understood, alternative confinement approaches[1-10]. Table I gives a representative cross-section of alternative fusion concepts (AFC's) that in one way or another have been or are being considered for the production of electrical power, chemical process heat and/or fissile material. Depending on the confinement scheme considered, systems studies of AFC's range from simple physics analyses, based on Lawson-like criteria, to detailed conceptual designs. With few exceptions most reactor studies of alternative concepts fall into the less formalized part of this spectrum. For this reason a quantitative intercomparison and ranking is not advisable at this time. The intent here, instead, is to describe briefly the essential elements of each AFC. For those concepts where reactor parameters are given, these values should be viewed as typical; the reactor embodiment and the associated operating parameters for a given AFC will most certainly evolve as insight develops from experiment, theory and systems studies.

The summary of the AFC's given on Table I has been organized into the following categories: toroidal, compact toroids, linear systems and very dense systems. A comprehensive treatment of each AFC, even to an extent allowed by past and ongoing systems studies, is beyond the scope of this review. Furthermore, the TMR is considered a primary backup to the Tokamak and, therefore, will not be reviewed here. With the exception of the Surmac concept, all AFC's considered operate on the DT fuel cycle, although advanced-fuel operation of several of the other AFC's might prove feasible and attractive. Lastly, although more comprehensive papers on some of the AFC's given in Table I (i.e., EBTR, FRM, TRACT, Linus, CTOR) can be found in these proceedings, for the sake of completeness these AFC's are also included in this review.

II. TOROIDAL SYSTEMS

The toroidal AFC's summarized in Table I are classified as steady state, long pulsed (10 s-100 s) or pulsed (~ 1 s). A sampling from each category is given in this section.

A. Steady-State Toroidal Systems

The Stellarator/Torsatron is treated as a generic concept; the EBTR, Tormac and Surmac are described separately.

1. Stellarator/Torsatron Reactors.

The Stellarator represents one of the earliest magnetic confinement concepts to receive attention[57-59] as a commercial power reactor. Unlike the Tokamak, the non-axisymmetric Stellarator achieves equilibrium in a toroidal geometry by externally inducing a rotational transform in the confining magnetic fields; ideally, no axial currents need be supported by the toroidal plasma column, as is required in a Tokamak, although until very recently all Stellarator experiments utilized such currents for ohmic heating. The first Stellarator reactor designs[57,58] proposed the use of separate toroidal and helical coil sets that were combined to form "figure-8" and racetrack configurations.

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TABLE I

SUMMARY OF ALTERNATIVE CONCEPTS FOR MAGNETIC FUSION

	INSTITUTION[a]	REF.
I. TOROIDAL		
A. STEADY-STATE		
• Stellarator	PPPL/CULHAM	11,12
• Torsatron	MIT/UWISC/PPPL/JAPAN	13,14
• Bumpy Torus (EBTR)	ORNL/NASA	15-18
• Toroidal Bicusp (Tormac)	(LBL/LASL)	19-21
• Surface Magnetic Confinement (Surmac)	UCLA	22,23
B. LONG PULSED		
• Reversed-Field Pinch (RFPR)	LASL/CULHAM/PADOVA	24,25
• Ohmically-Heated Torus (OHTE)	GAC	26
• Ohmically-Heated Tokamak (Riggatron)	INESCO	27
C. PULSED		
• Theta-Pinch (RTPR)	(LASL)	28
• High-Beta Stellarator (HBS)	(IPP GARCHING)	29
• Belt-Shaped Screw Pinch (BSPR)	JUTPHASS	30
II. COMPACT TOROID		
A. STATIONARY		
• Spheromak	PPPL	31,32
• Field-Reversed Mirror (FRM)	LLL/UILL	33,34
• Triggered-Reconnected Adiabatically-Compressed Torus (TRACT)	MSNW	35
• Electron-Layer Field-Reversed Mirror (Astron)	(LLL)	36
• Slowly-Imploding Liner (Linus)	NRL/USSR	37-40
B. TRANSLATING		
• Spheromak	UILL	41,42
• Field-Reversed Theta Pinch (CTOR)	LASL	43
• Moving-Ring Field Reversed Mirror (MRFRM)	PG&E/LLL	44
• Ion-Ring Compressor	CORU	45
III. LINEAR		
A. STEADY STATE		
• Tandem Mirror (TMR)	LLL/USSR/UWISC	46
• Multiple-Mirror Solenoid	(UCB/USSR/MSNW)	47,48
B. PULSED		
• Linear Theta Pinch (LTPR)	(LASL)	49
• Laser-Heated Solenoid (LHS)	(MSNW)	50
• Electron-Beam Heated Solenoid (EBHS)	(PI/USSR)	51
IV. VERY DENSE (FAST-PULSED, LINEAR) SYSTEMS		
• Fast-Imploding Liner (FLR)	(LASL)	52
• Dense Plasma Focus (DPF)		53
• Wall-Confined Shock-Heated Reactor (SHR)	PI/COLU	54
• Dense Z-Pinch (DZPR)	LASL/LLL	55
• Passive Liners	(MSNW/USSR)	56

[a] parentheses indicate concepts for which neither experimental nor systems-studies activities presently exist.

Early reactor calculations and cost estimates[11,12,60] for Stellarator reactors indicated the related potential problems of low power density and high magnet costs. These early survey studies were eventually overshadowed by discouraging physics results for Stellarators and contemporary progress in Tokamak confinement.

Consideration of the Torsatron concept[61] as a reactor allowed the elimination of the toroidal-field coil set, and, when coupled with new understanding of Stellarator/Torsatron physics, has generated more recent interest in this truly steady-state device as a reactor.[13,62,63] Although the magnetic surfaces in a Torsatron are topologically similar to those in the more complex Stellarator, the desired magnetic geometry can in principle be created by using only relatively "force-free" helical coils.[13] Even more recently, elimination of the helical coils in favor of toroidal coils that have been subjected to a distortion has allowed the Torsatron the promise of higher and more realistic system modularity. Specifically, implementation of a deformation (twist) into a simple toroidal-field coil set[64] allows the Torsatron magnetic geometry to be produced while eliminating the helical coil set in favor of a highly modular device.[14] In addition, more optimally oriented coil forces and lower stresses are anticipated for this modular Torsatron approach. These new advances have renewed interest in the reactor extrapolation of the Stellarator/Torsatron concept, a renaissance that coincides with experimental success in heating a low ohmic-current device,[65] the latter being a prerequisite for eventual steady-state reactor operation.

Qualitative advantages that can be invoked for the Torsatron reactor concept include:

- Steady-state magnetic fields and thermonuclear burn.
- Operation at ignition or high Q for low recirculating power.
- Plasma start-up on existing magnetic surfaces with predictable particle/energy confinement at all times.
- Impurity and ash removal by means of a magnetic limiter and helical poloidal divertor that occur as a natural consequence of the magnetic confinement topology.
- No major plasma disruptions that could lead to an intense, local energy dump on the first wall or in the blanket/shield/coil.
- No auxiliary positioning or field-shaping coils and moderate aspect ratio ($\gtrsim 10$), both of which ease maintenance access.

These advantages remain to be quantified in the context of a comprehensive reactor study;[14] incorporating crucial physics issues (e.g., scaling of beta with aspect ratio and the required or optimal rotational transform, magnetic shear, and magnetic-well depth), engineering constraints (e.g., coil design and stresses) and economics.

Parametric studies of an ignited, steady-state Torsatron have been summarized[14] for fixed values of rotational transform and 14.1-MeV neutron first-wall current in an $\ell = 2$ system. Alcator transport scaling ($\tau_E \propto nr_p^2$) has been assumed, and for a Torsatron ℓ equals the number of helical conductors (2ℓ conductors for an equivalent Stellarator). Parameters for a specific, interim reactor design point based on the modular Torsatron (i.e., deformed toroidal coils only) are displayed in Table II along with those of the $\ell = 2$ Heliotron-C[62] and the $\ell = 3$ T-1 Torsatron,[13] the latter two reactor concepts operating with only helical coils. The high value of beta and the large major radius result in a large thermal output for the Heliotron-C reactor. The moderate value of beta adopted in the R-3 design point is used to obtain nearly the same power output as the T-1 design in a smaller reactor with higher power density.

2. Elmo Bumpy Torus Reactor (EBTR). The ELMO Bumpy Torus (EBT) concept is a toroidal array of simple magnetic mirrors. The promise of a steady-state, high-beta reactor that operates at or near DT ignition emerges from this combination of simple mirrors and toroidal geometry. The creation of an rf-generated, low-density and energetic electron ring at each position between mirror coils is needed to stabilize the bulk, toroidal plasma against well-known instabilities associated with simple mirror confinement.

The EBT was first examined as a reactor over four years ago.[16] Interim revisions and reassessments have been made during the intervening years.[17-18] A bumpy-torus configuration that is stabilized by energetic electron rings combines a number of unique features that describe a fusion reactor with the following attractions: steady-state operation in an ignited or a high-Q mode; a potential for high-beta operation with the attendent efficient utilization of magnetic field energy; large aspect ratio to give an open and accessible geometry; an engineering assembly that is comprised of relatively simple and compact modules; ease of maintenance, modular construction and a relatively simple magnet system. Although the earliest EBTR designs[16,17] predicted relatively large power plants, the attainment of high magnetic aspect ratios in systems with lower physical aspect ratios through the use of aspect-ratio-enhancement (ARE) coils indicates that smaller reactors may be possible while simultaneously maintaining the above mentioned reactor features.

