A WHITE PAPER ON FRC DEVELOPMENT

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EXECUTIVE SUMMARY

The ultimate objective of fusion research is the application of fusion energy in a manner acceptable to society. This concerns not only its economic benefit, but also safety and environmental issues. The field reversed configuration (FRC) may be the ideal tool for confining a fusion plasma, especially one with low-hazard advanced fuels. This document expresses the views of a worldwide community of fusion energy scientists on near-term directions for research on the FRC.

The FRC is a variety of compact toroid that occupies a unique position in the parameter space of magnetically confined plasmas. It differs from other toroidal systems in possessing the following attributes: no mechanical structure in the center of the torus; no appreciable toroidal field; an engineering beta near unity; no rotational transform; all the equilibrium current (except possibly a seed current) maintained by classical diamagnetism; and a scrape-off layer exhausting outside the coil system. FRCs range from small gyro-orbit fluid-like plasmas to large-orbit ion ring-dominated plasmas. Because of their peculiar attributes FRCs offer the possibility of a step change in reactor attractiveness. In addition, FRC research adds unique insight into the physics of other fusion systems such as tokamaks, and offers a means of exploring fundamental plasma physics questions unrelated to fusion.

Review panels have repeatedly called for fusion system improvements in order to project economical fusion energy. However, even improved tokamaks may not overcome the shortcomings of low power density, high complexity, large unit size, and high development cost. Among alternative concepts based on low-density magnetic confinement, the FRC offers arguably the best reactor potential because of high power density, simple structural and magnetic topology, simple heat exhaust handling, and potential for advanced fuels. The unit size of FRC reactors may be smaller than those based on the tokamak. Low magnetic field and a simple structure also lead to lower costs. These advantages might be accentuated if an innovative reactor design such as a liquid wall vessel could be adopted. The enormous potential payoff as a reactor justifies a broad and sustained program on FRC sustainment, stability, and confinement.

Several FRC-related facilities are in operation around the world as well as other small theory efforts. Favorable results from theory and experiments have raised hopes for ultimate development into a practical fusion system. Parameters achieved include densities ranging from 5×10^{13} to $5 \times 10^{15}\ cm^{-3}$, temperatures up to $3\ keV$ (ions) and $500\ eV$ (electrons); and $\beta \sim 0.75\text{-}0.95$. Noteworthy achievements include: formation by θ-pinch, counter-helicity spheromak merging, and by rotating magnetic fields; simulation of large-orbit ion ring injection and trapping; stabilization of rotational instability; detection of global internal modes; tilting mode theory; global translation and acceleration along a guide field; identification of transport anomalies; and demonstration of the convective nature of energy loss.

In view of the foregoing, five action items are recommended. (1) FRC research should be continued and expanded both as an adjunct to mainline fusion research and as a stand-alone alternative fusion concept. (2) Existing FRC-related resources should be effectively utilized in an expanded program: including both facilities and the intellectual capital established in institutions and individuals with a strong commitment to FRCs. (3) New FRC facilities or upgrades of existing facilities should be considered on the merits of how they address the directions offered in this document. This should include consideration of a jointly-operated international FRC research facility. (4) Researchers and institutions with a history of activity on the tokamak should be encouraged to broaden their research to include FRC theory, diagnostic development, and systems studies. (5) Vigorous international collaboration on FRC research should be encouraged, including, at the least, annual workshops and long-term exchange visits.

I. MANDATE FOR FRC RESEARCH

Fusion offers a nearly inexhaustible source of energy. Developing this energy source depends on more than just acclaimed progress in plasma physics: it also requires public support. Such support demands an environmentally sound final product that is superior to competing energy sources. Moreover, in the present economic environment, the development path must be consistent with an austere budget. This White Paper focuses on the field reversed configuration (FRC). Given its present state of development, the FRC has good prospects for a desirable end product. In particular, among all conventional low-density magnetic confinement concepts, the FRC probably offers the best vista for an attractive fusion power reactor due to its potential for high power density, reduced complexity and lower development cost. Moreover, continued FRC research offers unique insights into the physics of spheromaks, spherical tokamaks and other related plasma configurations. This paper reflects the consensus of a worldwide community of researchers that are knowledgeable in FRC physics and interested in furthering fusion energy. The contents of the document identify the leading issues for FRC research over the next five years, and concludes with a roadmap for FRC development to guide this research.

A. DEFINITION

FRCs belong to the family of compact toroids. "Compact" implies the absence of internal material structures (*e.g.* magnet coils) allowing plasma to extend to the geometric axis. "Toroid" implies a topology of closed donut-shaped magnetic surfaces. FRCs are differentiated from other compact toroids by the absence of appreciable toroidal field within the plasma. A sketch of an FRC is shown in Fig. 1. Axial equilibrium requires the average plasma beta to be high. For an elongated (highly prolate) FRC β is given by $\beta = 1 - x_s^2/2$, where $x_s \equiv r_s/r_c$ is the ratio of separatrix to flux conservor radius. Thus β must be at least *0.5*, and typically falls between *0.8* and *0.9*.

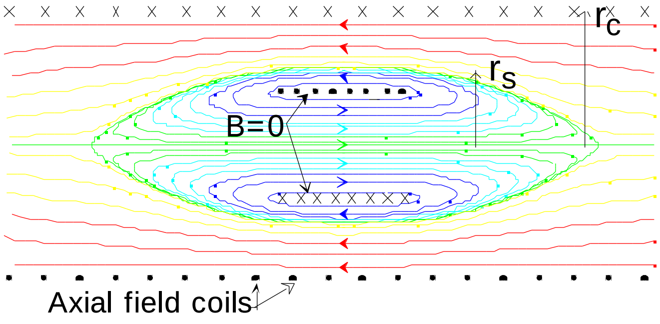

Figure 1. FRC Geometry

In common with toroidal systems FRCs have pressure comparable to the poloidal magnetic pressure (poloidal beta of order unity). However they differ markedly from toroidal systems in several respects: 1) the engineering β (pressure / magnetic pressure supplied by the coils) is near unity; 2) magnetic field lines close (or nearly so) after a single circuit of the magnetic axis (no rotational transform); and 3) the scrape-off layer connects to spindle-like jets at each end, which freely exhaust outside the coil system. The term FRC only specifies the magnetic configuration. The plasma itself may take a variety of forms, from MHD (small gyroradius) to "hybrid" (MHD plus a large orbit ion-ring component) to ion ring-dominated. An ion ring is composed of energetic ions with orbits comparable to the major radius. Each variation has its own attractive features.

