Magnetized Target Fusion
A Proof-of-Principle Research Proposal

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PoP Program Leaders and Editors:

K. F. Schoenberg and R. E. Siemon

PoP Participants and Contributors:

R. J. Bartlett, R. R. Bartsch, C. A. Ekdahl, R. J. Faehl, J.Finn, R. A. Gerwin, R. Kirkpatrick, I. R. Lindemuth, R. W. Moses, R. E. Reinovsky, K. F. Schoenberg, P. T. Sheehey, J. S. Shlachter, M. G. Tuszewski, G. A. Wurden, and F. J. Wysocki, Los Alamos National Laboratory; J. Degnan, G. F. Kiuttu, E. L. Ruden, and P. Turchi, Air Force Research Laboratory; P. Parks, General Atomics; J. H. Hammer, R. Moir, and D. Ryutov, Lawrence Livermore National Laboratory; Y.C.F. Thio, Massey University, New Zealand; R. D. Milroy, U. Washington; L. Green, Westinghouse Science and Technology Center.

Disclaimer: The budget estimates in this proposal are unofficial in the sense that they have not been reviewed and approved by the budgeting authorities of the various institutions involved. However, in every case the numbers have been checked by principal investigators and appropriate line managers of the respective institutions, so they should serve as useful estimates for planning purposes.

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Executive Summary:

We propose herein a three-year, $6.6 million per year, proof-of-principle (PoP) program to establish the scientific basis of Magnetized Target Fusion (MTF) as a faster and cheaper approach to fusion energy. To explore this truly different fusion concept, we will take advantage of compact toroid (CT) research developed by the magnetic fusion energy program (MFE) in the past 20 years. The CT plasma is the target, which we will implode using well-established liner technology developed by DOE and DoD defense programs research in recent years. The magnetic topology of the CT should provide enough thermal energy confinement to allow compressional heating of the plasma to fusion-relevant conditions. Fusion energy will be generated in a micro-second pulse during which pressure (plasma and magnetic) is inertially confined by the imploding liner wall. This specific CT approach to small-size, high-density fusion (by MFE standards) is intended to prove the principle of MTF by achieving significant performance ($n\tau > 10^{13}$ s-cm^{-3} , T ~ 5 keV) in just a few years at modest cost using available pulsed-power facilities. Success in understanding will require both experiments and large-scale numerical computation.

The density regime and time scale of MTF is intermediate between MFE and inertial-confinement fusion (ICF). Three technical considerations explain why the regime is important. First, fusion reactivity scales as density squared, which can be increased by many orders of magnitude over conventional MFE. Second, all characteristic plasma scale-lengths decrease with density. Hence, system size is naturally reduced at a high density. Third, magnetic insulation greatly reduces the required power and precision to compressionally-heat plasma to fusion-relevant conditions compared with ICF, and brings the pulsed-power requirements within reach of existing facilities. Thus, we conclude the intermediate density regime holds promise as a new low-cost avenue to fusion energy. The future path for engineering development of MTF as an economic power source is less well defined than for the more mature approaches of MFE and ICF. However, a number of possibilities are being discussed, and this research program will include scoping studies to identify the most promising approaches.

The research of this proposal is focused on several critical issues for application of a CT target plasma to MTF:

- formation at required density (~10^{17} cm^{-3}) and temperature (~300 eV),
- stability during formation and compression,
- energy confinement adequate for fast liner compressional heating,
- plasma impurity content and the general consequences of high-energy-density plasma-wall interactions

In pursuit of these research goals, Los Alamos will lead a multi-institutional team formed to elucidate the physics underlying these technical challenges. This team of collaborators is critical to the proposal and the assessment of MTF as a fusion approach. The total budget to support this research across all institutions is $6.6 M/year for three years.

Our principal target plasma candidate is the field-reversed-configuration (FRC). The FRC offers the promise of robust, closed flux surfaces, capable of maintaining their topology during compression. Past experiments have demonstrated that an FRC can be translated and trapped in a liner implosion geometry.

Most importantly, formation of an FRC using high-voltage theta-pinch technology is well established, and appears likely to extrapolate to the required target requirements. The existing database for energy confinement scaling suggests the FRC will work well in an MTF application. The cylindrical geometry of the FRC allows end-on diagnostic access even during energetic liner implosions. All together, the physics base developed by over twenty years of FRC research gives confidence that FRC targets have a reasonable chance of being compressed to fusion-relevant conditions.

High-speed liners, composed principally of aluminum, are the best candidates to compress the FRC target plasma. Defense-program-developed imploding liners have demonstrated the speed and convergence required for MTF PoP experiments. This knowledge base, coupled with well-benchmarked analytic and computational models of liner physics, provide confidence that liner performance suitable for an MTF PoP program is in hand. Furthermore, PoP liner-plasma compression experiments can be executed on existing pulsed-power facilities.

As detailed in the following proposal, the first two years of research will focus on creating an FRC target plasma suitable for compression. Here, we will form dense, elongated FRCs that are within known operational boundaries of dimensionless parameters, where energy confinement has been observed to be optimum. In parallel, a liner to compress the elongated FRC will be designed and tested without a plasma. Based on the success of the first two years of research, the third year will focus on integrated liner-on-plasma compression experiments. This research will give improved understanding of FRC formation, stability, and transport at high density and temperature. Performance expectations encompass temperature, density, and $n\tau$ values of 5 keV, 10^{19} cm^{-3}, and 10^{13} cm^{-3}-s, respectively. This performance represents more than a ten-fold increase of the $n\tau T$ triple product compared to the best existing FRC data. Los Alamos and the Air Force Research Laboratory in Albuquerque (Phillips site) form the experimental team who will develop the FRC plasma target and conduct liner experiments using primarily LANL experimental facilities for FRC target development and the AFRL Shiva-Star facility for energetic liner implosions.

In summary, MTF embodies an exciting new direction for fusion energy development at small scale and low cost. It enables the study of plasma confinement physics over a relatively unexplored region of density and magnetic field strength with a view to advancing CT physics in particular, and fusion energy research in general. The readiness for an MTF Proof-of-Principle program is predicated on the maturity of compact toroid physics and liner implosion technology, as well as the potential to achieve significant plasma performance with existing facilities at modest cost. Given the current circumstances that have led to a restructured fusion program, in which innovations with lower-cost development are encouraged, we believe the logic of investigating MTF is both propitious and compelling.

PART A: MOTIVATION AND GOALS

1. Motivation: A low-cost approach to fusion energy development.

Los Alamos is leading a multi-institutional team that proposes to develop a completely new direction for fusion energy called Magnetized Target Fusion (MTF). We specifically propose to form and preheat a compact-toroid plasma using well-established techniques developed over the past 20 years, and then compress it with imploding liner technology developed by DOE and DOD defense programs. We will explain why our particular approach offers the most direct path for proving the principle of MTF, but we acknowledge that there are many additional issues involved with MTF as discussed in a Community Based R&D Roadmap located at URL: http://fusionenergy.lanl.gov/R&DRoadmap.pdf

The technical reasoning that predicates MTF as a faster and cheaper approach to fusion energy development was recently published (see Appendix A). Basically, the reasons are threefold. First, fusion reactivity scales as density squared, which implies that unlike conventional magnetic fusion energy (MFE), energy gain can be achieved at high density in a short duration pulse. Second, all characteristic plasma scale-lengths (e.g. mean free path, gyro radius at fixed beta, c/ω_p, λ_{debye}, …) decrease with density. Consequently, the required plasma energy investment to achieve net fusion energy gain ($Q > 1$) decreases as a function of increasing plasma density. This statement is true for many different diffusive transport mechanisms (impurity radiation puts a limit on the acceptable impurity fraction independent of density). Third, the required power to achieve fusion-relevant conditions, roughly 1 - 10 TW, is much reduced compared with inertial confinement fusion (ICF), and readily available with existing pulsed-power facilities. Minimum power heating requirements can be seen as a function of density by noting Minimum Power ~ (Minimum Energy)/τ_E, where τ_E is the energy confinement time consistent with fixed $n\tau_E$.

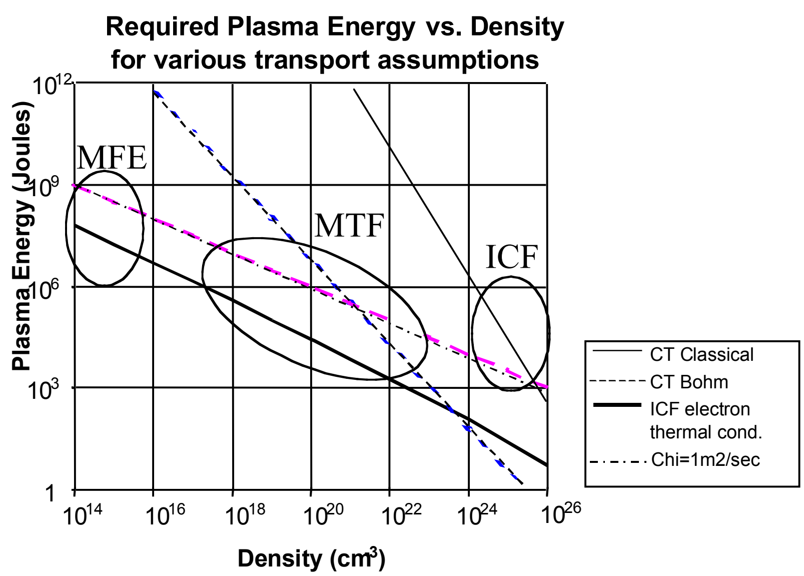


Fig. 1. Required thermal energy in a plasma to achieve Lawson ($n\tau = 3x10^{14}$ sec/cm^3) as a function of density at T=10 keV, assuming a sphere of unmagnetized plasma for ICF, and an FRC geometry with plasma $\beta = 1$ for magnetized plasma.

Figure 1 plots the minimum required thermal energy in a plasma to achieve Lawson ($n\tau = 3\ 10^{14}$ sec/cm^3) as a function of density for several thermal transport models. Here, poloidal β of 1 and plasma temperature of 10 keV is assumed, where β = plasma pressure/magnetic pressure. For the case of diffusivity $\chi \sim 1$ m^2/sec, typical of many tokamak experiments, the required thermal energy for breakeven must exceed roughly 1 GJ (approximately ITER). More interesting is the consequence of Bohm diffusivity. As shown in Fig. 1, there is a regime of density at around 10^{20} cm^{-3} where Bohm is good enough to achieve break-even with a very achievable energy investment. This is in strong contrast to conventional MFE densities, where Bohm is unacceptable in terms of the required energy. Unmagnetized plasma has the strongest scaling with density. Accordingly, ICF seeks to work at the maximum possible density where the required energy investment is small. The parametric scalings of required energy and power to achieve fusion breakeven all lead to the same conclusion: systems intermediate between present MFE and ICF allow for a lost-cost, fast-track development of fusion energy at modest scale. This addresses the critical problem of development cost confronting the worldwide fusion energy program. Given the current circumstances that have led to a restructured fusion program, in which innovations with lower-cost development are encouraged, the logic of investigating this new direction for fusion energy is compelling. Based on this thinking we have adopted the following mission for our MTF Proposal:

Mission of the MTF Proof-of-Principle Program

To explore the intermediate-density pathway to fusion conditions by liner compression of a compact toroid target, and to demonstrate the effectiveness of magnetic insulation for reducing driver requirements, thereby opening potential avenues to low-cost energy-producing plasmas and practical fusion power.

The target plasma will be compressed using a liner driver that symmetrically implodes the target to modest radial convergence (~10). Sophisticated numerical models to describe liner implosions have been developed and benchmarked by experiments. To understand the issues in an elementary fashion, one starts by considering conservation of liner momentum and energy in a three dimensional compression [Siemon97]. Here, momentum is given by:

$$\delta_o\, \rho_o\, v_L = [\text{Peak pressure} \times \tau_D]\, (R_f / R_o)^2$$

where δ_o is the initial liner thickness, ρ_o is the initial liner density, v_L is the imploding liner velocity, R_f is the final liner radius, R_o is the initial liner radius, τ_D is the dwell time required for liner momentum to be stopped by peak pressure, and peak pressure is $2n_fkT_f$ (plasma pressure and magnetic pressure are equal for the FRC case being considered). It is interesting to note that conservation of momentum provides a physical interpretation of the triple product (pressure times dwell time) in terms of initial liner momentum per unit area ($\delta_o\rho_o v_L$). Obviously, this equation plays a fundamental role in designing a liner for the purposes of thermonuclear fusion. Liner energy is given by:

$$2\, n_f k T_f = (\varepsilon/3G)(R_o/R_f)^2(\delta_o/R_f)\, \rho_o\, v_L^2$$

where ε is the fraction of liner kinetic energy converted to thermal energy at peak compression, and G is the geometric ratio of plasma volume to the product of surface times radius for an arbitrary shaped plasma. Peak pressure, or density at 10 keV temperature, is proportional to initial liner kinetic energy density ($\rho_o v_L^2$). The coefficients are geometric in nature and not the essential quantities. The essential requirement to create high-density plasma at 10 keV temperature is a liner velocity of order a cm/µs.

Detailed calculations take into account other constraints such as liner compressibility and heating by the currents used to accelerate the liner. On the basis of calculations ranging from spreadsheet descriptions using global conservation laws described above, to time dependent coupled circuit and plasma models, we have established the quantitative goals for our PoP experiment described below.