The presence of the high-beta electron rings at each midplane position is crucial to the MHD stability of the bumpy torus; a simple bumpy torus is unstable to drift and MHD modes. Diamagnetic currents, however, flow in the high-beta electron rings, each playing the role of a "coil" positioned within the toroidal plasma at each midplane location. The resulting depression in the magnetic field at the electron-ring location creates a local region of average-minimum field, giving a MHD-favorable decrease in the quantity $\oint d\ell/B$ with increasing plasma minor radius. Although this region of average-minimum field does not extend to the centerline of the toroidal plasma, a stabilizing effect upon the bulk plasma bounded by the electron rings nevertheless results. The stability of the high-beta toroidal plasma has been inferred to be limited by a value of the bulk plasma beta (at the midplane location) that approximately equals the electron-ring beta. These stability-related beta limits are based upon the assumption of rigid rings, are sensitive to the assumed pressure profiles but nevertheless served as the primary stability constraint applied to EBTR studies. Typically, for a midplane beta in the range 0.3-0.5, the average

TABLE II

SUMMARY OF TYPICAL STELLARATOR/TORSATRON FUSION REACTOR CONCEPTS

	KYOTO[62] HELIOTRON-C $\ell=2$	MIT[13] T-1 $\ell=3$	LASL[14] R-3 $\ell=2$
Minor radius (m)	2.8	2.3	2.0
Major radius (m)	28.0	29.2	16.2
Plasma volume (m^3)	4330	3049	1240
Density ($10^{20}/m^3$)	0.75	1.33	2.0
Temperature (keV)	20	7.3	10
Lawson parameter (10^{20} s/m^3)	1.0	3.0	4.5
Averaged beta	0.15	0.035	0.06
Plasma power density (MW/m^3)	2.0	1.4	3.2
Ignited/driven burn	IGN	IGN	IGN
Magnetic field (T)	2.9	5.0	5.3
Pulsed energy (MJ)	0	0	0
Burn time (s)	∞	∞	∞
Off time (s)	0	0	0
Neutron current (MW/m^2)	2	1.25	2
Thermal power (MWt)	8500	4300	4000
Net power (MWe)	2530	1280	1190
System power density (MWt/m^3)	0.5	0.35	0.55
Recirculating power fraction	0.15	0.15	0.15
Net plant efficiency (η_{TH} = 0.35)	0.30	0.30	0.30

toroidal beta (defined here with respect to the average magnetic field) for a mirror ratio of ~ 2 would lie in the range 0.13–0.22; these latter values are quite acceptable from the viewpoint of system power density and superconducting magnetic technology.

Given an acceptably small level of instability-driven energy/particle losses, the dominant loss from the toroidal plasma can be attributed either to diffusive processes or to unconfined particle orbits (i.e., particle orbits that intersect structural walls). The diffusive loss of particles and energy from the non-axisymmetric bumpy torus is determined by neoclassical processes in which the diffusive step size is influenced significantly by the magnitude and direction of guiding-center particle orbits in a toroidal geometry. The poloidal drift orbits, that effectively cancel toroidal drifts normally responsible for rapid classical losses in any toroidal geometry, are driven by $E \times B$ and ∇B forces, where the ambipolar electric field is primarily radial and gradient-B drifts result from the local bumpiness associated with the simple mirrors. Using this neoclassical transport theory, the expression relating the $n\tau_E$ product to the plasma temperature, T, the toroidal major radius, R_T, and the magnetic radius of curvature, R_c, is proportional to $T^{3/2}(R_T/R_c)^2$. This scaling, when coupled with the fact that most dimensionless parameters measured for EBT experiments, with the exception of the toroidal-plasma beta, are close to the projected reactor value, indeed promises a technologically attractive and economic reactor, typical parameters for which are shown on Table III.

TABLE III

TYPICAL REACTOR PARAMETERS FOR THE ELMO BUMPY TORUS (EBT) FUSION REACTOR CONCEPT[15-18]

Minor radius (m)	1.0
Major radius (m)	35
Plasma volume (m^3)	690
Density ($10^{20}/m^3$)	1.0
Temperature (keV)	30
Averaged beta	0.2
Plasma power density (MW/m^3)	5.0
Ignited/driven burn	IGN/DRVN[(a)]
Magnetic field[(b)] (T)	3.5
Pulsed energy (MJ)	0
Burn time (s)	∞
Off time (s)	0
Neutron current (MW/m^2)	1.2
Thermal power (MWt)	3100
Net power (MWe)	1100
System power density (MWt/m^3)	5.0
Recirculating power fraction	$\lesssim$ 0.10
Net plant efficiency (η_{TH} = 0.36)	0.32

(a) EBTR transport scaling shows a propensity for thermal runaway and hence, a potential need for operation in a slightly subignited mode.
(b) Average value based on a mirror ratio M = 2.

3. Toroidal Biscusp (Tormac). Like the Tokamak and the Stellarator/Torsatron, as well as the Reversed-Field Pinch, the Tormac[19-21] is a

toroidal device that confines plasma on combined poloidal and toroidal magnetic fields. By opening the outer poloidal field regions, however, the Tormac creates an absolute minimum-B configuration that is MHD-stable for large aspect ratio and plasma beta. The resulting toroidal line cusps support plasma on both closed field lines (i.e., high-beta, bulk plasma) and open field lines, confinement of the latter plasma being enhanced by mirroring effects in the sheath region that separates regions of open and closed field lines. The bulk toroidal plasma would be surrounded completely by a sheath of mirror-confined plasma, and the composite particle/energy loss time, τ_ℓ, should equal that of an ion-ion collision time, τ_{ii}, increased by the number of sheath inventories contained in the bulk plasma. This factor is ~ r_p/Δ_s, where r_p is a measure of the plasma minor radius, and Δ_s is the sheath thickness; Δ_s should be no greater than a few ion gyroradii, ρ_i. Given that $\tau_\ell \simeq \tau_{ii}(r_p/\rho_i)$, relatively small, high-beta and possibly steady-state reactor embodiments have been projected.[19-21]

Under the assumption of a steady-state that is sustained by neutral-beam injection, with an efficiency of ~ 0.7, reactor design curves have been computed as a function of key system variables[20]. For example, if the engineering Q-value, is selected to be ~ 4 (recirculating power fraction of 0.25) for T_i = 65 keV, then $r_p I_w$ = 4 MW/m and $r_p B$ = 3.1 T m. Furthermore, if I_w = 4 MW/m^2, then r_p = 1.0 m, B = 3.1 T, and the net power equals 130A, where A = R/r_p is the plasma aspect ratio. Hence, for A ≃ 4, systems with net powers of 520 MWe are predicted. Table IV gives Tormac reactor parameters for this case.[20] The optimistic parameters listed for Tormac result in part from the assumed beta of 0.7, which clearly remains to be demonstrated for this assumed steady-state device.

TABLE IV

TYPICAL REACTOR PARAMETERS FOR THE TOROIDAL BICUSP (TORMAC) FUSION REACTOR CONCEPT[20]

Minor radius (m)	1.0
Major radius (m)	4.0
Plasma volume (m^3)	80
Density (10^{20}/m^3)	1.3
Temperature (keV)	65
Averaged beta	0.7
Plasma power density (MW/m^3)	22
Ignited/driven burn	DRVN
Magnetic field (T)	3.1
Pulsed energy (MJ)	0
Burn time (s)	∞
Off time (s)	0
Neutron current (MW/m^2)	4.0
Thermal power (MWt)	1733
Net power (MWe)	520
System power density (MWt/m^3)	~ 1.4
Recirculating power fraction	0.25
Net plant efficiency (η_{TH} = 0.40)	0.30

Generally, moderate decreases in β can be compensated by modest increases in B, which for the sample case given above is already quite small. Increases in sheath thickness, degrade the reactor performance. Arguments can be made,[20] however, that τ_ℓ can be enhanced by a factor $(n/n_s)^2$, where n is the bulk plasma density, and n_s is the sheath density. Better theoretical sheath models are required before this issue can be resolved. A clearer understanding of the mirror-confined sheath physics as well as the startup, achievement and maintenance of the Tormac field/plasma configuration represent topics of future study. On the basis of the assumed parameters and present knowledge, however, the range of point designs appears promising from the viewpoint of acceptable recirculating power, modest total power and steady-state (driven) operation for reactors of small physical size, low fields and acceptable neutron wall loading.

4. Surface Magnetically Confined Systems (Surmac). The Surmac concept[22] represents one example of a general class of multipole configurations[2,6] in which electrical conductors are arrayed in either a linear or toroidal geometry to create a surface magnetic configuration with low magnetic field (i.e., high beta) in the bulk plasma volume. The Surmac may operate with considerably reduced synchrotron radiation emanating from the bulk plasma, and, therefore, this concept may be particularly suitable for confining the higher-temperature advanced-fuel plasmas (e.g., p-B^{11}).[66]

In essence, the Surmac forms a "magnetic bottle" by passing current in alternating directions through appropriately arrayed pairs of conductors. In this way a surface layer of rippled magnetic field lines is formed that provides the confinement of a bulk, high-beta (0.2-0.4) plasma. The curvature of field lines in Surmac is such as to provide plasma stability at the inner region of the magnetic surface (i.e., an average magnetic well is formed), but plasma is expected to be rapidly lost from the "bad-curvature" regions outside the array of paired conductors that create the surface magnetic fields. Stable, high-beta plasma has been confined experimentally at temperatures in the range 0.03-0.25 keV[22] using a deflagration gun as a plasma source. Staged heating of a Surmac reactor utilizing the p-B^{11} fuel cycle would be accomplished by neutral-beam injection up to ~ 10 keV followed by boron ion-beam injection (10 MeV, 10 A) through pulsed magnetic windows[6] to the operating temperature of ~ 300 keV. The close proximity of magnetically-levitated superconducting magnets to the plasma may preclude the use of DT or other neutron-rich fuel cycles, a limitation that couples with the above mentioned advantages to point Surmac towards the burning of advanced fuels. Reactor studies have not been extensive, but Table V gives a range of typical parameters projected[23,66] for a toroidal dodecapole (ℓ = 6) configuration using the p-B[11] fuel cycle. If the 6-MeV fusion-product alpha particles can be efficiently contained in this design, ignition may be possible. The technology required to protect the superconducting coils, which inherently must be located near the plasma, from severe thermal loading is anticipated to be difficult.