A key parameter that has been used to characterize the large orbit size or the kinetic nature of FRCs is the number of gyroradii between the field null and the separatrix of the FRC. This parameter, called s, is formally defined as

$$s = \int_{R}^{r_s} \frac{rdr}{r_s \rho_i} = 1.56 \frac{\varphi_p(\mathrm{mWb})}{r_s(\mathrm{m})\sqrt{A_i T_i(\mathrm{eV})}}$$

and is seen to be proportional to the poloidal flux. FRCs are experimentally stable at low *s*, and the most important question about the FRC approach is how they will remain stable as *s* increases. Large orbit particles have been proposed, in hybrid systems, to enhance stability.

B. CONTRIBUTION TO PLASMA SCIENCE

The importance of broadening the knowledge base of fusion plasma science beyond toroidal plasma physics has long been recognized. Major improvements in the stability and transport of conventional tokamaks have been achieved by confinement field shaping and a variety of other techniques. Fusion review panels have consistently recommended that further improvements are necessary to make a tokamak economically viable for fusion energy. One approach is to pursue high-β tokamaks and spherical tokamaks, where a leading objective with recognized economic benefits is to reduce the toroidal field. In pursuing such improvements FRC research occupies a unique position in the parameter space of magnetically toroidal plasmas. In particular, FRCs offer vital insights into the physics of truly high-β plasmas. Further, since FRCs lack a toroidal field, they offer insight into a kind of stability that may be independent of the standard ideal-MHD paradigm, which demands a large toroidal field. Besides its usefulness in advancing toroidal plasma science in general, FRCs can also play valuable ancillary roles in support of other confinement concepts: e.g. FRCs can be accelerated to high speed and injected into a tokamak to provide deep refueling.

Because of its extreme nature, FRC research advances plasma science in ways that may be unrelated to tokamaks. Regarding the general topic of high-β plasmas, FRCs are unique. They offer a magnetic topology that is singular for its lack of a rotational transform and magnetic shear. They also offer a means of researching fundamental plasma questions unrelated to fusion applications. Most notable among these is the reconnection of magnetic field lines, but other geophysical and astrophysical phenomena might be addressed as well.

C. FRC REACTOR PROSPECTS

One approach to fusion concept improvement is through incremental improvements such as offered by reverse-shear profiles in a tokamak. However, even improved tokamaks may not overcome the shortcomings of low power density, high complexity, large unit size, and high development cost. Therefore a step change away from the tokamak concept may be necessary. The FRC offers such a step change. Although the FRC concept is not new, it has not yet been investigated in a reactor relevant regime. Even so, despite uncertainties about its stability and confinement, the enormous potential payoff justifies pursuing the FRC as a reactor concept.

Among alternative fusion concepts based on conventional low-density magnetic confinement, the FRC offers arguably the best reactor potential for several reasons. (1) *High power density*, with engineering beta of order unity. (2) *Geometric simplicity*: singly connected plasma; linear geometry; simple, maintainable fusion power core. (3) *Magnetic simplicity*: no toroidal field; no interlinking magnets; possibility that plasma terminations will not damage the structure. (4) *Heat exhaust handling*: natural axial flow divertor with heat collection outside the core. (5) *Advanced fuel potential*: high-beta makes the FRC arguably the best magnetic-confinement system credibly capable of advanced fusion fuel operation. Collectively, the above features lead to reactors that are smaller than an advanced-fuel tokamak: small size leads to lower cost. (6) *Lower-cost developmental path*: if the FRC offers the potential for the simplest, lowest-cost magnetic confinement reactor, then its R&D path would be shorter and cheaper.

II. FRC ISSUES AND PROGRESS

A. FUNDAMENTAL ISSUES AT THE OUTSET

The following is a listing of FRC issues that one might perceive at the outset based on a general knowledge of fusion plasma physics and technology. The list emphasizes areas where FRCs possess attributes that are unique compared with other fusion concepts.

1) Stability. According to the ideal-MHD stability paradigm, FRCs are unstable because of predominantly unfavorable magnetic curvature and the absence of a "stabilizing" toroidal field. Therefore the leading question is--can FRCs be stabilized by factors excluded by the standard paradigm, whether naturally (phenomena arising of their own accord) or artificially (by external intervention)?

2) Formation/start-up. Since FRCs are generated in a singly-connected chamber and have inherently high beta, start-up is quite different from systems with toroidal plasma chambers, a large toroidal field, and approximately force-free magnetic fields. Plasma pressure must be produced concurrently with the confining magnetic field to prevent over-compression and radiative collapse. A major question is--can a suitable start-up method be developed which scales to reactor-relevant plasmas.

3) Sustainment/current drive. An important question is can a suitable current drive method be developed that is applicable to large, high temperature FRCs? Rotating magnetic fields (RMF) drive currents in rotamak devices, but have not been demonstrated in hot, reactor grade plasmas. Neutral beam injection (NBI) has also been proposed, but not demonstrated for FRC sustainment. a further possibility is sustainment by repeated spheromak merging.

4) Transport. Transport is the central issue for all fusion concepts. The uniqueness of the FRC implies that it may take different forms than in toroidal plasmas. Empirical scaling laws show low transport coefficients at high plasma density, but would imply insufficient lifetimes for lower density steady state reactors. Thus an essential question is--what are the dominant energy transport mechanisms that arise naturally, and do these extrapolate to an attractively small reactor? If inherent transport rates are too rapid, can they be reduced by external and sustainable controls?

5) Technological burden. The final issue is broader. The aforementioned "physics" issues introduce, in some cases, unique techniques that must be applied. A further question then is--what technological burdens arise from the FRC's unique features, and are they surmountable? Examples include the unique start-up method, an artificial stabilization technique (if needed), and a specialized current drive method. High wall loading, which must be withstood to exploit high power densities where empirical confinement scaling is favorable, is an issue common to all compact devices.

B. PROGRESS IN FRC PHYSICS AND TECHNOLOGY

FRC experiments and theory results have been favorable, raising hopes for its ultimate development into a practical fusion system. Previous reviews of FRCs and FRC-related research include a review of FRC/Ion Ring research [1], a review of compact system physics and technology [2], a comprehensive review of FRC experiments and theory presented in 1988 [3], and a recent brief review of progress since then [4]. Experiments, primarily in θ-pinches, have achieved the following ranges of FRC parameters:

density	*0.05-5 x* 10^{15} cm^{-3}
temperature:	*50-3000 eV* (ions); *50-500 eV* (electrons)
average beta	*0.75 - 0.95*
separatrix:	radius, *3-20 cm*; length, *20-400 cm*
poloidal magnetic flux	*< 10 mWb*

The following physics and technology achievements are noteworthy.