2. Proof-of-Principle Goals:

The PoP research discussed in this proposal is focused on establishing a scientific basis from which the potential of MTF, as an attractive fusion power source, can be evaluated. For our approach of liner implosion of a CT target, the critical scientific plasma physics issues to address are:

- formation at required density (~10^{17} cm^{-3}) and temperature (~300 eV),
- stability during formation and compression,
- energy confinement adequate for fast liner compressional heating,
- plasma impurity content and the general consequences of high-energy-density plasma-wall interactions

The fourth critical technical issue of interactions between the plasma and an imploding liner wall depends in detail upon the target plasma magnetic configuration. We have chosen the FRC, in part, because it allows a continuum of possibilities. An FRC has a well-defined separatrix and a sheath of magnetic flux that separates it from the surrounding metal boundary. The flux external to the separatrix acts as a divertor for wall-related impurities. The radial position of the separatrix can be adjusted by the amount of trapped flux external to the separatrix. This provides a “knob” to evaluate questions of plasma-wall interactions and the various equilibria and transport phenomena that happen when plasma pressure is directly supported by a mechanical wall. The breadth of this physics from a theoretical perspective is given in Appendix C. The scientific issues here have elements in common with those of tokamak divertors, albeit with a much higher central density.

Broadly stated, the research effort consists of four phases:

1. **Formation of an FRC using well-established theta-pinch technology at parameters suitable for compression**. Based on the existing FRC knowledge base, as discussed in Parts B and C, the formation goals are n ~ 10^{17} cm^{-3}, T ~ 300 eV, x_s (normalized separatrix radius) ~ 0.5 – 0.8, l_s (separatrix length) ~ 30 cm, and τ_E > 10µs.

2. **FRC translation and trapping into a liner suitable for compression**. We have designed the FRC to remain within empirically-established operational limits with the objectives of improving the understanding of FRC stability and achieving good confinement during compression. This requires translation of the formed FRC into an elongated flux-conserving liner with dimensions r ~ 5 cm and L > 30 cm.

3. **Demonstration that an elongated liner can be imploded in vacuum with a radial convergence of 10 and velocity exceeding 0.3 cm/µs.** Defense programs research has demonstrated stable implosions of the required convergence and velocity with length to diameter ratios of roughly 1 (Part

B-2). Here, we apply that technology to demonstrate implosions with length to diameter ratios of between 3 and 4.

4. **Integrated compression experiments where the formed and translated FRC is compressed by an imploding liner.** The goal of this research phase is to prove the MTF principle for a specific plasma target system. That is, substantial heating and increased $n\tau$ will result from liner implosion of a well-formed FRC plasma according to present understanding of plasma physics. We expect to heat the FRC to temperatures of ~5 keV, and in the process achieve $n\tau \sim 10^{13}$ sec/cm^3. This performance represents more than a ten-fold increase of the $n\tau T$ triple product compared to previous FRC experiments done without liner implosion. An important component of this objective is to advance fusion science by theoretical understanding and computer modeling of the experimental results.

The principal goals, scientific issues, and requirements of the proposed research plan are summarized in Table 1.

Table 1. Summary of research goals, issues, and requirements for MTF PoP Research

Research Goals	Scientific/Technical Issues	Principal Facility	Principal Diagnostics	Modeling Codes
FRC formation Suitable for Compression T ~ 300 eV $n \sim 10^{17}$ cm^{-3} $\tau_E > 10$ µs	FRC formation at high density Stability for S*/E < 3.5 Confinement $\tau_E \sim 0.5\ R^2/\rho_i$ Impurity Content $Z_{eff} < 2$	Colt (LANL)	Excluded flux B probe array Interferometry Thomson scattering Bolometry Optical spectroscopy	Analytic(0D) MOQUI
FRC Translation and trapping into a liner with r_{wall} = 5cm, r_s ~ 3 cm l_s = 30cm	Maintaining stability Impurity content	Colt (LANL)	B probe array Bolometry Interferometry Spectroscopy	Analytic(0D) MOQUI
Vacuum liner compression from $r_{initial}$ = 5cm to r_{final} = 0.5 cm with V > 0.3 cm/µs	Rayleigh-Taylor and kink stability for L/D ~ 3, Convergence $R_i/R_f \sim 10$	Shiva-Star (AFRL)	3-axis radiography end-on framing photos magnetic probe pin arrays	CONFUSE(0D) RAVEN(1D) MACH-2(2D) RMHD(2D) LASNEX(2D)
Integrated Compression of FRC in liner to T ~ 5 keV, $n \sim 10^{19}$ cm^{-3} $\tau_E \sim 1$ µs	Stability Transport Impurity content (liner mix)	Shiva-Star (AFRL)	3 axis radiography End-on interferometry Spectroscopy Bolometry Neutron emmsion	MSG (0D) MAGIT (0D) MHRDR (1D) RAVEN(1D) RMHD(2D) TRAC-II ASCI codes

3. The PoP team and budgets.

For the first three years, the multi-institutional tasking and the estimated total budget is summarized in Table 2. While reactor considerations are not central to a PoP effort, we include about 8% of this effort to examine the issues of practical energy application.

Table 2. Budgets and tasks for each institutional team member.

Institution	Task	Annual budget for 3-year PoP ($millions)
LANL	CT plasma formation development	3.0
	CT Integrated compression experiments	
AFRL	CT Liner-prototype development	1.0
(Previously Phillips Laboratory)	Integrated compression experiments	
	Impurity measurements/assessment	
LANL	CT liner design	1.1
	Plasma and liner integrated modeling	
	Systems studies	
LLNL	Plasma-liner interaction theory and modeling	0.4
	System studies	
General Atomics	Theory of wall-plasma interactions	0.1
U. Washington	FRC MHD modeling	0.1
Westinghouse	Energy systems analysis	0.3
University supporting research	Related exploratory concept development	0.6
	Total	**$6.6 M**

PART B: KEY SCIENTIFIC ISSUES

In this section we summarize, for our specific approach, the key scientific issues for the development of MTF as a fusion concept. For each issue, the status and open issues are discussed with a view to defining a PoP research program. In our proposed research plan, we have chosen a compact toroid for the target plasma. Compact toroids (CTs) offer the promise of robust, closed flux surfaces that maintain their topology during compression. After considering both the field-reversed configuration and spheromak types of CTs, as well as other candidate target plasmas (see Appendix B), we have selected the field-reversed configuration (FRC) as our principal CT target candidate for the reasons given below. The required quantitative parameters for FRC targets can be approximated assuming adiabatic compression during liner implosion, but we base the estimates here on a Zero-D liner-implosion model described at the beginning of Part C.

1. Plasma Target: The Field Reversed Configuration

a. Background. The FRC is an elongated compact toroid (Fig. 2) that is formed without toroidal field [Tuszewski88]. The FRC consists of a closed-field-line torus inside a separatrix and an open-field-line sheath outside the separatrix. Equilibrium in a FRC is a balance of magnetic field *pressure* and plasma pressure in the radial direction, and field-line *tension* and plasma pressure in the axial direction. Thus, in a straight cylinder, it follows as first derived by Barnes [Barnes79], that average pressure inside the separatrix is $\langle\beta\rangle = 1 - x_s^2/2$, where $x_s = r_s/r_c$, and r_c is the effective coil (or conducting wall) radius.

FRC research is actively pursued worldwide [see ICC white paper by Hoffman et. al.]. Fundamental properties of FRCs are closely related to the field-reversed sheath observed in the solar down-wind tail of the magnetosphere [Horton94]. Significant progress has been made in FRC experiments and theory, resulting in stable plasmas with good confinement properties.

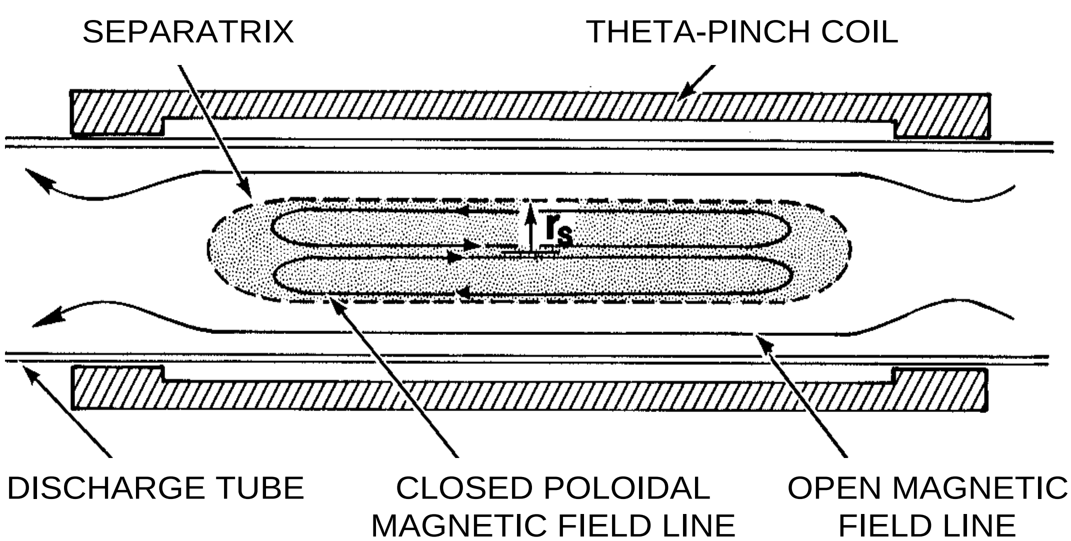


Fig. 2. FRC geometry showing separatrix radius and flux-conserving boundary.

The FRC is chosen for our proposed research because it offers many potential advantages as an MTF target plasma. The FRC is a compact torus, and therefore it has a closed-field-line topology without internal material objects. The compact torus configurations are ideally suited to liner compression. The FRC can be readily translated along its symmetry axis as has been demonstrated in many experiments. This permits the separation of plasma formation and liner-implosion regions. Formation of an FRC using high-voltage theta-pinch technology is well established, and appears likely to extrapolate to the required target requirements. The FRC is formed inductively and is largely free of impurity line radiation. Furthermore, the FRC separatrix is a natural divertor isolated from wall boundaries. The FRC has very high (~ 10) internal plasma beta, which allows efficient heating of plasma as opposed to magnetic field, and also serves to reduce substantially synchrotron radiation losses. The FRC undergoes an axial contraction during radial compression because of increased field line tension during compression. Thus, a purely cylindrical liner implosion results in 2.4-D compressional heating. A full 3-D compression could be achieved with shaped liners, if desired. By using the purely cylindrical liner, diagnostic access is improved during compression, which is an important feature for experimental progress, even if the energy requirements are somewhat increased. The FRC plasma length can be made smaller than the liner length, which may be important to avoid impurity influx from the liner ends. All together, the physics base developed by over twenty years of FRC research gives confidence that FRC targets have a reasonable chance of being compressed to fusion-relevant conditions.

b. Status of FRC formation. FRCs have been formed successfully during the last 40 years by the field-reversed theta-pinch method. This technique has been improved in the last decade with more uniform preionization, non-tearing reconnection from end cusps, and axial dynamics control [Tuszewski88]. Successful FRC theta-pinch formation models have also been developed [Siemon80, Steinhauer83, and Tuszewski88b]. Other valuable FRC formation techniques are being developed, including coaxial slow sources, rotating magnetic fields, and formation by counter-helicity merging. However, the proven theta-pinch FRC formation technique is a logical choice for our proposed research because formation and translation into the liner region can be accomplished in a few μs; a time short compared to the expected FRC lifetime.

Most FRCs studied over the last 20 years were formed with pulsed-external magnetic fields, where $B_e < 1$ T and gas fill pressures $p_0 \sim 1 - 10$ mTorr. These conditions yielded FRC plasma temperatures T ~ 0.1 - 1 keV and plasma densities n ~ (1-5) $\times 10^{15}$ cm^{-3}. For MTF, FRC targets will require $B_e \sim 3 - 5$ T, $p_0 \sim 200$ mTorr, yielding T ~ 300 eV and n ~ 10^{17} cm^{-3}. We note that FRCs with MTF relevant parameters were formed successfully in many early (1960's) and intermediate (1970's) theta-pinch experiments [Tuszewski88]. Although they were less well diagnosed than in more recent experiments, they give us good reason to believe that MTF target FRCs can be generated with the required parameters.

c. Open Issues of FRC formation. Compared with most previous FRC experiments, the relative amount of initial magnetic-piston heating (referred to as "implosion" heating in the literature) compared to resistive dissipation will be somewhat smaller in the FRC formation to be used here. The required initial temperature (~300 eV) and trapped flux correspond to a bias field B_o = 0.5-1.0T. An important issue is to check whether formation works as expected according to empirical models and two-dimensional numerical MOQUI calculations (detailed later) in the higher-density regime. Dominant resistive heating has been successfully demonstrated at low density in the TRX-2 device [Hoffman86].

A second issue is whether the fairly collisional regime of the initial FRC (ion mean free path λ_i ~ 1cm compared to separatrix radius r_s ~ 3cm) has the same favorable properties during formation as observed at lower density. A third issue is how rapidly the FRC can be formed, translated, and trapped in the liner volume. Given the fairly short lifetime expected, rapid translation is desirable. A 4° conical theta pinch appears adequate [Rej86] to accelerate the FRC out of the formation region in about 2μs with axial speed comparable to V_A ~ 10 cm/μs. Two-dimensional MHD MOQUI simulations suggest that liner compression could be underway about 8 μs after FRC formation. This time scale is less than the anticipated FRC lifetime of 20-30 μs.

d. Status of FRC stability. Typical FRCs shows remarkable robustness with relatively good confinement properties over an established domain of dimensionless plasma parameters. The domain of good FRC stability and confinement is shown in Fig. 3 in terms of the size parameter S* and elongation parameter, E. Here, $S^* = r_s/(c/\omega_{pi})$, where r_s is the separatrix radius and c/ω_{pi} is the ion electromagnetic skin depth, and $E = l_s/(2r_s)$, where = l_s is the separatrix length.