B. Long-Pulsed Toroidal Systems

In terms of power density, relative simplicity and symbiosis with the basic confinement scheme, ohmic dissipation of toroidal plasma currents represents a highly desirable heating scheme. Two long-pulsed toroidal concepts are described that propose ohmic heating as the sole means to obtain an ignited thermonuclear plasma for reactor application: the Riggatron (high-field Tokamak) and the Reversed-Field Pinch (RFP). A variation of the RFPR has recently been proposed that would use an external helical winding to achieve a more controllable rotational transform in a reversed-field state; this concept[26] is called OHTE (Ohmically-Heated Toroidal Experiment), and, depending upon the selection of key plasma parameters and technological constraints for the reactor, OHTE would operate in a technology regime somewhere between the Riggatron and the RFPR.

TABLE V

TYPICAL REACTOR PARAMETERS[(a)] FOR THE SURFACE MAGNETICALLY CONFINED (SURMAC) FUSION REACTOR CONCEPT[66]

Minor radius (m)	3x4
Major radius (m)	9
Plasma volume (m^3)	2700
Density ($10^{20}/m^3$)	1
Temperature (keV)	200-300
Averaged beta	0.2 - 0.4
Plasma power density (MW/m^3)	0.7
Ignited/driven burn	(may ignite)
Magnetic field (T)	5
Pulsed energy (MJ)	0
Burn time (s)	∞
Off time (s)	0
Neutron current (MW/m^2)	0
Thermal power (MWt)	2000
Net power (MWe)	600
System power density (MWt/m^3)	NA
Recirculating power fraction	0.15
Net plant efficiency (η_{TH} = 0.35)	0.30

(a)Unlike the other concepts summarized herein, the Surmac parameters are based on an advanced p-B[11] fuel cycle.

1. The High-Field Ohmically-Heated Tokamak Reactor (Riggatron).

Although in principle a Tokamak, the Riggatron[9,27] approach represents a sufficient change in engineering approach and "conventional" Tokamak physics to warrant consideration here as an AFC. The combined use of high toroidal current density (8 MA/m^2) and high toroidal field (16-20 T) copper coils positioned near the first wall allows net energy production in a relatively short burn period from a high-beta ohmically-heated system. The severe thermal-mechanical environment in which the relatively inexpensive Fusion Power Core (FPC) must operate necessarily dictates an engineered short life. The plasma chamber and the D_2O-cooled copper magnets would be small because of the increased plasma density (2-3(20)^{21} m^{-3}) and high beta (0.15-0.25). The 6-10 tonne FPC would generate 1-2 GWt, the fusion neutron power being recovered in a fixed lithium blanket located outside the magnet system. Recovery of joule and neutron heating in the copper coils is also an essential element of the overall power balance. The short-lived, disposable FPC would operate in clusters of 4-6 fusion modules, with two additional stand-by modules and a rapid "plug-in" capability promising high plant reliability/availability without *in situ* remote maintenance.

The optimum design window for the Riggatron reactor was investigated by means of a one-dimensional model that has been benchmarked with PLT and Alcator Tokamak data. These burn physics results have been coupled to materials, neutronics and economics constraints to specify key engineering requirements. Limiting the smallest FPC size on the basis of space required by the ohmic-heating transformer and specifying the largest size from considerations of tritium breeding, magnet thickness and practical limits on total power (i.e., 1-2 GWt) leads to major radii in the range 0.57-0.95 m and aspect ratios of 2.0-2.5. Practical considerations of material strengths, first-wall heat fluxes (20-40 MW/m^2, no divertors) and plasma volume access *versus* ripple constraints (180 toroidal field coils, 0.1% ripple, 30% vacuum pumping area) results in a well defined parameter space for reactor operation.[9] Table VI summarizes a specific Riggatron design point. A cost-constrained operating mode emerges as follows: magnet power is applied for a low-density ohmically-heated ignition; gas puffing or pellet injection increases and sustains the plasma density and fusion power; simultaneously, the toroidal and poloidal fields are reduced to increase beta and to reduce the tokamak safety factor, q, to operational levels; burn control requires 10-100 Hz response frequencies; the burn would be terminated by impurity buildup after ~ 30 s.

TABLE VI

TYPICAL PARAMETERS FOR THE RIGGATRON (HIGH-FIELD TOKAMAK) REACTOR CONCEPT[9]

Minor radius (m)	0.34
Major radius (m)	0.85
Plasma volume (m^3)	2.0
Density ($10^{20}/m^3$)	20-30
Temperature (keV)	12-20
Averaged beta	0.2
Plasma power density (MW/m^3)	460
Ignited/driven burn	IGN
Magnetic field (T)	16.0
Pulsed energy (MJ)	200
Burn time (s)	36
Off time (s)	3
Neutron current (MW/m^2)	68
Thermal power (MWt)	1325
Net power (MWe)	355
System power density (MWt/m^3)	14
Recirculating power fraction	0.33
Net plant efficiency (η_{TH} = 0.40)	0.27

TABLE VII

TYPICAL PARAMETERS FOR THE REVERSED-FIELD PINCH REACTOR (RFPR) CONCEPT[25]

Minor radius (m)	1.5
Major radius (m)	12.7
Plasma volume (m^3)	564
Density ($10^{20}/m^3$)	2.0
Temperature (keV)	15-20
Averaged beta	0.3
Plasma power density (MW/m^3)	4.5
Ignited/driven burn	IGN
Magnetic field (T)	3.0
Pulsed energy (MJ)	14700
Burn time (s)	21.6
Off time (s)	5.0
Neutron current (MW/m^2)	2.7
Thermal power (MWt)	3000
Net power (MWe)	750
System power density (MWt/m^3)	0.50
Recirculating power fraction	0.17
Net plant efficiency (η_{TH} = 0.30)	0.25

2. Reversed-Field Pinch Reactor (RFPR). The Reversed-Field Pinch (RFP) is similar to a Tokamak in that a toroidal axisymmetric configuration is used to confine a plasma with toroidal current by a combination of poloidal and toroidal magnetic fields. Using a passive conducting shell, the RFP replaces the $q \geq 1$-2 Tokamak constraint by one that requires $dq/dr \neq 0$; the variation of the magnetic shear should not exhibit a minimum in a region enclosed by a first-wall conducting shell. By removing the q constraint, the RFP can operate with a current density that is sufficient for ignition by ohmic heating, unrestricted aspect ratio, higher beta and appreciably lower magnetic fields at the superconducting windings.

Reactor prognoses based on these degrees of design freedom have been made by two independent studies[25]. The aforementioned RFPR advantages of lower magnet costs and the possibility of ohmic heating to ignition are compensated to some extent by the need for a passive electrically-conducting shell located near the plasma edge; the impact of this shell on the overall system modularity and thermal efficiency remains to be fully resolved.[24] As for many of the less developed AFC's, an uncertainty for the RFP is the poorly understood scaling of energy loss during and after startup and the related impact both may have on achieving ignition by ohmic heating alone.

The point-plasma model used to generate the basis for the reactor design given in Table VII has been superceded by a one-dimensional (radial) MHD burn simulation[67]. Agreement between the two models is good, with the one-dimensional simulations predicting somewhat higher Q-values because of lower fields and toroidal currents required for ignition. Although the long-pulsed unrefueled design given in Table VII is characterized by a high Q-value and acceptable power costs, technological implications of first-wall thermal cycle and pulsed fields gives a strong impetus to examine the potential for truly steady-state operation. Recent suggestions[68] for Tokamak rf current drive and limiter/divertors should also be applicable to the RFPR. Additionally, the unique phenomenon of pitch convection[69] may also provide a means to sustain a steady-state toroidal current in a RFP configuration.

3. Pulsed Toroidal Systems. The early quest on the part of fusion reactor designers to attain the economic advantages of very high beta simultaneously with the physics advantages of toroidal confinement led to concepts like the toroidal theta-pinch reactor (RTPR)[28] and the High-Beta Stellarator (HBS).[5,29] It was generally found that the fast-pulsed nature of the RTPR (i.e., ~ 1-2 μs shock heating, 30-ms adiabatic compression, ~ 0.5 s burn time) resulted in technological problems that may outweigh the high-beta ($\gtrsim$ 0.8) advantages for that particular system. Additionally, the absence of MHD stability without fast feedback for the particular field configurations then under experimental investigation indicated other reactor-related problems for both the RTPR and the HBS, although the latter was proposed for steady-state operation. The most recent reactor embodiment of the high-beta adiabatically-compressed toroid is the Belt-Shaped Screw Pinch (BSPR).[30] Like the earlier RTPR design, the BSPR is heated by a fast radial implosion, but a toroidal bias magnetic field is applied to reduce the final values of beta and thereby to enhance stability. After the ~ 2-μs implosion phase, the plasma is adiabatically compressed in 0.1 s, an ignition/burn phase would be sustained for ~ 17 s, and the implosion/compression/ignition/burn

TABLE VIII

TYPICAL PARAMETERS FOR THE BELT-SHAPED SCREW PINCH (BSPR) REACTOR CONCEPT[39]

Minor radius (m)	1.5×7.5
Major radius (m)	10
Plasma volume (m^3)	1178
Density ($10^{20}/m^3$)	2.5
Temperature (keV)	9
Averaged beta	0.5
Plasma power density (MW/m^3)	5.1
Ignited/driven burn	IGN
Magnetic field (T)	4.6
Pulsed energy (MJ)	112,000
Burn time (s)	18
Off time (s)	8
Neutron current (MW/m^2)	2.0
Thermal power (MWt)	6000
Net power (MWe)	1120
System power density (MWt/m^3)	NA
Recirculating power fraction	0.57
Net plant efficiency (η_{TH} = 0.45)	0.19

phase would be repeated. Typical reactor parameters for the BSPR are given on Table VIII.