1) Formation by θ-pinch. Using advanced formation techniques, the θ-pinch method has been improved to the point that the parameters listed in the table have been achieved. These include methods for improved gross symmetry of the pre-ionization plasma [5] and control of the axial shock dynamic process [6]. Note that since no auxiliary heating method was applied, the reported temperatures reflect heating intrinsic to the start-up process

2) Formation by counter-helicity merging. This technique has been demonstrated on TS-3 [7]. Its attributes are the efficient conversion of the toroidal field energy of the initial spheromaks to ion energy of the resulting FRC, and higher poloidal fluxes than achievable using the θ-pinch formation method. Further, a central ohmic heating coil was used to amplify the FRC current by a factor of 2-3 and to sustain it for about *200 μs*.

3) Stabilization of the rotational mode. The rotational mode that normally appears in FRC experiments has been stabilized by applying modest multipole fields, as demonstrated on several experiments in the early 1980's and confirmed by theory [8].

4) Detection of global internal modes. The most feared instabilities have been disruption-threatening global ideal modes, particularly tilting. These are predicted to be internal modes in typical FRCs and thus difficult to detect. Although no non-intrusive internal diagnostic has been available, Mirnov probe array systems have been developed to detect the external signatures of internal modes. In two instances these were sufficient to distinguish between a range of global modes [9].

5) Tilting mode theory. Many analytical and numerical treatments have addressed tilting, which is widely regarded as the most dangerous mode threatening disruption of FRCs. Ideal-MHD theory predicts instability, although equilibria with more blunt separatrix shape and hollow current profile exhibit significant improvement in tilting stability [10]. The most successful tilting theories have included finite Larmor radius (FLR) effects, using either kinetic ions [11] or a gyroviscous fluid [12]. The latter led to the prediction of marginal stability conditions consistent with observed stable FRCs. The FLR stability explanation, however, fails to explain other evidences of robust stability. The key may lie in the fast relaxation of the FRC into a minimum energy state that is stable to all fluid modes [13]. This is discussed in Sec. II-C.

6) Translation and acceleration. Experiments on several facilities had demonstrated that an FRC can be formed inside a θ-pinch coil, translated along a guide field, and then stopped by a mirror field. Recent experiments have explored this procedure in detail [14] showing it to have great potential for equilibrium control (plasma radius, length, density) and heating (thermalization of the kinetic energy of translation). These experiments ejected the initial FRCs at super-Alfvenic speeds into a chamber with a static magnetic field lower than in the source coil by factors up to 25. Despite the violence of the ejection, the FRC settled into a quiescent state with negligible magnetic flux loss. The same robustness was also evident in FRCs translated through a tube with varied crossection and then compressed up to 1000 times (in volume) by a metal liner [15]. Recent experiments exploring the use of cold, dense, accelerated FRCs for tokamak fueling purposes have produced FRCs with kinetic s values as high as 8 that have survived both the formation and acceleration process [16].

7) Identification of transport anomalies. These include a) anomalous cross-field plasma transport rate, b) anomalous decay of the poloidal magnetic flux, and c) anomalously slow particle out flow along field lines in the scrape-off layer. In none of these instances does a satisfactory theory exist, except in the first where preliminary work has been done. A low-beta low-frequency-drift turbulence theory gave a reasonable prediction of plasma loss times for a limited experimental data base [17]. The empirical energy diffusivities are in the range $3 - 7\ m^2/s$ in larger FRCs with an improving trend with increased size [18]. This transport rate is remarkably low considering that these are small dense objects with minor radii of only a few ion gyroradii. Confinement properties in a translated and trapped low density FRC have proved better than empirical scaling relations from other facilities, which is encouraging for developing small, steady-state reactors [14].

8) Convective thermal loss. Experiments indicate that both in the interior [18] and along the scrape-off layer [19] the energy transport rate is proportional to the particle diffusion rate. This has two important implications: a) the burden of energy confinement is shifted to the question of particle confinement; and b) the FRC can be a thermally-isolated system, i.e. no contact by thermal conduction with cold external boundaries.

C. CURRENT FRONTIERS IN FRC DEVELOPMENT

The frontiers described here are "hot" topics presently under investigation with favorable initial results and the potential of a major impact on FRC development.

1) Flow stabilization. Flow, an important stabilizing influence [20], has largely been overlooked in stability analyses. Recent analyses of the effect of flow on stability has shown that the kink mode in z-pinches can be stabilized with a sufficiently sheared axial flow [21]. Sheared flow may also stabilize the sausage mode. Flow shear may provide stabilization by behaving like the magnetic shear arising from the axial field in a z-pinch, i.e. the conventional (Kruskal-Shafranov) method of stabilization. These results have important implications not only for z-pinches, but for related configurations as well, including tokamaks and FRCs. Sheared flow may cause both improved global stability and reduced transport.

2) FRC as a relaxed state. The possibility that the FRC may be a relaxed state of minimum energy is under investigation [13]. The new theory employs a two-fluid model, extending the familiar one-fluid theory which has invariant magnetic helicity. The two-fluid theory has two invariants, the ion and electron helicities: these generalizations of the magnetic helicity include the effect of mechanical momenta. This theory was motivated by experimental observations that suggest relaxation phenomena in FRCs: (1) transient global modes producing a restructuring rather than a disruption [9]; (2) quiescent FRCs exhibit profile consistency [22]; and (3) the relaxation of a spheromak (formed by merging) to an FRC, in which the toroidal field (and magnetic helicity) decays [7]. Minimum energy equilibria in simplified geometries display qualitative features variously of laboratory FRCs and reversed-shear tokamaks in addition to spheromaks and reversed-field pinches. The essential ingredient of relaxed states with finite-β is sheared flow. The two fluid theory of minimum energy states may form the basis for a new stability paradigm.

3) Ion Ring supported FRC. An Ion Ring system may be a "hybrid" system (Ring plus background plasma) [23] or a ring-dominated system (very little background) [24]. FRC stability questions might be resolved by the stiffening effect of an energetic ion ring carrying a substantial fraction of the current. Studies of plasmas with a significant fraction of large orbit ions has shown the stabilizing potential of such rings [25]. Moreover, there is evidence that energetic ring-like ions slow down and diffuse classically, leading to improved confinement properties. The recently completed FIREX facility (see Sec. III) extends previous ion-ring experiments [26]. It is designed to study Ion Rings as a means of forming and stabilizing an FRC. Ion-ring injection might also be used to sustain the current. It also offers a unique opportunity to study the peculiar phenomena associated with large orbit particles in magnetically confined plasmas.

4) New kinetic stabilization effect. Kinetic effects (characterized by the parameter s) associated with finite ion orbits are well known stabilizing influences, whether the orbits are relatively small (FLR) or large (ion rings). A new, recently discovered class of kinetic effects is driven by the electron grad-B drift, and is unrelated to orbits. In the high curvature regions near the ends of the FRC the electron grad-B drift frequency is much higher than the frequency of MHD-perturbations. Therefore, the electron response is strongly non-MHD. This produces the so called "charge uncovering" effect, which is a potentially important source of improved stability [27].