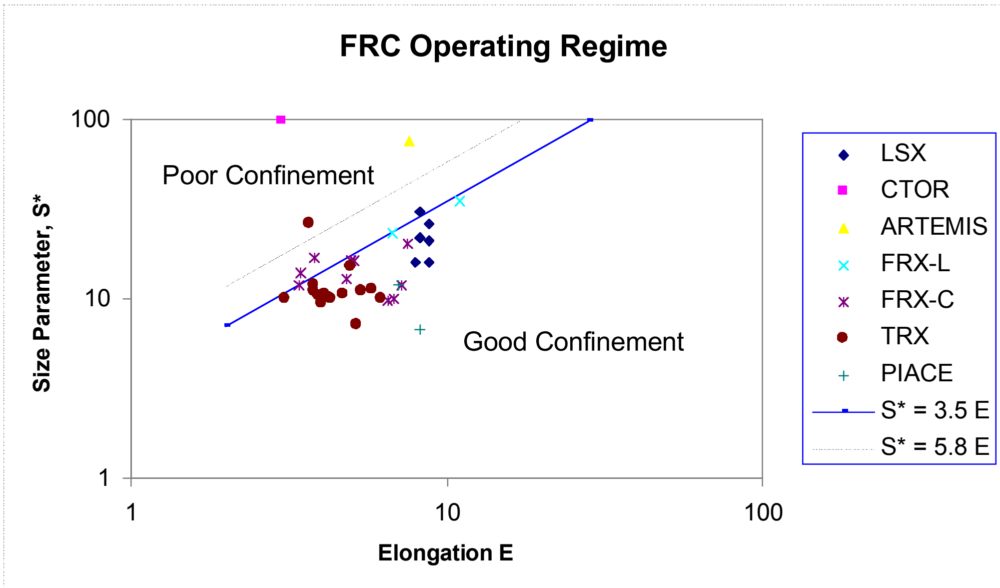


Fig. 3. FRC regime of good confinement.

These parameters arise naturally in FLR stability calculations. S* is approximately related to the small-s FRC stability parameter (often mentioned in earlier literature) by S* ~ 10 s. The advantage of S* is that it can be easily defined experimentally using just excluded flux and side-on interferometry diagnostics. Most FRC experiments are observed to lie in the region S*/E < 3.5, that corresponds to the marginal finite-Larmor-radius FRC tilt stability limit with a gyroviscous ion fluid formalism [Ishida92]. This limit (depending on internal B profile) is also in agreement with significant tilt growth rate reduction seen in kinetic calculations [Barnes86].

There is no consensus, at present, whether the experimental data base shown in Fig. 3 reflects an FRC stability limit, whether it arises from global modes such as the internal tilt and/or from more localized modes such as interchanges, or whether it just coincides with technical limitations in FRC formation. A smooth transition from good to bad FRC confinement that correlates with increased Mirnov magnetic activity, has been observed when S*/E > 3 - 5 in the FRX-C/LSM experiment [Tuszewski91a]. Signatures very similar to those in 3-D MHD tilt simulations were observed at low gas fill pressures, but higher-order mode activity dominated at higher gas pressures. The best results from the LSX device [Slough93, Hoffman93a], indicated in Fig.3, are also consistent with the empirical limit S*/E < 3.5. However, those FRCs showed high-order Mirnov disturbances that did not clearly correlate with FRC confinement properties.

The experimental domain (S*/E < 3.5 in Fig. 3), where robust FRC's with good confinement properties are observed, remains to be definitively correlated with basic FRC stability theory. In addition, theoretical studies are underway [Ishida92, Steinhauer97] to clarify whether the S*/E stability limit can be pushed up to values substantially greater than 3.5, either naturally from additional effects such as Hall and parallel kinetics, or from separatrix shaping and internal current hollow profiles. Valuable experimental research has been recently proposed to clarify the FRC stability domain in a wide S* and E domain [Yamada98].

We adopt S*/E < 3.5 as a conservative empirical constraint on FRC formation, translation, and compression for the present proposal. Analytic adiabatic FRC compression laws [Spencer83] suggest that S*/E actually decreases during wall compression as roughly $r_c^{0.4}$. On the other hand, S*/E is predicted by the same laws to increase significantly ($\sim x_s^{-2}$) during flux compression. The latter result may explain the poor flux confinement observed in past flux compression experiments [Rej92]. For liner compression we will operate (FRX-L points in Fig. 3) safely below the conservative boundary.

e. Open issues of FRC stability. While the exact nature of the apparent S*/E limit shown in Fig. 3 remains uncertain, preliminary calculations, detailed later in this proposal, suggest that the fusion yield is very sensitive to the exact value of S*/E achieved while retaining good FRC confinement. An important physics issue for MTF, as well as for the international FRC community, is to determine how high S*/E can actually be. Fortunately, interesting liner compression experiments with significant fusion yield are possible with just S*/E < 3.5. Much better results may be obtained with somewhat higher S*/E values. Thus, determining the S*/E stability limit for MTF-grade plasma is an important experimental issue.

Another open issue is to what degree liner compression may be limited by the n = 2 rotational instability that terminates many FRC experiments. This instability can be controlled with multipole fields, but this technique is probably impractical in a liner experiment. The n = 2 rotational instability proved to be a limiting factor during some flux compression experiments [Rej92]. However, it proved rather harmless during translation experiments [Rej86], especially for cases with values of $x_s = r_s/r_c \sim 0.6$ -0.7. Wall compression proceeds with fairly constant x_s values, unlike flux compression, so we plan to adjust the initial liner magnetic field to control x_s. Thus, it should be possible to avoid premature destruction of the compressed FRC from rotational instabilities.

f. Status of FRC transport. In the domain S*/E < 3.5 where robust FRC behavior is observed (Fig. 3), the FRC energy confinement time is approximately τ_E (μs) $\sim 0.5R^2/\rho_i$ (cm), where ρ_i is calculated with the external B and internal T_i. [Siemon86, Tuszewski88, Hoffman93b]. This empirical relation was first suggested in transport calculations with anomalous resistivity from the Lower Hybrid Drift microinstability [Hamasaki79]. However, this microinstability has not been clearly identified [Carlson87].

Most FRC experiments indicate that the energy confinement is largely of convective nature, that is τ_E is dominated by particle loss [Tuszewski88, Steinhauer92, and Slough95]. FRCs typically show comparable particle τ_N and internal flux τ_ϕ confinement times $\tau_N \sim \tau_\phi \sim R^2/\rho_i$. Nonconvective thermal losses are smaller in most FRC experiments, and appear mostly in the electron channel, presumably from a combination of thermal conduction and impurity radiation.

FRC radial pressure balance yields $\rho_i \sim n^{-1/2}$, so that $S^* \sim Rn^{1/2}$, $\tau_E \sim R^2n^{1/2}$, and $n\tau_E \sim R^2n^{3/2} \sim S^{*3}/R$. Past FRC experiments have typically achieved $n\tau_E$ values of a few 10^{11} s- cm^{-3} with S* ~ 20 - 40 and R ~ 5 - 10 cm. The empirical scaling law $n\tau_E \sim S^{*3}/R$ suggests that large values of $n\tau_E$ can be achieved in a liner, with small values of R. For example, $n\tau_E \sim 10^{14}$ cm^{-3}s and S*/E < 3.5 corresponds to S* ~ 40, R ~ 0.2 cm, and l_s ~ 5 cm in an FRC liner compression with n ~ 4x10^{19} cm^{-3}. We argue that achieving $n\tau \sim 10^{13}$ s-cm^{-3} would prove the principle that high density is advantageous, assuming improved understanding of this density scaling is achieved during the research program.

It is interesting to note that $n\tau_E \sim 10^{14}$ cm^{-3}s value in a "conventional" FRC reactor with n ~ 10^{15} cm^{-3} would require S* ~ 300 and R ~ 1 m. Meeting the constraint S*/E < 3.5 would require l_s > 100 m for those FRC reactor cases. The design burn points of two FRC reactor studies, CTOR [Hagenson81] and ARTEMIS [Momota92] are indicated in Fig. 3 to illustrate the previous statement. These design points lie well outside of the S*/E < 3.5 domain because relatively small FRC lengths (10's of meters) were chosen in those low-density reactor studies to keep the overall reactor power under a gigawatt.

g. Open issues of FRC transport. While empirical FRC scaling is well documented, transport properties are not well understood from the perspective of fundamental physics. This was the case a decade ago [Tuszewski88] and remains the case today. We assume in the present proposal that the above empirical scaling laws apply during the entire FRC liner compression. Zero-dimensional (0-D) calculations, detailed later in this proposal, suggest that significant particle losses do not substantially affect the overall fusion performance because of a concomitant increase in axial heating.

A key question is whether the FRC confinement properties of past experiments with T_e < 500 eV and T_i < 2 keV will apply near peak compression where $T_e \sim T_i \sim$ 5 keV is anticipated. Will thermal losses remain mostly convective, or will non-convective losses dominate? Electron thermal conduction may prove to be a limiting factor. Impurity radiation is another key issue for MTF that will be discussed in the next Section. It is also possible that ion thermal conduction may become a dominant energy loss mechanism if ion temperature gradients comparable to r_s arise from a cold boundary. Control of x_s may prove essential to avoid large T_i gradients. Alternately, increasing x_s to values approaching unity may increase thermal conduction but suppress density-gradient-driven convective losses.

h. Status of FRC impurity content and radiation loss during formation. Most FRCs produced by the field-reversed theta-pinch technique show relatively clean plasmas. This is presumably because of the inductive plasma formation where wall contact is limited to a few 100 ns during field reversal. After that the FRC separatrix is well separated radially and axially from the walls. FRCs intrinsically tend towards cleanly formed magnetically confined plasma.

Radiation losses have been occasionally measured or inferred in FRC experiments to be 5 - 10% of the total energy losses [Tuszewski88]. Somewhat higher radiative loss fractions have been measured in the slower formation LSX experiment [Slough92]. In all cases, Z_{eff} values in the range 1 - 1.5 have been inferred. Line radiation is consistent with either < 1% oxygen or ~ 0.04% Si concentrations, the dominant wall species of the quartz liner used for formation.

The impurity content of the proposed FRCs are likely to be comparable or less than in previous experiments. Somewhat larger bias fields may cause larger quartz impurity release, but the gas fill pressures and the final FRC densities are two orders of magnitude higher than in recent FRC experiments. Hence, the impurity concentrations are likely to be smaller.

i. Open issues of FRC impurities during formation. Time-dependent calculations are needed to assess the impact of line radiation on FRC formation at MTF-relevant parameters. Even small concentrations of high-Z impurities may yield significant radiation power losses. However, it is likely that most important impurity concerns will arise from the liner-plasma interactions during compression rather than from initial FRC target plasma formation.

2. Liner Implosions: DP Developed Capabilities

a. Background. The broad scientific utility of high-speed liners with large kinetic energy has led to significant investment in liner physics studies and liner technology advancement. High-performance liners have, to date, been imploded by 5-15 MA of current from capacitor banks and greater than 100 MA of current from explosively powered flux compressors. Currently, operational capacitor bank facilities include Pegasus (4.5 MJ) at Los Alamos and Shiva-Star (9.2 MJ) at the Air Force Research Laboratory (AFRL) in Albuquerque. Under DOE sponsorship, Los Alamos is designing and constructing the 24 MJ Atlas facility with anticipated operation in 2001. Explosive flux compression generators producing 10-20 MJ are operational at Los Alamos and 50-100 MJ systems are in development. Similarly, explosive pulse power systems with greater than 100 MJ have been demonstrated at the All Russian Scientific Research Institute of Experimental Physics (VNIIEF) in Sarov, Russia. These systems have successfully imploded near-solid-density metal liners to MTF-relevant velocities. Shiva-Star is expected to be sufficient for the initial PoP implosion experiments envisaged in this proposal as discussed in Part C. Atlas and the explosive pulse power systems are expected to be adequate for follow-on proof-of-performance class experiments in the future. Thus, wide ranges of power systems are and will be available to meet the needs of MTF experiments.

b. Status of implosion liner performance. The axial z-pinch provides an effective and convenient configuration for driving liners with pulsed electrical energy. Here, the driving current is applied in the axial direction, giving rise to azimuthal magnetic fields outside the liner. Practical time-scales (microseconds), coupled with normal metal resistivity, (2-10 μΩ-cm), insure that the current distribution is limited to the outer surface at early times. For example, the magnetic diffusion skin depth in aluminum (2.7 μΩ-cm) is about 0.3 mm in 1 μs for a step increase in the vacuum field. The currents and fields diffuse into the millimeter thick conducting liner during the course of the implosion. Implosion velocities of 1 cm/μs have been demonstrated on present facilities while maintaining most of the liner at or above solid density, and while maintaining a significant fraction of the liner material below ambient melt temperature [Reinovsky96]. This velocity performance is sufficient for our proposed MTF PoP integrated compression experiment.

The drive pressure in the z-pinch configuration is applied to the outer surface of the liner by the magnetic field in a manner similar to a high-pressure but mass-less fluid. The acceleration of the outer surface (interface) is directed from the low-density (mass-less) fluid into the higher-mass-density metal liner. This is the magnetic analogy of the classical Rayleigh-Taylor (RT) fluid interface instability with an Atwood number equal to one. While the development of flute instabilities ($m > 0$) in the cylindrical liner is inhibited by the azimuthal driving field, the development of sausage instabilities ($m = 0$) on the outer surface poses an ultimate limitation on achievable liner convergence. Nevertheless, because material strength of solid liners inhibits instability growth, a convergence sufficient for an MTF PoP experiment (~10) is achievable with present liner-driver technology.

For the hydrodynamic RT instability, it has been shown analytically that fluid strength can reduce the growth rate of sufficiently small (wavelength and initial amplitude) perturbations as long as driving pressure is less than or the same order as the material strength [Chandrasekhar61]. The case of the magnetohydrodynamic RT is more complicated because the large currents needed to achieve interesting accelerations heat, and ultimately melt, part of the liner material, reducing or perhaps eliminating both the yield strength and shear modulus in the heated part of the liner. Furthermore, as the current diffuses into the liner, the time dependent behavior of material strength has a spatial dependence as well. Numerous analytic models of the hydrodynamic RT have been presented [Miles66, Drucker80, and Lebedev93] and some detailed comparisons with experiments have also been performed [Lebedev93, Robinson89, and Barns74].