III. COMPACT TOROIDS

The generic name "compact toroid" (CT) has recently been applied to the 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.[70] Interest in this configuration, as applied to a conceptual fusion reactor, however, rekindled when the Spheromak[31] was proposed as a means to retain the developing physics base for Tokamaks, while simultaneously shedding certain technological difficulties. Since the Spheromak reactor was first proposed, the fusion community has identified[71] the general area and potential of compact toroids, the Spheromak being one element of the CT class of plasma configurations.

In addition to a great diversity of plasmoid formation, heating and confinement schemes, the fundamental physics of particle energy transport and stability equilibrium are not well known for most subsets of the CT class. Because of a desire for reactor plasmas with maximum power density, the MHD-like branch of CT's has received greater attention from the reactor viewpoint. The B_ϕ = 0 MHD-like elements of the CT family are classified as Field-Reversed Configurations (FRC).

Both the stationary and translating Field-Reversed Mirror (FRM)[33,34] concepts are also classified as FRC's. Reactor studies of the Spheromak configuration,[32] and one variation of a FRM-like translating Spheromak have been recently reported.[41] This particular Spheromak embodiment is similar to a high-beta FRM with toroidal field, and its performance parameters are not unlike those reported for the moving-ring FRM reactor.[44] After summarizing the reactors that have been proposed for the Astron-like (ion-ring) branch of the CT family, three specific FRC reactors are described: Linus (stationary); TRACT (stationary); and CTOR (translating).

A. Astron-Like Devices

The first considerations for using a field-reversed plasmoid to produce power were based upon the Astron[72,73] concept. 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 simple magnetic mirrors; an electron layer is thereby generated. 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 field line closure occurs. More detailed analysis of this particular approach revealed, however, that the slowing-down time of fast electrons, because of synchrotron radiation, would be shorter than that required for an energy breakeven, unless the electron energies are 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.

To avoid the synchrotron radiation problem, the injection of high-energy ions was proposed.[35] Ion-ring energies near 300 MeV were found to give optimal confinement properties. Producing and sustaining these ion rings solely by particle accelerators was deemed unfeasible[45] because of the difficulties in making an acceptable energy balance. 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.[45] By producing the ion-ring at somewhat lower energies (~ 30 MeV) using particle beams, the inefficiencies become less significant, since the bulk of the plasma energy would be added to the ring by adiabatic compression. A summary of expected reactor parameters for this latter approach is listed in Table IX.

The azimuthal current in both the Astron and ion-ring devices 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 FRM in fact 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 the parameter $S = a/\rho_i$, which measures the number of ion-gyroradii enclosed by the plasma radius, a. A class of particles with $S \lesssim 1$ exists in an Astron device, while the FRM configuration would operate with S ~ 5-10. In the absence of a

TABLE IX

TYPICAL PARAMETERS FOR ION-RING COMPRESSOR REACTOR CONCEPT[45]

	COMPRESSION/ BURN CHAMBER
Deuteron energy (MeV)	30/300
Total fast-ion charge (C)	1.5/1.5
Major ring radius (m)	10/3
Radial ring thickness (m)	10/3
Axial ring length (m)	15/4.5
Temperature (keV)	< 1/20
Density ($10^{20}/m^3$)	0.1/0.63
Fusion power per ring (MW)	0/300
Total energy per ring (MJ)	50/540
Ring lifetime (s)	0.1/5
External magnetic field (T)	0.14/1.4
Magnetic field at ring (T)	0.20/0.67
Axial current (MA)	10/10
First-wall radius (m)	15/4.5
First-wall loading (MW/m^2)	0.1/2.3
Compression time (s)	0.2-0.5
Duty cycle	0.8-0.9
Ring energy gain	3

conducting shell, finite-Larmor-radius stabilization may be important to the FRM stability, and an upper limit on S is generally taken to be ~ 10. The reactor implications of these constraints on S for the FRM approach have been addressed in Ref. 44 and 71.

B. Slowly-Imploding Liner Reactor (Linus)

The use of a "dynamic coil" to heat a FRC by strong adiabatic compression has been under study as a reactor at NRL[37,39], at LASL[38] and at the Kurchatov Institute[40]. Table X summarizes typical reactor parameters along with parameters for CTOR and TRACT. The liquid-metal liner is imploded by a mechanical or gas-dynamic drive onto a FRC plasmoid, transferring the liner kinetic energy to the plasmoid through magnetic flux compression of the high-beta plasma. The Linus reactor promises a high-power density with unique solutions to several technology problems. This concept envisages the nondestructive and reversible compression/re-expansion of a quasi-cylindrical liquid-metal (Li or LiPb) liner that is rotationally stabilized against Rayleigh-Taylor modes at peak compression. A high-pressure helium reservoir (~ 15 MPa) would serve as the liner energy storage. The FRC plasmoid can be produced in situ using rotating relativistic electron beam techniques[74] or formed externally by a Field-Reversed Theta Pinch (FROP).[75] Depending on the specific approach,[38,39] the initial state of the plasmoid requires 0.4-0.5-keV temperature, 0.5-T magnetic field, average beta of ~ 0.6-0.8 and a length of 8-10 m. The plasmoid is compressed on a ~ 20-ms timescale to a final state (15-20 keV, 50 T and $\beta \approx 0.6$) at which point a vigorous thermonuclear burn occurs during the short (~ 0.5-1.0 ms) dwell time at peak compression. Provided that the radial dimensions are appropriately chosen, the alpha-particle energy added to the plasmoid from the DT burn is sufficient to compensate for the mechanical losses incurred during the liner implosion, driving the liner outward and repressurizing the helium reservoir. The liquid-metal liner is sufficiently thick ($\gtrsim$ 1 m) at peak compression to shield neutronically the permanent structure and liner implosion mechanism. In addition, the liner material (Li or LiPb) functions as a tritium-breeding blanket, primary heat-transfer medium and "recycled" first wall that is capable of accommodating severe thermal loadings.

The NRL group proposes two approaches to the Linus concept. The more recent NRL proposal uses tangential injection to create the rotating liquid liner. This approach would operate with two oppositely-directed annular free-pistons and would avoid the problems anticipated with high-temperature, high-strength rotary seals and bearings associated with earlier designs that used radial pistons to drive the implosion. Axial pistons would also develop an axial convergence of the liner material, which would allow the liner energy to follow the axial contraction of a FRC plasmoid that occurs during radial compression. A compression that is driven by a tangential injection also eliminates the need to rotate a large fraction of the reactor structure, while simultaneously leading to a more spherically-symmetric implosion (reduced exposure of reactor structure to "water-hammer" pulsed pressure at peak compression) and allowing the liner to follow more closely an axially-contracting FRC plasmoid during compression with reduced end-streaming of the fusion neutrons. The LASL parameter list given in Table X is based on independent modeling[38] of an alternative Linus configuration in which a radially-collapsing shell with tangential injection provides the liner drive.

C. Triggered-Reconnection Adiabatically Compressed Toroid (TRACT) Reactor

Like the Linus concept, the TRACT approach[35,76] to the utilization of a CT for net power production envisages the stationary (nontranslating) adiabatic compression of a preformed FRC to ignition. Table X also gives typical reactor parameters for this ~ 1-Hz batch-burn system. Utilizing a longer burn period (~ 0.5 s) and lower magnetic fields (5.3 T) than Linus, a hybrid superconducting(dc)/normal(ac) coil system would provide the required flux compression to achieve ignition in a plasmoid of initial 0.72-m radius. A first-wall copper coil cancels and subsequently reverses for a few milliseconds the field generated by an exo-blanket superconducting coil, during which time a low-temperature plasma is created. The superconducting flux is re-established in the plasma chamber in two stages: a fast (shock) stage and a slower (adiabatic compression) stage. During the shock phase the plasma column and trapped (reversed)

TABLE X

TYPICAL PARAMETERS FOR A NUMBER OF REACTOR CONCEPTS BASED ON THE USE OF FIELD-REVERSED CONFIGURATIONS[9]

	Linus[(a)]	TRACT[35,76]	CTOR[43]
Minor radius (m)	0.08/0.037	0.14	0.31
Major radius (m)	0.19/0.11	0.36	0.52
Length (m)	3.1/10.0	1.88	6.0
Plasma volume (m^3)	0.35/0.50	1.52	12.0
Density ($10^{20}/m^3$)	2400/1900	28	10
Temperature (keV)	15/20	8-40	12-14
Averaged beta	0.55/0.60	0.77	0.8
Plasma power density (MW/m^3)	4000/6500	560	230
Ignited/driven burn	DRVN/IGN	IGN	IGN
Magnetic field (T)	54/60	7	4.2
Pulsed energy[(b)] (MJ)	1400/1700	570	240
Burn time (s)	0.0004/0.0010	0.5	2.0
Off time (s)	1.0/0.5	0.5	6.2
Neutron current (MW/m^2)	305/259	10.0	2.0
Thermal power (MWt)	1790/3350	520	1050
Net power (MWe)	507/910	130	310
System power density (MWt/m^3)	4.1[(c)]/4.1	1.70	0.70
Recirculating power fraction	0.15/0.22	0.19	0.15
Net plant efficiency (η_{TH})	0.28/0.27(0.33/0.35)	0.25(0.30)	0.30(0.35)

(a) NRL/LASL parameters

(b) Initial liner kinetic energy (mechanical).

(c) Calculated using reactor volume including the gas reservoir used to drive the liner. If the smaller volume enclosed by the unimploded liner is used as the basis, this parameter would be increased by a factor ~ 5.

bias flux are radially compressed; significant shock heating results. During the shock heating and subsequent adiabatic compression, cusp coils at each end of the 8-m-long plasma chamber may be needed to reinforce the trapped flux while expanding the forward flux, leading to a delay in the reconnection of field lines. At the time when the external field induced by the fast shock-heating power supply reaches a peak value, trigger coils are activated, and field-line reconnection occurs. An elongated FRC results, which rapidly compresses axially to achieve an equilibrium configuration, this axial compression providing significant heating. As the first-wall bias coil continues to discharge to zero current, the full superconducting field is retrieved, and a moderate amount of radial compressional heating follows. The resulting ~ 1.5-m-long plasmoid would attain ignition and burn for 0.5 s, this cycle being repeated every second.