5) Rotating magnetic field (RMF) current drive. RMF may offer a practical current drive method [28]. Here a small rotating transverse field component is generated by oscillating currents driven in longitudinal conductors located near the wall. Under certain frequency and collisionality conditions, the transverse field penetrates the plasma and drives an electron current in a manner similar to an induction motor. In several experiments, called rotamaks [29], FRCs have been generated in this way. The RMF not only caused the reversal of the magnetic field on the axis, but sustained the FRC for times as long at the RMF drive was continued. The resulting

FRCs have been relatively cold and roughly spherical. Recently the possibility of applying RMF to a pre-existing hot FRC for current drive has received renewed attention. In principle, RMF is an efficient current drive method since it drives the bulk electrons, and not just an energetic tail of the distribution. New experiments on the Translation, Confinement, and Sustainment (TCS) facility will apply RMF to demonstrate current drive on a pre-existing FRC. TCS is a modification of the previous Large s Experiment (LSX) [30]. Theoretical studies of RMF current drive are ongoing [31].

6) Neutral-beam injection (NBI) sustainment. NBI of a few megawatts would extend the lifetime of the plasma for much longer than one millisecond. This will significantly broaden the scope of the experiment by enabling active control of plasma stability with toroidal rotation and also by providing an additional means of current drive and beam heating. If a high-current (*~100 A*) neutral-beam of *30-60 kV* energy range is injected into the FRC plasma, it is possible to sustain this configuration for a long period of time (*>10 msec*). This NBI would induce a spinning of the plasma with high velocity of up to the order of the Alfven speed, which would in turn help stabilize the global MHD modes. NBI would also decrease the value of *s*.

7) Traveling wave direct energy conversion. An innovative method for direct conversion of 15-MeV fusion protons has been proposed [32] and is being investigated in theory and experiment [33]. A traveling wave is set up by a series of open grids; it is synchronized to extract energy from a fast stream of protons. In principle, highly efficient conversion is possible when the stream first passes through a properly phased pre-buncher grid. This concept exploits the fact that most of the fusion energy in an advanced fuel system is in the form of charged particles.

III. EXISTING FRC PROGRAM RESOURCES

A. LABORATORY RESOURCES

Several FRC-related facilities are in existence around the world. Each is supported by a group with two or three senior scientists. The following is a listing of these resources and their general capabilities.

BN (TRINITI research center, Troitsk, Russia). This multi-coil θ-pinch facility has been used to investigate improved formation control techniques, internal plasma parameters (magnetic field structure and local electron energy distribution) and other compact toroid systems (spheromak and tokamak-like). It is planned to modify BN to expand the regime of good-quality FRC formation. The BN group has emphasized formation using heating by nonadiabatic axial compression.

TL (TRINITI research center, Troitsk, Russia). This conical-coil θ-pinch employs independent active end-control coils for dynamic formation. It has recently been used to study start-up with varied time scales. It is presently being modified to add a confinement chamber.

TOR (TRINITI research center, Troitsk, Russia). This multi-coil θ-pinch facility has been used to study strong heating (intrinsic to the start-up process) up to "neutron"-producing ion temperatures, and formation procedures with magnetic insulation at the chamber wall.

NUCTE-3 (Nihon Un., Japan). This θ-pinch facility has been used to detect global modes with a Mirnov array, control the separatrix shape with auxiliary coils, and examine the effect of multipole fields on stability and confinement. It is presently being modified to include a translation section. The Nihon group has emphasized variations of the formation technique, and innovative controls.

FIX (Osaka Un., Japan). This facility generates FRC's in a θ-pinch source, which are then translated into a large confinement chamber where they expand and are trapped. A variety of confinement and heating experiments are planned or currently underway. The decreased density after expansion ($5 \times 10^{19}\ m^{-3}$) permits neutral beam injection to be used. An end-on neutral beam injector is being developed for this purpose. Also, an additional coil was recently installed inside the metal confinement chamber for axial adiabatic compression of the FRC. This axial compression improved the confinement. Further experiments on the effect of mirror fields and plasma shape on the confinement are now being carried out.

TS-3/TS-4 (Tokyo Un., Japan). The TS-3 facility uses paired z-θ-pinch discharges for start-up, generating FRCs, spheromaks, and ultra low-aspect ratio tokamaks. FRCs were formed by counter-helicity merging of two spheromaks. An OH current transformer is available to amplify currents in FRCs and other plasmas. TS-3 has also been used to study the physics of magnetic reconnection. Recent FRC-related themes at Tokyo include: (1) transition from merging low-beta spheromaks to a high-beta FRC and associated energy conversion processes; (2) heating and current amplification by merging and by OH transformer; (3) relaxation bifurcation and its relation to FRC robustness; and (4) formation of intermediate configurations between an FRC and a spherical torus in the second stability regime. TS-3 has recently been upgraded to a larger device, TS-4.

LSX/mod (Un. Washington, USA). This formation-translation facility (θ-pinch source) is the largest FRC device in the world. For the last three years it has been used to accelerate FRCs to test a tokamak refueling concept. It is presently being converted (TCS) to conduct research tasks immediately germane to FRCs. These include 1) addition of a confinement chamber at the end of the translation section, 2) additional equilibrium coils in the confinement chamber for control of the separatrix shape, and 3) rotating magnetic fields for current drive and possibly start-up. The LSX group at Washington has emphasized diagnostics (*e.g.* internal structure, instability detection), formation controls, and translation.

STX (Un. Washington, USA). This new RMF start-up facility is called the Star Thruster Experiment because of its partial funding by NASA to investigate space relevant start-up procedures for space fusion propulsion applications. STX will utilize very powerful, but short-lived RMF power supplies to try and overcome the ionization and radiation barriers that have limited other rotamak facilities to low plasma temperatures.

MRX/SPIRIT (Princeton, USA). MRX (Princeton, USA). This flux-core based facility has been built to perform three-dimensional magnetic reconnection experiments. It can generate spheromaks, low-aspect ratio tokamaks, and FRCs. Single FRCs have been formed by merging two smaller spheromaks with opposite helicities. SPIRIT is a proposed fusion concept exploration project that will enable exploration of important new regimes of FRC plasmas [34]. FRC plasmas will be generated by merging counter-helicity spheromaks produced by inductive discharges utilizing flux cores. A unique feature of this project is the capability to investigate systematically the MHD stability and confinement features of FRC's with large trapped flux (up to *50 mWb*) over a wide range of the key parameters, r_S/ρ_i, the ratio of plasma size to ion gyro-radius and the plasma elongation ($0.5 < E < 4$). A large range in $r_S/\rho_i = 4 - 60$ ($s = 1 - 15$) should be possible by the counter-helicity merging technique. In its second phase of operation this program is designed to accommodate neutral beam injection.