Since 1994, an extended family of experiments have been conducted in the Los Alamos High-Energy-Density Physics (HEDP) program to explore the physics issues associated with accelerating liners. The high-precision liners developed in these experiments have also been applied to drive a variety of hydrodynamic and material-property experiments such as those identified above. Nearly 100 separate experiments have been performed on the Los Alamos Pegasus capacitor bank at driving currents up to 12 MA (0.5-2.5 MJ of stored energy) and velocities exceeding 10 km/s. In these experiments, a 3-gram aluminum liner (0.4-mm initial thickness) was accelerated to velocities from 0.4 to about 1 cm/μsec (50-100 kJ/cm). A significant number (approximately 15) of the Pegasus experiments were focused on of the RT instability of an imploding liner. Experimental results, with pre-imposed sinusoidal perturbations (10-50 micron amplitude and 0.5 - 6 mm wavelength), were in notable agreement with both the analytic and computational predictions of perturbation growth in both the elastic-plastic and fully melted fluid regime.

A limited number of very large-scale liner physics experiments have been performed jointly with VNIIEF, using explosively powered flux compression generators at 50-100 MA (25-50 MJ). In the largest of these experiments, a 1-kg aluminum liner was accelerated to 0.8 cm/μsec (32 MJ of kinetic energy at 3-5 MJ/cm). The liner initial radius was 20 cm and measurements were made at a radial convergence of about 4:1. The final radius in this experiment (5-6 cm) was specifically chosen to demonstrate liner performance appropriate for a large-scale MTF compression experiment. The Russian literature contains numerous references to comparable experiments, essentially demonstrating the reproducibility of high-current liner-compression techniques. During about the same period, several experiments with shaped- and mass-profiled liners conducted at the AFRL (10-15 MA currents at about 5 MJ stored energy) demonstrated the feasibility of axial mass contouring to achieve quasi-spherical implosions.

The combination of experience with imploding liners at kinetic energies ranging from 50 to 5000 kJ/cm, coupled with detailed comparisons between analytic theory, computational simulation, and experimental data for liner stability, provide reasonable confidence that liner technology appropriate for compression of MTF target plasmas is presently available.

c. Open issues of liner performance. The imploding liners appropriate for MTF compression experiments are similar to those being developed for HEDP experiments at Los Alamos. The HEDP research will continue to develop the technology needed for (large) high-velocity liners (approaching 50-

100 MJ kinetic energy). However, FRC-specific liners with larger length to diameter ratios, will require some development beyond liners for HEDP applications. Liner studies with bias magnetic field to determine the achievable compressed value of magnetic field in the specific geometry to be used for FRC compression are also important. Wall heating by eddy currents is severe for the mega-gauss fields to be used. Liner melting will reduce mechanical strength and increase electrical resistivity. These effects will limit the maximum fields that can be achieved by compression. Liner melting may also enhance impurity concerns and affect liner stability. Computational models to quantify these concerns are available and will need to be used and checked by liner experiments before integrated liner-on-plasma experiments are started. Also, liner-electrode interactions and the injection of metal vapor at the ends of the liner into the volume where plasma is to be compressed will require careful study. The proposed MTF program will include design and prototyping of liners appropriate to an MTF compression experiment based on the analytic, computational, and experimental databases from HEDP. For a selected driver/target configuration, the demonstration of required liner properties (velocity, symmetry, shape, vacuum integrity, and uniformity) will be a pre-requisite to a plasma compression experiment.

3. Integrated Compression

This first serious attempt to design and conduct integrated compression experiments depends upon target plasma development activities combined with the experience base of high-energy liner implosion technology. The integrated experiments will provide extremely interesting data on imploding MTF systems. Experimental data is needed to support the computational evaluation of MTF as an approach to achieving fusion energy. While significant advances in MTF physics are expected from these first integrated compression experiments, it is not realistic to expect early experiments to reach high fusion reactivity. Rather, our goal is to develop a scientific basis for MTF from which its potential can be evaluated. This entails assessing liner-plasma stability, plasma impurity content, and plasma transport under fusion-relevant implosion conditions.

a. Status of liner-plasma interactions. A small number of FRC liner compression experiments were done on the TOR-liner device [Alikhanov83, Es'kov81]. An FRC was translated into a 5-cm-radius liner with the following estimated parameters: $B_e \sim 0.5$ T, $n \sim 4\text{x}10^{15}$ cm^{-3}, $T_e \sim T_i \sim 50$ eV, $r_s \sim 4$ cm, and $l_s \sim$ 20 cm. These parameters correspond to S*/E ~ 3. A medium-speed (~ 1 mm/μs) quasi-spherical liner compression (compression ratio ~5 - 10) was achieved with a shaped liner. A global neutron yield of about $2\text{x}10^8$ was reported. Zero-D modeling [Es'kov83] confirmed that this neutron yield is consistent with volume compression ratios of about 1000 and plasma temperatures of 1.5 - 3.5 keV, depending on assumed cross-field transport. Unfortunately, very few plasma measurements have been reported and these encouraging results were not pursued.

b. Open issues of liner-plasma interactions. Our plasma compression scheme entails injecting a formed FRC into an imploding liner. A significant challenge is impurity release from the liner into the plasma target. Armstrong [Armstrong87] believed that ejecta from the liner walls prior to the FRC arrival, was an issue. However, he evaluated the ejecta for the case with explosive drive when shock waves reach the inner liner surface. Shocks and associated ejecta are minimized with the electric drive proposed here.

Understanding of liner issues described above, such as metal jets produced by the liner motion along the end glide-plane electrodes, will be critically tested in liner-on-plasma experiments. Obviously the issue of liner melting will also be important, both on the outside from the axial currents that drive compression, and on the inside from induced currents associated with the rising external field between the FRC separatrix and inner liner radius.

4. Theory and Computation: Status and Issues

a. Status. The proof of principle evaluation of MTF in a timely fashion and at minimum cost will require a strong synergism between experimental, theoretical, and computational efforts. We envision a cycle in which large-scale numerical computations guide experimental design, followed by detailed comparison of the experimental data with the corresponding computational predictions. Based on these comparisons, further development of the theory and modification of the computational tools will follow as appropriate. Finally, to complete the cycle, analysis of the experimental results will be used to guide the experimental evolution. This paradigm involving large-scale computation has been well proven in ICF and other DOE defense programs research activities.

Because of the dynamic nature of MTF experiments, extending the experiment/compute/experiment paradigm to MTF is optimum when both the plasma formation step and the liner implosion step are computed from t=0. That is, computations should begin at the plasma formation stage. The computations should include physical effects not normally considered in modeling of steady-state magnetized fusion systems. Examples of such effects include: material properties (equation-of-state, strength, resistivity, radiation, thermal conductivity, etc.) for solids, liquids, and partially ionized plasmas; shocks and dynamic non-equilibrium fluid flows; and convective energy loss from the plasma to its cold surroundings.

Fortunately, many computer codes already developed for ICF and other DOE programs are directly applicable to MTF research. For example, the LASNEX code (the computational tool that provides the theoretical basis for the national ICF program and the NIF) has confirmed that the potential parameter space for operation of magnetized targets is much more extensive than that for unmagnetized targets [Kirkpatrick91]. The MHRDR code (LANL), TRAC-II code (LLNL), and the MACH-2 code (AFRL) have predicted many of the observations (e.g., inductive probes, interferometry, x-ray emission, visible emission, neutron production) of the Russian MAGO plasma formation scheme that, to the extent that the computations are valid, has many of the properties required for a pre-implosion plasma [Lindemuth95]. The MACH-2 and TRAC-II codes have successfully modeled the RACE compact torus experiment. The one-dimensional code RAVEN and two-dimensional radiation magnetohydrodynamic (RMHD) computer codes have been used at Los Alamos to understand and interpret liner experiments in the implosion velocity range required for MTF [Faehl97]. The MOQUI code has been used to design FRC experiments and to interpret the behavior of FRC formation and translation from t = 0 (Milroy82). A number of zero-dimensional circuit/liner codes (eg. MSG, CONFUSE at LANL) are available to identify parameters for liner-on-plasma systems.

The strong synergism between MTF research and the on-going imploding liner research funded by DOE Defense Programs means that MTF will benefit from the major advancements in computing expected through the ASCI initiative. Already, ASCI codes are looking to pulsed-power-driven experiments, involving magnetic fields and magnetized plasmas, to contribute to the database required for code validation. Fully 3-D computer codes, which can model the combined liner and plasma dynamics of an MTF system, are expected to become operational in the same time frame as this proposal.

b. Issues. An obvious technical challenge for MTF is enhanced radiation due to impurities derived from plasma-liner interactions. Little data and essentially no theoretical work are available to estimate the amount of impurities that can be introduced into the plasma from the possible sources that have been identified. Initial theoretical work suggests that MTF plasma may actually expel impurities from the plasma core [see Appendix C and Vekshtein90]. The short confinement times of MTF mean that wall-confined plasmas, or plasmas in very close proximity to the wall (i.e., pusher or liner), may be acceptable and desirable. The pioneering work at Columbia University [Gross75, Feinberg76] offers hope that transport from a hot plasma to a confining wall by thermal conduction may be "classical." However, 2-D computations [Lindemuth78] show that under certain circumstances, transport to the wall may be enhanced by 2-D convective flows. Understanding hot plasma interacting with a cold wall as discussed in Appendix C is rich in physical phenomena and is a principal focus of our proposed theory-modeling effort.

Mating a plasma formation system with a magnetically-driven imploding liner is the fundamental requirement of MTF. Considering the limited experience in this area, and recognizing that not all of the physics issues can be satisfactorily addressed by theory and computation without experiments, our goal is to move toward liner-on-plasma experimentation as soon as plasma formation and liner implosion are separately and satisfactorily understood. Computational modeling of the integrated compression experiments will be an essential component of understanding the complex physics of plasma stability and wall interactions. Codes for this purpose will involve modifications of existing and ASCI-class codes from DOE's Defense Programs.

PART C: RESEARCH PROGRAM

We propose below an MTF PoP program based on the FRC target plasma. The experimental effort consists of three phases: (1) the FRC is formed in a conical theta pinch, (2) the FRC is translated and trapped in a liner suitable for implosion, and (3) the FRC is compressed by the liner to high temperature and density. To quantify the plasma parameters desired, we use a Zero-D model for FRC performance.

Zero-D modeling of FRC performance.

This 0-D model for cylindrical FRC liner (or wall) compression is based on past FRC research [Rej84] and is very similar to that used in an earlier evaluation of FRC liner compression [Armstrong87]. The calculation starts with an FRC at rest inside a liner and ends when a radial compression of 10 is achieved. The main assumptions of the model are:

(1) 2-D elongated FRC equilibrium at all times,
(2) thin liner with constant radial velocity v_L,
(3) S*/E < 3.5 at all times,
(4) FRC transport: $\tau_E \sim 0.5R^2/\rho_i$, $\tau_N \sim \tau_\phi \sim R^2/\rho_{i,}$, and
(5) liner resistivity and heating are considered.

The last assumption affects diffusion of the magnetic field in the sheath separating the liner from the FRC into the liner. The FRC formation requirements are calculated a posteriori, assuming identical FRC parameters after formation and before compression. This implies translation at constant external pressure and equal dimensions for the formation and initial liner regions. Similar translation has been demonstrated [Rej86]. An example of FRC parameters obtained from the 0-D model is given in Table 3.

Zero-D Modeling parameters

Liner assumptions:	initial dimensions: 1-mm-thick aluminum, 30-cm-length, 10-cm-diameter
	mass: 250 g
	velocity: 0.3 cm/μs
	kinetic energy: 1 MJ
	compression time: 15 μs
	dwell time (r_{c2}/v_L): 2 μs
Equivalent DT fusion yield:	neutron yield: 3×10^{16}
	fusion energy: 0.1 MJ
	Q (fusion/liner energies): 0.1
	Efficiency (plasma/liner energies): 0.08
Conical theta pinch coil:	radius: 4 - 6 cm; length: 30 cm
	COLT Facility
	voltage: single feed, 32 kV; electric field: 1 kV/cm
	main field risetime: 2.5 μs
	deuterium gas fill pressure: 300 mTorr
	lift-off bias field: 0.8 T

Table 3. Zero-D calculations of FRC parameters

Parameter	before compression	after compression
coil radius (cm)	5	0.5
separatrix radius (cm)	2.3	0.2
coil length (cm)	30	30
separatrix length (cm)	30	4.2
B external (T)	5.4	520
peak density (10^{17} cm^{-3})	1.2	350
T_e (keV)	0.3	8.6
T_i (keV)	0.3	10.6
plasma energy (kJ)	7.4	80
τ_E (μs)	28	4
particle inventory (10^{19})	5.0	1.7
internal flux (mWb)	10	6.4
S*	23	35
E	6.7	11
S*/E	3.5	3.3

Discussion and scaling arguments. These 0-D calculations have tentatively identified an interesting PoP design point. The location of this design point before and after compression is indicated in Fig. 3 as FRX-L. The FRC initial state is chosen to satisfy S*/E = 3.5. During compression, S*/E decreases slightly, so that the FRC remains in the empirical domain of good FRC confinement. The ratio S*/E decreases less than predicted by the adiabatic scaling laws because of the significant energy losses in the example of Table 3 (τ_E only about twice the compression time). Reduced losses can be obtained with higher liner velocities: this would reduce the values of S*/E during compression but would also somewhat reduce the Q values (increased liner energy).