The TRACT parameters given in Table X apply to a prototype reactor that would generate net electric power in relatively small sizes and at low cost.[76] A fusion energy of 538 MJ is produced from each batch burn. The magnetic energy required to null and reverse the superconducting field is 570 MJ. Joule losses incurred in the first-wall copper coil would be small because of the hybrid magnet approach and transient nature of the current nulling. Economic recirculating power fractions are calculated for a 90% pulsed-energy transfer efficiency. Thermal and direct-energy recovery from the burning plasma has not been considered, but should lead to somewhat reduced recirculating power fractions.

The method for heating a FRC plasmoid proposed by the TRACT approach leads to a relatively small pilot plant of moderate cost that may operate on the basis of near-term technology.[76] A large commercial plant that distributes the pulsed power supply costs over several reactor modules benefits from an economy of scale that predicts acceptable direct capital costs. The advantages of significant heating promised by axial compression (reduced voltage needed to drive a radial shock) and the use of the hybrid magnet approach (reduced magnetic energy transfer and joule losses), innovations which indeed may be significant, are counterbalanced by problems that have been identified for other similar systems[28] (in-core voltage, pulsed energy storage/transfer, thermal cycle, etc.).

D. The Compact Toroid Reactor (CTOR)

The CTOR system[43] would use a Field-Reversed Theta Pinch (FROP) to produce external to the reactor a FRC plasmoid that is subsequently translated through a linear burn chamber. This approach differs from both the Linus and TRACT systems; the high-voltage plasmoid source and compressional heater are removed from the burn chamber to a less hostile environment. To minimize the technological requirements imposed by the plasmoid source and the associated pulsed power, a flared axial compressor would maintain the first-wall magnet coil close to the plasma for stability while the translating plasmoid is adiabatically compressed to ignition prior to entering the linear burn chamber. Translation of the ignited plasmoid in the high-temperature burn chamber allows portions of the conducting shell that have not experienced flux diffusion to be continually "exposed". A nearly steady-state (thermal) operation of the first wall and blanket is possible by adjusting plasmoid speed and injection rate. Locating the stabilizing conducting shell outside the blanket permits room-temperature operation and minimizes the translational power, which appears as joule losses in the exo-blanket shell, losses that can be supplied directly by alpha-particle heating through modest radial expansion of the plasmoid inside a slightly flared conducting shell, blanket and first wall. Superconducting coils are placed outside the blanket, conducting shell and shield to provide a continuous bias field that is compressed between the conducting shell of radius r_c and the plasmoid with separatrix radius r_s; gross MHD stability would thereby be provided throughout the burn without requiring active feedback stabilization. The plasmoid motion terminates in an end region where expansion directly converts internal plasma energy to electrical energy.

Parameter studies of the CTOR concept were performed using a point-plasma model that incorporates analytical equilibrium expressions.[75] Table X also summarizes typical CTOR parameters. A FROP plasmoid ($T = 1.6$ keV, $r_s = 2.5$ m, $\ell = 9.7$ m), is adiabatically compressed to 8 keV ($r_s = 0.85$ m, $\ell = 5.0$ m) in 0.1 s using a rotating machine for a power supply. This ignited plasmoid enters the burn chamber with an initial velocity equal to 2-5 times ℓ/τ_s, where the electrical skin time, τ_s, describes the decay of flux within the area between the first wall and plasma separatrix. The plasmoid velocity is subsequently reduced by tailoring the flare of the shell to maintain a constant first-wall neutron loading along the length of the burn chamber. Plasmoid motion proceeds until the velocity falls below ℓ/τ_s, at which point the reactor length is defined. Energy confinement time scalings corresponding to classical, Alcator ($\tau_E \simeq 3(10)^{-21} n r_p^2$) and 200 Bohm times ($\tau_E \simeq 3.2 r_p B/T_e$) were parametrically investigated. Both Alcator and 200 Bohm confinement scalings result in plasma and reactor performances that are relatively insensitive to reactor length; these burns are thermally stable and eventually quench because of thermal loss. As the energy confinement time is reduced from $\tau_E \simeq 1$ s (classical) to $\tau_E \simeq 0.2$ s (Alcator) and 0.1 s (200 Bohm), respectively, the increased plasma losses are supplied by increasing the FRC power density. This capability results in a reactor that is remarkably invariant to the assumed plasma transport as the plasmoid density and injection rate are adjustable to give a desired (axially-uniform) wall loading and total power.

IV. LINEAR MAGNETIC FUSION

Since the inception of controlled thermonuclear fusion research, the attractiveness of plasma confinement in linear geometries has been apparent. The excessive plasma length required to sustain the plasma density at thermonuclear temperatures against free-streaming endloss for times sufficient to achieve a net energy breakeven led to early abandonment of Linear Magnetic Fusion (LMF) in favor of closed-field geometries. The attractions of LMF, however, remain: proven heating methods, neutrally-stable plasma equilibrium, high plasma density and beta, accessible and convenient geometry. Two LMF workshops[77,78] have addressed the primary obstacles to LMF: axial particle/energy confinement and total system length. Although free-streaming endloss has been the subject of experimental and theoretical study, methods of particle/energy endloss reduction relative to the free-streaming case until recently have received little in-depth consideration. If fact, the development of the previously-described FRC represents one solution to the LMF endloss problem, and the past focus and direction of LMF has been preempted by present activities in the area of compact toroids.

Conceptual LMF reactor designs reflect a rich array of potential heating and axial confinement options.[79] Heating to ignition by a combination of beams (neutral atoms,[47] relativistic electrons,[51] lasers[50]), fast implosions coupled with adiabatic compression[49] and high-frequency heating[80] have been investigated. Endloss reduction by the following techniques has been proposed: material endplugs, re-entrant endplugs, electrostatic trapping, simple mirrors, multiple mirrors, cusped fields, reversed fields, high-frequency stoppering, plasma-gun injection. Only the first five of these end-stoppering methods have received consideration in a reactor embodiment, and experimental studies have yet to be conducted under reactor-like plasma conditions.

As a quantitative example of a "typical" LMF reactor system, the Linear Theta-Pinch Reactor (LTPR) with axial (electron) thermal conduction[81] to re-entrant endplugs (REP) is summarized in Table XI. Were it not for the plasma endloss, the heating and (radial) confinement principles for the LTPR would be similar to those envisaged for the toroidal Reference Theta Pinch Reactor[28] and more recently for the TRACT reactor.[35,76] A preionized DT gas is heated by a fast (~ 1-2 μs) implosion to ~ 1 keV; the preheated plasma is subsequently compressed adiabatically to ignition and a burn cycle occurs along a plasma radius/temperature trajectory determined by the dynamics of an energetic, high-beta plasma. The LTPR study invokes the re-entrant endplug, wherein the endloss particles and energy are

TABLE XI

TYPICAL PARAMETERS FOR THE LINEAR THETA-PINCH REACTOR (LTPR)[49] CONCEPT WITH RE-ENTRANT ENDPLUGS[(a)]

First-wall radius (m)	0.5
Length (m)	150
REP radius (m)	5.0
Plasma volume (m^3)	260.
Implosion field (kV/mm)	0.1
Temperature (keV)	10-26
Density ($10^{20}/m^3$)	50
Averaged beta	0.9
Ignited/driven burn	IGN
Magnetic field (T)	8.0
Compression time (s)	0.03
Burn time (s)	0.4
Off time (s)	12.4
Neutron current (MW/m^2)	2.5
Thermal power (MWt)	3606
Net power (MWe)	1080
System power density (MW/m^3)	1.1
Recirculating power fraction	0.25
Net plant efficiency (η_{TH} = 0.40)	0.30

(a) Based on ten times cross-field thermal conduction in REP regions.

directed by a small radius-of-curvature conduit to a second, parallel plasma column. The plasma within the REP region must necessarily be in "toroidal" equilibrium but in all likelihood would be subjected to anomalous cross-field transport losses, which for the proposed design reported in Table XI is assumed to equal ten times classical values.

The LTPR reactor parameters shown in Table XI have been determined by a time-dependent axial burn code. Both the implosion and adiabatic compression coils operate at room temperature and are located outside the [illegible] radius first wall and 0.4-m thick blanket, operate near 300 K, and require 0.9 GJ and 44 GJ of pulsed energy, respectively; reversible recovery of the adiabatic compression energy at 95% efficiency is specified. The 0.4-s burn reduces but does not eliminate the problems associated with pulsed thermal loading of the first-wall, energy-transfer/storage and magnet stress.[28] The present uncertainties of the REP approach, the close coupling of the implosion preheating to the reactor core (high-voltage insulated blanket) and the need for an efficient energy-transfer/storage system represent important issues for the LTPR.

V. VERY DENSE (PULSED, LINEAR) SYSTEMS

Of the five fast-pulse (~ 1-μs burn time) concepts listed on Table I only the Fast-Liner Reactor (FLR),[52] the Wall-Confined Shock-Heated Reactor[54] (SHR) and the Dense Z-Pinch Reactor (DZPR)[55] have been subjected to preliminary reactor scaling studies. Consequently, only these three concepts are described.