FIREX (Cornell Un., USA). This recently completed facility (Field-reversed Ion Ring EXperiment) injects an ion beam from a diode through a magnetic cusp to form an ion-ring. It is a first step toward the realization of a field-reversed ion ring or FRC/Ion Ring hybrid in which a significant fraction of the azimuthal current is carried by large orbit ions. The ion ring can provide stability to an FRC. It also has the potential to provide a start-up technique, current drive, and equilibrium control for FRCs.

ROTAMAK (Flinders University, Australia). Spherical FRCs have been produced and sustained for *40 msec* in both *10* and *50 liter* spherical glass chambers using up to *200 kW* of RMF power. The amount of current has been demonstrated to scale with the applied axial confinement field, limited only by the available RMF power. Presently these plasmas are relatively cold, but this should change if more RMF power were available to overcome initial ionization and radiation barriers. Notably, the plasma properties and the magnetic configuration adjusted themselves to accommodate the transferred RF power producing RMF penetration accordingly. By adding a toroidal magnetic field to the basic rotamak configuration, spherical tokamak configurations have been generated in the rotamak device.

B. THEORY AND COMPUTATION

Small ongoing theory efforts (generally individual) are scattered around the world. Within the last five years active work has proceeded at (or publications have appeared from) institutions in the US (Cornell Un., Krall Associates, and Un. Washington), Japan (Niigata Un., Kyoto Un., and Nagoya Un.), Russia (TRINITI, Moscow State Technical Un.), Brazil (Campinas Un.), and Australia (Flinders Un.). Beside these, theorists elsewhere possess FRC-relevant expertises developed in previous years, though they are not presently active in FRC research. In addition to strictly plasma theory, ARTEMIS, a systems study of a D-3He FRC reactor, was carried out in Japan in the early 1990s. Most members of this multi-institutional team are still active in FRC research. A small engineering study of D-T FRC reactors is also just beginning at the Un. of Wisconsin, with support form Un. Washington and Un. Illinois.

A major 3D nonlinear-MHD + Hall effect code was developed in the 1980s [35]. While this code has not been operated for several years, it remains a valuable resource for FRC studies. An attractive option for FRC kinetic modeling on ion orbit and transport timescales is the hybrid PIC code based on a fluid-electron, particle ion representation [11]. Recently, a sophisticated new object-oriented code designed to run on massively parallel computer architectures was developed and is in use to study FRC/Ion Ring systems [36]. In addition to these, there exist a wealth of tokamak codes that could, in principal, be adapted for use in FRC studies.

C. INTERNATIONAL CONNECTIONS

International collaborations on FRC research have taken place between the US, Japan, Russia, Australia, Austria, Argentina, and Brazil. The most active interaction has been between the US and Japan. Indeed the well-established US-Japan interaction on FRCs might be listed among the accomplishments of FRC research. It has fostered perhaps a dozen US-Japan workshops in the last dozen years and a number of extended laboratory visits, and has led to the publication of perhaps 20 archival papers with a mixed US-Japan authorship. These collaborations survived even the five-year hiatus in alternate concepts research in the US.

IV. FRC RESEARCH DIRECTIONS

Each issue raised in Sec. IID implies particular directions in both theory and experiment and, by extension, in technology development and systems studies. What follows is a definition of what needs to be done in these areas to address the immediate, five-year issues.

A. EXPERIMENT DIRECTIONS

1. Basic FRC structure and phenomena

Much has been learned about the gross stability and confinement of FRCs as a result of intensive study with increasingly sophisticated diagnostics. Even so the interior structure itself remains largely a "black hole" about which little is known beyond indirect inferences. Regarding the spatial structure, only multichord interferometry, emission tomography, and internal magnetic probing of translating FRCs, have been applied, and these only in a limited way. Much more could be learned by simultaneous use of corroborating diagnostics on reproducible plasmas in a large enough FRC device. A sufficient set of the diagnostics heretofore applied on an introductory basis includes multichord interferometry possibly augmented by emission tomography (both radial and longitudinal), multi-point Thomson scattering, and an array of external magnetic probes located as close as possible to the FRC separatrix. Of existing and contemplated experiments, FIX at Osaka Un., TCS at Un. Washington, and (if built) SPIRIT at Princeton are good choices for such corroborating diagnostics. Such a phalanx of diagnostics is difficult or impossible to construct and operate by a single institution under current funding limitations, collaboration between institutions should be established.

Little or nothing is known about the internal magnetic structure, fluctuations, electrostatic potentials, and flows. A knowledge of these basic properties is essential to understand FRC physics with reasonable confidence. The core plasma, edge plasma, scrape-off layer, exhaust jet, and halo plasma properties all play key roles and call for investigation. A reproducible, quiescent, long-lived FRC is the ideal environment for applying these diagnostics to the core plasma, although facilities that don't satisfy all these conditions are useful for applying specific diagnostics. Internal magnetic structure diagnostics are needed, including both existing intrusive techniques (*e.g.* short-time motional Stark effect). Injection of pellets, beams, or tracer impurities may be attractive alternatives to expensive multi-point systems. Another is spectrally resolved Doppler shifts to detect flows. The most promising diagnostics for the edge plasma, scrape-off layer and jet are probably particle collecting probes. Since these are incompatible with existing start-up methods, they had best be applied to translated plasmas. Some of these diagnostics have seen limited use on various FRC facilities, but little has been published to date concerning them or the results of their use. Here again, more informal and formal collaborations between researchers would be helpful. A promising example, funded through a NSF grant, is the fielding of part of the TIP (Transient Internal Probe) device (Un. Washington) on the FIX experiment (Osaka Un.), now in progress.

2. Equilibrium modification and extension of operating regime

a) Plasma shaping. Separatrix control by programming the equilibrium field coil system has been a fruitful avenue of research on tokamaks, producing both greater understanding of the physics as well as performance improvements. Typical θ-pinch-formed FRCs have been confined in straight flux conservors, *i.e*. strictly passive equilibrium control resulting in a prolate equilibrium. A new operation regime with oblate FRCs can be studied in the proposed SPIRIT device, based on counter-helicity merging. MHD stability of tilting has been predicted in oblate FRCs, independent of *s*. Equilibrium field controls should be applied to θ-pinch-formed FRCs by adding auxiliary coils to supplement the basic flux conservor. By this means separatrix shape control could be obtained. Then the effect of modified separatrix shape on stability and transport could be investigated.

b) Structure and bulk parameter modification. No artificial controls have been applied to modify the internal structure of FRCs. Moreover, the electron and ion temperatures have been strictly the product of heating intrinsic to the start-up process and the natural thermal loss rates. Modifying these properties is essential to study the distinct effects of T_I , T_e, current, and profile on confinement. One fruitful method for modifying these properties is injection and merger of ion rings with the FRC; another is RF heating; and a third is neutral beam injection. RMF will also affect the current distribution. As repeatedly demonstrated on tokamaks powerful RF and nb injection can modify the internal structure, flows, and distribution function. Moreover, both ion ring and nb injection shed light on large-orbit particle effects. These methods also have potential for heating and current drive.

c) Large-s physics. FRC stability has often been ascribed to finite ion Larmor radius (FLR) effects, which weaken with increased size. From the ideal-MHD theory of global modes FLR stability of elongated ($E > 1$) FRCs is achieved if s/E is less than some value (*s* is the minor radius divided by the average internal ion gyroradius and *E* is the separatrix elongation). Tilting-stable θ-pinch-formed FRCs approached the predicted instability threshold. Experiments are needed over a range of *s/E* that spans the predicted threshold. This can be done either by raising *s* or reducing *E*. The former requires either a larger θ-pinch with significant formation enhancements, or the addition of RMF to increase the flux. The latter can be done in the merging-formed FRCs, which can have much smaller *E*.