The impact of the parameters S* and E can be estimated by considering the scaling of the fusion yield for fixed temperatures and a fixed radial compression ratio. We assume that losses are small by requiring the initial FRC confinement time to exceed the compression time by a constant factor of 3. The FRC final parameters scale as the initial parameters, so that we drop subscripts 1 and 2. Then, the fusion yield $E_f \sim n^2 V \tau_{dwell}$. With $\tau_{dwell} \sim r_c/v_L$, $V \sim r_s^2 l_s$, $S^* \sim r_s^2 n^{1/2}$, and S*/E = c, one obtains $E_f \sim c^4 E^5/(x_s v_L)$. From $\tau_E \sim \tau_{dwell}$ and $\tau_E \sim S^* r_s$, one further obtains $x_s v_L \sim 1/S^*$. Hence, the fusion yield scales as $\mathbf{E_f \sim c^5 E^6}$, where E is the FRC elongation before compression.

This expression shows the importance of maximizing c in the FRC formation experiments that would occur in the first part of the project. If FRCs with good confinement properties can be obtained with c = 5.8 (dashed line in Fig. 3) rather than the assumed c = 3.5 (solid line in Fig. 3), an order of magnitude increase in fusion yield could be obtained. This indicates that an important aspect of the proposed research coincides with a crucial issue in FRC research. Further insight into this issue, whether it is stability, confinement, or formation, will be gained during the proposed experiments.

The above fusion yield scaling also shows the importance of elongation E. If FRC physics constrains c to a given value, E_f can still be significantly increased by increasing the FRC elongation. For fixed liner dimensions, this implies low values of x_s, as in the example of Table 3. For fixed FRC separatrix radius before compression, this implies longer liners. Ultimately, E_f would be limited only by the magnetic field pressures that can be achieved at peak compression (B ~ length).

1. Target Plasma

a. Target Plasma Goal. The principal goal of the first two years of experimental research will be to develop the formation of an FRC target plasma in a liner that is suitable for implosion. Specifically:

- forming an FRC with the properties shown in Table 3, and
- translating the formed FRC into a liner suitable for compression.

b. Target Plasma Approach. The first FRC formation experiments will be performed with a straight theta-pinch coil in a symmetric configuration without axial motion. Independent cusp coils at each end will be used to insure fast and symmetric non-tearing field line reconnection [Tuszewski88]. A theta-pinch coil radius of about 5-cm and a coil length of 30 cm may be used for the first experiments. A dielectric tube (quartz or alumina) of 4.5 cm radius will be inserted inside the coil. The coil would be connected to the existing Colt bank via collector plates and 40 load cables, yielding main field risetimes of 2-3 µs. The reversed bias fields will be generated from a slow ignitron-switched capacitor bank (FRX-C compression modules) connected to the coil collector plate.

FRC formation will be explored with external fields B_e up to 5 T, reversed bias fields of up to 1 T, and deuterium gas fill pressures of 100 - 400 mTorr. Several key FRC physics issues will be explored during these preliminary formation experiments. These issues include FRC heating and internal flux retention, axial dynamics following field line connection, dielectric tube heating and possible impurity release during field reversal, FRC global energy confinement, stable period before the n = 2 rotational instability, and FRC global stability as function of S*/E.

Most FRC formation issues can be assessed with two basic diagnostics: an excluded flux array that yields β and $r_s(z)$, and a side-on laser interferometer to estimate the plasma density. Then, both $S^* \propto r_s n^{1/2}$ and $E = l_s/(2r_s)$ can be obtained as function of time. The FRC particle confinement time can also be assessed with those two diagnostics. In addition, the excluded flux array will provide information on internal flux annihilation, axial dynamics during formation, and energy confinement during the equilibrium phase. The two diagnostics would also yield an estimate of the plasma total temperature ($T_e + T_i$) from radial pressure balance. The excluded flux array could be easily built with a single flux loop and an array of B_z probes. Laser interferometers at 0.44 µm (HeCd) and 3.39 µm (HeNe) can be constructed using available Colt and old FRX-C hardware.

During the second year of the experimental program, other diagnostics will be used, such as single-point Thomson scattering to measure electron temperature and CV Doppler broadening and neutron yield, to estimate the ion temperature. Optical emission and bolometry are expected to estimate the impurity species and the radiated power. The latter may prove a crucial issue for the proposed FRC targets formed with bias fields of about 1 T. Such large bias fields are likely to cause large thermal pulses [Steinhauer83] on the dielectric inner surface during reversal. Initial estimates indicate that wall temperatures of several thousand degrees could occur transiently with a quartz tube. Substantially lower temperatures (by factors of at least 5) would occur with an alumina tube.

FRC formation in a conical theta-pinch and subsequent translation into a metal flux conserver of similar dimensions would be performed during the second year of the proposed research. A cone angle of about 4 ° should be sufficient to provide the axial force required to accelerate the FRC out of the coil and to translate it into the flux conserver in less than 10 μs. The FRC will be trapped, either with an end mirror field or with shaping of the end portion of the flux conserver. The translated FRC confinement properties must be assessed inside the flux conserver, with an excluded flux array and laser interferometry. Numerical simulations with the MOQUI code will guide the experimental translation and trapping studies.

A key variable is the initial external field B_0 that is established inside the flux conserver prior to FRC translation. The external field controls to a great extent, the translation velocity, FRC trapping, translated FRC volume, and the ratio of translated FRC separatrix radius to flux conserver radius. The FRC confinement and the onset of the n = 2 rotational instability will be studied as function of B_0. The translation and trapping processes must be optimized, with flux conservers of various shapes, prior to liner implosion tests. Liner studies, performed in parallel with the above FRC formation studies, will contribute significantly to the definition of the flux conserver geometry.

c. Target Plasma Facilities. Target plasma formation will use the Los Alamos Colt facility. This facility includes a single Maxwell Shiva capacitor bank module, vacuum/load chamber, screen-room, "standard" diagnostic set, and data recording equipment. The capacitor bank is a two-stage Marx consisting of 12 6-μF capacitors in each stage. The maximum charge voltage is 60 kV per stage, and when switched, erects to twice the charge voltage. Switching is provided by a Maxwell rail-gap switch. The maximum stored energy at full charge is 0.25 MJ. The total system inductance is roughly 100 nH, including the inductance of a typical load assembly. The bank can deliver (without too much stress) 2 MA of current rising in 2.5 μs. The output of the bank is cable-coupled to a vacuum/load chamber (61 cm diameter by 80 cm long) by 40 RG-17/14 coaxial cables. At the load chamber, the power feed is converted to a generic coaxial feed (outer electrode is ground, inner electrode is positive). The specific experimental load assembly is bolted to the generic coaxial feed. This facility has previously been used for Dense-Plasma-Focus experiments, vacuum-power-flow experiments, plasma-flow-switch experiments, and z-pinch MTF target experiments. Removal of one experimental load assembly and installation of a different experimental load assembly is usually accomplished in 2-3 days.

In addition to the Maxwell Shiva module, the facility has ten FRX-C "compressor modules" (10 kV, 50 kJ capacitor modules switched and crowbarred with ignitron switches). These modules are available for driving bias coils on a timescale longer than the liner L/R time; perfect for FRC formation. One such module is already wired to a charging power supply and controls system, and is ready to drive a load.

The floor space of Colt is 2100 sq-ft. There are 56 channels of high-speed signal recording. Present diagnostics include, drive-current Rogowski coils, B-dot probes with a minimum of 2-mm insertion into the plasma edge, 1 channel of HeCd (442 nm) laser interferometer, visible framing camera, visible near-UV monochrometer, two 7-channel filtered soft-xray diode arrays. Thomson scattering is under (re) construction, using the previous LANL CTX 25 J pulsed ruby laser and multipoint spectrometer, and will be operational by the end of FY 1998.

The traditional FRC formation method requires a main-drive capacitor bank, a preionization bank, and several sets of bias coils powered by two independent capacitor banks. Thus, to produce FRC plasmas, the appropriate load structure must be designed and fabricated for installation in the Colt facility. An

FRC- producing load assembly will require a parallel-plate feed driving a theta-pinch coil, coupled with a set of bias coils. In this case, we would disconnect the 40 output cables from the usual load-chamber and reconnect them to a short parallel-plate feed driving the theta-pinch coil. A separate vacuum chamber is required, but the existing pumping stand (roughing and turbo pumps) would be used.

2. Liner

a. Liner Goal. Develop the vacuum implosion of a 30-cm long, 10-cm diameter, 1-mm thick aluminum liner with a velocity of 3 mm/µs and radial convergence of 10.

b. Liner Approach. Typical liners used for DP applications have near-unity length to diameter ratios. FRC compression requires a length-to-diameter ratio of approximately 3. During the first two years, the Shiva-Star driver will be used to develop vacuum implosions of an FRC-relevant liner with length, width, and thickness dimensions of 30cm, 10cm, and 1mm respectively. Initial one-dimensional calculations (Fig. 4) indicate that Shiva-Star can drive this 250g aluminum liner to the required implosion velocity of 3mm/µs. In conjunction with prototyping the FRC liner, diagnostics will be fielded to measure impurity content in the liner compression zone. An initial assessment will be made of impurities associated with ejecta and glide-plane electrode interactions during vacuum implosions.

c. Liner Facilities (Shiva Star Overview). The experimental pulsed-power facilities at the Air Force Research Laboratory (Phillips Research Site, Kirtland AFB, NM) consist of: 1) two laboratory buildings with several capacitor banks ranging from tens of kilojoules, tens of kilovolts to 9 megajoules, 2) tens of megamps with direct discharge current risetimes of 1 to several microseconds; and 3) several moderately compact Marx banks with outputs in the few 100 kilovolt to megavolt, few ohm to tens of ohms, 100 nanosecond to microsecond range.

The 9 megajoule Shiva Star capacitor bank has a capacitance of 1300 microfarads, can be charged up to 120 kilovolts, can tolerate 75% voltage reversal, and has a bank plus transmission line inductance of 3 nanohenries. It is normally used with a series safety fuse that limits its current in fault mode to 40 megamps. Direct discharge currents in past experiments have ranged from 12-15 megamps to implosion loads to 30 megamps to inductive store-opening switch loads, with current rise times ranging from 3 to 10 microseconds, depending on load inductance. Plasma flow switches have been used to sharpen current rise times to 250 nanoseconds, delivering 10 megamps to implosion loads. Shiva Star has flexible charging and triggering options, enabling the use of portions of the bank for lower energy, faster risetime discharges, and the use of non-destructive loads. The Shiva Star bank also has a 0.75-megajoule auxiliary capacitor bank integrated into its structure. This auxiliary bank, called the plasma formation bank, has been used to form compact toroids for subsequent acceleration, and has been used to form plasma working fluid for subsequent compression by solid liner implosions. This auxiliary bank can be used to form a variety of initial plasma - magnetic field configurations for subsequent compression.

The AFRL facilities include radiofrequency shielded enclosures with numerous fast transient digitizer and analog recorders for data acquisition. They include substantial vacuum and power supply hardware; pulsed current, voltage, and magnetic field diagnostics; rotating mirror and gated microchannel plate tube fast photography; optical, RF, vacuum-ultra-violet, X-ray, gamma, and neutron spectroscopy equipment; pulsed radiography equipment; fast closure shutters and shielding to protect and enable use of these diagnostics in the blast and debris environments encountered in higher energy (multi-megajoule) experiments.

There are extensive complementary theoretical and computational abilities and resources. These include one-, two-, and three-dimensional radiation MHD and particle-in-cell codes which have been developed, and are being further developed, to guide and interpret experiments. There is extensive development of parallel versions of these codes, and of parallel processing, high performance computing techniques. A simple one-dimensional code that has proven useful for first-cut estimates has been used to examine the dynamics of the liner described above when driven by the Shiva Star main energy bank. The results are shown in Fig. 4.

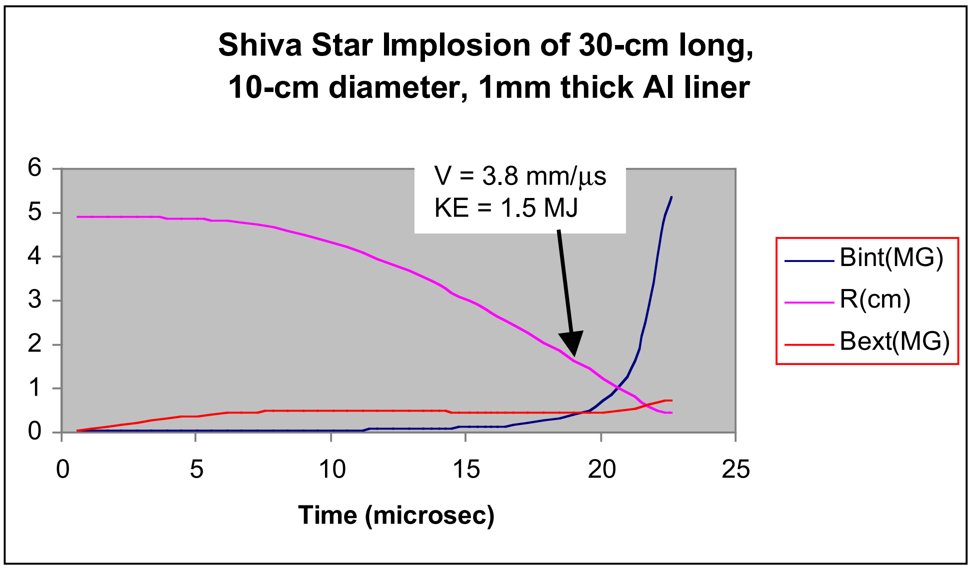


Fig. 4. One-dimensional simulation of liner implosion (AFRL) showing liner radius R(t), external B_θ(MG) driving field, and internal B_z vs. time.