A. Fast-Liner Reactor (FLR)

The use of magnetically-driven metallic liners for the adiabatic compression of DT plasmas to thermonuclear conditions has been studied by a number of investigators.[82-85] The FLR[52] approach follows that of the Kurchatov group[93] and emphasizes fast ($10^3 - 10^4$ m/s), destructive implosions of thin metallic shells onto DT plasma. This concept combines the characteristics of inertial confinement and heating with the more efficient energy transfer associated with magnetic approaches. A small (0.1-0.2 m radius) cylindrical liner is imploded radially to velocities of ~ 10^4 m/s by self-magnetic fields resulting from large axial currents driven through the liner. The liner implodes onto a ~ 0.5 keV, ~ 10^{24} m^{-3} D-T plasma that is initially formed in situ or alternatively could be injected into the liner. As the liner implodes in 20-40 μs, adiabatic compression raises the plasma to thermonuclear temperatures, and a vigorous burn ensues for 2-3 μs. During the implosion the plasma pressure is confined inertially by the metal liner and endplug walls. An imbedded azimuthal magnetic field provides radial and axial thermal insulation. The FLR studies have focused primarily on the development of realistic plasma/liner models and the burn optimization based thereon.[52] On the basis of physics design curves derived from these optimizations, the interim FLR operating point summarized on Table XII has evolved.

The major engineering and technology problems in order of perceived importance are: plasma preparation; the economics of destroyed

TABLE XII

TYPICAL PARAMETERS FOR THE FAST LINER REACTOR (FLR) CONCEPT[52]

Initial liner radius (m)	0.2
Initial liner thickness (mm)	3.0
Liner length (m)	0.2
Initial azimuthal field (T)	13.0
Initial liner energy (GJ)	0.34
Liner Q-value	10.7
Pure fusion yield (GJ)	3.56
Enhanced fusion yield (GJ)	3.92
Temperature (keV)	~ 15
Density ($10^{20}/m^3$)	$8(10)^6$
Ignited/driven burn	IGN
Burn time (s)	$2(10)^{-6}$
Off time (s)	10.0
Thermal power (MWt)	430
Net power (MWe)	129
System power density[(a)] (MWt/m^3)	5.8
Recirculating power fraction	0.25
Net plant efficiency (η_{TH} = 0.40)	0.30

(a) The system power density is based on the total volume enclosed by a 2.6-m radius containment vessel of 0.3-m wall thickness.

leads and liner; blast containment; the switching and transfer of energy (0.5 GJ, 20-30 μs); and frequent (10-20 s) liner and leads replacement. Each of these issues is briefly addressed. Four possible plasma preparation schemes are considered: co-axial (Marshall) gun injection, shock-tube injection, exploding D-T threads, and in situ plasma formation by electron or laser beams. The destroyed leads structure would represent the major but tenable (less than 30% of electricity cost) recycle cost. An interleaved leads structure has been optimized[52] on the basis of realistic recycle cost for the conductor and for insulator refabrication. Detailed structural analyses of the blast vessel and blast mitigation by intervening coolant spray have been made. These studies indicate that nearly spherical vessels of 2.5-3.0 m radius and 0.2-0.5 m wall thickness would perform adequately under a ten-year fatigue constraint. The rapid energy transfer suggests the use of slow (~ 0.1 s) homopolar motor/generators switched into a storage inductor; the storage inductor would be rapidly switched through a transfer capacitor into the time-varying liner inductance. Reversible recovery of this energy is not required for the design given in Ref. 52.

B. The Wall-Confined Shock-Heated Reactor (SHR)

Similar to the FLR approach, the SHR concept[54] would confine plasma pressure by material walls with heat transfer from the hot plasma to the confining walls being reduced by imbedded magnetic field. The SHR proposes shock heating of a dense DT plasma to temperatures (~ 10 keV) where significant net yield (Q_p > 20) would occur; alpha-particle heating per se is not expected and (like the DZPR) "ignition" in a technical sense is not required. A ~ 2-m diameter annular cylinder of length ~ 1 m and annular gap ~ 0.6-m would be used to confine an axial shock. This ionizing shock would be driven axially at a velocity of ~ $0.7(10)^6$ m/s by a 2.7-MV voltage applied across the annulus. Typical SHR parameters are given in Table XIII.

The DT gas in the annular region (~ 10^{21} m^{-3}) along with the thermally-insulating bias field (3.2 T) would be swept down the annular tube by the magnetic piston. The shock reflects off the tube endwall and is allowed to re-expand and fill the annular chamber. After a period of free-expansion, shock reflection and dissipation of a portion of the internal bias field, a 10-keV plasma would result if thermal conduction to the tube walls is no more than 100 times classical predictions. The dynamics of the ignited plasma and the length of the useful burn cycle are strongly dependent upon both micro- and macro-instabilites, mechanisms of cooling-wave propagation, particle losses and alpha-particle dynamics. Without refueling, a burn period of ~ 1 s is predicted, leading to a recirculating power fraction of ~ 0.3 and a gross thermal output of 780 MJ/pulse. Under these conditions a 2.6-s cycle time with 1.6 s allowed for re-fueling would give a fusion-neutron current of 7.5 MW/m^2 at the shock-tube wall and a net power output of ~ 80 MWe. As for most of the fast-pulsed approaches, high-voltage and thermal loads present the major tradeoffs associated with this relatively compact and high power density system.

TABLE XIII

TYPICAL REACTOR PARAMETERS FOR THE SHOCK-HEATED, WALL-CONFINED FUSION REACTOR CONCEPT[54]

Minor radius (m)	1.2
Major radius (m)	0.3
Plasma volume (m^3)	5.3
Density ($10^{20}/m^3$)	20
Temperature (keV)	10
Averaged beta[(a)]	5.0
Plasma power density (MW/m^3)	62
Ignited/driven burn	IGN
Magnetic field (T)	3.2
Pulsed energy (MJ)	NA
Burn time (s)	0.5
Off time (s)	2.57
Neutron current (MW/m^2)	7.5
Thermal power[(b)] (MWt)	328
Net power[(b)] (MWe)	85
System power density (MWt/m^3)	NA
Recirculating power fraction	0.32
Net plant efficiency (η_{TH} = 0.38)	0.26

(a) Exceeds 1.0 because of wall-confinement.
(b) Power per module. A plant may include twelve such modules.

C. Fast-Pulsed Systems (DZPR)

The Dense Z-Pinch Reactor (DZPR)[55] reveals a number of surprising deviations from conventional fusion reactor wisdom; alpha-particle heating may be detrimental to the overall system performance, and the optimum high-Q operating point may yield amounts of fusion power that are undesirably small. The DZPR concept is eloquently simple, representing one of the earliest confinement schemes considered.[86] A large electrical current (~ 1.5 MA) is initiated along a sub-millimeter, laser-formed current channel within a high-pressure (≥ 1 atm) DT gas. The ohmically-heated constant-radius filament would produce 20-40 times the energy initially delivered as magnetic field and ohmic dissipation. Both analytic and numerical studies[55] indicate a well-defined optimum that relies on current programming to achieve a constant radius (~ 0.1 mm) burn. A system with a plasma Q-value in excess of 30 would require an energy of 240 kJ to be delivered within ~ 300 ns and a stable burn period of 2 μs in the absence of alpha-particle heating and coronal diffusive/gas-ingestion processes. Ohmic dissipation provides the sole heating; shock and compressional heating along conventional lines appear to be undesirable. Recent MHD stability analyses have indicated greater stability for diffuse pinches or for filamentary discharges initiated in dense gases[48]; finite-Larmor-radius effects[49] or plasma flow[50] may also lead to enhanced stability. This potential for improved stability has encouraged preliminary reactor studies.[55,91]

Analytic, zero-dimensional and one-dimensional plasma simulations have been made over a wide range of operating parameters[55], the latter two simulation models incorporating a realistic electrical circuit (Marx bank, water transmission line) and being calibrated with a small but encouraging experiment.[92] The results of parametric burn simulations using the comprehensive zero-dimensional model, which have been verified with the radial MHD burn code, are depicted on Table XIV. An experimentally achievable starting radius of 0.1 mm was selected. The results of parametric systems studies,[55] of which those given in Table XIV are typical, appear to be virtually independent of all variables other than the applied voltage, energy and line density. These results also appear to be relatively insensitive to the assumed current risetime and crowbar time, primarily because of the assumed batch burn and high fuel burnup. Detailed engineering designs have not yet been made, although the Marx-bank/water-line will lead to a number of obvious design, operational and economics constraints.

TABLE XIV

TYPICAL REACTOR PARAMETERS FOR THE DENSE Z-PINCH REACTOR (DZPR) FUSION REACTOR CONCEPT[55]

Minor radius (m)	$1.0(10)^{-4}$
Length (m)	0.1
Plasma volume (m^3)	$3.1(10)^{-19}$
Density ($10^{20}/m^3$)	$1.7(10)^7$
Temperature (keV)	10-30
Averaged beta	1.0
Plasma power density (MW/m^3)	$1.2(10)^{10}$
Ignited/driven burn	DRVN
Magnetic field (T)	~ 3000
Pulsed energy (MJ)	0.24
Burn time (s)	$2(10)^{-6}$
Off time (s)$^{(a)}$	0.1
Neutron current$^{(a)}$ (MW/m^2)	2.5
Thermal power (MWt)	44
Net power (MWe)	16
System power density$^{(a)}$ (MWt/m^3)	10.4
Recirculating power fraction	0.13
Net plant efficiency (η_{TH} = 0.35)	0.30

$^{(a)}$evaluated at the first structural surface.

VI. CONCLUSIONS

A wide variety of alternative approaches to magnetic fusion has been briefly described. Given the rapid progress towards fusion power being made by the mainline Tokamak approach with a strong backup being provided by the Tandem Mirror (TMR), and given a fertile and promising reserve of AF approaches, the options for the technical success of fusion power indeed are broad. The physics basis for each AFC relative to the Tokamak varies widely, however, and against this background of physics and technology uncertainty are projected relatively unquantified but important economic uncertainties. To varying degrees each AFC promises for different reasons an attractive alternative approach to fusion power; only through the generation of needed experimental evidence, however, can the claims and prognoses of higher power density, more compact, more reliable and ultimately more economical systems projected by each AFC be more firmly assessed.