3. Ion Ring systems

Although previous facilities have produced ion rings, they have never had the current producing capability to reverse the magnetic field. Therefore the first priority for Ion Rings is to demonstrate field reversal. Once this has been achieved and the conditions for field reversal characterized, studies can be initiated on ring properties (its longitudinal dynamics, lifetime, and stability), ring manipulation (bulk translation, magnetic compression) and the ring effect on the background plasma (electron temperature, transport). The next stage would be experiments merging ion rings with a pre-existing FRC. This would test the potential of ring merging as a means of (a) sustaining the internal flux (equivalent to current drive) and (b) heating.

4. Dense FRC's

FRCs have interesting potential for "filling" centimeter-size imploding liners. This scheme can eventually lead to development of an extremely compact pulsed fusion reactor with attractive economics. The pre-implosion FRC should have a radius and length of roughly *1 cm* and *4-5 cm*, respectively, plasma density $10^{18}\ cm^{-3}$, and temperature *50-100 eV*. Studies of the formation and evolution of such FRC's would also considerably broaden the parametric domain of the experimental data base, and offer stronger validation of scaling laws.

5. Fusion-relevant start-up method

The traditional FRC formation method uses θ-pinch technology. Alternative technologies might be more suitable for a fusion system. One such exploits the possibility that an ion ring (see Sec. IV-A-3) might be used as an armature on which to build up the plasma current for FRC start-up. Here, previously demonstrated start-up techniques, θ-pinches and two other methods, are discussed.

a) θ-pinch formation. Although ostensibly a high-voltage technology, θ-pinches have been used to form hot, *low-Z* FRCs with lower-voltage ignitron switched capacitor banks and somewhat slower start-up recipes. This technology alone, however is not sufficient for a reactor, but could serve as a starting point for flux build-up methods. Further modifications that may enhance the basic θ-pinch approach include conical coils, and end-coil control methods, which offer an independent temperature control by exploiting the conversion of axial kinetic energy to thermal energy. The same might also be accomplished by merging two colliding FRCs.

b) Merging formation of FRCs. Oblate FRCs have been formed in MRX, and TS-3 and TS-4 using counter-helicity merging of spheromaks. This low-voltage, slow-time scale technique may be attractive for start-up in a fusion system. The mechanism for this merging formation is the efficient conversion of initial toroidal magnetic energy of merging spheromaks to ion thermal energy of the produced FRC. The focus of the proposed SPIRIT device is to investigate this technique in detail. Further large scale confinement studies in SPIRIT and TS-4 are needed to characterize the limitations and determine the size and temperature scalability of the oblate FRCs.

c) Rotating magnetic field (RMF) start-up. Low-voltage start-up has been demonstrated in rotamak experiments. These FRCs have typically been quasi-spherical (confined in a Helmholtz coil) and low temperature (~ *10eV*). This is a promising start-up method but it is only useful if plasmas temperatures (T_i and T_e) somewhat above *100 eV* can be produced. It may only be a matter of applying sufficient power (through the RMF) to pass the radiation barrier. The potential of higher-power RMF for burning through such barriers needs investigation both theoretically and experimentally. Alternatively, electron cyclotron heating (ECH) offers an established means to create an initial temperatures above radiation barriers.

6. Current drive

Excepting in rotamak devices, previous FRC experiments have all been decaying, unsustained plasmas. Since a method of sustaining the configuration is needed in a fusion plasma, the time has come for demonstration of current drive on an FRC. A suitable proof-of-principle demonstration should sustain the current for *1 msec*.

a) Rotating magnetic field (RMF) current drive. RMF has been demonstrated as both a start-up and sustainment method in rotamak plasmas. In order to be accepted as a current drive method it should be demonstrated on a pre-existing, hot (*>100 eV*) FRC plasma, a hot ECH-generated plasma in a static magnetic mirror or in a hot plasma which is, itself, produced by the application of a high-power RMF. Principal issues in such an experiment include verifying the optimum RMF rotation frequencies and field amplitudes, observing initial RMF penetration and its timescale, and determining the power level needed for sustainment.

b) Neutral beam (nb) current drive. Intense nb injection as a means of modifying the internal structure and bulk parameters of an FRC was called for in Sec. IV-A-2-b. These experiments would also allow a preliminary assessment of the current drive potential of nb injection. However, higher flux and hotter FRCs than are presently producable using the θ-pinch formation technique are required for good coupling.

c) Sustainment by counterhelicity merging. The repeated production of spheromaks by plasma guns and their subsequent merging with the main FRC plasma is an alternative sustainment method. A principal issue is whether the poloidal flux of the main plasma is actually be increased by this method.

7. Direct conversion system

Efficient direct conversion is essential for an advanced fuel reactor to be economically competitive. Conventional electrostatic conversion may be impractical as a stand-alone system because of high-voltage breakdown problems arising if such a system were expected to handle unthermalized fusion products. An innovative approach to this problem is the traveling wave direct energy conversion (TWDC) concept. A proof-of-principle experiment is needed to test this method at conditions that simulate fusion-like parameters. Important engineering issues related to the TWDC also should be addressed: minimizing power losses associated with the large recirculating high-frequency power in a TWDC; and the engineering feasibility of the high-transparency grid structure.

8. Heating

Ultimately a heating method is needed to elevate the temperature from the post-start-up level (100’s of eV to *1 keV*) to fusion ignition. However, in terms of the near term of FRC development, this issue has lower priority than the others described here. Nevertheless, some of the experiments called for here would also generate ancillary information on potential heating techniques. These include intense nb injection, ion-ring injection, resistive heating by RMF, ECH, and heating by the thermalization of dynamic energy produced by merging or translation.