3. Integrated Compression

a. Goal of Integrated Experiments. Demonstrate that substantial heating and increased nτ results from liner implosion of an FRC according to present understanding of FRC physics.

b. Approach to Integrated Experiments. ***Cylindrical compression:*** The FRC will first be compressed radially in the third year by a near-cylindrical liner. We envisage this experimental campaign to use the Shiva-Star facility. For this case, the FRC would be in near 2-D elongated equilibrium during most of the compression, with x_s values anywhere from 0.4 to 0.9 by selecting initial liner bias field and radius. The latter can be done by proper timing of the FRC arrival into a liner in motion. Compressional (2.4-D) plasma heating can be achieved by cylindrical liner implosion because axial compression contributes an additional 0.4-D [Spencer83]. This option combines geometrical simplicity, considerable flexibility, and a high possibility of minimum impurity influx from the liner. In particular, the FRC separatrix during compression would quickly move away from the liner ends where metal vapor may result from liner/electrode interactions. In addition, the FRC separatrix divertor could also be more isolated from the inner liner radius, if thermal contact or impurities prove a major concern. Open-field-line FRC physics could be tested with low-Z coatings on the inner liner surface.

A complete set of FRC formation hardware will be procured and fabricated for such tests. FRC formation and translation will probably be performed with the liner in motion. The initial experiments will focus on proper timing and isolation of the different electrical circuits. The liner energy and radial velocity will be progressively increased, on successive shots, to estimate FRC heating and liner-plasma interactions for different compression ratios and ratios of separatrix to wall radii.

Development of plasma diagnostics to estimate FRC heating and confinement will be completed in time for integrated compression testing. The external magnetic field and the plasma density will be measured during plasma compression. Optical emission, end-on framing cameras, end-on inferometery, and neutron diagnostics will be available for the initial tests.

Quasi-spherical compression: Based on cylindrical compression results, the FRC could be compressed in nearly 3-D by a shaped liner. The FRC separatrix would remain close to the liner at all times during compression. This option has been explored theoretically [Alikhanov83] and experimentally [Es'kov81] to some extent. Recent 2-D MHD simulations with the MOQUI code [Milroy 82], shown in Fig. 5, indicate that an FRC target can be formed and moved in to a shaped liner in less than about 8 μs. The translated FRC could have values of x_s as high as 0.9 inside the liner by choosing a small initial liner bias magnetic field. This option offers the potential for high liner compression efficiencies, for small liner volumes, for wall stabilization of possible instabilities such as rotational modes, and for quasi-spherical wall compression that maximizes plasma heating (full 3-D compression). Threats include possible FRC stability concerns due to small elongations and impurity influx from the liner. In particular, liner end effects need to be carefully evaluated. The decision to move forward with a quasi-spherical compression will be guided by the initial integrated compression experimental results and modeling of plasma-liner interactions.

c. Facilities for Integrated Experiments. This experimental campaign is envisaged to use the Shiva-Star facility described above.

4. Theory and Modeling Approach

The theoretical effort, like the experimental effort, can be separated into three parts: (a) plasma formation, (b) liner implosion, and (c) liner-on-plasma compression. In each of these three areas, the effort can be broken into the following tasks:

(1) experimental design and parameter selection;
(2) detailed analysis and interpretation of experimental results;
(3) based upon task 2, evaluating the limitations of the computational models that formulating appropriate modifications;
(4) development and application of analytic theories to provide simple interpretations of experimental results;
(5) development of complex, highly non-linear models that are amenable only to numerical solution by incorporation into existing or yet-to-be-developed (e.g., ASCI) computer codes, and
(6) computationally exploring alternate configurations based on task 2.

Our starting point for computational modeling of MTF is the strongly coupled, highly non-linear equations of resistive, non-ideal MHD. The most elemental system consists of a continuity equation, an equation of motion, an energy equation, and Faraday's law. The equation of motion includes the plasma self-pressure force and the Lorentz force and requires, for liners, a model of the material strength. The energy equation requires an equation-of-state and models of the thermal conductivity and radiative emission and includes, for liners, heating due to internal stresses. The simplest form of Ohm's law requires a resistivity model for magnetic field diffusion and requires the inclusion of Ohmic heating in the energy equation.

In general, the ion and electron temperatures can be different, in which case the single energy equation must be replaced by two energy equations that include the coupling of energy between the ions and electrons in addition to thermal conductivity, radiation (electrons), and Ohmic heating (electrons). Also, it may be necessary to include even a third energy equation that describes the temporal and spatial variation of the radiation energy density. In fact, most simulations of liners are "two-temperature" simulations where two energy equations are used, one to describe the material temperature and one to describe the radiation temperature.

For most plasma simulations, the transport coefficients (e.g., thermal conductivity, and resistivity) are "classical," i.e.; the prescriptions derived by Braginskii are used. However, the Braginskii presentation must be supplemented with models that incorporate partial ionization effects, because experience in modeling MTF-like plasmas has already shown that the traditional assumption of complete ionization, as an initial condition for a computation, is not satisfactory. In addition, experience in modeling the FRC has shown that it is necessary to invoke an "anomalous resistivity" to stimulate the experimentally observed field-line tearing and formation.

Some of the more successful FRC and other CT experiments have shown that standard MHD models do not adequately explain the plasma behavior, even when anomalous resistivity is included. Hence, we cannot discount the possibility that using available hybrid and kinetic codes may be required to adequately understand MTF plasma behavior. Unfortunately, these codes have not reached the level of development where they can be routinely used for experimental design, analysis, and interpretation (tasks 1, 2, 4) with the close correspondence between computation and experimental geometry and timescale expected from the MHD codes.

Existing models for material properties (e.g., equation-of-state, resistivity, strength) of candidate liner materials, such as aluminum and tungsten, have not always proven to be satisfactory. Although the properties at standard atmospheric conditions are well known, the temperature, density, and pressure of the liner material will change substantially during the course of the liner's acceleration and implosion, and the liner material will enter thermodynamic regimes for which the material properties have not been well characterized. We anticipate that many of the computational issues related to liners will have to be solved independently of this proposal in the ongoing Defense Program's liner research, but we also anticipate a need for MTF-specific research along these lines.

The preceding discussion should make it clear that using the available computational tools to perform the many "numerical experiments" needed to ensure the success of this proposal requires not only highly sophisticated understanding of the physical issues involved, but also a high level of empiricism and skills developed from "hands-on" experience. In conducting tasks 1-4, we will make use of the extensive expertise already developed in non-MTF contexts in the modeling of plasmas and liners.

Once experimental data becomes available from plasma formation experiments, the modeling focus will shift to task 2: analyzing the data and interpreting the experimental results. The detailed work here involves direct comparisons between observations and computations and, where necessary, resolving any discrepancies. Often, the computational analog requires a sophisticated "post-processor" computation. For example, the computational analog of a light-emission diagnostic requires not only the density and temperature profiles determined through the "computer experiment," but also calculations of emission and absorption of light integrated over the line of sight of the experimental diagnostic.

When discrepancies between simulations and observations are attributed to code deficiencies, modifications will be formulated (tasks 3, 6). Because the ultimate goal is to move to liner-on-plasma experimentation as quickly as possible, the decision that a candidate plasma is "suitable for subsequent implosion" will most likely be made only after a close correlation is achieved between observations and simulations and after a projection (task 4) of attractive performance for a conceivable liner-on-plasma system.

In most simulations of the plasma formation stage, only the plasma behavior will be computed, and the walls surrounding the plasma or coils within the plasma will be represented as external or internal boundary conditions. Hence, in computational parlance, the plasma simulations are "single-material." However, the detailed simulation of liners and liner-on-plasma systems requires a "multi-material" approach. In a typical liner-on-plasma simulation, the plasma will be, of course, hydrogenic, but the liner will be metallic (e.g., aluminum) and the liner electrodes, or "glide planes," will be of higher density (e.g., stainless steel). The already existing capabilities to perform multi-material simulations enhance the prospects for rapid progress in all areas of MTF.

The theoretical and computational effort will begin by designing the FRC target plasma. Because the MOQUI code has already proven successful in this application, it will be the principal tool most exercised. An example of a recent MOQUI computation showing how an FRC can be formed in a density regime that is of interest to MTF is shown in Fig. 5. This example of work in progress assumes the Colt bank generates 5T in 2.5 microseconds with a bias field of 1T and initial fill pressure of 250 mTorr on the left hand conical theta pinch. The FRC is formed with T~250 eV, and $n \sim 2 \times 10^{17}$ cm^{-3}. The geometry and liner bias fields are being iterated upon to develop a realistic liner shape that should be capable of trapping an FRC and imploding it using a variable-thickness liner shaped in a 5-cm region at each end near stationary electrodes. Flux imbedded in the liner on a slow time scale before FRC injection creates a magnetic well that centers the FRC in the liner. The idea is to achieve a uniform cylindrical implosion in the central 30 cm of the liner with electrical connection preserved by the deformed liner at the ends.

Because fully integrated liner-on-plasma multi-dimensional computations will be costly and manpower intensive, a hierarchy of computational procedures will be employed, beginning with simple zero-dimensional system modeling and ending with the most complete, multidimensional integrated computation possible. An example of an intermediate computation is shown in Fig. 6. One-dimensional magnetohydrodynamic computations were done with the LANL code MHRDR, which has been previously benchmarked on a number of experiments in which the plasma density was in the MTF regime [Lindemuth 95].

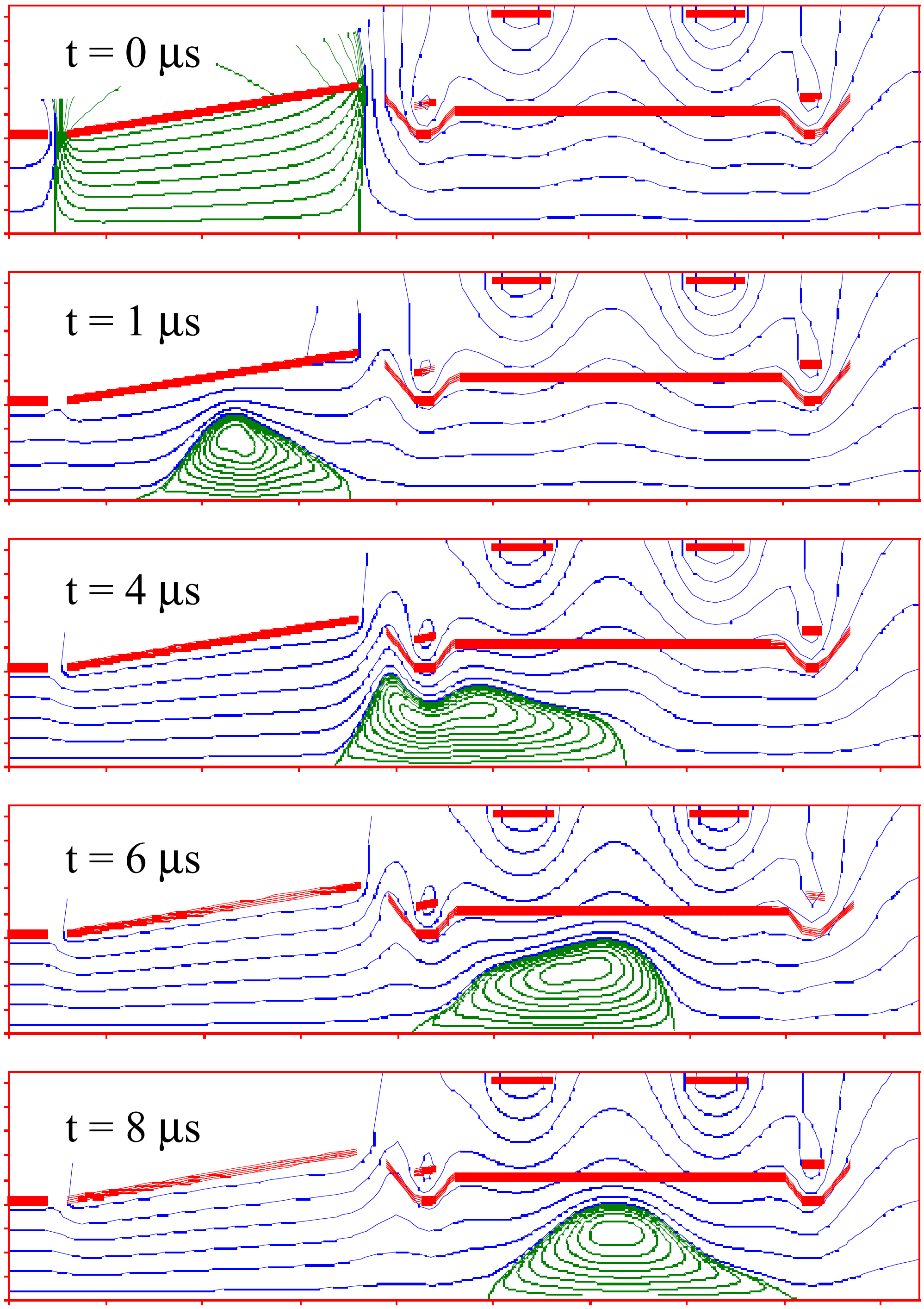


Fig. 5. MOQUI Calculation of FRC formation and injection into liner-compatible geometry. The conical theta pinch is on the left, and the liner is on the right.