REFERENCES

1. F. L. Ribe, "Recent Developments in the Design of Conceptual Fusion Reactors," Nucl. Technol., 34, 179-208 (1977).

2. F. F. Chen (ed.), "Alternate Concepts in Controlled Fusion," Electric Power Research Institute report EPRI-429-SR (May, 1977).

3. P. J. Persiani, W. C. Lipinski and A. J. Hatch, "Survey of Thermonuclear-Reactor Parameters," Argonne National Laboratory report ANL-7807 (1972).

4. W. F. Cove, "Advanced Fusion Concepts Program," Proc. 3rd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, I, 51-57 (May 9-11, 1978).

5. W. Käppendörfer, "System Analysis of Magnetically Confined Pulsed Reactors," Pulsed Fusion Reactors, Euratom report EUR 5307e, 682-694 (1974).

6. F. F. Chen, "Alternative Concepts in Magnetic Fusion," Physics Today, 32, 36-42 (May, 1979).

7. N. A. Krall and G. W. Stuart, "Evaluation of Alternative Fusion Concepts," Electric Power Research Institute report (to be published, 1981).

8. R. A. Krakowski, R. L. Hagenson, R. L. Miller, and R. W. Moses, "Systems Studies and Conceptual Reactor Designs of Alternative Fusion Concepts at LASL," Proc. 7th IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-37/I-2, III, 333-341 (August 23-30, 1978).

9. R. A. Krakowski, et al., "Reactor Systems Studies of Alternative Fusion Concepts," Proc. 8th IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-38 Y-4 (July 1-10, 1980).

10. Fusion Reactor Design Concepts, Proc. Technical Committee Meeting and Workshop on Fusion Reactor Design, Madison, WI, IAEA-TC-145 (October 10-21, 1977).

11. A. Gibson, "Permissible Parameters for Economic Stellarator and Tokamak Reactors," Proc. BNES Nuclear Fusion Reactor Conf, 233-241 (September, 1969).

12. A. Gibson, R. Hancox, and R. J. Bickerton, "On the Economic Feasibility of Stellarator and Tokamak Fusion Reactors," Proc. 4th IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-28 K-4, III, 375-392 (June 17-23, 1971).

13. P. A. Politzer, L. M. Lidsky and D. B. Montgomery, "Torsatrons and the TOREX Proof of Principle Experiment," Massachusetts Institute of Technology report PFC-TR-79-2 (March, 1979).

14. R. L. Miller and R. A. Krakowski, "The Modular Stellarator/Torsatron Fusion Reactor Concept," Los Alamos Scientific Laboratory report (to be published, 1981).

15. J. R. Roth, "Alternate Approaches to Fusion," NASA report TM X-73429 (1976).

16. D. G. McAlees, N. A. Uckan, E. S. Bettis, C. L. Hedrick, E. F. Jaeger, and D. B. Nelson, "The Elmo Bumpy Torus Reactor (EBTR) Reference Design," Oak Ridge National Laboratory report ORNL/TM-5669 (November, 1976).

17. N. A. Uckan, E. S. Bettis, R. A. Dandl, C. L. Hedrick, R. T. Santoro, H. L. Watts and H. T. Yeh, "The Elmo Bumpy Torus (EBT) Reactor - A Status Report," Proc. 3rd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, 1, 74-82 (May 9-11, 1978).

18. N. A. Uckan, D. B. Batchelor, E. S. Bettis, R. A. Dandl, C. L. Hedrick and E. F. Jaeger, "The ST20 Bumpy Torus (EBT) Reactor," Proc. 7th IAEA Conf. on Plasma Physics and Controlled Fusion Research, IAEA-CN-37/I-3, III, 343-356 (August 23-30, 1978).

19. M. A. Levine, I. G. Brown, and W. B. Kunkel, "Scaling for Tormac Fusion Reactors," Proc. 2nd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, 1, 353-358 (September 21-23, 1976).

20. R. L. Miller, R. A. Krakowski and C. G. Bathke, "A Parametric Study of the Tormac Fusion Reactor Concept," Los Alamos Scientific Laboratory report LA-7935-MS (August, 1979).

21. R. L. Miller, R. A. Krakowski and C. G. Bathke, "Tormac Fusion Reactor Design Points," Trans. Amer. Nucl. Soc., 33, 98-99 (1979).

22. A. Y. Wong, et al., "High-Beta Confinement Experiments in Multipole Surmac - A Concept for an Advanced Fuel Fusion Reactor," Proc. 8th IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-38/AA2 (July 1-10, 1980).

23. A. N. Hershkowitz and J. M. Dawson, "Fusion Reactor with Picket-Fence Walls," Nucl. Fus., 16, 639-642 (1976).

24. R. L. Hagenson and R. A. Krakowski, "The Reversed-Field Pinch Reactor (RFPR) Concept," Los Alamos Scientific Laboratory report LA-7973-MS (August, 1979).

25. R. Hancox, R. A. Krakowski, W. R. Spears and R. L. Hagenson, "The Reverse-Field Pinch Reactor," Nucl. Eng. and Design (to be published, 1980).

26. T. Ohkawa, "OHTE; A New Fusion Concept," personal communication, General Atomic Company (May, 1980).

27. R. W. Bussard and R. A. Shanny, "Conceptual Design of Modular Throwaway Tokamak Commercial Fusion Power Plant," Inter. INESCO, Inc. report (April 27, 1978).

28. R. A. Krakowski, R. L. Miller, and R. L. Hagenson, "Operating Point Consideration for the Reference Theta-Pinch Reactor (RTPR)," Proc. 2nd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, I, 357-370 (September 21-23, 1976).

29. M. Kaufmann and W. Köppendörfer, "Fusion Reactor Characteristics in Dependence on Beta and Aspect Ratio," Proc. 6th European Conf. on Controlled Fusion and Plasma Physics, Moscow, USSR, I, 341-344 (July 30 - August 4, 1973).

30. H. Bustraan, et al., "A Reactor Study on the Belt-Shaped Screw Pinch," Netherlands Energy Research Foundation report ECN-77 (October, 1979).

31. M. N. Bussac, H. P. Furth, M. Okabayashi, M. N. Rosenbluth, and A. M. M. Todd, "Low-Aspect-Ratio Limit of the Toroidal Reactor: The Spheromak," Proc. of the 7th Inter. Conf. on Plasma Physics and

[illegible] Nuclear Fus. [illegible] IAEA [illegible] ([illegible]).

32. M. Katsurai and M. Yamada, "Conceptual Design Study of Spheromak Reactor," Princeton Plasma Physics Laboratory report PPPL-[illegible] (19[illegible]).

33. W. [illegible], G. A. Carlson, [illegible], J. [illegible], W. S. Neef, and [illegible], "Preliminary Design Calculations for a Field-Reversed Mirror Reactor," Lawrence Livermore Laboratory report UCRL-[illegible] ([illegible]).

34. G. A. Carlson, W. C. Condit, R. S. Devoto, J. H. Fink, J. D. Hanson, W. S. Neef, and A. C. Smith, Jr., "Conceptual Design of the Field-Reversed Mirror Reactor," Lawrence Livermore Laboratory report UCRL-[illegible] (1978).

35. H. J. Willenberg, A. L. Hoffman, L. C. Steinhauer, and P. H. Rose, "TEA I: A Small Fusion Reactor Based on a Compact Torus Plasma," Proc. US-Japan Joint Symp. on Compact Toruses and Energetic Particle Injection, Princeton Plasma Physics Laboratory, Princeton, NJ, 233-236 (December 12-14, 1979).

36. N. C. Christofilos, "Astron Plasma Parameters Confined in the Closed Magnetic Well of a Proton E Layer," Proc. of Energy 70, Intersoc. Energy Conversion Eng. Conf., Las Vegas, NV, 1-36 (1970).

37. A. E. Robson, "A Conceptual Design for an Imploding-Liner Fusion Reactor," 425, Megagauss Physics and Technology, Plenum Press, NY (1980).

38. R. L. Miller and R. A. Krakowski, "Reassessment of the Slowly-Imploding Liner (LINUS) Fusion Reactor Concept," Los Alamos Scientific Laboratory report (to be published, 1980).

39. P. J. Turchi, et al., "Review of the NRL Liner Implosion Program," 735, Megagauss Physics and Technology, Plenum Press, NY (1980).

40. I. M. Artiugina, V. [illegible] Zheltov, V. V. Kantan, A. V. Komin, M. Koren', M. V. Krivosheev, A. B. M[illegible], and A. N. Smirnov, "Thermonuclear Power Station Based on a Reactor with a Partially Evaporating Liner," Voprosy Atomnoi Nauki i Tekhniki. Seriia: Termoiadernyi Sintez, 1, 3, 62-71 (1979).

41. A. M. M. Todd, R. E. Olson, J. G. Gilligan, and G. H. Miley, "The Spheromak Fusion Reactor," Proc. 15th Intersoc. Energy [illegible] ([illegible]).

42. [illegible] and G. H. Miley, "Operating Parameters for a Moving Plasma [illegible] Heater [illegible] Reactor [illegible]," Trans. Amer. Nucl. Soc., [illegible].

43. R. L. Hagenson and R. A. Krakowski, "Conceptual Physics Design of a Compact Toroidal Fusion Reactor ([illegible])," Los Alamos Scientific Laboratory report LA-[illegible] ([illegible]).

44. A. C. Smith, Jr., G. A. Carlson, [illegible], W. S. Neef, [illegible], and [illegible], "Preliminary Conceptual Design of the Moving Ring Field-Reversed Mirror Reactor," Pacific Gas and Electric Company report [illegible] ([illegible]).

45. H. H. Fleischmann and T. Kammash, "System Analysis of the Ion Ring Compressor Approach to Fusion," Nucl. Fus., 15, [illegible] (1975).