B. THEORY DIRECTIONS

1. Equilibrium and stability theory.

The theory of FRC or FRC/Ion Ring equilibrium and stability needs continued attention both in analytic and numerical studies. Analytic studies are particularly needed to extend the recent studies showing the important stabilizing influence of sheared flow. Also needed are studies of high-frequency modes and their effects in FRC/Ion Ring systems.

a) Equilibrium codes. Although a number of FRC equilibrium codes (Grad-Shafranov equation solvers) have been reported in past years, numerical solutions of FRC equilibria have proved troublesome. A more robust and flexible equilibrium code that also accepts flow is needed. Flexibility is essential because more complex equilibrium field coils are anticipated in future experiments. A work-horse equilibrium code would form an effective basis for stability studies. Priority should be given to adapting existing codes developed for tokamaks rather than developing a completely new code. Further, methods for finding relaxed and partially relaxed states should be developed.

b) Recommissioning MHD codes. A 3D-MHD code for simulating FRC global mode stability was last operated in the late 1980s. Since then considerable new information has become available about the current profiles, flows, and other features of FRC equilibria observed in actual experiments. In brief, the equilibria to which these codes were applied are not relevant to laboratory FRCs in several ways. Therefore the existing 3D-MHD code needs to be recommissioned and operated more-or-less continually as a check on analytical stability theories. In particular, the emergence of new stability concepts such as sheared flows and minimum energy states need testing with standard stability codes. The purpose for maintaining and operating such codes is to achieve sufficient agreement with experiment to allow the claim of predictive capability.

c) Advanced kinetic codes. Sophisticated 3D hybrid codes are needed for the study of equilibrium and low-frequency stability. One such, developed specifically to model FRC/Ion Ring systems is presently in use. This code needs continued development, and it or codes of like kind need to be applied to FRCs in a more general context. A global kinetic stability code provides another method for stability analysis that does not break down near the field null or the separatrix. The method is to expand the perturbed distribution function in eigenfunctions of the equilibrium Liouville operator. In addition, codes developed previously at Princeton will be adapted to study FRCs. Linear MHD stability results can be obtained by modifying the NOVA-K code to adapt it to the FRC configuration. Non-linear stability results will be obtained by modifying the MH3D-K code to include full ion-orbit particles. The latter is the present gyrokinetic-MHD hybrid option developed under the “Multi-level 3D Plasma Simulation Project” at Princeton.

d) RMF drive code. At present there is no code to couple the physics of RMF drive with the equilibrium shape of an FRC. Methods have been developed to follow the penetration of the RMF into a 1-D plasma column with specified density and collisionality. These methods should be incorporated in standard 2-D formation codes such as MOQUI. There is some evidence that applying RMF not only drives electron current but may also stabilize the configuration. This possibility certainly warrants investigation.

2. Current drive theory

Further theoretical investigation of the RMF current drive technique is required. A 2D (r-θ) time-dependent two-fluid model is needed that takes into consideration processes such as ionization and particle, momentum and energy balance. Important questions concern the transient penetration timescale of RMF, and the anomalous (or classical) nature of the resistivity. Theoretical studies of current drive should address two further matters about how to exploit the unique properties of FRCs: (a) how to benefit from the large natural diamagnetic current by, possibly, driving a very modest seed current near the magnetic axis; and (b) how can current drive at the edge take advantage of relaxation effects (such as reconnections) to achieve bulk current drive.

3. Transport

a) Dominant transport mechanism. As in any magnetically confined plasma, transport in an FRC is complicated by the presence of multiple regions each of which may be governed by somewhat different phenomena. In an FRC, confinement may be dominated by the transport rate in the edge plasma (between the low-field core and separatrix). In none of the regions is the mechanism known with certainty (although low-frequency drift turbulence is a promising candidate in the edge plasma). The dominant transport mechanisms need to be established with reasonable confidence. This includes consideration of collisionality regimes and the extrapolation toward fusion conditions. Some aspects of transport are being explored in studies with quite a different purpose, e.g. parts of the geomagnetosphere resemble the low magnetic field core of an FRC.

b) Nonlocal theory. There is an urgent need for a nonlocal theory of transport in view of the sharp gradients (ion gyroradius scale) that arise naturally in FRCs. The basic elements for such a theory have been formulated but not yet applied. With such work, analysis of the interplay between MHD and anomalous resistivity could be done, as well as a profile-consistent analysis of turbulent transport itself.

c) Scrape-off layer plasma and energy flow. Electron thermal loss in experiments appears to be limited by ambipolar effects in the scrape-off layer. Electrostatic fields may also play a role in regulating the anomalously slow plasma outflow. This effect may be accentuated in the presence of suprathermal ions such as produced by an ion ring or unthermalized fusion products. Also of interest is the inference of a double-layer like plasma in the exhaust jet region of the scrape-off layer that isolates hot from cold plasmas. A theory accounting for finite ion gyroradius and self-consistent electric fields is needed to explain observed anomalies compared to fluid theories.

d) Nonlinear Theory. There is an urgent need to study single particle dynamics in FRCs, including the spectra of stochastic processes. This will allow formulation of boundary conditions for kinetic equations, and then calculation of species distribution functions and a nonlocal dielectric tensor. With this it will become possible to study wave spectra and the spatial structure of eigenmodes for different wave branches. For unstable modes this will include nonlinear analysis of wave-particle-wave interactions, determination of the wave saturation level (if it exists), and the energy and particle fluxes.

4. Simulation of ongoing experiments

A nonlinear 2D-MHD + Hall effect code (MOQUI) is presently in active use to simulate ongoing experiments on LSX/mod. This "workhorse" tool would be valuable for experimental interpretation at other facilities as well. In addition, the possibility of adapting existing tokamak codes should be considered. The availability of parallel computation has enabled the implementation of fairly realistic (3D, toroidal geometry) simulations from "first principles" (gyrokinetic particle models) on the turbulent timescale. Full cross section 2D fluid simulation of transport in toroidal geometry is also being developed. Some of these tools might be applied to FRC simulations, thus exploiting the large investment in code development and modeling.

5. Burning plasma physics

The next five years do not call for extension of FRC experimental plasmas into the fusion temperature regime. Therefore the investigation of phenomena arising in a burning plasma has lower priority. Even so, certain topics should be addressed in anticipation of later experiments on FRCs in a more fusion-like regime.

a) Fusion product effects. Several topics need study. (i) Prompt losses of energetic particles (fusion products and energetic components of the basic plasma): this is needed to determine the distribution of high energy particles entering the direct converter and the proper boundary conditions for the kinetic equations for fusion products. (ii) Solution of kinetic equations for the fusion products plus the power deposition in the core plasma itself: this is an essential element in the power balance of a burning FRC plasma. (iii) Instabilities associated with non-Maxwellian distribution functions: in saturating these may cause turbulent behavior and enhance transport.

b) Power flow analysis of a burning FRC. This includes several topics: power and particle balances based on kinetic/power models; estimation of the highest possible levels of power amplification; and formulation of the requirements for an FRC reactor (types and level of external heating power, injection currents, value of plasma beta, magnetic configuration).

c) Cyclotron radiation transport. Although cyclotron radiation losses are should be low in an FRC because of high-beta, this needs confirmation by more detailed theory. In particular the transport of cyclotron radiation should be treated in a self-consistent manner, including a realistic magnetic structure, self-absorption, heating, radiation polarization, and wall reflection.