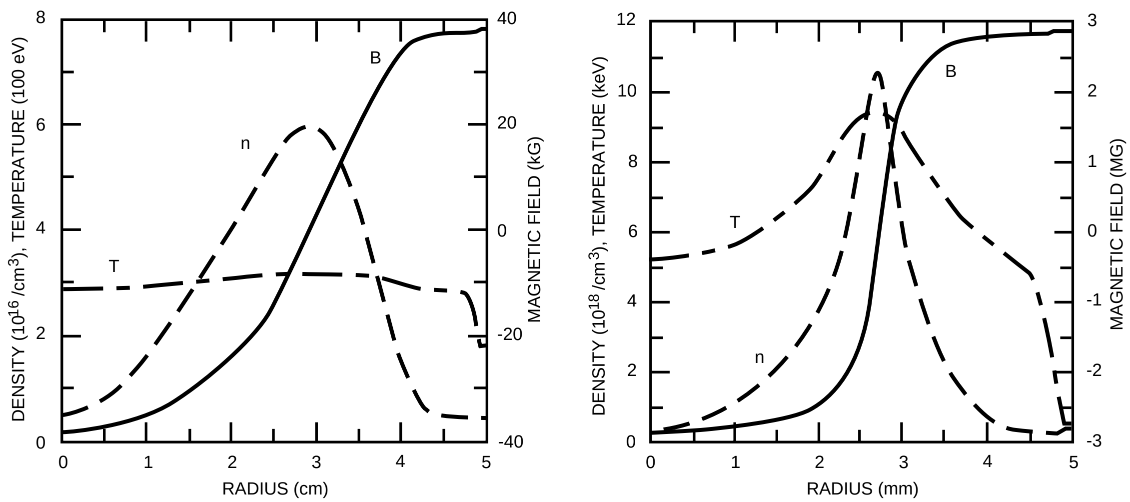


Fig. 6. FRC profiles of density (n), temperature (T), and poloidal magnetic field (B) at: (a) t=2 μs, immediately prior to implosion at 3 mm/μs; (b) t=17 μs, when liner has reached a radial convergence of 10.

The purpose of the computations in Fig. 6 is to begin exploring the behavior of FRC plasmas under liner implosion conditions that result from a nearby low-temperature liner boundary. The computations were initialized at t=0 with radial profiles of density, temperature, and magnetic field representative of those in an FRC immediately after injection into a liner. The model is only one-dimensional, which makes the poor approximation that all field lines are infinitely long. Thus there is no distinction for transport in the axial direction inside and outside the separatrix. Classical perpendicular transport in the radial direction ("classical" Braginskii) is included in the computations under the assumption that the wall is at zero temperature. Resistive diffusion, Ohmic heating, and Bremsstrahlung radiation were also included in the computations. Other than demonstrating an example of code capability, the calculation demonstrates mainly that classical cross-field transport is negligible even for the very small dimensions and medium-high density that might occur between an FRC separatrix and the nearby liner wall.

Some details of the calculation are interesting to consider. The initial profiles were allowed to relax for 2 μs, leading to the profiles shown in Fig. 6. At 2 μs, the outer wall was computationally moved radially inward at a velocity of 3 mm/μs, thereby simulating the compression of the FRC plasma by a cylindrical liner. At 17 μs, the time at which the liner stops at a radius of 5 mm and a convergence of 10, the profiles had evolved into those shown in Fig. 6. An adiabatic compression would have led to a density increase of 100 (10^2), a magnetic field increase of 100 (10^2), and a temperature increase of 22 ($10^{4/3}$). The profiles show approximately adiabatic behavior. However, the adiabaticity is affected in part by the thermal conduction and resistive diffusion, and the profiles show some steepening because the magnetic field under compression conditions is "stiffer" than the plasma, with the field having an effective γ of 2, compared to the plasma γ of 5/3. These computations illustrate a basic difference between MTF and ICF. Whereas ICF requires strong, carefully timed shocks to raise the fuel to fusion temperatures, MTF is essentially a slow, adiabatic process that is relatively insensitive to the acceleration profile of the liner.

5. Schedule, Key Decisions, and Budget

Figure 7 shows in pert-chart form the main tasks and key decision points.

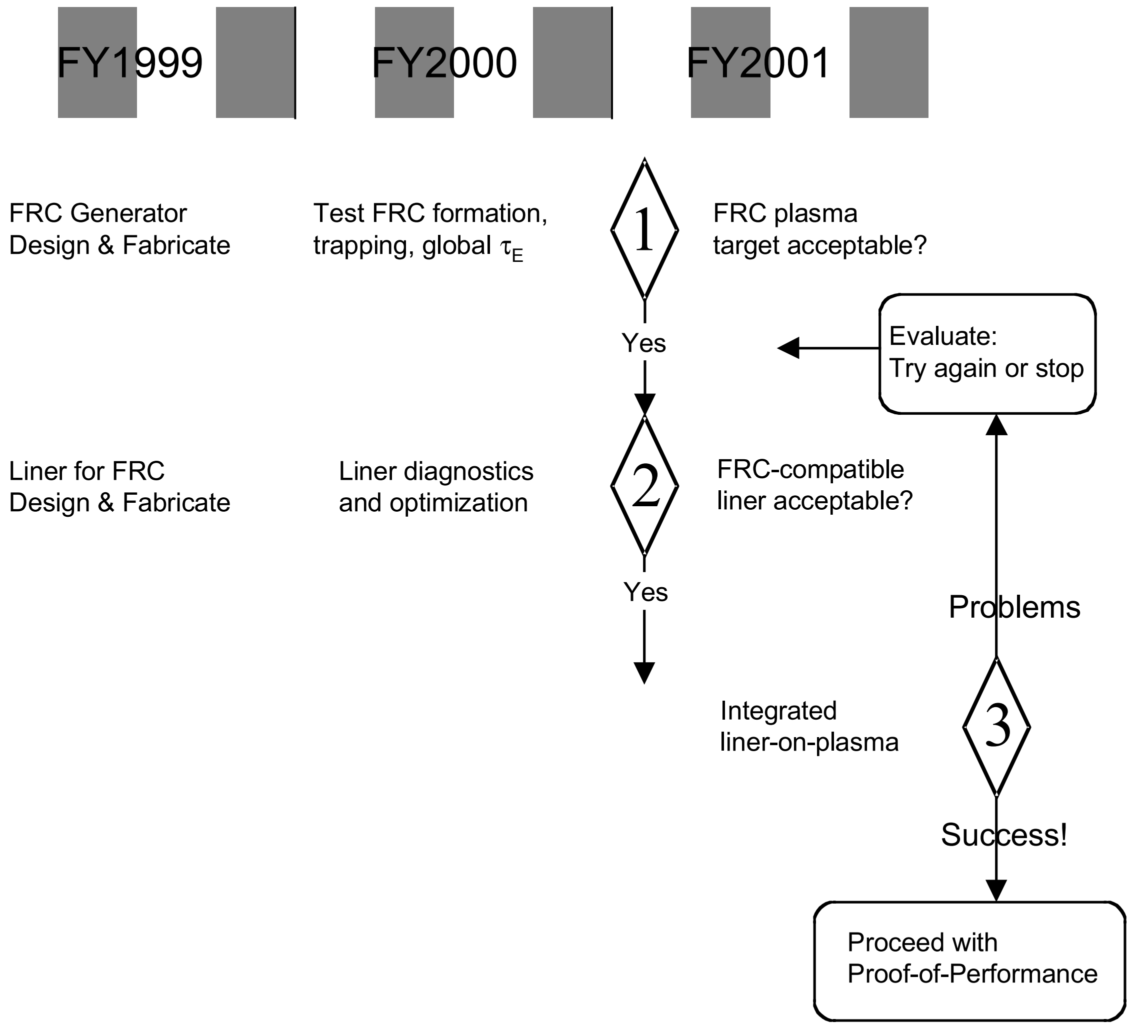


Fig. 7. MTF Schedule and logic diagram for tasks and key decisions 1,2, and 3.

The three key decisions are critical points in time when information is available to decide on how to proceed. See Table 4 for a detailed discussion of criteria for success. For decisions 1 and 2 at the end of the second year, it is understood that problems may require a reevaluation and further iterations before proceeding to integrated liner-on-plasma experiments. If 1 and 2 are favorable, then a 1-year campaign of integrated liner-on-plasma experiments will be carried out. At the end of that time a careful evaluation is called for to evaluate MTF and to decide whether or not to proceed with Proof-of-Performance. In the same time frame the ATLAS pulsed-power facility will become operational at Los Alamos, which would make a Proof-of-Performance program cost effective as well.

Table 4. Major tasks, milestones, and key decision points.

Start Date	Task, milestone, or decision	Description
FY99Q1 (yr and quarter)	Task: Design and Fabricate FRC Target Plasma Hardware	Reconfigure LANL Colt bank and diagnostics for FRC experiments. Design and order vacuum components, quartz tubes, conical theta pinch coil, and dummy liner.
FY99Q1	Task: Design and Fabricate Liner for FRC targets	Use 2D numerical simulation to obtain detailed design of shaped liner. Prepare diagnostic system for liner implosion tests on Shiva Star.
FY99Q4	Milestone: Form first FRC plasma in liner-compatible geometry.	Minimum initial diagnostics are diamagnetic loop, axial probe array, and one chord of side-on interferometry.
FY99Q4	Milestone: Implode first FRC-compatible liner	Minimum initial diagnostics in addition to current waveform are magnetic probes, 3-axis radiography, and axial framing photography.
FY00Q1	Task: Test FRC formation, translation, trapping, and global energy confinement.	Additional diagnostics include axial interferometry, single-point Thomson scattering, bolometery, impurity spectroscopy, and neutron diagnostics.
FY00Q1	Task: Liner diagnostics and optimization	Additional diagnostics include pin arrays, pressure transducers and spectroscopy to detect metal vapor near electrodes, and injected magnetized plasma for development of xray impurity diagnostics.
FY00Q4	Key Decision: Is the FRC plasma target acceptable for integrated liner-on-plasma experiments?	Criteria: No signs of gross instability; After FRC is centered in liner: Density ~ 10^{17} cm^{-3}, T ~ 300 eV, τ_E ~ 10 μs.
FY00Q4	Key Decision: Does FRC-compatible liner implosion appear acceptable?	Criteria: Reasonably symmetric cylindrical convergence of 10:1, B_{max} ~ 5 MG, central volume (away from electrodes) free of metal vapor.
FY01Q1	Task: Integrated Liner-on-Plasma Experiments	Install FRC system and diagnostics on Shiva Star at AFRL. Conduct campaign of approximately 20 high-energy liner-on-plasma shots.
FY01Q4	Key Decision: Is the MTF Proof-of-Principle adequately demonstrated?	Criteria: Computer simulations in agreement with plasma parameters as given in Table 1, thus providing a basis for proceeding to Proof-of-Performance

The budgets for this work will be detailed in normal Field Work Proposals and similar documentation provided by the various team institutions. Table 5 summarizes the main components of the budget with a breakdown for the two largest budget categories of experimental activities at AFRL and LANL. The reason the funding level can be so low despite the ambitious objectives just described is the considerable leveraging of existing competencies and facilities that have been created by Defense Programs (DOE) and the Air Force (DOD). Another important aspect that keeps the cost low, but is hard to quantify, is that the proposed support is in many cases for part-time involvement of the participants. In effect, this project will only be paying for what is needed to do the MTF work, and the balance of people's time will be supported by other projects, some related, and some not. We propose to begin this initial Proof-of-Principle examination of MTF without creating a "stand-alone" organization with the implied commitment for ongoing funds.

Table 5. Major budget components ($K)

Institution	Item	FY99	FY00	FY01
	Experiments			
AFRL	Salaries and Fringe	300	300	300
	Hardware and consumables	400	375	375
	Diagnostics	25	50	50
	Travel, publications, etc.	25	25	25
	Total Direct	750	750	750
	Indirect	250	250	250
	AFRL Subtotal	**1000**	**1000**	**1000**
LANL	Salaries and Fringe	1000	1000	1000
	Hardware and consumables	400	200	200
	Diagnostics	100	100	100
	Travel, publications, etc.	100	100	100
	Total Direct	1600	1600	1600
	Indirect	1400	1400	1400
	LANL Subtotal	**3000**	**3000**	**3000**
	Experiments Total	**4000**	**4000**	**4000**
	Theory & Computing			
GA	Wall-plasma interactions	100	100	100
LANL	Plasma and liner modeling	1000	1000	1000
LLNL	Plasma theory and modeling	300	300	300
U. Washington	FRC Formation & Translation	100	100	100
	Theory & Computing Total	**1500**	**1500**	**1500**
	Energy Systems Scoping Studies			
LANL	Pulsed-system perspective	100	100	100
LLNL	ICF and liquid-wall perspective	100	100	100
Westinghouse	Team leader of activity	300	300	300
	Energy Scoping Studies Total	**500**	**500**	**500**
Undetermined	**Supporting Exploratory Research**	600	600	600
	Grand Total	**6600**	**6600**	**6600**

An unusual aspect of budgeting is the cost for equipment destroyed in high-energy liner implosions. Fortunately, the apparatus needed for FRC formation, while relatively complicated, is fairly small in dimension (see Fig. 8) and cost. The hardware cost per assembly unit is estimated at $25K based on experience with systems of similar-size.