46. G. A. Carlson, et al., "Tandem Mirror Reactor with Thermal Barriers," Lawrence Livermore Laboratory report UCRL-52836 (September, 1979).

47. B. G. Logan, I. G. Brown, A. J. Lichtenberg and M. A. Lieberman, "Plasma Confinement in Multiple Mirror Systems II, Experiment and Reactor Calculations," Phys. Fluids, 17, 1302-1313 (1974).

48. A. J. Lichtenberg, M. A. Lieberman and B. G. Logan, "Multiple Mirror Plasma Confinement," Proc. of the High-Beta Workshop, ERDA-76/108, 502, Los Alamos, NM (July 28 - August 1, 1975).

49. R. A. Krakowski and R. L. Miller, "Fusion Reactor Plant Design for the Linear Theta-Pinch Reactor (LTPR)," Los Alamos Scientific Laboratory report LA-UR-78-2296 (1978).

50. A. Hoffman, P. Rose, and L. Steinhauer, "Status of Laser Solenoid Fusion Concept," Trans. Amer. Nucl. Soc., 27, 49-51 (1977).

51. J. Benford, T. S. T. Young, B. Ecker, D. Dakin, I. Smith, S. Putnam, and V. Bailey, "Electron Beam Heating of Linear Fusion Devices," Proc. 1st Inter. Topical Conf. on Electron Beam Research and Technol., Albuquerque, NM (November, 1975).

52. R. W. Moses, R. A. Krakowski, and R. L. Miller, "A Conceptual Design of the Fast Liner Reactor (FLR) for Fusion Power," Los Alamos Scientific Laboratory report LA-7686-MS (February, 1979).

53. C. Maisonnier, "Plasma Focus and Thermonuclear Fusion," [illegible], Euratom report EUR [illegible].

54. R. [illegible], "A Quick-Heated, Wall-Confined Fusion Reactor Conceptual Plant Design," Physics International report PIIR-[illegible] (June, 1979).

55. R. L. Hagenson, A. S. Tai, R. A. Krakowski, and R. W. Moses, "The Dense Z-Pinch (DZP) as a Fusion Power Reactor: Preliminary Scaling Calculations and Systems Energy Balance," Los Alamos Scientific Laboratory report LA-8186-MS (January, 1980).

56. G. Vlases, private communication, University of Washington (1979).

57. L. Spitzer, D. Grove, W. Johnson, L. Tonks, and W. Westendorp, "Problems of the Stellarator as a Useful Power Source," USAEC report NYO-6047 (1954).

58. R. G. Mills, "Economic Prospects for Thermonuclear Reactors," Princeton Plasma Physics Laboratory report MATT-60 (February, 1961).

59. K. Miyamoto, "Recent Stellarator Research," Nucl. Fus., 18, 243-284 (1978).

60. H. C. Cole, J. W. Hill, and M. J. Terry, "Plasma Heating by Neutral Injection in a Stellarator Reactor," Proc. 6th Symp. on Fusion Technology, Aachen, FRG, Euratom report EUR 4593e, 479-488 (September, 1970).

61. C. Gourdon, D. Marty, E. K. Maschke, and J. Touche, "The Torsatron without Toroidal Field Coils as a Solution of the Divertor Problem," Nucl. Fus., 11, 161-166 (1971).

62. A. Iiyoshi and K. Uo, "Heliotron as a Steady Fusion Reactor," Proc. 5th Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, IAEA-CN-33/G4, III, 619-635 (November 11-15, 1974).

63. A. V. Georgievskii, Yu. M. Loktionov and V. A. Supruneko, "Characteristics of a Hypotheoretical Thermonuclear Stellarator Reactor in the 'Plateau' Regime," Kharkov Physico-Technical Institute report KhFTI 76-38 (1976), [English Translation in UKAEA Culham Laboratory report CTO/1299 (November, 1976)].

64. W. Wobig and S. Rehker, "A Stellarator Coil System without Helical Windings," Proc. 7th Symp. on Fusion Technology, Grenoble, France, 333-343 (October 24-27, 1972).

65. D. V. Bartlett, G. Cannici, G. Cattanei, D. Dorst, G. Grieger, H. H. Hacker, et al., "Neutral Injection in the Wendelstein VII-A Stellarator with Reduced Ohmic Current," Proc. 8th Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-38/H-2-2 (July 1-10, 1980).

66. R. W. Schumacher, private communication, UCLA (September 5, 1980).

67. R. A. Nebel, R. L. Hagenson, R. W. Moses, and R. A. Krakowski, "Comparison of Zero-Dimensional and One-Dimensional Thermonuclear Burn Computations for the Reversed-Field Pinch Reactor (RFPR)," Los Alamos Scientific Laboratory report LA-8185-MS (January, 1980).

68. C. A. Baker, et al., "STARFIRE, A Commercial Tokamak Power Plant Design," Nucl. Eng. and Design (to be published, 1980).

69. C. Gimblett, "Some Necessary Conditions for a Steady State RFP," Proc. RFP Theory Workshop, Los Alamos Scientific Laboratory (April 28 - May 2, 1980).

70. H. Alfven, "Magnetohydrodynamics and the Thermonuclear Problem," 2nd UN Conf. on the Peaceful Uses of Atomic Energy, 31, 3-5 (1958).

71. H. Furth, "The Compact Torus Concept and the Spheromak," Proc. US-Japan Joint Symp. on Compact Toruses and Energetic Particle Injection, Princeton Plasma Physics Laboratory, Princeton, NJ, 1-7 (December 12-14, 1979).

72. N. C. Christofilos, "Astron Thermonuclear Reactor," Proc. 2nd UN Conf. on the Peaceful Uses of Atomic Energy, 32, 279-290 (1958).

73. R. J. Briggs, et al., "Astron Program Final Report," Lawrence Livermore Laboratory report UCRL-51975 (August 25, 1975).

74. J. D. Sethian and A. E. Robson, "Use of Relativistic Electron Beam to Create Magnetically Confined Plasma Inside Imploding Liners," J. Magnetism and Magnetic Materials, 11, 416 (1979).

75. W. T. Armstrong, et al., "Compact Torus Experiments and Theory," Proc. 8th IAEA Conf. on Plasma Physics and Controlled Fusion Research, IAEA-CN-38/R-3 (July 1-10, 1980).

76. H. J. Willenberg, L. C. Steinhauer, A. L. Hoffman, T. L. Churchill, and P. H. Rose, "TRACT: A Small Fusion Reactor Based on Near-Term Engineering," Proc. 15th Intersoc. Energy Conversion Eng. Conf. 3, 2214-2220 (August 18-21, 1980).

77. USERDA Special Report, "Linear Magnetic Fusion: A Summary of the [illegible] Held at Seattle, Washington [illegible] (May 9-11, 1977).

78. G. Sawyer (ed.), "Workshop on [illegible] of Linear Magnetic Fusion Systems," Santa Fe, NM October 12-14, 197[illegible].

79. R. A. Krakowski, "A Survey of Linear Magnetic Fusion Reactors," Proc. 3rd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, I, [illegible] (May 9-11, 1978).

80. A. R. Jacobson, C. J. Buchenauer, J. N. Downing, and K. S. Thomas, "Auxiliary Heating of a Theta-Pinch by Radial Magnetoacoustic Standing Waves," Phys. Rev. Lett., 37, 897-899 (1976).

81. R. L. Miller and R. A. Krakowski, "Thermal Conduction and Alpha-Particle Constraints for the Ignition of a D-T Linear Magnetic Fusion (LMF) Reactor," Nucl. Fus., 18, 1722-1725 (1978).

82. J. W. Shearer and W. C. Condit, "Magnetically Driven Liners for Plasma Compression," Energy Storage, Compression and Switching Plenum Publishing Corporation, NY, 105-117 (1977).

83. S. G. Alikhanov, V. P. Bakhtin, V. M. Brounstein, I. S. Glushkov, R. Kh. Kurtmullaev, and A. L. Tanin, "Studies of Model Thermonuclear Systems with Liners," Proc. 6th Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion, IAEA-CN-35-I19-2, III, 517-526 (October 6-13, 1976).

84. D. L. Book, A. L. Cooper, R. Ford, D. Hammer, D. J. Jenkins, A. E. Robson, and P. J. Turchi, "Stabilized Imploding Liner Fusion Systems," Proc. 6th Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-35-E19-1, III, 507-516 (October 6-13, 1976).

85. [illegible] and [illegible], "[illegible] of a Dense [illegible] Plasma [illegible] to a High [illegible]," [illegible].

86. O. A. Anderson, W. R. Baker, S. A. Colgate, J. Ise, Jr., and R. V. Pyle, "Neutron Production in Linear Deuterium Pinches," Phys. Rev., [illegible].

87. C. W. Hartman, [illegible], and R. H. Munger, "High-Density Fusion and the Z-Pinch," Proc. 5th IAEA Conf. on Plasma Phys. and Controlled Nuclear Fusion Research, IAEA-CN-33-[illegible], II, [illegible] (November 11-15, 1974).

88. W. M. Manheimer, M. Lampe, and J. P. Boris, "Effect of a Surrounding Gas on Magnetohydrodynamic Instabilities in Z-Pinches," Phys. Fluids, 16, [illegible] (1973).

89. C. W. Hartman, "Finite Larmor Radius Stabilized Z-Pinches," Lawrence Livermore Laboratory report UCRL-[illegible] (197[illegible]).

90. A. A. Newton, J. Marshall, and R. L. Morse, "Observation of Coaxial MHD Plasma Flow," Proc. 3rd European Conf. on Controlled Nuclear Fusion and Plasma Physics, 119 (1969).

91. C. W. Hartman, G. Carlson, M. Hoffman, R. Werner, and D. Y. Cheng, "A Conceptual Fusion Reactor Based on the High-Plasma-Density Z-Pinch," Nucl. Fus., 17, 909-917 (1977).

92. L. E. Hammel, private communication, Los Alamos Scientific Laboratory (1979).