C. TECHNOLOGY DEVELOPMENT DIRECTIONS

1. Rotating magnetic field (RMF) source development

The most efficient and technologically friendly method of generating an RMF needs to be determined and developed. A research program to address this question should incorporate the following tasks: (1) design and construction of a suitable high power RF source and drive coils capable of a sustained pulse longer than 1 msec; (2) demonstration of the RMF technique in a plasma column of moderate size (0.5-m diameter and 1.5-m length); (3) investigation of alternate methods for generating the RMF which are more efficient and capable of delivering higher power. These directions are presently being pursued in a joint U. Washington / LANL effort.

2. Neutral Beam Injection (NBI)

In the short term there is a need for low energy high current NBI to sustain FRC's in steady state. In longer term high energy, high current negative ion source NBI should be used maintain the configuration.

3. Ion Ring technology

Ion rings have been successfully produced by injection through a magnetic cusp: consideration of improvements of the basic technology merits continued attention. In addition, new technologies associated with Ion Ring concepts need work on design of pulsed magnet coils, and power supplies suitable for ring compression and translation. Further, repetitively-pulsed power supplies are needed for multi-ring formation. In this area repetition rate technologies developed for ion beam driven ICF and material processing might be exploited.

D. SYSTEMS STUDY DIRECTIONS

Although the inherent features of an FRC endow it with great potential for an attractive reactor, it is needed to show this rationally and quantitatively. For an alternative fusion concept to be considered for extensive development, it should satisfy the following criteria. (1) *Reactor test*--assuming that the physics "works", it must offer marked advantages over a tokamak, i.e. a step change improvement in cost and complexity; (2) *Physics test*--based on the existing theoretical and experimental data base, the physics must be considered plausible; and (3) *Development path test*--the development path, from physics-oriented experiments to ignition to an ETR facility to a DEMO, should offer significant advantages over a tokamak. FRC systems studies can elucidate at least the first and third of these tests.

1. FRC systems code

An integrated study of critical physics and engineering issues is needed. Ideally, such an analysis is performed with a systems code. Such codes have proved invaluable in identifying interfacial problems that might otherwise be overlooked until late in research and development projects. A systems analysis facilitates the formulation of a quantitative reactor assessment using, *e.g.*, system sizes, masses, costs, mass power densities, costs-of-electricity and economy of scale. Accordingly, an FRC-capable systems code should be developed. Since systems code shells already exist, this requires only the addition of FRC-relevant modules for plasma physics, engineering, fuel cycle, and costing. Regarding the plasma module: given the limited FRC physics database, the results can be formulated in terms of uncertainties in the input database. The engineering modules should include moderately detailed models for the several engineering systems (see Sec. IV-D-2 following). The use of an uncertainty analysis will highlight minimum performance requirements for major parameters such as confinement and stability in terms of their impact on the reactor product. A systems analysis can also help in formulating the FRC development path by quantifying the size/cost parametrics of the complex of machines leading to a DEMO. Although the FRC is an ideal candidate for advanced fuels burning, consideration should also be given to the D-T fuel cycle.

2. Engineering design

Several crucial, long lead-time engineering issues exist, including radiation damage, activation, shielding, safety, environment, tritium-breeding blanket design, direct energy converter engineering, plasma-surface interactions, current drive, and maintenance. Some of these have aspects unique to FRCs that would not receive consideration in the mainline fusion program. An alternative design that may allow a step change in reactor attractiveness is the use of liquid walls. With a liquid wall of seven neutron mean free paths thickness, the structural walls behind the liquid could last *30* years with a wall load of $30\ MW/m^2$ or more [37]. This would result in lower cost magnets and other components on a per unit power basis in addition to higher capacity factor and less cost for new blankets and less cost for remote manipulators, hot and cold cells. The impact on economics would be a reduction in cost of electricity of *35%* or more. Regarding FRCs the important question is if liquid walls can be made to be compatible with FRC operation. One issue seems not to be a problem with a low conductivity liquid like Flibe: an RMF antenna for current drive could be located deep in the liquid.

3. FRC/Ion Ring system

An ion-ring based approach that has received some attention in recent years is the colliding beam reactor concept [23]. Here the ring ions play the dual roles of supporting the FRC magnetic configuration as well as generating the fusion reactions. The reactor concept where an FRC composed mostly of thermal plasma is supported by an ion ring has not yet received detailed study. In this case, injected ion rings could control stability as well as drive current.

4. International collaboration: advanced fuels

In view of the recent Japanese ARTEMIS study of a commercial D-3He FRC reactor and the expertise built up there, the Japanese FRC design team should be close collaborators in any future reactor study. Although FRCs are expected to perform well in D-T power plants, the Japanese chose the D-3He fuel cycle for the ARTEMIS design for several reasons: because of the excellent match between D-3He fuel and FRCs; because of a desire for the most environmentally favorable concept; and because D-3He almost completely circumvents the neutron wall loading problem. The particular advantages of a D-3He FRC system are (1) the linear geometry facilitates direct conversion of the charged-particle power; (2) the increased power density arising from high beta somewhat compensates for lower fusion cross-section, and (3) despite the high charged-particle power, the surface heat flux is moderate because the axially flowing plasma carries most of the energy losses out the ends of the coil system.

V. ACTION ITEMS

This document, prepared by the world-wide FRC community, defends the value of the FRC to plasma science in general and its particular potential as a fusion reactor concept. It also summarizes the present state of the concept with respect to important issues, and gives fruitful directions for research. As a result of these factors, the following five action items are recommended.

- The FRC research program should be continued and expanded both as an adjunct to mainline fusion research and as a stand-alone alternative fusion concept.
- Existing FRC-related resources should be exploited in an expanded program: this includes both experimental facilities and the intellectual capital established in institutions and individuals with a long-standing commitment to FRC research.
- New FRC facilities or upgrades of existing facilities should be considered on the merits of how they pursue the directions offered in this document. This should include consideration of a jointly-operated international FRC research facility.
- Researchers and institutions with a history of activity on the tokamak should be encouraged to consider broadening their research to include FRC theory, diagnostic development, and systems studies.
- Vigorous international collaboration on FRC research should be encouraged, including, at the least, annual workshops and long-term exchange visits.

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VII. SIGNATORIES

We the undersigned are in significant agreement with the assessment of the status, key issues, and future directions in FRC research as expressed in this White Paper.

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