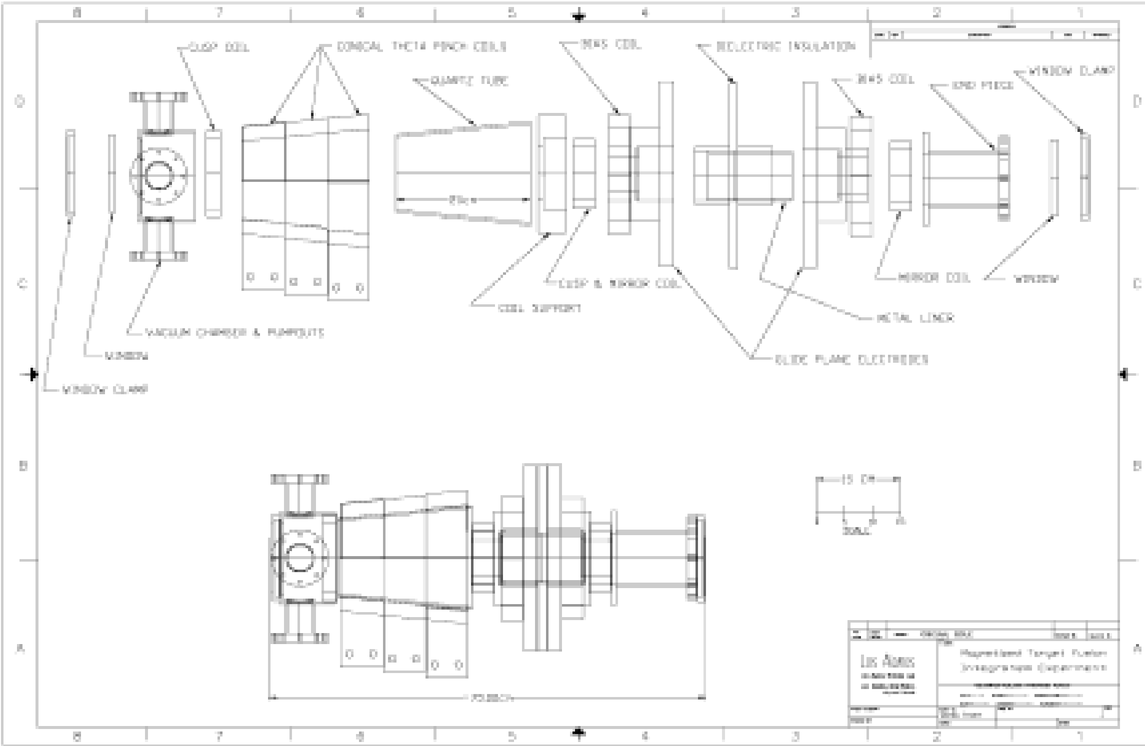
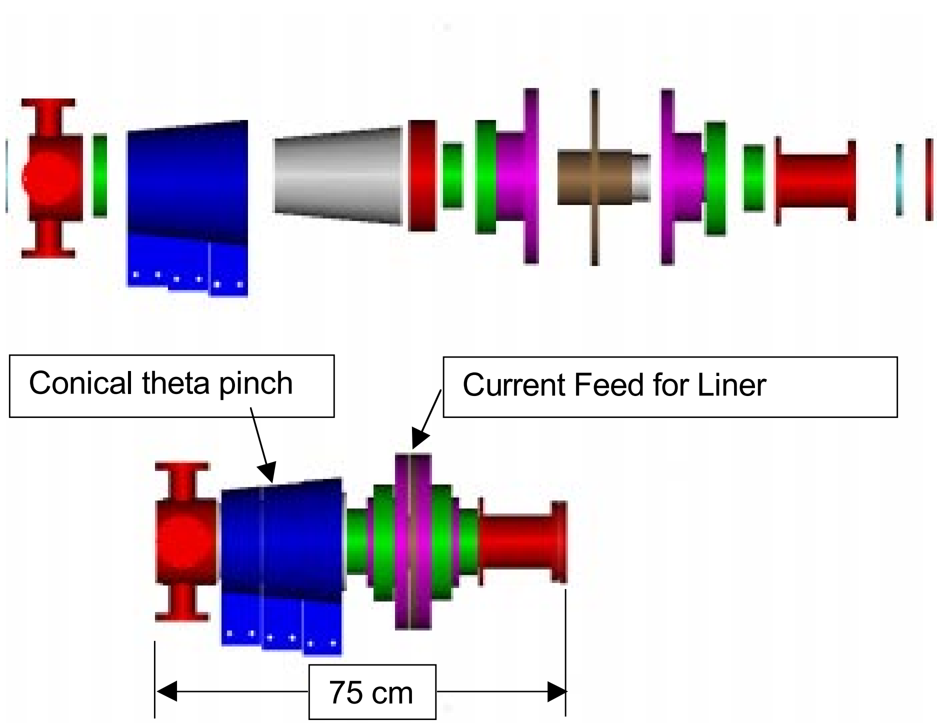


Fig. 8. Conceptual layout of an FRC plasma source mated to a liner assembly. Both the line drawing (above) and 3D view (below) show an expanded view and an assembled view.



PART D: POTENTIAL FOR PRACTICAL FUSION POWER

While reactor considerations are not central to this proposal, it is important that some effort be devoted to this task. Conceptual-level reactor studies, conducted in parallel with basic scientific programs, have two primary objectives. The first is to identify key technological issues requiring further research and development. The second is to provide ongoing assurance that the end product being worked toward (i.e. an electricity producing power plant) is both economically and environmentally attractive. Both of these require close communication and iteration between researchers and designers as concepts are refined and improved, issues are resolved and new ones arise. The end-product concept is also needed to define a meaningful development path. In this process, the experience of industry in taking a new energy technology from conceptual design to commercial application provides an important perspective. For Westinghouse, this has most recently included fission reactors (water and liquid metal), advanced gas turbines, solid oxide fuel cells, thermoelectrics, and photovoltaics

An early MTF reactor study [Moses79] identified two key technology feasibility issues: (1) material selection and mechanical design of the leads/liner structure, including recovery and recycling of the materials; and (2) pulse power requirements, which were beyond the state-of-the-art at the time of the study. While these were based upon a specific point design, they are generic issues that must be addressed by any MTF reactor concept.

Plasma conditions for MTF are generally described as midway between those of magnetic and inertial fusion systems (in terms of plasma density and time scales), but are much closer to Inertial Fusion Energy (IFE) as a reactor embodiment. Both are inherently pulsed systems, and offer the same potential for liquid wall protection schemes with regard to radiation damage and high heat flux removal. IFE issues of chamber beam transport and targeting are traded against MTF issues of power-feed and pulse containment. Both have key feasibility issues requiring very different solutions. The IFE driver (laser or particle beam) analogue is the pulsed power system required to drive the liner implosion. In this case, the much lower power requirements of MTF offer the possibility of more "conventional" low-cost power sources.

While similar in some respects, there are important differences between IFE and MTF for reactor design. These include pulse rep rate and energy output/pulse (Fig. 9). Typical values for an IFE system are 5-10 Hz and 300-500 MJ/pulse for a 1000 MWe reference plant, with 5-10 MJ on target. In contrast, MTF will might work with outputs in the 10 GJ range with rep rates less that 1 Hz. Energy input to the liner depends upon the extent of the burn, and hence the energy multiplication. However, 100's of MJ may be required, making the pulse power system a challenge.

These similarities and differences in requirements between IFE and MTF present new opportunities, as well as new challenges, in power plant design. The similarities permit us to make use of the extensive design studies that have been performed over the past 20 years as starting points for an MTF design, particularly liquid-wall protection schemes. Differences can be exploited. For example, one of the limitations in the design of the IFE chamber was related to clearing debris and re-establishing stable liquid jet flow between shots. With a simple gravity flow arrangement, the rep rate was limited to be at least 1Hz [Monsler78]. In order to overcome this limitation, a complex oscillating jet flow system was adopted [Moir94]. With the MTF rep rate larger than 1 Hz, we can revert to the simpler concept.

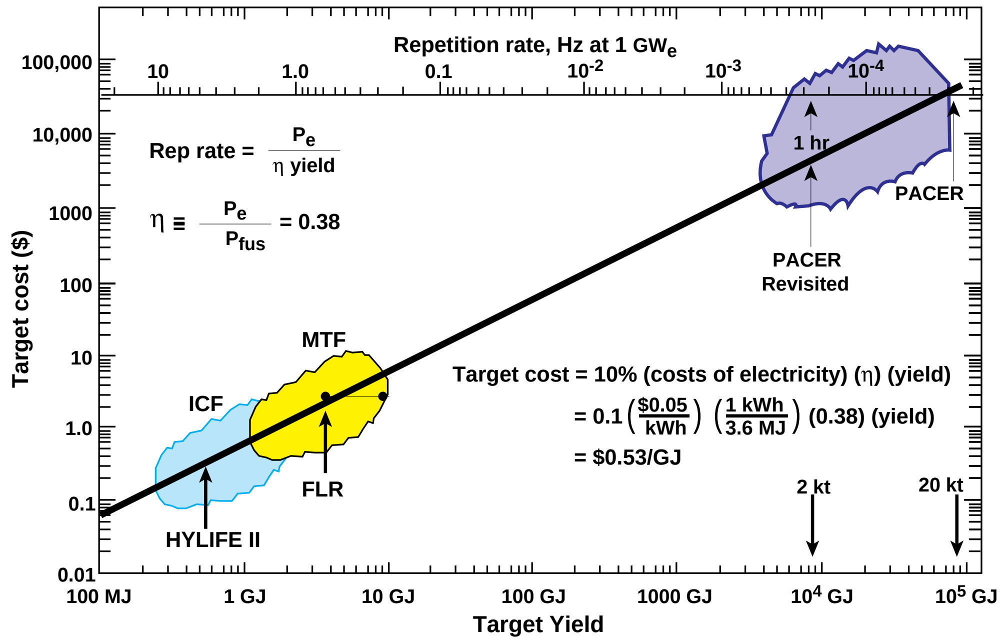


Fig. 9. Allowable expense of consumables per pulse vs. target yield in Joules.

For these large-yield, low-cycle shots we can also make use of the work done in examining nuclear explosives as an energy source [Hubbard74]. The most recent embodiment of this concept, Pacer Revisited [Call90] utilizes an underground steel-lined cavity with a simple vertical array of thin (2-mm diameter) molten salt (flibe) jets for wall protection and heat removal. In our case, we would substitute plasma/liner/electrodes for bomb insertion. For a 2 Kton device (8 TJ), a chamber volume of 250,000 cubic meters was required. Scaling by yield, a 10 GJ chamber might have a volume of about 300 cubic meters (a 4-meter radius sphere). By way of comparison, the ITER vacuum vessel has a volume of about 1500 cubic meters.

Large pulses of energy (5-80 GJ), are also ideally suited to another power conversion concept, that of MHD power generation as proposed originally by Velikov and studied recently by Logan [Logan93]. In this approach, the large fusion pulse is used to flash vaporize a solid, nearly spherical blanket surrounding the leads/liner structure. The blanket then becomes the working fluid, at about 1 ev (12,000 K) temperature and 100 bar pressure. A quasi-steady-state source of plasma for MHD energy conversion is maintained by a several-shot plasma inventory in the reactor cavity. While a high MHD energy conversion is obtained, the overall conversion efficiency is low, partially because of high heat rejection of the working fluid. This could be improved with the addition of a steam bottoming cycle. Compared to the "conventional" liquid wall/steam cycle energy conversion systems above, this concept also raises many new issues with regard to the MHD channel, as well as the high chamber wall operating temperature (2500 K). However, this concept has the extremely interesting appeal of doing power conversion without a conventional steam cycle and the associated balance of plant costs. Clearly it deserves attention as a design option for an advanced system.

Inherent to any pulsed system is the need for some form of thermal or electrical energy storage so that a nearly constant power output can be supplied to the grid. The problem becomes more challenging as the pulse power goes up and the rep rate goes down. In most cases it can be handled in a cost-effective manner by having the coolant inventory in the primary system high enough to maintain (nearly) constant temperatures across the primary heat exchanger. At some point, the inventory of coolant may become sufficiently high to impact cost and safety and more detailed designs are needed to resolve the issue. The MHD system, as described above, deals with this problem by maintaining an inventory of plasma in the reaction chamber sufficient to maintain a constant pressure and temperature input to the MHD channel.

Another key element, if the MTF concept is to become a viable energy source, is the development of a suitable pulse power system, including pulse production, storage, conditioning, and switching. As discussed above, earlier studies indicated the requirements were beyond the state-of-the-art at the time. These studies focused on the homopolar generator/inductive storage and purely capacitive energy storage options. Developments since that time in pulsed AC machines, Superconducting Magnetic Energy Storage Systems (SMES), and switching warrants investigation of these technologies. Advances have also been made in the earlier systems considered. A study is needed to reexamine this issue, focusing particularly on the technical feasibility, risk, and cost of rotating machine, capacitor bank, and SMES-based pulse power systems. Solid state switching options should also be included. Designs should be compared in a trade-off analysis and the best options selected. Even by present standards, the very high voltage (up to 200 kV) and extremely high current (up to 250 MA) required for a reactor represent a major design challenge.

PART E: COMMUNITY R AND D PLAN

In the past few years, a growing number of researchers have been attracted to high-density pulsed magneto-inertial fusion (MIF) approaches. The term MIF is used to represent the all-inclusive set of pulsed high-pressure (inertially confined) approaches to fusion that involve magnetic field in an essential way. MTF is the subset that involves an imploding liner for pdV heating and magnetic field for suppression of thermal conduction.

By means of numerous professional meetings and personal interactions, a general consensus has emerged that a PoP experiment using liners to compress a CT is the desirable first step. In response to an OFES request, a community-based R&D Roadmap (URL http://fusionenergy.lanl.gov/R&DRoadmap.pdf) was prepared and presented at the April 1998 Innovative Confinement Concepts meeting at Princeton.

Collaborations important for success of this MTF PoP proposal include a broad-based scientific exchange going well beyond the specific collaborations and deliverables of this PoP program. The growing MIF community includes scientists in various universities such as UC Irvine, U. Nevada, Reno, UC Berkeley, and researchers abroad including Russia, France, and New Zealand. A large closely linked group is the ongoing compact toroid research at the Univ. of Washington, LLNL, PPPL, Univ. of Texas, UC Berkeley, Osaka University, Univ. of Tokyo, and elsewhere. These scientists provide an important source of intellectual vitality and peer review. In addition, there is the pulsed-power community with its various specialties such as high-pressure hydro studies, pulsed high-magnetic fields, and fast Z pinches for producing x-ray radiation (most notably at SNL).

A national Council for MIF, patterned after the organization of NSTX, is proposed to assist OFES in guidance of this program. The Council, appointed by OFES, would request and review proposals for the "undetermined" Exploratory Concept funding of Table 5, and this advice would be forwarded to OFES. There is a strong feeling in the MIF community that continued exploratory work is required if MTF or MIF are to succeed. For MTF the physics of wall-plasma interactions, the variety of plasma targets, options for composite liner materials, and so forth, all suggest that a growing program will be needed for a Proof-of-Performance step, If this proposed Proof-of-Principle program is successful, such an effort would be readily justified.

PART F: LITERATURE CITED

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